ΠΑΝΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΟΙΝΩΝΙΚΩΝ ΚΑΙ ΠΟΛΙΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ
PANTEIO UNIVERSITY OF SOCIAL AND POLITICAL SCIENCES

Περιβαλλοντικά Βιώσιμη Οικονομική Ανάπτυξη και η συνεισφορά των φυσικών πόρων στην παραγωγή και στην ανάπτυξη: Το ζήτημα της σπανιότητας των φυσικών πόρων και οι επιπτώσεις του στις δυνατότητες για μια Βιώσιμη Ανάπτυξη

Από

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Natural resources in the production process. Aggregate scarcity and constraints in the context of Sustainable Development

By

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Ελληνική Περίληψη της Διδακτορικής Διατριβής

Greek Extended Abstract

«…Η νεότερη Δύση, εδώ και αιώνες, διέπεται από δύο κοινωνικές φαντασιακές σημασίες εντελώς αντίθετες μεταξύ τους, έστω και αν αλληλοεπηρεάζονται: το πρόταγμα της ατομικής και συλλογικής αυτονομίας, τον αγώνα για τη χειραφέτηση του ανθρώπου, χειραφέτηση διανοητική και πνευματική, αλλά και πρακτική, μέσα στην κοινωνική πραγματικότητα· και το παράφρον καπιταλιστικό πρόταγμα της απεριόριστης εξάπλωσης μιας ψευδο-ορθολογικής ψευδο-κυριαρχίας πάνω στη φύση, που έχει πάψει εδώ και καιρό να αφορά μόνο τις παραγωγικές δυνάμεις και την οικονομία και έχει γίνει πρόταγμα συνολικό (και για αυτό ακόμη πιο τερατώδες), απόλυτης κυριαρχίας πάνω στα φυσικά, στα βιολογικά, στα ψυχικά, στα κοινωνικά και στα πολιτιστικά δεδομένα…»

Κορνήλιος Καστοριάδης

Εισαγωγή

Το ζήτημα της σπανιότητας των φυσικών πόρων αποτελεί ένα θέμα μείζονος σημασίας, ειδικά αν ειδωθεί μέσα στο πλαίσιο της οικονομικής ανάπτυξης και ευημερίας. Ιστορικά, η νεοκλασική οικονομική θεωρία αγνοούσε συστηματικά την καθοριστική συμβολή των φυσικών πόρων στην παγκόσμια οικονομική μεγέθυνση, που συντελέστηκε από την πρώτη βιομηχανική επανάσταση και συνεχίζεται έως σήμερα. Τα σοβαρά περιβαλλοντικά προβλήματα (εξωτερικότητες) που κληροδότησε σταδιακά η εκρηκτική οικονομική μεγέθυνση του 20ου αιώνα στις επερχόμενες γενεές, σε συνδυασμό με την αθροιστική σπανιότητα των μη-ανανεώσιμων φυσικών πόρων, υπερτονίζουν την επιτακτική ανάγκη για την διερεύνηση του κατά πόσο πρέπει, και είναι εφικτό, να εγκαινιαστεί μια νέα μορφή Περιβαλλοντικά Βιώσιμης Οικονομικής Ανάπτυξης. Η εξαιρετικής σπουδαιότητας αυτή συζήτηση οδήγησε στη δημιουργία αντίπαλων στρατοπέδων γνωστικής “πόλωσης”, χωρίζοντας την επιστημονική κοινότητα ανάμεσα στους υπερασπιστές της χαλαρής και σε εκείνους της ισχυρής βιωσιμότητας. Αυτή η διαλεκτική σύγκρουση σαφώς προίκισε την οικονομική επιστήμη με διεπιστημονικό πλουραλισμό, γεννώντας νέα συναρπαστικά γνωστικά πεδία που συνδυάζουν την Βιολογία, την Οικολογία, την Περιβαλλοντική επιστήμη και τους φυσικούς νόμους της θερμοδυναμικής, με την παραδοσιακή οικονομική θεωρία. Μέσα σε αυτό το ευρύ πλαίσιο αναφοράς, η παρούσα διδακτορική έρευνα στοχεύει στην περαιτέρω διερεύνηση της συνεισφοράς των φυσικών πόρων (ενέργειας και μάζας), στην παραγωγική διαδικασία και κατ’ επέκταση στην πρωτόγνωρη, για το σύνολο της ανθρώπινης ιστορίας, οικονομική μεγέθυνση που συντελέστηκε κατά τον τελευταίο αιώνα. Ειδικότερα, απώτερος στόχος της παρούσας διατριβής είναι η εμπειρική διερεύνηση των δυνατοτήτων που εμφανίζει η παγκόσμια οικονομική ανάπτυξη (Μεγέθυνση), για αποσύνδεση (decoupling) από την κατανάλωση φυσικών, ενεργειακών και υλικών, πόρων. Επιπρόσθετα, η εμπειρική ανάλυση εστιάζει σε χωρικό επίπεδο, εξετάζοντας την υλική και ενεργειακή ένταση της οικονομικής παραγωγικής διαδικασίας, στα πλαίσια επιλεγμένων εθνικών οικονομιών και συγκρίνει τις ομοιότητες ή/και διαφορές που αυτές παρουσιάζουν, τόσο σε επίπεδο κατανάλωσης ύλης και ενέργειας, όσο και σε κοινωνικό-οικονομικό επίπεδο δημογραφικής εξέλιξης, κατά κεφαλήν κατανάλωσης, ευημερίας, και ούτω καθεξής. Τέλος, φιλοδοξεί να αντιπροτείνει νέα μεθοδολογικά εργαλεία εμπειρικής διερεύνησης, εμπλουτίζοντας την διεθνώς πλέον αποδεκτή και καθιερωμένη μεθοδολογία Material Flow Analysis (MFA), καθώς και να ασκήσει μια γόνιμη κριτική στα εμπειρικά αποτελέσματα του διαχρονικού διαλόγου που αφορά την αιτιώδη σχέση μεταξύ της κατανάλωσης ενεργειακών πόρων και της οικονομικής μεγέθυνσης (The E-GDP Causality nexus), μέσα στο πλαίσιο σύγχρονων θεωρητικών διαλόγων όπως η από-ανάπτυξη (de-growth). Πέραν της εμπειρικής, η πρωτότυπη θεωρητική συνεισφορά της παρούσας διατριβής έγκειται στην ανάλυση και την ανάδειξη της έννοιας της διαστασιμότητας των προϊόντων (Human Scale Production) ως απόρροια της βιοφυσικής ανθρώπινης διάστασης (Biophysical Human Scale), για πρώτη φορά στην ιστορία της θεωρητικής και εμπειρικής ανάλυσης των εννοιών της από-υλοποίησης (dematerialization), της αποσύνδεσης (decoupling) της οικονομικής διαδικασίας από την χρήση φυσικών πόρων και κατ' επέκταση της αθροιστικής σπανιότητας των φυσικών πόρων.

Καινοτομίες

Οι καινοτομίες που αισιοδοξεί να εισαγάγει η διδακτορική διατριβή μπορούν να ειδωθούν διακριτά σε δύο συνοπτικά επίπεδα. Το πρώτο αφορά τον προσδιορισμό ενός νέου θεωρητικού πλαισίου, αναφορικά με τον επιστημονικό διάλογο πάνω στο φαινόμενο της σταδιακής αποσύνδεσης της οικονομικής διαδικασίας από την χρήση/εξάρτηση των φυσικών πόρων (decoupling effect), με την εισαγωγή, οριοθέτηση και ανάλυση της έννοιας της διαστασιμότητας που ενσωματώνει η παραγωγική διαδικασία, κάτι που επιχειρείται για πρώτη φορά στην διεθνή βιβλιογραφία. Μέσα σε αυτό το θεωρητικό πλαίσιο, η διατριβή επιχειρεί, παράλληλα και επιπρόσθετα σε δεύτερο επίπεδο, μια εκτεταμένη (σε παγκόσμιο καθώς και σε πολλά διακριτά εθνικά επίπεδα, ομάδες εθνικών οικονομιών κ.α.) εμπειρική ανάλυση, εισάγοντας νέους δείκτες μέτρησης της αποσύνδεσης που αποτυπώνουν ρεαλιστικότερα το φαινόμενο αυτό (decoupling) και οδηγούν σε ριζοσπαστικά, και εκ διαμέτρου αντίθετα με τις επικρατούσες αναλύσεις, εμπειρικά συμπεράσματα. Τέλος, επιχειρεί να διερευνήσει, υπό το πρίσμα της τεχνικής της Μετά-Ανάλυσης (Meta-Analysis), την συνέπεια (ή μη) του μακροχρόνιου εμπειρικού διαλόγου πάνω στην αιτιώδη σχέση μεταξύ κατανάλωσης ενέργειας και οικονομικής ανάπτυξης (The E-GDP causality debate), ανιχνεύοντας παράλληλα το εάν και κατά πόσο ο διάλογος αυτός μπορεί να συνεισφέρει εμπειρικά σε σύγχρονους θεωρητικούς διαλόγους όπως η από-ανάπτυξη (degrowth) και η «αδιαφορία» για την ύπαρξη ή μη ανάπτυξης (O Van den Bergh την ορίζει ως "a-growth").

Ως απόρροια του γεγονότος ότι η παρούσα διδακτορική διατριβή δεν περιορίζει την ανάλυση της σε κάποιο τοπικό ή εθνικό φαινόμενο αλλά αντιθέτως επιχειρεί μια διανοητική υπέρβαση, με την υλοποίηση μιας ολιστικής ανασκόπισης της χρήσης ενέργειας και ύλης σε παγκόσμιο επίπεδο - πραγματευόμενη τις πολλαπλές διαστάσεις που έχει το ζήτημα της αθροιστικής σπανιότητας των φυσικών πόρων – επιχειρεί μια ευρεία μακροοικονομική ανάλυση. Ο ευρέως διαδεδομένος όρος «κοινωνικός ή/και βιομηχανικός μεταβολισμός (Social/Industrial Metabolism)», από τις πλέον σύγχρονες εμπειρικές και μεθοδολογικές προσεγγίσεις της κοινωνικής οικολογίας (Social Ecology) σκιαγραφεί με τον καλύτερο τρόπο τη κοινωνικό-οικονομική συνεισφορά της διατριβής. Η ευημερία και το βιοτικό επίπεδο μιας κοινωνίας, ο πολιτισμός και η τέχνη, κάθε πολυποίκιλη και πολυδιάστατη σύγχρονη ανθρώπινη δραστηριότητα, βασίζεται πάνω στην απρόσκοπτη και αδιάλειπτη χρήση ενεργειακών και υλικών πόρων (ο επονομαζόμενος κοινωνικός ή/και βιομηχανικός «μεταβολισμός»). Η σπανιότητα των φυσικών πόρων θα αποτελέσει ίσως μια από τις μεγαλύτερες προκλήσεις που θα γνωρίσει η ανθρωπότητα στην ιστορία της, θέτοντας σε δοκιμασία το πολυδαίδαλο και πολυσύνθετο πολιτισμικό-κοινωνικό-οικονομικό σύστημα που έχει οικοδομήσει και θα αναζωπυρώσει ηθικά ζητήματα (ανά)κατανομής των πόρων, και ως εκ τούτου εμμέσως, του παραγόμενου προϊόντος τόσο στο παρόν όσο και στην λεγόμενη διαγενιακή κατανομή του (οι συνέπειες της κατανάλωσης του σήμερα στις επερχόμενες γενεές). Στο ευρύ αυτό πλαίσιο προβληματισμού, η διδακτορική διατριβή επιχειρεί να αποτελέσει μια μικρή συνεισφορά προς την ρεαλιστικότερη αποτίμηση του προβλήματος της σπανιότητας, υπογραμμίζοντας, αναδεικνύοντας και προωθώντας εκείνες τις ρεαλιστικές παραμέτρους που θα μπορούσαν να θέσουν τις βάσεις για μια ουσιαστικότερη περιβαλλοντικά βιώσιμη οικονομική ανάπτυξη, που θα λαμβάνει υπόψη της τις ανάγκες όχι μόνο της παρούσας, αλλά και των επόμενων γενεών.

Στην συνέχεια παρατίθεται μια περιγραφική ανασκόπηση του σώματος της διδακτορικής διατριβής, ανά κεφάλαιο.

Διάρθρωση Διδακτορικής Διατριβής

Πρόλογος (Preface)

Ως εισαγωγικό σημείωμα της παρούσας διδακτορικής διατριβής έχει επιλεγεί η προσπάθεια αποσαφήνισης των όρων «Οικονομική Ανάπτυξη» και «Οικονομική Μεγέθυνση». Εννοιολογικά, οι δύο αυτοί όροι χρησιμοποιούνται ως ταυτόσημοι μέχρι και το τέλος της δεκαετίας του ’60. Τα περιβαλλοντικά προβλήματα που σταδιακά αναδύθηκαν την δεκαετία του ’70 ως απόρροια της ραγδαίας εκβιομηχάνισης των δυτικών οικονομιών, υπογράμμισαν την επιτακτική ανάγκη για μια άλλου είδους προσέγγιση στο πλαίσιο της οικονομικής παραγωγικής διαδικασίας, η οποία βρήκε την έκφραση της στην γέννηση νέων προσεγγίσεων, που εννοιολογικά συνοψίζονται στον ορισμό της βιώσιμης ανάπτυξης. Στο ευρύ αυτό πλαίσιο που θέτει ο πρόλογος αυτός, επιχειρεί πολύ συνοπτικά να αποσαφηνίσει τις διαφορές μεταξύ των όρων “οικονομική μεγέθυνση” και “οικονομική ανάπτυξη”, σαν το πρώτο καθοριστικό στάδιο πριν παρουσιάσει τις έννοιες της αειφόρου/βιώσιμης ανάπτυξης και τις αντιπροσωπευτικές σχολές της χαλαρής και της ισχυρής βιωσιμότητας, στο πλαίσιο της οικονομικής επιστήμης.

Τέλος, η μικρή αυτή εισαγωγή επιχειρεί μια πρώτη σκιαγράφηση του βασικού ερωτήματος που διερευνά η παρούσα διδακτορική διατριβή, τουτέστιν, το ζήτημα της αθροιστικής σπανιότητας των φυσικών (υλικών και ενεργειακών) πόρων ειδομένο μέσα από τον εμπειρικό διάλογο της αποσύνδεσης (decoupling) τους (ή μη) από την οικονομική διαδικασία.

1ο Κεφάλαιο.

Ιστορική αναδρομή των θεωριών οικονομικής μεγέθυνσης

Το πρώτο κεφάλαιο της διδακτορικής διατριβής επιχειρεί μια συνοπτική ανασκόπηση των θεμελιωδών εκείνων θεωρητικών υποδειγμάτων που επιχείρησαν να αναδείξουν τους προσδιοριστικούς παράγοντες της οικονομικής διαδικασίας και να ερμηνεύσουν την συντελούμενη οικονομική μεγέθυνση. Για λόγους ευχρηστίας, το κεφάλαιο αυτό έχει χωριστεί σε τρείς μεγάλες ενότητες - ιστορικές περιόδους - της οικονομικής σκέψης: Η πρώτη περίοδος, η επονομαζόμενη και ως κλασική περίοδος της οικονομικής θεωρίας, συμπεριλαμβάνει την τεράστια θεωρητική συνεισφορά των πρώτων οικονομικών υποδειγμάτων που θεμελίωσαν οι μεγάλοι Κλασικοί Οικονομολόγοι (Smith, Malthus, Ricardo, Mill, Marx). Η δεύτερη περίοδος, που ξεκινάει με την συνεισφορά των επονομαζόμενων "Μαρτζιναλιστών" (Warlas, Pigou, Jevons, Pareto, κ.α), παρουσιάζει συνοπτικά την θεμελιώδη συνεισφορά της λεγόμενης Νεοκλασικής Περιόδου της Οικονομικής Θεωρίας της Μεγέθυνσης (Marshall, Harrod-Domar model, Solow-Swan model, κτλ), προσπαθώντας παράλληλα να ενσωματώσει την επίδραση που άσκησε το έργο του Κέυνς, αλλά και οι εναλλακτικές θεωρίες οικονομικής μεγέθυνσης του Schumpeter και του Rostow. Τέλος, η Τρίτη περίοδος παρουσιάζει συνοπτικά τις θεωρίες της Ενδογενούς Οικονομικής Μεγέθυνσης που, από την δεκαετία του '90 και εντεύθεν, επιχειρούν να καλύψουν το κενό της πρώιμης νεοκλασικής περιόδου, με την ενδογενοποίηση της τεχνολογικής προόδου (γνώσης), ως μεταβλητής, στα μοντέλα οικονομικής μεγέθυνσης.

Έμμεσος, αλλά ουσιαστικά απώτερος, στόχος του 1ου κεφαλαίου είναι να εντοπίσει τον ρόλο που διαχρονικά έπαιξε η συνεισφορά (ή η κατά περιόδους πλήρης αγνόηση) των φυσικών πόρων στην θεμελίωση των οικονομικών υποδειγμάτων/μοντέλων που προσπάθησαν να ερμηνεύσουν την διαδικασία της οικονομικής μεγέθυνσης.

2ο Κεφάλαιο.

Ιστορική ανασκόπηση των διαφορών της Νεοκλασικής και της Βιοφυσικής σχολής σκέψης, στο πλαίσιο της αθροιστικής σπανιότητας των φυσικών πόρων.

Το Δεύτερο κεφάλαιο επιχειρεί μια ειδικότερη προσέγγιση, αναφορικά με το ζήτημα της αθροιστικής σπανιότητας των φυσικών πόρων. Συγκεκριμένα, παραθέτει μια σύγκριση μεταξύ των θεμελιωδών διαφορών που υπάρχουν ανάμεσα στην επονομαζόμενη "Νεοκλασική σχολή οικονομικής σκέψης" και την "Βιοφυσική σχολή οικονομικής σκέψης", οι οποίες μπορούν να συνοψιστούν στα εξής 2 σημεία: Πρώτον, το ζήτημα της συνεισφοράς της τεχνολογικής προόδου˙ Δεύτερον, το ζήτημα της υποκατάστασης μεταξύ του Φυσικού και του ανθρωπογενούς κεφαλαίου. Ο ρόλος της συνεισφοράς των φυσικών πόρων και η καθοριστική συμβολή της τεχνολογικής προόδου στην βελτίωση της παραγωγικότητας εξετάζεται διαχρονικά μέσα στο πλαίσιο της Νεοκλασικής σχολής σκέψης και αποτυπώνεται με σαφήνεια ο πυρήνας της βασικής επιχειρηματολογίας αυτής της σχολής, που εδράζει στην αισιόδοξη προοπτική που προσφέρει η συνεχής και αδιάλειπτη τεχνολογική πρόοδος. Στον αντίποδα αυτής της αισιοδοξίας, τοποθετείται η απαισιόδοξη προοπτική της βιοφυσικής σχολής σκέψης, που εδράζει στους νόμους της θερμοδυναμικής, στην αθροιστική σπανιότητα των φυσικών πόρων και στους περιορισμούς που υπάρχουν στις δυνατότητες υποκατάστασης του φυσικού κεφαλαίου με ανθρωπογενές κεφάλαιο. Επιπρόσθετα, το 2ο κεφάλαιο επιχειρεί να ενσωματώσει στον πλούσιο αυτό διάλογο μια μικρή κριτική στις νεοκλασικές συναρτήσεις παραγωγής, παρουσιάζοντας επιγραμματικά την συνεισφορά των flow-funds συναρτήσεων παραγωγής, όπως προτάθηκαν την δεκαετία του '70 από τον Nicholas Georgescu-Roegen.

Παράλληλα, στο πλαίσιο των περιορισμών που υπάρχουν για την απρόσκοπτη τεχνολογική πρόοδο, το 2ο κεφάλαιο κλείνει επιχειρώντας να παρουσιάσει συνοπτικά τον σύγχρονο διάλογο πάνω στο φαινόμενο της αναπήδησης (rebound effect), γνωστό και ως Jevons' Paradox.

3ο Κεφάλαιο.

Βιβλιογραφική ανασκόπιση της εμπειρικής ανάλυσης της αποσύνδεσης της οικονομικής διαδικασίας από τις εισροές φυσικών πόρων

Το 3ο κεφάλαιο αποτελεί μια συνοπτική ανασκόπιση των εμπειρικών εκείνων μεθόδων που προσπαθούν να μετρήσουν και να αναλύσουν τις εισροές των φυσικών πόρων που χρησιμοποιούνται στην οικονομική διαδικασία. Ειδικότερα, η μέθοδος «Ανάλυση ροής υλικών» - Material Flow Analysis (MFA) – αποτελεί το πλέον σύγχρονο εργαλείο συστηματικής καταμέτρησης όλων των ροών φυσικών πόρων (ενεργειακών και υλικών) που υπεισέρχονται στο οικονομικό σύστημα. Η σύγχρονη αυτή μέθοδος έχει πλέον υιοθετηθεί επίσημα από το σύνολο των μεγάλων διεθνών οργανισμών (όπως τα Ηνωμένα Έθνη, η Eurostat, ο OECD, κ.α.) και έχει καταστήσει εφικτή την κατασκευή σύγχρονων και επικαιροποιημένων βάσεων με ποσοτικά δεδομένα. Αυτές οι σύγχρονες βάσεις δεδομένων μας επιτρέπουν να εξετάσουμε εξονυχιστικά τα θεμελιώδη ερωτήματα που έθεσαν οι θεωρητικοί διάλογοι αναφορικά με το ζήτημα της σπανιότητας των φυσικών πόρων (βλέπε 2ο Κεφάλαιο), εδράζοντας επάνω σε μια εμπειρική πλέον βάση. Το διαχρονικό και επίκαιρο ερώτημα της δεκαετίας του ’70, αναφορικά με την αθροιστική σπανιότητα των φυσικών πόρων και τις δυνατότητες υποκατάστασης των φυσικών πόρων με ανθρωπογενές κεφάλαιο, αναβιώνει σε κάποιο βαθμό μέσα από τον διάλογο για την αποσύνδεση (decoupling) της οικονομικής διαδικασίας από την χρήση φυσικών πόρων. Πράγματι, με βάση τις σύγχρονες εμπειρικές αναλύσεις, η παγκόσμια οικονομία καθώς και το σύνολο των ανεπτυγμένων χωρών, παρουσιάζουν μια διαχρονική απεξάρτηση από την χρήση φυσικών πόρων.

4ο Κεφάλαιο

Η Μεθοδολογία της Διατριβής και οι θεωρητικές συνεισφορές της.

Στο πλαίσιο της σύγχρονης ανάλυσης του φαινομένου της «αποσύνδεσης», η παρούσα διδακτορική διατριβή επιχειρεί μια καινοτόμα θεωρητική (και εμπειρική στα κεφάλαιο 5-6) συνεισφορά, με την εισαγωγή της έννοιας της φυσικής "*διαστασιμότητας*" της παραγωγικής διαδικασίας, ως αποτέλεσμα της βιοφυσικής ανθρώπινης διάστασης. Σαφώς ανθρωποκεντρική, η έννοια της διαχρονικά αμετάβλητης βιοφυσικής διάστασης που έχουν τα ανθρώπινα όντα οριοθετεί, ουσιαστικά, ένα κρίσιμο όριο κάτω από το οποίο οι ενεργειακές και υλικές ανθρώπινες ανάγκες αδυνατούν να ικανοποιηθούν. Τα οικονομικά αγαθά που ικανοποιούν τις ανθρώπινες ανάγκες οφείλουν να πληρούν κάποια συγκεκριμένα φυσικά χαρακτηριστικά που να ανταποκρίνονται στην πραγματική φύση των αναγκών αυτών. Η παραβίαση αυτών των ουσιαστικών χαρακτηριστικών, που οφείλουν να ενσωματώνουν τα αγαθά προκειμένου να ικανοποιούν τις βιοφυσικές ανθρώπινες ανάγκες, οδηγεί σε μια σφαλερή απεικόνιση της πραγματικότητας, με αποτέλεσμα να υπερεκτιμώνται οι δυνατότητες βελτίωσης της αποδοτικότητας που παρουσιάζει η παραγωγική διαδικασία. Εντοπίζοντας αυτήν την έλλειψη στην σχετική βιβλιογραφία, η παρούσα διδακτορική διατριβή επιχειρεί να θεμελιώσει μια νέα προσέγγιση η οποία απεικονίζει, σε ένα βαθμό με ρεαλιστικότερους όρους, αυτούς τους περιορισμούς που θέτει ο άνθρωπος, ως ένα ον με ειδικές και απαραβίαστες βιοφυσικές διαστάσεις οι οποίες ενσωματώνονται και αντανακλώνται μέσα από τις ανάγκες του. Προκειμένου να συλλάβει, έστω έμμεσα, την έννοια της φυσικής διαστασιμότητας των παραγόμενων προϊόντων, η διδακτορική διατριβή εισάγει την χρήση του κατά κεφαλήν ΑΕΠ, ως μια βελτιωμένη αναπαράσταση του απώτερου προϊόντος το οποίο παράγει το οικονομικό σύστημα: οικονομική ευημερία/χρησιμότητα για τους ανθρώπους. Το συνολικό ΑΕΠ αποτελεί στην ουσία την άθροιση των χρηματικών μονάδων των τελικών αγαθών που παράγει το οικονομικό σύστημα, δίνοντας έτσι μια περισσότερο αφηρημένη εικόνα του μεγέθους μιας οικονομίας, αποκρύπτοντας παράλληλα τις κρίσιμες διαστάσεις και τα χαρακτηριστικά των αγαθών που αθροίζει. Στο πλαίσιο αυτό, το κατά κεφαλήν ΑΕΠ υπερτερεί του συνολικού ΑΕΠ διότι επιτυγχάνει να ενσωματώσει:

- Τις δημογραφικές τάσεις μιας εθνικής οικονομίας
- Το "μέσο καλάθι προϊόντων" που καταναλώνει ο μέσος κάτοικος μιας χώρας
- Την οικονομική ευημερία που απολαμβάνει ο μέσος πολίτης

- Τις ανθρώπινες ανάγκες, και εμμέσως, τις φυσικές διαστάσεις που οφείλουν να έχουν τα παραγόμενα αγαθά προκειμένου να υπηρετήσουν τις αμετάβλητες βιοφυσικές ιδιότητες/διαστάσεις του ανθρώπινου όντος.

Για πρώτη φορά στην ιστορία του σχετικού διαλόγου επάνω στην αποσύνδεση (decoupling) και την από-υλοποίηση (dematerialization), εισάγεται η έννοια της φυσικής διαστασιμότητας που ενσωματώνουν τα αγαθά, ως απόρροια της βιοφυσικής διάστασης των ανθρώπων. Αυτή η έννοια επιχειρεί να ψηλαφήσει, εμμέσως πλην σαφώς, το κρίσιμο κατώτατο όριο που υπάρχει στις δυνατότητες για περαιτέρω από-υλοποίηση και αποσύνδεση της οικονομικής διαδικασίας από τους φυσικούς πόρους, θέτοντας παράλληλα κρίσιμα ερωτήματα για τις συνέπειες των δημογραφικών τάσεων στο ζήτημα της αθροιστικής σπανιότητας των φυσικών πόρων, πέρα από τα διακριτά όρια μιας κοινής νέο-μαλθουσιανής λογικής.

5ο Κεφάλαιο

Εμπειρική Ανάλυση: Η υπόθεση της (μη-ενεργειακής) μάζας

Το 5ο κεφάλαιο εξετάζει, διακριτά από τους ενεργειακούς πόρους, την σχέση του συνολικού παραγόμενου προϊόντος με τους μη-ενεργειακούς φυσικούς πόρους. Ως μη-ενεργειακούς φυσικούς πόρους ορίζουμε εκείνες τις εισροές μάζας (ύλης) που δεν συνεισφέρουν στην παραγωγική διαδικασία ως ενεργειακοί πόροι, αλλά αντιθέτως αποτελούν τα υλικά εκείνα τα οποία διαμορφώνουν το περίβλημα πάνω στο οποίο ενσωματώνονται τα παραγόμενα αγαθά. Τα υλικά που ουσιαστικά δημιουργούν την υλική υπόσταση των αγαθών που ικανοποιούν τις ανθρώπινες ανάγκες (Ορυκτά, Βιομηχανικά Μέταλλα, υλικά κατασκευών, μη-ενεργειακή βιομάζα, άσφαλτος, πλαστικό, τσιμέντο κ.α.). Το κεφάλαιο αυτό επιχειρεί μια ιστορική αναδρομή στην διαχρονική χρήση μάζας από τις ανθρώπινες κοινωνίες και εξετάζει διακριτά την ένταση εννιά (9) διαφορετικών μετάλλων, καθώς και την ένταση τριών (3) υλικών εισροών εξαιρετικής σπουδαιότητας για την σύγχρονη παραγωγική διαδικασία: Παγκόσμια κατανάλωση τσιμέντου, πλαστικών υλικών, χημικών και οργανικών λιπασμάτων στην γεωργική παραγωγή. Η καινοτομία του 5ου κεφαλαίου έγκειται στο ότι αποτελεί *την πρώτη εμπειρική προσπάθεια ανάλυσης της σχέσης μεταξύ μη-ενεργειακής μάζας - οικονομικής μεγέθυνσης, στην σχετική βιβλιογραφία.* Η ένταση της μάζας στην οικονομική διαδικασία εξετάζεται διακριτά για την παγκόσμια οικονομία και τις εθνικές οικονομίες των ΗΠΑ και της Ιαπωνίας, μέσα από το πρίσμα της υπάρχουσας αλλά και της προτεινόμενης μεθοδολογίας. Η ανάλυση υιοθετεί και ενσωματώνει σύγχρονες τεχνικές (από τον OECD, UNEP, κτλ) που αποτιμούν και αξιολογούν την παρατηρούμενη αποσύνδεση, όπως ο Decoupling Index (UNEP, 2011a) και ο Decoupling Factor (OECD, 2002). Επιπρόσθετα, το 5ο κεφάλαιο εξετάζει στο παράρτημά του, την υλική ένταση του συνόλου των υλικών πόρων (συμπεριλαμβανομένων και των ενεργειακών πόρων), που εισρέουν στο οικονομικό σύστημα και μετρώνται με τον δείκτη Εγχώριας Κατανάλωσης Υλικών πόρων (Domestic Material Consumption – DMC), για 17 ανεπτυγμένες και αναπτυσσόμενες εθνικές οικονομίες, που αποτελούν ένα καλό πλαίσιο σύγκρισης της προτεινόμενης μεθοδολογίας με την υφιστάμενη.

Μέρη του 5ου κεφαλαίου βρίσκονται υπό κρίση σε 2 διεθνή επιστημονικά περιοδικά με κριτές, και έχουν δημοσιευτεί στα πρακτικά διεθνών και εθνικών επιστημονικών συνεδρίων με κριτές. Επιπρόσθετα, ένα μέρος του 5ου κεφαλαίου θα αποτελέσει τον πυρήνα ενός επιστημονικού συγγράμματος, το οποίο θα εκδοθεί από τον βρετανικό εκδοτικό οίκο Springer-UK.

6ο Κεφάλαιο

Εμπειρική Ανάλυση: Η υπόθεση των ενεργειακών φυσικών πόρων

Συμπληρωματικά με το 5ο κεφάλαιο, το 6ο κεφάλαιο έρχεται να ολοκληρώσει την συνολική εικόνα της ροής φυσικών πόρων που εισρέουν στο οικονομικό σύστημα, με την ανάλυση της έντασης των ενεργειακών φυσικών πόρων στην παραγωγική διαδικασία. Ως ενεργειακούς φυσικούς πόρους ορίζουμε όλες εκείνες τις εισροές φυσικών πόρων που η χρήση/κατανάλωση τους προσφέρει την απαραίτητη ενέργεια/ισχύ προκειμένου να παραχθεί χρήσιμο έργο (Ορυκτά καύσιμα –πετρέλαιο, άνθρακας, φυσικό αέριο–, πυρηνική ενέργεια, υδροηλεκτρική ενέργεια, γεωθερμία, ηλιακή ενέργεια, αιολική ενέργεια, κ.α.). Οι ενεργειακοί φυσικοί πόροι, συνεπώς, επιτελούν μια διακριτή λειτουργία από τις εισροές μάζας (5ο κεφάλαιο), μέσα στα πλαίσια της οικονομικής διαδικασίας, μιας και συνεισφέρουν εκείνη την απαραίτητη ενέργεια που ουσιαστικά κινεί την μηχανή της Οικονομικής Μεγέθυνσης. Αρχικά το 6ο κεφάλαιο επιχειρεί μια ιστορική αναδρομή αναφορικά με την σπουδαιότητα των ενεργειακών πόρων, από την ανακάλυψη της φωτιάς έως τα ορυκτά καύσιμα, στα πλαίσια της εξέλιξης του ανθρώπινου πολιτισμού και, παράλληλα, της οικονομικής διαδικασίας. Επιπλέον, επιχειρείται μια σημαντική ανασκόπηση και ανάλυση των διαφορετικών μεθόδων μέτρησης και άθροισης του ενεργειακού ισοδύναμου που εμπεριέχει κάθε, διαφορετικός σε ποιότητα, ενεργειακός φυσικός πόρος, καθώς και οι διαφορετικές μορφές ενέργειας που είναι χρήσιμες για τον άνθρωπο (Κινητική, Θερμική, Χημική, κ.α.). Στο παραπάνω πλαίσιο, εξετάζονται και αξιολογούνται οι διάφορες σύγχρονες μέθοδοι άθροισης των, διαφορετικής ενεργειακής αποδοτικότητας και ποιότητας, φυσικών πόρων υπό το πρίσμα του ωφέλιμου έργου που αυτοί δύνανται να παράγουν (Exergy), τις θερμικές απώλειες που έχει η κάθε διαδικασία κατανάλωσης ενέργειας ως αποτέλεσμα της εντροπίας, του δεύτερου νόμου της θερμοδυναμικής, το ισοδύναμο της ηλιακής ακτινοβολίας που αυτοί ενσωματώνουν (Emergy), και ούτω καθεξής. Στην συνέχεια, εξετάζουμε διακριτά την μακροχρόνια αθροιστική, και ανά πόρο, ενεργειακή ένταση της οικονομικής μεγέθυνσης της παγκόσμιας οικονομίας, καθώς και τις εθνικές οικονομίες των ΗΠΑ, της Ιαπωνίας, και της Ινδίας. Η ανάλυση υιοθετεί και ενσωματώνει σύγχρονες τεχνικές (OECD, UNEP, κ.α.) που αξιολογούν την παρατηρούμενη αποσύνδεση, όπως ο Decoupling Index (UNEP, 2011a) και ο Decoupling Factor (OECD, 2002). Επιπρόσθετα, το 6ο κεφάλαιο αναλύει το ενεργειακό προφίλ και την ενεργειακή ένταση δεκαεννέα (19) μεγάλων ανεπτυγμένων και ραγδαία αναπτυσσόμενων οικονομιών, για το διάστημα 1965-2012, συγκρίνοντάς τες στο πλαίσιο της υπάρχουσας αλλά και της προτεινόμενης μεθοδολογικής προσέγγισης της εκτίμησης της αποσύνδεσης (decoupling).

Ένα μέρος του 6ου κεφαλαίου (παγκόσμια οικονομία) έχει δημοσιευτεί στο διεθνές επιστημονικό περιοδικό με κριτές Energy Journal, καθώς επίσης και στα πρακτικά 2 διεθνών επιστημονικών συνεδρίων με κριτές. Επιπλέον, ένα δεύτερο άρθρο (που *εξετάζει εθνικές οικονομίες) βρίσκεται ήδη υπό κρίση στο Journal Of Cleaner Production*.

7ο Κεφάλαιο

Η Κριτική διερεύνηση της συνεισφοράς του εμπειρικού διαλόγου πάνω στην αιτιώδη σχέση μεταξύ Ενέργειας-ΑΕΠ, στον θεωρητικό διάλογο της από-ανάπτυξης, υπό το πρίσμα της Μετά –Ανάλυσης μεθοδολογίας.

Η καινοτομία του 7ο κεφαλαίου έγκειται σε τρία διαφορετικά επίπεδα:

- Αποτελεί την μεγαλύτερη δημοσιευμένη ανασκόπηση που έχει γίνει στην διεθνή βιβλιογραφία, αναφορικά με τις μελέτες που εξετάζουν την αιτιώδη σχέση μεταξύ Ενέργειας-ΑΕΠ (The causal relationship between E-GDP), για την χρονική περίοδο 1978-2011.

- Αποτελεί την πρώτη και εκτενέστερη δημοσιευμένη μελέτη, στην ιστορία του σχετικού διαλόγου, που επιχειρεί να εξετάσει τα συνολικά αποτελέσματα των 158 δημοσιευμένων επιστημονικών άρθρων, υπό το πρίσμα της Μετά-Ανάλυσης μεθοδολογίας (Meta-Analysis). Η κωδικοποιημένη βάση, μια μήτρα 7 Χ 686 (6 ανεξάρτητες μεταβλητές, μια εξαρτημένη, 686 υποπεριπτώσεις που παρήχθησαν από τις 158 δημοσιευμένες μελέτες), που κατασκευάστηκε για τις ανάγκες της ανάλυσης, υπάρχει ελεύθερα διαθέσιμη στο διαδίκτυο.

- Επιχειρεί να συλλάβει τα αποτελέσματα της Μετά-Ανάλυσης, ως μια πρώτη προσπάθεια εμπειρικής θεμελείωσης του σύγχρονου, θεωρητικού προς το παρόν, διαλόγου πάνω στην έννοια της Από-ανάπτυξης (de-growth).

Στο πλαίσιο των τριών αυτών επιπέδων, το 7ο κεφάλαιο χρησιμοποιεί δύο διαφορετικές μεθόδους για την εκτέλεση της Μετά-Ανάλυσης: την Rough set data analysis και την Multinomial logistic regression. Αναφορικά με την πρώτη μέθοδο η οποία αξιοποιεί γνώση από την επιχειρησιακή έρευνα και τα σύνθετα μαθηματικά της τεχνητής νοημοσύνης, οι κανόνες που παρήγαγε αποτυγχάνουν να συλλάβουν μια επικρατούσα μακροχρόνια τάση σχετικά με την κατεύθυνση της αιτιώδους σχέσης μεταξύ Ενέργειας-ΑΕΠ. Η εφαρμογή της δεύτερης μεθόδου επιβεβαιώνει τις παραπάνω παρατηρήσεις. Πράγματι, και οι δύο μέθοδοι που εφαρμόστηκαν αποτυγχάνουν να δώσουν μια σαφή και στατιστικά σημαντική απάντηση αναφορικά με μια κοινή μακροχρόνια τάση που να εξηγεί αντιπροσωπευτικά το σύνολο του διαλόγου αυτού. Τα αποτελέσματα του 7ου κεφαλαίου έρχονται να ενισχύσουν τους προβληματισμούς που διαφαίνονται στην σχετική βιβλιογραφία τα τελευταία χρόνια αναφορικά με τα αντικρουόμενα και πολλές φορές εκ διαμέτρου αντίθετα αποτελέσματα που δημοσιεύουν οι σχετικές μελέτες. Τέλος, το εγχείρημα σύνδεσης των εμπειρικών αποτελεσμάτων του 7ου κεφαλαίου με τον θεωρητικό διάλογο της Από-ανάπτυξης δεν ευδοκιμεί, αφού ο σχετικός διάλογος της αιτιώδους σχέσης Ενέργειας-ΑΕΠ αποτυγχάνει, ως σύνολο, να δώσει ξεκάθαρα και ουσιαστικά συμπεράσματα.

Το σύνολο του 7ου κεφαλαίου έχει δημοσιευτεί στο διεθνές επιστημονικό περιοδικό με κριτές Journal of Cleaner Production, καθώς και στα πρακτικά ενός διεθνούς και ενός εθνικού επιστημονικού συνεδρίου με κριτές.

8ο Κεφάλαιο

Συμπεράσματα

Το 8ο και τελευταίο κεφάλαιο της διδακτορικής διατριβής αποτελεί τον επίλογο και την συνοπτική ανακεφαλαίωση των βασικών συμπερασμάτων που εξάγει η παρούσα εργασία. Παράλληλα επιχειρεί να σταχυολογήσει τα ερωτήματα και τους προβληματισμούς εκείνους που πιθανόν να έχουν ενδιαφέρον για μελλοντική έρευνα, στα πλαίσια των σύγχρονων διαλόγων που έθιξε και ανέλυσε το παρόν πόνημα.

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Abbreviations

BHS: *Biophysical Human Scale*

Btu: *British thermal unit*

cap: *capita*

CHANS: *Coupled Human and Natural Systems*

DE: *Domestic Extraction*

DEC: *Domestic Energy Consumption*

DEU: *Domestic Extraction Used*

DF: *Decoupling Factor*

DI: *Decoupling Index*

DMC: *Domestic Material Consumption*

DMI: *Direct Material Inputs*

DR: *Decoupling Ratio*

EFA: *Energy Flow Analysis/Accounting*

EI: *Energy Intensity*

EIA: *U.S. Energy Information Administration*

EJ: *Exa-joule*

ft*: foot*

GDP: *Gross Domestic Product*

h*: hour*

Ha: *Hectare*

HSP: *Human Scale Production*

J: *joule*

Kcal: *kilocalorie*

Kg: *Kilogram*

MF: *Material Flows*

MFA: *Material Flow Analysis (or Accounting)*

MI: *Material Intensity*

Mtoe: *Million tons of oil equivalents*

MWh: *Megawatt per hour*

NRf: *Natural Resources flow*

OECD: *Organization for the Economic Co-operation and Development*

Pers: *Persons*

RF: *Resources Flows*

SERI: *Sustainable Europe Research Institute*

t: *ton (tonne)*

TMR: *Total Material Requirement*

TMS: *Total Materials Supply*

TPES: *Total Primary Energy Supply*

UN: *United Nations*

UNEP: *United Nations Environmental Programme*

USGS: *United States Geological Survey*

WB: *World Bank*

WRI: *World Resources Institute*

yr*: year*

"...Let us take the six days of Genesis as an image and use it to picture what has actually happened over the past four billion years. One day roughly equals six hundred and sixty million years. Our planet was born on Monday at zero hour. During Monday, Tuesday and Wednesday a.m. the Earth was being formed. Life began at midday on Wednesday and developed in all its organic beauty over the next three days. Only on Saturday at four in the afternoon did the first reptiles appear. Five hours later at nine p.m., when the sequoias were rising from the ground, the large reptiles disappeared.

Man only emerged at three minutes to midnight on Saturday evening. At a quarter of a second before midnight, Christ was born. At a fortieth of a second before midnight, the industrial revolution occurred.

> *Now it is midnight on Saturday, and we are still surrounded by people who think that what they have been doing for a fortieth of a second can go on indefinitely..."*

David Brower

Preface

Growth, Development and the Sustainability problem

Shaping the core question

1. Defining economic growth and development

The endeavor to define the terms "*economic growth/development*", should take as its initial point of reference the neoclassical economic theory. Under the spectrum of neoclassical economic theory, economic growth is defined as the increment (growth) of produced goods, hence the absolute increment of Gross Domestic Product (GDP), and consequently, the increase of the per capita welfare (GDP per capita) of an economy (*Reppas, 2002 - in Greek*). Until the late 1960's the terms "*economic growth*" and "*economic development*" were used as conceptually synonymous, while the theoretical models of that period recognized industry as the most productive sector which contributes to the rapid growth of GDP (*ibid*).

According to the American Heritage Dictionary of the English Language (*See Costanza et al. 1997-p.111*), the term "*grow*" means literally "*to increase naturally in size by the addition of material through assimilation or accretion*". On the other hand, the term "*develop*" means "*to expand or realize the potentialities of (or bring gradually to) a fuller, greater, or better state*". Although the proper definition of (economic) growth and development remains an open debate in the relevant literature (*Somashakar, 2006*), we could adumbrate these two notions in a brief sentence: proportional changes of GDP – especially of GDP per capita – are referred to in the economic growth literature, while the notion of development deals with the analysis of living standards, well-being and other features that do not necessarily form an object of monetary measurement or quantitative increment (*Colombatto, 2006 – p. 243*). In that context, economic growth mainly concerns the (quantitative) changes in the consumer's surplus, while economic development refers to (qualitative) evolutions in the institutional context of an economy (*ibid*).

According to Halkos (2013 – in Greek), "*economic development*" is defined as the process that increases real GDP per capita, thus the economic welfare, over a long period of time. Furthermore, beyond the increment of production, the concept of economic development incorporates all the technological, institutional, and structural changes taking place within the production process and the distribution process of the produced goods. "E*conomic growth*" is defined as the process during which the increased product is produced with the increment of the utilized input flows in the production process, as well as improvements in the efficiency of the use of the input flows (*ibid*).

Reppas (2002) describes a more extensive framework, beyond the terms growth and development. Contemporary dialogues on economic growth-development propose new terminology that aspires to incorporate the previous definitions into a broader and more integrated context. Among the prevailing terminologies are the notions of "*Total*" or "*Holistic*" Development (*Sachs, 2000*). Figure 1 depicts this integrated framework (*Reppas, 2002 – in Greek*): GDP increases until the exhaustion of the inputs (economic growth); further augmentation of the production calls for innovation, technological change and greater efficiency (economic development); however, if we want to move onto the far side of these two concentric circles, we ought to improve (develop) the overall social-political-ecological environment of an economy, thus, move towards the Total or Holistic Development (Fig. 1).

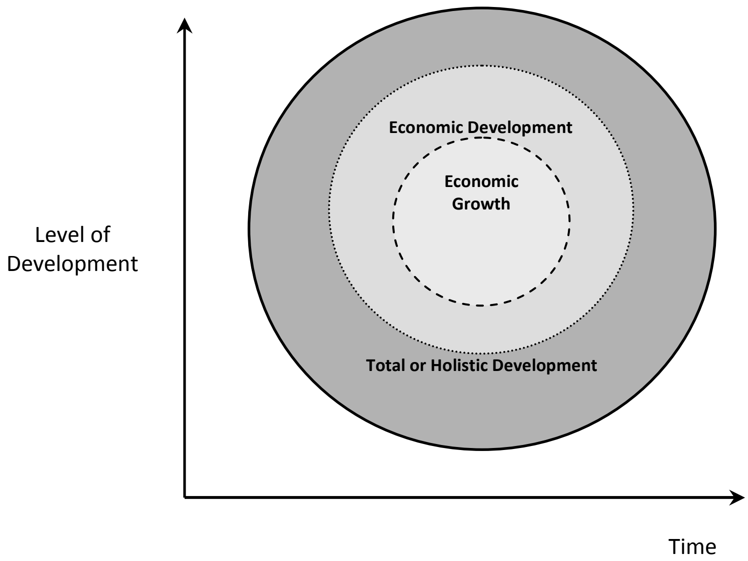

Figure 1 *Defining the notions: economic growth; economic development; total or holistic development. (Source: reconstructed by the author from Reppas, 2002 – p. 57)*

2. Towards a Sustainable Development regime.

The extension of the "*growth versus development*" debate leads to "*Sustainable Development*", a term that is quite popular among politicians and scientists despite the fact that it is still rather new and lacks an accurate definition. Evidently, the concept of sustainable development is still being developed (ssustainability is on its way to comprising a new separate scientific branch within environmental sciences), while the definition of the term is constantly being revised, extended, and refined (*World Bank, 2000*). According to the classical definition given in the well-known Brundtland Commission's report (*Brundtland, 1987*), development is sustainable if it "*meets the needs of the present without compromising the ability of future generations to meet their own needs.*" The Brundtland report received remarkable popularity since it was the first official recognition of the fact that the scale of the world economy is already unsustainable. However, the report also recognizes the need for further economic expansion (by a factor of 5 to 10) in order to improve the poor ones (the developing countries), while it does not deal too much with the alternatives of serious population control and redistribution of wealth (*Costanza et al., 1997*).

The endeavour towards an era of sustainable development is sharply reflected in the different approaches of the "*weak*" (technology-optimists) and "*strong*" (entropy-pessimists) sustainability schools of thought. With the critical issue of the substitutability of natural capital by man-made capital being the main conflict between them, each approach attempts to solve the issue of natural resources scarcity within a different theoretical basis and underlying assumptions (*Ayres, 2007; Bithas, 2012 – In Greek*). The 2nd chapter of the present dissertation provides a detailed analysis of the differences between these two approaches.

Undoubtedly, a positive economic growth rate is the basic prerequisite of a wealthy economy, in today's complex globalized economic reality. Yet a critical question still remains unanswered: up to what level should an economic system grow? To rephrase the question, should the economic (sub) system obey certain physical laws that set limitations and restrictions beyond a given level of growth, or is perpetual economic growth possible given continuous technological progress? Indeed, these questions reflect to some extent the core of the conflict between the weak versus strong sustainability approaches. In line with these crucial questions, a recent on-line commentary in Herman Daly's website provides an illustrative example concerning the lack of an optimal scale approach in macroeconomics (*Daly, 2010*): "*All of microeconomics is devoted to finding the optimal scale of a given activity – the point beyond which marginal costs exceed marginal benefits and further growth would be uneconomic. Marginal Revenue = Marginal Cost is even called the "when to stop rule" for growth of a firm. Why does this simple logic of optimization disappear in macroeconomics? Why is the growth of the macroeconomy not subject to an analogous "when to stop rule"? We recognize that all microeconomic activities are parts of the larger macroeconomic system,* *and their growth causes displacement and sacrifice of other parts of the system. But the macroeconomy itself is thought to be the whole shebang, and when it expands, presumably into the void, it displaces nothing, and therefore incurs no opportunity cost. But this is false of course. The macroeconomy too is a part, a subsystem of the biosphere, a part of the Greater Economy of the natural ecosystem. Growth of the macroeconomy too imposes a rising opportunity cost that at some point will constrain its growth*". Daly's commentary actually summarizes, to some extent, the hot and timely debate between Robert Solow and Nicholas Georgescu-Roegen in the 1970s, concerning the aggregate scarcity of natural resources and the restrictions that physical laws set on economic growth. The continuity of this historical debate is essentially reflected in the different conceptual approaches of the weak "*technology optimists*" and the strong "*entropy pessimists*" sustainability schools of thought.

3. The core question of the present dissertation

The last few decades have seen the construction of detailed and accurate databases that account the natural resources flows enter into the economic system. These updated datasets and resources accounting frameworks, such as the widely used Material Flow Analysis (MFA), provide nowadays the opportunity for an empirical validation of the early theoretical contributions to the investigation of the natural resources-economy link. Essentially, the underling optimism of the contemporary literature that investigates the so-called Decoupling effect could be seen, to some extent, as the empirical revival of the historical debate between Solow and Georgescu-Roegen, concerning the impact of the scarcity of natural resources on economic growth. The contemporary literature on decoupling asserts that there is a gradual de-link between the consumption of resources and economic growth, supporting to some extent the "*technology optimists*" of the weak sustainability school of thought. Evidently, this conclusion is empirically confirmed for the vast majority of developed, as well as for many developing, economies.

However, despite the estimated decoupling trends in most cases examined, there is another inconvenient empirical estimate which essentially questions the decoupling potentials: the social/industrial metabolism, namely the per capita resources consumption, is dramatically increasing for the vast majority of the examined (developed and developing) economies (with Japan, the UK, and Germany being some notable exceptions). Furthermore, these increasing per capita consumption trends are based more and more on nonrenewable resources.

Based on this contradiction between the estimated decoupling and per capita consumption trends, the present dissertation aspires to question the decoupling potentials of the economic process. To this end, the thesis adopts the Material Flow Analysis (MFA) methodological framework and the most up-to-date datasets on resources flows, in order to establish and evaluate a new decoupling evaluation framework, as an alternative and complementary to the already existing one. The proposed theoretical conception incorporates, for the first time in the history of the relevant literature, the importance of the demographic dynamics in the decoupling estimates, while it shapes the argument of the biophysical human scale as a crucial threshold for the dematerialization potentials of an economy. According to the results of the present study, there is less optimism concerning the decoupling of economic growth from the use of natural resources, since its alternative empirical estimates assert that energy and mass resources are coupled with the economic system, once the economic output is envisioned at the downscaled level of the per capita economic welfare-utility.

The dissertation is structured as follows:

The 1st Chapter presents a brief historical review of the theories of economic growth, from the early Classical era to the latest theories of endogenous growth, while it traces indirectly the role of natural resources in these theories.

The 2nd Chapter focuses on the different theoretical assumptions of the neoclassical and the biophysical schools of thought. It mainly focuses on the issues of aggregate scarcity of natural resources, the substitutability between natural and man-made capital and the efficiency improvements caused by technological change.

The 3rd Chapter serves as the empirical extension of the theoretical debate on the natural resources scarcity, presented in Chapter 2. The 3rd Chapter presents in detail the Material Flow Analysis (MFA) framework and the relevant indicators that evaluate the resources-economy link through the decoupling effect.

In line with Chapter 3, the 4th Chapter presents the theoretical assumptions and the methodological contribution of the present dissertation. Moreover, it analyses the abstract nature of GDP as an index which evaluates the economic output of the production process, while it proposes the utilization of the per capita GDP as a better representation of the actual economic output: the welfare-utility of human beings. Furthermore, the 4th Chapter presents the concepts of Biophysical Human Scale (BHS) and the Human Scale Production (HSP).

Chapters 5-6 provide the empirical evaluation of the proposed methodology and the comparison of the results with the mainstream MFA framework (3rd Chapter). Specifically, Chapter 5 estimates the Material Intensity (MI) of the non-fuel materials (for the global level, the USA and Japan), and the total MI of various economies. Chapter 6 estimates the Energy Intensity (EI) of various economic levels.

The 7th Chapter presents the contemporary, still theoretical, concepts of degrowth and a-growth and aspires to trace the empirical implications that the E-GDP causality debate may have on these concepts. Due to that purpose, it performs the most up-to-date literature review and the first extensive meta-analysis investigation of the historical causality debate.

Finally, Chapter 8 functions as an epilogue which briefly summarizes the overall conclusions of the present dissertation.

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1ST CHAPTER

Theories of Economic Growth

A Brief Historical Review

"…I think there are definite signs that (growth theory) is just about played out, at least in its familiar form. Anyone working inside economic theory these days knows in his or her bones that growth theory is now an unpromising pond for an enterprising theorist to fish in…"

Robert Solow, 1982

1.1 The classical period of economic theory of growth

The very first foundations set by the rigorous theoretical conceptions of the great classical theorists of economic thought, had as main aim the investigation of the evolution of capitalism over the long run, through a wide point of reference beyond strict economic processes, within the context of social, political and institutional conceptions that human societies and activities take place. The accumulation of capital, the production and distribution of goods, the division and the wages of labor, the rent of land, are among the main axes that the theories of that time evolved, with the ultimate goal to discover and delineate the final boundaries of capitalism, as an economic system. This period of fruitful research produced economic models that had as a potential outcome projections for the stationary state, either violent collapse and evolution to other organizational, institutional and production structures (*Reppas, 2002*).

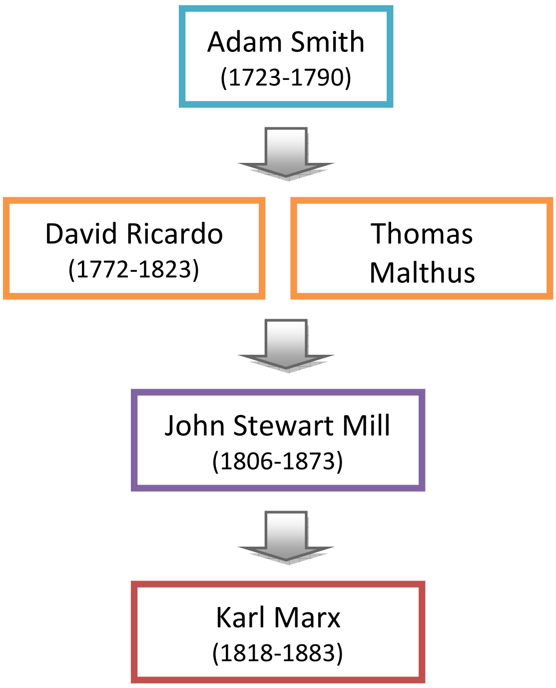

Figure 1.1 *The classical Theorists of economic thought.*

According to the Encyclopedic Dictionary of Economics (*Ghodke, 1985-p:188*), the term Classical Economics includes all the followers of Adam Smith through J.S. Mill. Following modern literature, we conclude this category with the addition of Karl Marx. Figure 1.1

attempts a depiction of the cornerstone theories of those early pioneer economists that Marx[1] called the "classical school of economic thought". This section captures the evolution of classical economic thought through time, providing a brief representation of the very first theoretical models, created by the great theorists of this first era of economic thought, which formed the foundations of what economic science is today.

1.1.1 Adam Smith

It goes without saying that Adam Smith is considered as the "*father*" of economic science. With the publication of his seminal and prestigious study "*An inquiry into the Nature and Causes of the Wealth of Nations*", which printed in 1776 and took 12 years of extensive writing in order to be completed, Smith sets the first foundations of the contemporary economic theory (*Heilbroner, 2000*). Behind the apparent chaos of every day's economic activity in England of 18th century, Adam Smith managed to envision a self-regulated process which leads selfish individual interests into a deterministic equilibrium. The "invisible hand" of a free, without interventions, self-regulated market was just about to born. According to Smith, the prices of the products, the wages of labors, and the quantities of the produced goods are determined by the free transactions take place in the free markets. It is widely accepted that Smith raised two very important theoretical bases, through his effort to comprehend the economic growth process. These two theoretical contributions, of paramount importance for economic science, were (*Chaudhuri, 1989*):

- The concept of division of labor
- The division between "productive" and "unproductive" labor force.

The basic assumptions of Smith's economic model are (*Ibid*):

1. Pursuit of profit can be taken as granted in a market economy. Any activity must yield a "surplus" to someone (where surplus=value of product – cost of production).
2. Labor is an important input of economic production.
3. Production involves time. Time is measured in discrete periods
4. There is a closed economy (no foreign trade transactions)
5. Labor divided between "productive" and "unproductive".

[1] As Keynes denotes in the first chapter of "The General Theory of Employment, Interest and Money", in 1936

6. Advances have to be made to labor. The advances are made by capitalists who engage labor for production.
7. There is no fixed capital. Only wage goods that are available in order to employ labor at the beginning of the period.

According to Smith, the wage ratio and the labor productivity emerge as the two key elements of economic growth (*Chaudhuri, 1989*). The concept of technological progress comprises the specialization of labor within the production process. The technological advance improves the labor productivity and minimize the time of its involvement, but does not displace the need for labor force. *The production equipment is complementary to labor and does not substitute it by any means*. In conclusion, Smith argued that the wealth of a nation depends on labor productivity and the quantity of the available "*productive labor*" (*Evdorides, 2000*). It is worth mentioning that Smith was against hoarding, yet he recognized savings as an incentive of investment. As far as the issue of overpopulation concerned, Smith firmly believed that there is also a self-regulated process, where the demand for "*humans*" (labor), as in the case of any other exchanged commodity, regulates the increment or decrement of humans (labor force, hence human population). Smith's theoretical model ends up, after 2 centuries according to his own predictions, in the stationary state (*Reppas, 2002*).

1.1.2 David Ricardo

The fundamental question that David Ricardo investigates is the determination of the reasons causing the variation in the synthesis of the allocation of the produced goods, among three basic social classes of his time: the landlords; the capitalists; and the labours. In that context, Ricardo conceived two fundamental, for the evolution of the economic science, concepts (*Reppas, 2002*):

- **The labor theory of exchange value:** Determinant factor of the value of the products, beyond the direct (labor) work that required during the production process, is the indirect (labor) work that has been already incorporated in the tools and the machinery that utilized during the production process, as well.

- **The theory of rent and diminishing returns in agriculture**: Soil is a significant input in the production process and it has two essential properties: it is limited in quantity and inhomogeneous in quality. Therefore, the soils that exploited first are the most fertile and accessible ones. Furthermore, according demand trends and after the fertile soils have been excessively used, the production process moves progressively in the exploitation of the less productive (less fertile) land. Consequently, the rent is paid due to these two properties that land possesses (Figure 1.2).

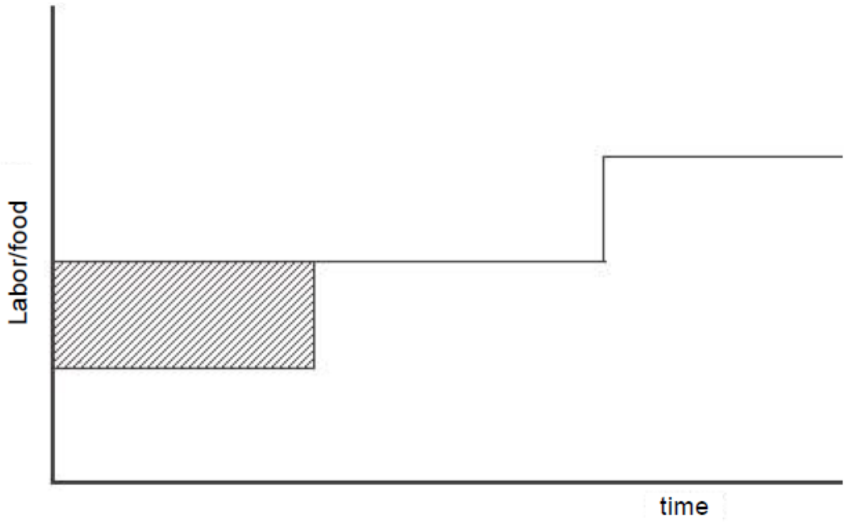

Figure 1.2 *Ricardo's explanation of rent, represented by the shaded area (Source: Costanza et al., 1997-p.34)*

Following Smith's distinction of labor force in productive and nonproductive, Ricardo distinguishes the production factor "*land*", in "*land that is utilized as an input in the production process*", and "*land which is not used as an input in the production process*". The basic assumptions of the Ricardian theoretical model of economic growth could be summarized as (*Chaudhuri, 1989*):

- The Ricardian model of economic growth contains two broad production sectors: agricultural and construction (in accordance with the two classes that Ricardo recognizes as dominant in the economic process: landlords and capitalists, respectively).
- The capital revenue is given.
- The real wages are given.

In conclusion, Ricardo envisioned three basic elements that increase the rate of economic growth:

- The soil fertility
- The technological improvement of agricultural methods and techniques.
- The free foreign trade.

Ricardo's economic growth model is dominated by the diminishing returns of the soil (land) and by the pressure of population growth. Albeit Ricardo initially ignores the consequences of the technological progress on the productivity of the production factors, however, in the third edition of his seminal study "*On the principles of Political Economy and Taxation*", in 1821, he introduces and analyses the technological changes influenced by the criticism of Malthus (*Evdorides, 2000*). Finally, Ricardo's theoretical model ends up at the stationary state, albeit not with the same intensity that Smith assumed. Apparently, by recognizing the improvements that the technological progress entail in the production process, Ricardo assumes that it is possible to postpone, at least for some time, the long-run trends that irrevocably will lead in a non-growth period, thus, the stationary state. Concerning the population issue, Ricardo obviously affected by the pessimistic projections of his close friend, Thomas Malthus (*Heilbroner, 2000*).

In a nutshell, Ricardian theory made two major contributions to the analysis of growth (*Chaudhuri, 1989*): It shows that process of economic growth is terminal, it is not likely to continue for ever; and, the economy approaches a particular level of output, at which further growth ceases; this is the Ricardo's classical "*stationary state*". It is worth mentioning here that, both Marxian and neoclassical theory, fail singularly to take into account the peculiarities of a (Ricardian) land based economy (*Eltis, 1984*).

1.1.3 Thomas Malthus

In 1798, by publishing an anonymous treatise under the title "*An essay on the principle of population as it affects the future improvements of society*", Thomas Malthus captures his dismal belief that society is eternally damned to struggle between human instincts, which lead in a constant population growth, and the limited insufficient food stock that nature provides (*Heilbroner, 2000*). The human beings increase their numbers geometrically, while the arable land, thus food production, increases only arithmetically, and until one certain limit (Figure 1.3). Despite the fact that Malthus is well known for his pessimism, however, there is also an optimistic side concerning his work that is being usually neglected; he recognizes that the seamless technological progress postpones, to one point, the diminishing returns cited by Ricardo. These two observations of Malthus – the overpopulation issue and the technological progress – affected deeply Ricardo, who reshaped many of his initial assumptions.

According to Malthus, the main problem of economic growth is the possibility of insufficient demand (known as periods of general glut), as a result of excessive savings or rapid increase of investments that will lead in increasing production (the supply rate increases faster that the demand rate)[2]. To overcome this problem, Malthus argues that the insufficient demand could be covered by the expenditure of the labor force that is employed in the service sector (non-productive consumption), the public works, and trade (*Evdorides, 2000*).

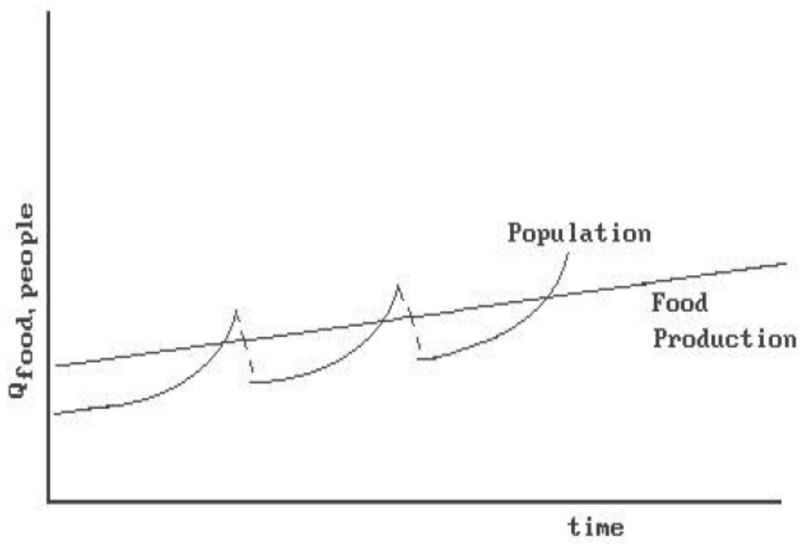

Figure 1.3 *Malthus's model of population growth and collapse (Source: Costanza et al., 1997-p.34)*

Despite his significant contribution, Malthus did not manage to build an adequate theoretical model that could explain, through assumptions, the occurred economic growth. However, Malthus managed to point out a crucial limiting factor which literary "haunting", since then, the potentials for an infinite economic growth process: overpopulation. The

[2] Malthus managed to capture an economic phenomenon that would have a tremendous impact in future economic analysis: economic cycles. Marx has further investigated this early observation of Malthus.

pessimism of the Malthusian analysis affected extensively many forthcoming schools of economic thought (i.e. neo-Malthusianism, etc), while it has been confirmed periodically in specific places, and history yet confirm it at global level, as many distinguished scholars argue (*Costanza et al., 1997*). It goes without saying, that his pioneering analysis for population growth and scarcity remains influential and timeless.

1.1.4 John Stuart Mill

Belonging to a group of philosophers and visionaries intellectuals, known in the relevant literature as the "Utopian Socialists[3]", John S. Mill sets as the ultimate objective of the political economy, the betterment of the individuals, especially those belonging to the working class (*Heilbroner, 2000*). With his most substantial economic study "*Principles of Political Economy with some of their Applications to social philosophy*", published in 1848, Mill achieves a remarkable "blending" of the dominant socialistic approaches of his time with the principles of the Ricardian political economy, by adopting the narrative pattern that Smith established with the "Wealth of the nations" (*Reppas, 2002*). Mill's viewpoints concerning the determinant factors of economic growth, not substantially different by Ricardo's basic perspective, could be summarized in three general points (*Heilbroner, 2000; Reppas, 2002; Evdorides, 2000*):

- The improvement of the productivity of the production factors

- The quantitative increase of the production factors

- The socio-political factors that promote economic growth

A fundamental contribution of his model, concerning the diminishing returns, is the introduction to the economic recession periods. Mill considers the periodic economic recessions as an integral part of the capital accumulation process, and moreover, an endogenous phenomenon of capitalism (*Reppas, 2002*). Following the early observations that Malthus made, Mill sets the foundations of the substantial investigation of economic recession periods, a research that will further developed by Marx and, later on, by Schumpeter.

[3] Like Robert Owens, Henri de Saint Saimon, and Charles Fouriet, among others.

According Mill, the economic growth process is limited. However, his main query does not try to answer the question "when the economic growth will stop", but in his own words: "... when the growth stops what will be the state of mankind?" (*Reppas, 2002–page: 226*). Given the fact that Mill believed in the possibility of behavioral change of society, his theoretical model ends up in different conclusions that the respective ones proposed by Malthus and Ricardo. Mill does not adopt their pessimism concerning the overpopulation issue since he was confident that the working class could be educated, hence, voluntarily adjust their population. Consequently, the accumulation process will increase the wages – hence the overpopulation danger disappears – and will lead the model into a higher level of stationary state. At this stationary state, where the Malthusian fear of overpopulation is removed– thanks to an educated working class, Mill traces the very first stage of a mild form of premature socialism that will turn human beings into more creative directions, beyond the pursuit of economic growth (*Heilbroner, 2000*).

1.1.5 Karl Marx

Undoubtedly, Karl Marx is among the most influential economists of the classical political economy. With his work on the structure, the function and the evolution of the capitalistic system, deeply affected -and still does- not only the economic thought, but a whole spectrum of social and political sciences, political parties and radical movements. John M. Keynes, in the introduction of his essay "The general theory of employment, interest and money" writes: the term "*classical economics" was coined by Marx to refer to Ricardo and his predecessors, including Adam Smith*" (*Keynes, 1936*). Following systematically the contributions of his predecessor classical economists, Marx founded a theoretical model that aspired to explain the way that the capitalistic system functions, and to project its future evolution. Marx's model is based on the methodology and the assumptions of the other classical economists, such as the expanded theory of value of Ricardo and the more humanitarian approaches of Mill. However, Marx goes beyond the theoretical basis of his predecessors and enhances his work with new evidence (*Reppas, 2002*). In comparison to the great theorists we have already introduced, Marx is the most pessimist concerning his theoretical model, which does not end up in any kind of stationary state. Instead, he prejudges the fall and the catastrophe of capitalism, while simultaneously he envisions the dawn of a new era, the era of the proletariat[4] through the upcoming advent of the classless society of the future. The voluminous work of Marx, under the unconditional support and contribution of Friedrich Engels, is well-known as the "dialectical materialism": "dialectical" because it incorporates the ideas of the great German philosopher Georg W. F. Hegel, and "materialism" because it is based on the social and natural environment, not on the intangible universe of ideas (*Heilbroner, 2000; Reppas, 2002*).

The main purpose of the present section is to provide only a very brief representation of the voluminous work that Marx published, focusing on the basic key-point of his theoretical-philosophical model. In synopsis, the main pillars of the Marxist theoretical model are (*Reppas, 2002-page: 272*):

- **Theoretical basis**

  - The dialectical method

  - The theory of value and surplus

- **Basic principles and laws govern the capitalism**

  - The accumulation and the reproduction of capital

  - The synthesis of the capital

  - Declining rate of profit

- **Economic crises in the capitalistic production process**

  - The endogenous trend of capitalism to produce economic crises and their periodicity.

  - The crises and the final collapse of the capitalistic system.

Marx invented a new context of social analysis that shed light on neglected aspects of the economic science. By realizing the implications that may have the exploitation of the labor force as a commodity in the capitalistic societies, Marx managed to widen the narrow

[4] Etymologically and historically, the Latin term "proletarius" defined those people that their property was below the lowest level, hence their children were listed instead of their property (proli =descendant, offspring; arius =poor). Initially the term had a negative meaning, until Marx used it as sociological term in order to describe the class of wage-earners, whose income was exclusively coming from selling their labour force as a commodity. (Source: http://en.wikipedia.org/wiki/Proletariat)

context of the labor value theory of Smith and Ricardo. His seminal analysis on economic crises is actually the first substantial attempt of analyzing the so-called economic cycle's phenomenon[5] (*Heilbroner, 2000*).

1.2 The neoclassical school of thought

The period of the great classical economists actually reaches to an end by the end of 19th century. The dawn of the new era of economic thought is gradually dominated by neoclassical economics. Under the term "*neoclassical economics*", the relevant literature identifies those economic theories that mainly focus on the mechanism of prices determination, the income and the output distribution through the supply and demand mechanisms, the utility maximization theory, and generally, the theoretical endeavor of achieving a general equilibrium. The term "*neoclassical theory*" formally introduced in literature by Thorstein Veblen[6] in 1900, in an essay which tries to relate the so-called "*marginalists*", that follow the tradition of Jevons, Warlas and, subsequently, Pareto and Marhall, with the so-called "Austrian school" of Carl Menger.

With the advent of neoclassical theory, the general reference framework, that was initially built by the classical economists, shrinks. What is more, neoclassical economics distinguished from the classical version by removing the population as a subject variable that essentially concerns the economic analysis (*Samuelson, 1985-p.166*). In this new era of economic analysis the predominant role belongs to the investigation of the pure economic phenomena. Neoclassical theory actually changes the focus of the analysis from the long run into the short run period of an economic system that tends into full employment equilibrium, without economic recessions and crises. (*Reppas, 2002*). With the contribution of marginal analysis and mathematics, the neoclassical school of thought mainly deals with optimization issues. Neoclassical economists neglect the timely evolution of macroeconomic phenomena and mainly deal with issues such as utility maximization, minimization of the production cost,

[5] As we have already argued, Malthus was the first one who pointed out the periodical crisis phenomenon, while Mill accordingly further investigated that issue. Nevertheless, the first in depth analysis of economic crises, that early delineated the economic cycle stages, belongs to Marx.

[6] T. Veblen, 1900. "*Preconceptions of Economic Science*" in which he related marginalists in the tradition of Alfred Marshall et al. to those in the Austrian School.

profit maximization, issues of general equilibrium, and so on. Despite the substantial differences between classical and neoclassical economic theory, there is a common ground which is illustrated by the adhesion of both schools of thought in Say's law (supply creates its own demand), at least until Keynes strongly questioned that framework (*Evdorides, 2000 – p. 3*).

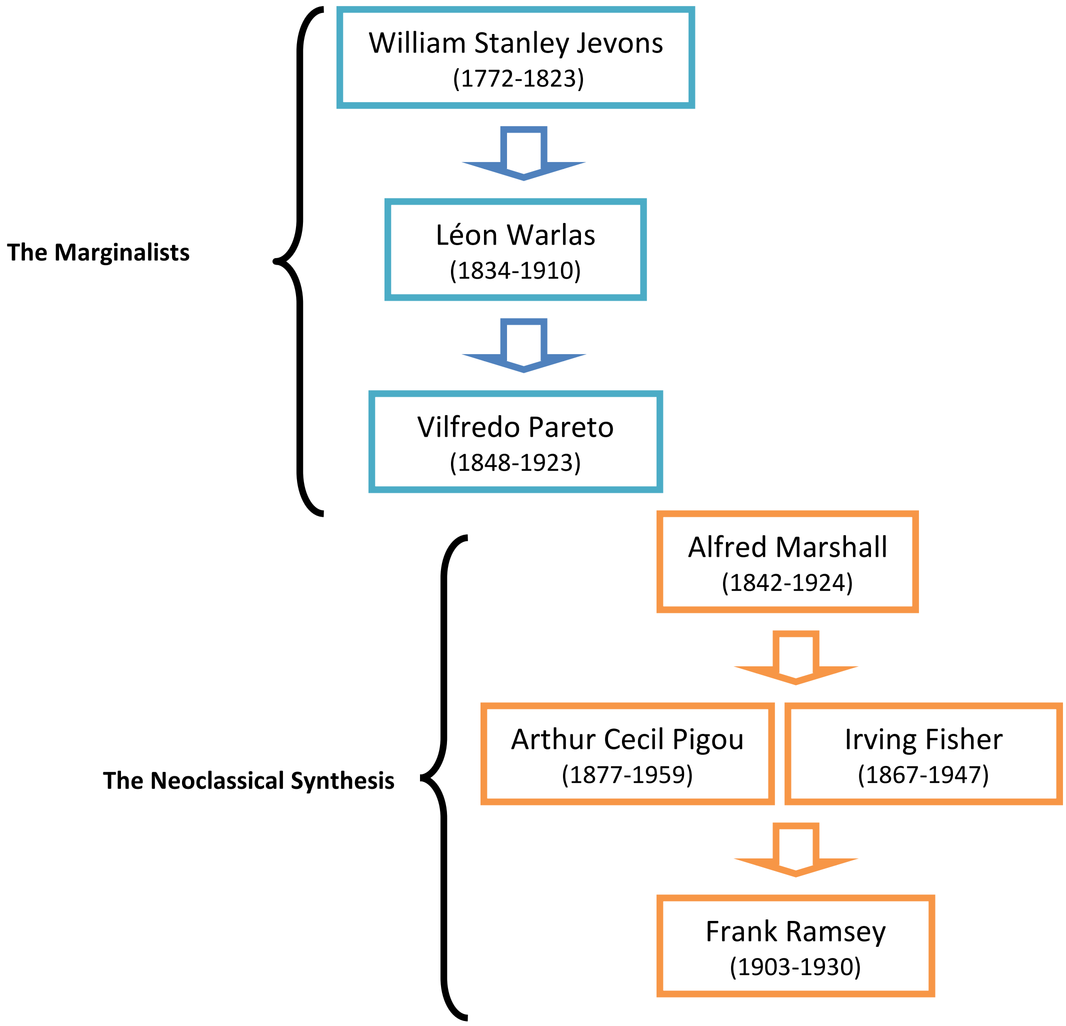

Figure 1.4 *The first generation of Neoclassical Economists*

The causes of that turn, from the long run to the short run period, should be traced in the economic reality of these years. (*Reppas, 2002).* A thorough overview of the historical reality reveals a pervasive optimism for a potential continuous and uninterrupted economic growth, based on technological change, that conjures the fears of population growth or the diminishing returns of the soil, as were articulated by the great classical economists, in particular Malthus and Ricardo. A firm belief, that dynamic full employment equilibrium of mathematical precision could be achieved, surrounds the economic science.

In the following section we present the dawn of the first neoclassical period, ending up in the early 20th century, with the advent of radical Keynesian analysis. Nevertheless, there are two theoretical contributions that are considered as the sound exceptions of the examined period. The first theory developed by the Austrian economist Joseph Schumpeter and later on another growth theory was proposed by W.W. Rostow. These two contributions will be discussed separately from the relevant neoclassical context. Figure 1.4 depicts the most representative and influential economists of the early era of neoclassical economics.

1.2.1 The Marginalists

Leon Warlas

The period of the classical economists was succeeded by the era of the so-called marginalist economists. The marginalists' era could be placed approximately between 1830 and 1930 (*Beinhocker, 2006).* A Central physiognomy of that period was the French economist Lèon Warlas. With the publication of his radical essay "*Elements of pure economics"* (*Warlas, 1874),* Warlas turns the interest of economic analysis, from philosophy, to mathematics. It should be denoted that most of the classical economists were considered themselves more as philosophers rather than as exact scientists, while the mathematics of the classical period were limited in a few arithmetic examples based on elementary algebra, without any sophisticated mathematical functions (*Beinhocker, 2006).* In order to better understand the endeavor of Warlas, in changing the context of the economic analysis, someone ought to place it in the broad context of the remarkable scientific achievements occurred during that period. Indeed, following the monumental discoveries of Newton, sciences managed to develop a new "mathematical" language that describes, through mathematical functions, more and more physical phenomena. That mechanical representation of nature entailed science with optimism concerning the ability of mathematics to interpret all natural phenomena. In that context, Warlas, inspired by the innovations in mathematics, physics and mechanics, was convinced that since the mathematical functions could accurately reflect the orbits of atoms and the planets' movement, then they could also depict the emotions, the choices and the preferences of human beings in the economic system. The mechanistic view of the concept of "general equilibrium" had just been born.

Warlas, by introducing the notion of equilibrium, from physics into economics, sets the foundations of the mainstream economic analysis. His theoretical model assumes that there is a competitive static equilibrium in a multi product – multi sectoral system with stable prices, where labor and product markets have neither shortages nor surpluses. Furthermore, Warlas "invents" an auction process[7] which determines prices in a public manner (he assumes that all actors have perfect information). Surprisingly though, while the Warlasian equilibrium model was widely adopted, its empirical validation occurred many decades later (*Arrow and Debreu, 1954*). The influence of his remarkable research was so strong that most of the next generations of economists were almost convinced that the actual economy balances exactly – or at least closely – to a Warlasian Equilibrium (*Solow, 1970*). The Warlasian model, although remained very influential, it does not attempt an interpretation of economic growth, while, under the light of contemporary analysis, it has been severely questioned (*Beinhocker, 2006; Ayres and Warr, 2009).*

William Stanley Jevons

During the same period with Warlas, William Stanley Jevons, using Bentham's definition for utility, includes in his seminal essay *"Theory of Political Economy"* (*Jevons, 1871)* mathematical functions, inspired by the functions explaining the forces of gravitational attraction. With his study, Jevons aspired to set the human behavior so predictable, hence measurable, as a physical law like gravity is. In Jevons' conception, self interest provides the incentive, the force[8], which motivates human beings to maximize their happiness or utility. Yet, we also live in a world with finite resources, hence, constrains on our actions. The solution to this problem is then to find this combination of goods and services that maximize our utility, within the constraints imposed by finite natural resources.

Jevons's substantial contribution was to portray the issue of economic choice as an exercise in a constrained optimization. In his own words, in "*Principles of Economics*": *"…The notion of value is to our science (economics) what that of energy is to mechanics…"* (Beinhocher, *2006)*. Furthermore, another important early contribution of Jevons was his observations on

[7] Known as "*Tatônnement*" in the French prototype text.

[8] *"…Just as the gravitating force of a material body depends not alone on the mass of the body, but upon the masses, relative positions and distances of the surrounding material bodies, so utility is an attraction between a wanting being and what is wanted…"* (Beinhocker, *2006*).

the efficiency improvements of coal use – an important criticism on the energy efficiency consequences, known anymore as "*The Jevons's Paradox*" – that will be fully discussed later on in the 2nd Chapter.

Vilfredo Pareto

Vilfred Pareto was an Italian contemporary of Warlas and Jevons. Pareto was better versed in physics than Warlas and Jevons, since he had been trained as an engineer first and written his doctoral dissertation on "*The elasticities of equilibrium of solid bodies"* (*Beinhocker, 2006).* Pareto managed to carry the Jevons's initial theoretical treatment of utility one step forward, through an ingenious rational argument: he distinguished four kinds of trades (Broadly known later on as the *Pareto Superior Trades*) that the people can do (*Beinhocker, 2006- page 35)*:

- win-win trades (Welfare increases)
- win-no lose trades (Welfare increases)
- None gains but someone loses (Welfare decreases)
- Some parties win while some lose, but without the ability to determine what the net impact to welfare is.

In the context of these trades, Pareto contended that rational people would only engage in trades of the first two types, both of which raise the total welfare. Consequently, he concluded that in free markets, all participants would keep trading until they had exhausted all the Pareto superior trades.

In brief, the so-called Pareto Optimal is the point at which no further trades can be made without making someone's position worse off. The Pareto Optimal is, hence, not necessarily the point of maximum welfare for the entire group of the traders, as there might be some trades that would harm some of the participants for the benefit of others, but would raise the total sum of group's utility. In conclusion, since there is no precise way to measure utility, the Pareto Optimal is the best that one can do in a free society where there is no dictatorship that could possibly order a different allocation of welfare, in favor of one group against another (*Niehans, 1990*).

This section was briefly presented the theories of the most influencing representatives of the so-called "*Marginalists*". In a nutshell, Warlas declared that his "*pure theory of economics is a science which resembles the physico-mathematical sciences in every respect*". Jevons claimed that he had created a "*calculus of moral effects*". And Pareto proclaimed that "*The theory of economic science thus acquires the rigor of rational mechanics*" (*Mirowski, 1989-pages: 219-221).* In their view, the marginalists succeeded in turning economics into a true mathematical science (*Beinhocker, 2006).*

1.2.2 The pure neoclassical synthesis

Alfred Marshall

"…Mekka of the economist lies more on economic biology rather than in economic dynamics…" (Marshall, 1920). This is a notion repeatedly used in Marshall's work and reflects his belief that economic development is a continuous and homogenous process, like the biological prototypes of living organisms. For Marshall there are three main factors that ensure the harmonious – without disturbances- economic growth (*Reppas, 2002):*

- The idea of dynamic equilibrium
- The principle of Substitution
- The internal and the external economies

In the context of these three factors, Marshall proclaims that economic growth is a process in which all economic activities gradually grow without discontinuity, disturbances or economic crises. In fact, Marshall summarizes the basic doctrine of neoclassical economists; economic growth is a continuous and almost automated process (*Schumpeter, 1954).*

According to Marshall, there is not clear evidence to believe that the economy somehow approaches a stationary state, a firm belief of most of neoclassical economists. It goes without saying, that the rigorous technological progress and achievements fed on an optimism that the offset of the diminishing returns implied by nature is possible thanks to the increasing return of human knowledge. Undoubtedly, this optimism is reflected in Marshall's work. In fact, Marshall bridged Jevons's model of single market in isolation (partial equilibrium) with Warlas's model of many interlinked markets (general equilibrium). Moreover, he was also the one who first draw the well-known crossed supply and demand curves graph (see figure 1.5) (*Breinhocher, 2006)*. However, it should be stated that Marshall did recognize – indirectly though – that the population growth issue may cause an increase in land's rent, in the future (*Marshall, 1920).*

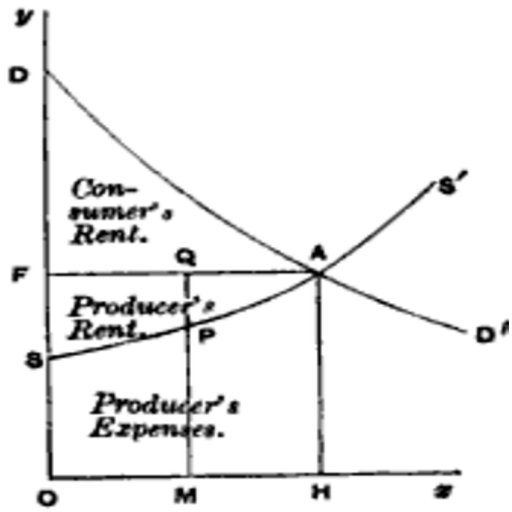

Figure 1.5 *Marshall's prototype graph of supply and demand curves (Source: Marshall, 1920)*

Arthur Cecil Pigou

Arthur Cecil Pigou was considered as one of Alfred Marshall's best students. Albeit his influence in Environmental Economics is still enormous, Pigou is not actually considered as a "*growth*" economist. Nonetheless, it worth mentioning, that when Marshall retired as a professor of political economy in 1908, Pigou was named as Marshall's replacement. Through his position, Pigou was responsible for disseminating many of Marshall's ideas and thereby provided the leading theoretical basis for what came to be known as the "*Cambridge school of economics*"[9].

Pigou's most influential work was "*The Economics of Welfare*" (1920). In this remarkable study, Pigou developed Marshall's early concept of "*externalities*". Under the notion externalities, Pigou defines the costs imposed (or benefits conferred) on others that are not

[9] Source : http://www.britannica.com/EBchecked/topic/460259/Arthur-Cecil-Pigou (Accessed June 2014)

accounted for by the person who creates these costs (or benefits)[10]. In that context, Pigou argued that negative externalities (costs imposed) should be offset by a tax (there after known as Pigovian tax), while positive externalities should be offset by a subsidy. Other than that, Pigou applied his economic analysis to a number of other problems, including unemployment, and public finance. Nevertheless, in the early 1960s, Pigou's analysis was criticized by Ronald Coase, who argued that taxes and subsidies are not necessary if the partners in the transaction—that is, the people affected by the externality and the people who cause it—can bargain over the transaction (The Coase Theorem).

Yet, another Pigou's contribution that was about to stimulate Frank Ramsey's posterior work on growth theory, posed by an interesting observation he made: "*Generally speaking, everybody prefers present pleasures or satisfactions of given magnitude to future pleasures or satisfactions of equal magnitude, even when the latter are perfectly certain to occur. But this preference for present pleasures does not - the idea is self-contradictory - imply that a present pleasure of given magnitude is any greater than a future pleasure of the same magnitude. It asserts only that our telescopic faculty is defective, and we, therefore, see future pleasures, as it were, on a diminished scale....This reveals a far-reaching economic disharmony. For it implies that people distribute their resources between the present, the near future, and the remote future on the basis of a wholly irrational preference*." (*Pigou, Economics of Welfare, 1920: p.24-5*)[11].

The externality concept remains central to modern welfare economics and particularly to environmental economics, while the most substantial externality of the economic production is consider the waste output (air pollution, water contamination, etc.).

Irving Fisher

Fisher is widely regarded as the greatest economist that America has produced. Much of standard neoclassical theory has origin from his theories, ideas and mathematical frameworks. Specifically, most modern models of capital and interest are essentially variations on Fisher's theme, the conjunction of inter-temporal choices and opportunities. Likewise, his theory of money and prices is the foundation for much of the contemporary monetary economics, including the well-known "*Fisher equation*". What is more, Fisher

[10] Source : Wikipedia http://en.wikipedia.org/wiki/Arthur_Cecil_Pigou (Accessed June 2014)

[11] Source: http://cruel.org/econthought/essays/growth/optimal/optimintro.html (Accessed July 2014)

expounded thoroughly the mathematics of utility functions and their maximization. Other than that, Fisher also developed methodologies of quantitative empirical research (*Tobin, 1987*).

However, what is really interesting from the viewpoint of growth theory is Fisher's doctoral dissertation (1892), which constitutes an exposition of Walrasian general equilibrium theory. Nevertheless, the remarkable issue of this thesis was Fisher's preface: he underlines the fact that he was unaware of Walras general equilibrium theory while writing the dissertation (*Tobin, 1987*). Furthermore, Fisher's approach on general equilibrium is quite different, and hence original, from that of Warlas. In particular, his approach was connected with the interest he developed in analogy between thermodynamics and the economic system (*BIATEC, 2002*). In order to better illustrate his dissertation, Fisher constructed a hydraulic analogue model that physically depicted how demand or supply shock in the ten interrelated markets, the mutual change of prices, incomes and consumption preferences of various consumers (*BIATEC, 2002*). Unfortunately though, both the original model and a second one constructed in 1925 have been lost to posterity (*Tobin, 1987*).

Frank Ramsey

Modern growth theory actually began with the single product – single sector model proposed by Frank Ramsey in 1928. The main assumption of Ramey's model is that there is a single all-purpose capital and a homogenous labor combined to produce a single all-purpose good (*Ayres and Warr, 2009*). In that sense, Ramsey's theoretical model assesses that growth is a perpetual motion engine with no role for natural resources inputs or any kind of waste output. As Ayres and Warr (2009) reveal, the trick, in order to generate a sort of growth process, is to assume – as in Warlas case – that every product is produced from other products made within the economic system plus capital and labor contribution. These assumptions will haunt neoclassical economic theory during the decades to come as Ayres and Warr (2009) reveal.

Furthermore, Ramsey first came up with the idea that economic growth proceeds along an optimal path, by testing actually Pigou's aforementioned idea that people tend to save too little and under-invest due to their "myopia" about the future (Ramsey, 1928). Besides his short passage from life -due to his fragile health he died at the age of 27- Ramsey deserves a small reference here as he managed to deeply affect the evolution of neoclassical economic theory, for decades after his death.

1.3 The transition. From Schumpeter and Rostow's differentiation to Keynes milestones.

An important step, before the introduction of the pure neoclassical theory of growth, is essential in order to present three scholars whose work is being diverse from the prevailing neoclassical context.

1.3.1 Joseph Schumpeter

Schumpeter recognized the contradiction between equilibrium and growth. Through his most significant publications "*The Theory of Economic Development*" (1936), "*Business Cycles*" (1939) and the "*Capitalism, Socialism and Democracy*" (1947), Schumpeter diverse his theory from other classical and neoclassical analyses (*Reppas, 2002*). In fact, he actually works with neoclassical concepts but uses them to analyze problems ignored by neoclassical theory. Specifically, while Schumpeter accepts the basic assumptions of neoclassical theory of growth – especially the theory of general equilibrium – he contradicts the neoclassical notion of perpetual growth without intermissions and recessions. The instability of economic growth is a cyclical phenomenon according him. He mainly recognizes that (*Chaudhuri, 1989)*:

- Technological Progress and Institutional innovations are the essence of the Phenomena.

- These create both growth and instability

Schumpeter observed that economic growth is not just a matter of increasing production's quantity; innovation should play a decisive role in that procedure. Not all the innovations used, finally, in production. When and only when, an innovation is taken up, does become actually an innovation. He distinguishes innovations in large (e.g. internal combustion engine) and small ones. Basically, the large ones create booms in the capitalistic economy. A new innovation being adopted by manufacturers creates a gradual boom in growth, until a new equilibrium state reached in a higher level of out put[12]. Consequently, in Schumpeter's own words: "*growth comes to economy not in a steady stream but in gales of creative destruction*" (*Beinhocker, 2006*).

In order to thoroughly communicate the value of Schumpeter's observation about innovations, someone should focus in the fact that, at that time, the Neoclassical Economists tended to apprehend innovations as an external (exogenous) factor of economic growth. This early contribution of Schumpeter about the endogenous nature of innovations, its implications in economic system and consequently on economic growth, was to stimulate later on the so-called endogenous growth theory, within the realm of neoclassical theory (*Beinhocher, 2006*).

Besides innovations, Schumpeter also adopts and develops the cyclical phenomenon introduced by Marx. In that context, Schumpeter (1939) actually adopts and evolves the tradition that started with the early observations of Malthus and Mill, continued by Marx, to describe the phenomenon he named the "*business cycles*". Apart from this, Schumpeter's analysis was in stark contrast with Marx's theoretical model. Schumpeter claimed that the result of capital's reward was not based on the exploitation of labor surplus; it was mainly the result of introducing new innovative procedures in goods' production (*Heilbroner, 2001*). The origin of the wealth, according to Schumpeter lies in the heroic efforts of individual entrepreneurs (*Beinhocher, 2006*). Finally, his theoretical model ends up with a gradual transition[13] from capitalism to socialism.

All in all, Schumpeter's ideas rigorously described though, had suffered by a crucial shortcoming; they were never translated into rigorous mathematic equations, hence could never be reconciled with the neoclassical mathematical framework (*Beinhocher, 2006*).

1.3.2 Walt Whitman Rostow

W.W. Rostow is well known about his effort to explain economic growth through five stages of evolution. In 1959, Rostow published "*The Stages of Economic Growth*": A Non-

[12] This reminds the N- shape dialogue in EKC's which is indirectly based on Schumpeter's assumptions. When an innovation reaches the maturity level, instability occurred, until another innovation create a new boom in economic production, and so on.

[13] Unlike Marx, Schumpeter foresees no violent revolutions and devastation but a gradual transition to socialism.

Communist Manifesto, which proposed the Rostovian take-off model of economic growth, one of the major historical models of economic growth (*Rostow, 1959, 1960, 1978*). From one point of view, Rostow attempts a linear historical analysis, analogous to Marx's socio-economic evolution, albeit based on neoclassical theory. While this model takes as granted the basic assumptions of neoclassical growth theory, it is cited – together with Schumpeter's model – as an exceptional effort to criticize (theoretically though) the neoclassical theory. In particular, Rostow's model argues that economic growth occurs in five basic stages of varying length (*Reppas, 2002*):

- Traditional society
- Preconditions for take-off
- Take-off
- Drive to maturity
- High mass consumption

Nevertheless, Rostow's five stages were fiercely criticized due to their descriptive character and, mainly, because of the lack of a coherent theoretical model that mathematically tests his assumptions about growth stages (*Reppas, 2002*).

1.3.3 John Maynard Keynes

Neoclassical economic theory engaged the presumed existence of a self-adaptive economic system in which interest rate and capital accumulation automatically equilibrates with investments and savings. Within that economic system of perfect competition, economic growth is always achieved in a full-employment level (*Reppas, 2002*).

The rightness of neoclassical theory was exceedingly challenged by John Maynard Keynes. Despite the fact that Keynes is not regarded as a growth economist, his breakthrough analysis established him as, probably, the most influential economist of his time. Keynes' contribution could be briefly summarized as "*deficit spending by governments in order to stimulate demand (during recessions), followed by a surplus period in governmental budget that pays off the accumulated debt, during periods of high employment and inflationary pressures*" (*Ayres and Warr, 2009*). Like Malthus' early observation, Keynes asserted that under-consumption causes unemployment and leads to recessions (hence, impedes growth). Nevertheless, the ongoing debate between the so-called "*Supply siders*" (tax cuts) and the "*demand siders*" (deficit spending), that presents the contemporary criticism in Keynes' work, is beyond the scope of this chapter.

However, what is actually important for current analysis is that Keynes' analysis highlights the income as an essential determinant factor of saving, besides interest rate, while he criticizes neoclassical theory for full-employment equilibrium, as this state of equilibrium is not achievable by default. Under the light of new evidence, that the progressive work of Keynes brought out, his contribution constitutes an actual milestone for growth theory, due to the very fact that his analysis about unemployment and recessions stimulated the subsequent studies of Harrod (1939) and Domar (1946), known as the Harrod-Domar model that dominated growth theory in neoclassical economics during the post-Keynsian period and will be presented into the next section.

1.4 The post-Keynesian Transition of neoclassical theory

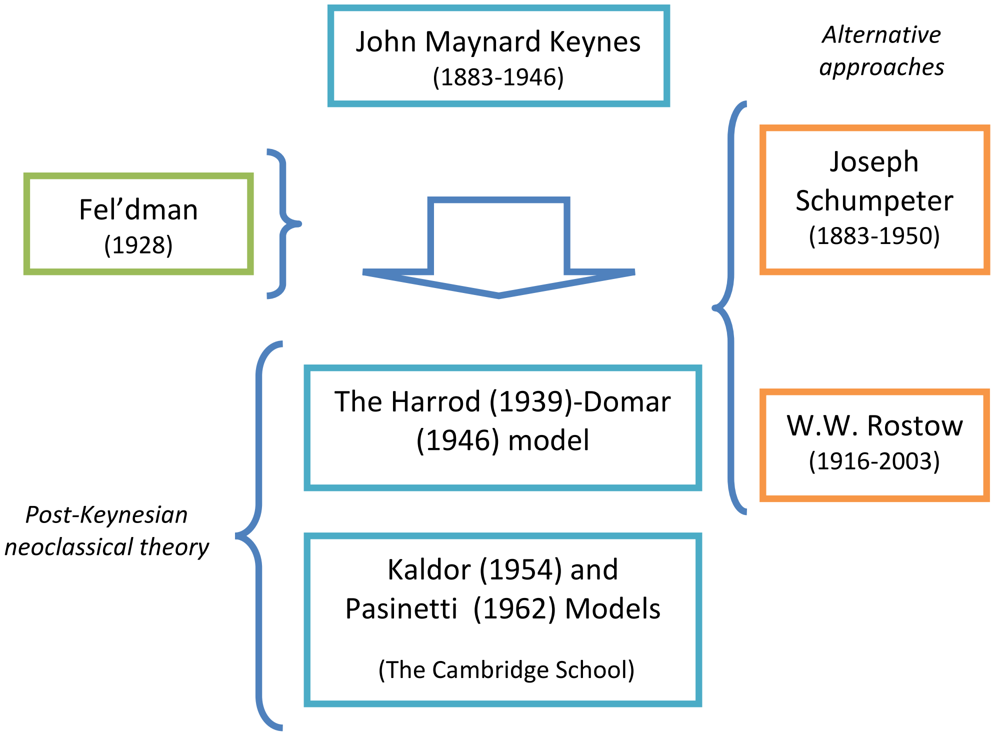

Figure 1.6 *The post-Keynesian transition of neoclassical economic theory and the alternative approaches of Schumpeter and Rostow*

The role of land gradually receded in comparison with the role of industrial capital, as the 19th century went on. By the early 20th century, growth per capita was supposed to be driven by the accumulation of industrial capital (*Reppas, 2002)*. Apart from the work of Keynes, the most influential models of the 1930s and `40s were based on a formula actually attributed to Fel'dman's (1928) model, which developed for the Soviet Union and emphasizes the investment in heavy industry as a source of economic growth. The novelty in Fel'dman's work is that he proposed, for the first time, an equation of the rate of growth of the economy to the savings rate divided by the capital-output ratio, or (equivalently) the ratio of annual savings to capital stock (*Ayres and Warr, 2009*). In this section we examine the most representative models of the post-Keynesian era which are deeply influenced by the Fel'dman's early empirical contribution and Keynes' theoretical conception (Figure 1.6).

1.4.1 The Harrod-Domar Model

The queries imposed by the Keynesian analysis challenged the dominant neoclassical model. They came up with a new problem: which is the appropriate increment rate for goods production, investments and capital, in order to ensure the equation between supply and demand, as well as the full-employment of the increasing labor force? The first post-Keynesian neoclassical models, that attempted to scrutinize the restrictions raised by Keynes, were developed by **Henry Roy Forbes Harrod** (1939) and **Evsey David Domar** (1946), broadly known as the Harrod-Domar model. They actually developed the first macroeconomic model to formally analyze the growth problem, following the Keynesian approach that the market mechanism is not able to attain full employment of labor (*D' Agata and Freni, 2003*). More specifically the model proposes that the growth rate is estimated as: growth rate = annual savings rate/annual Capital stock rate (*Chaudhuri, 1989*). Nevertheless, the actual inventor of this influential formula was Fel'dman (1928) hence, Harrod and Domar to some extend "*rediscovered*" this recipe (*Ayres and Warr, 2009*).

The main questions that this model attempts to answer are in brief (*Chaudhuri, 1989*):

- Do entrepreneurs react to disequilibria in such a manner as to restore equilibrium?

- Is full employment possible?

Due to this questioning, the main assumptions of Harrod-Domar model can be summarized as (*Reppas, 2002*):

- The labor force grows at a constant rate

- Savings are solely depended on national income

- The ratio of inputs (capital and labor) remains constant in time independently to what the growth rate of output is[14].

One of the basic conclusions of the Harrod-Domar model was the instability of the equilibrium level in the long run. Although this pioneering model lighted the way in which modern growth theory developed, it was severely criticized for being excessively simplistic and rigid. Furthermore, the fact that the model failed to explain the economic development of post-war period, while its conclusions were quite contradictory to neoclassical theory[15] underlined the imperative for the development of mathematical models that are closer to the main assumptions of neoclassical theory. As it will be shown later on in this chapter, the subsequent works of Solow and Swan came as the remedy that would heal the gap, between theory and estimations, created by the H-D model (*Reppas, 2002)*.

1.4.2 Kaldor and Pasinetti Models

The work of Kaldor and Pasinetti is broadly cited as the "Cambridge models" of economic growth. In seeking a growth theory that explains the real dynamics of economies, Nicholas Kaldor criticized Harrod-Domar's model on the grounds that it explains only the growth of an a-cyclical economy (*Kaldor, 1954*). The general assumption of Kaldor's model is that there is full employment and that investment depends on the level of savings (Evdoridis, 1995 – pp. 13-14). Moreover, for the relatively constant economic growth of total employment observed in post-war western economies, was that the income distribution was optimal (Jones, 1993). Because of the socio-economic factors underlying the phenomenon of growth,

[14] This assumption implies that, in line with neoclassical theory, technology does not permit the substitution between the inputs (Ρέππας, 2002 – page: 365-366). Furthermore, the instability is cumulative and Harrod concentrates on the problems of adjusting capacity to expectations of demand and, thus, largely ignores the technical progress (Chaudhuri, 1989).

[15] Due to the instability it results, the Harrod-Domar model renders state intervention in order to control inflation and unemployment. This conclusion evolves in stark contrast with neoclassical theory which pressumes that free competitive markets lead economy in the desirable growth rate.

he asserts that a satisfactory growth theory cannot be constructed without a business cycle[16] theory (*D' Agata and Freni, 2003*). What is more, his major contribution consists in solving the stability problem of the Harrod-Domar model, which previously described. Besides the major criticism on Kaldor's model (Samuelson and Modigliani, 1966), the simplicity of his model made it attractive in various subsequent theoretical analyses.

Kaldor's approach has been developed and pursued further by Luigi Pasinetti (1962). Pasinetti's contribution came from his willingness to correct what he called "the logical stumbling block" of Kaldor's theory (*Reppas, 2002*). His approach makes an explicit division of society into capitalists and workers and, hence, assumes that a part of profit should owned by workers due to their past savings, which apparently contributed in the creation of capital (*Jones, 1993*). Nevertheless, his study consists a notable turn, from the original attempt to construct a growth theory, to a more business cycle theory.

To the end, these two models did not manage to evaluate with accuracy the contribution of profit as a factor of economic growth, while, according to their structure, actually tend to explain more the income distribution rather than the economic growth (*Evdoridis, 1995*)

1.5 Neoclassical Growth Theory: The foundation of the Solow-Swan model

The main thrust of neo-classical theory is towards demonstrating that a growing economy is not inherently unstable, as Harrod suggested. Chaudhuri (1989) summarizes the main assumptions of neoclassical growth theory of this period:

1. Y=C+I,

   Where, Y= Output, one homogeneous commodity; C=Consumption; I=Investment

2. Classical savings function. Economy saves a constant fraction of its income.

   S=sY, Where: s= the propensity to save.

3. S=I. Savings are always equal to Investment

4. As in the Harrod's model, the labor force grows at a constant rate (the growth rate of population, actually). $\Delta L/L=n$

[16] Actually, Kaldor follows, by this assumption, the fundamental Schumpeterian assumptions.

5. For each level of technology, there is a continuous aggregate production function, relating the level of inputs (Capital, Labor), to the level of output.

This section presents in brief the enormous contribution of the so-called Solow-Swan model in growth theory, as well as the so-called á la Ramsey growth models, appeared later on.

1.5.1 The Solow-Swan model

It goes without saying that the standard model of growth in the neoclassical paradigm is the single-sector model developed half a century ago by Robert Solow (*Solow, 1956, 1957*). A very similar model was set forth about the same time by Trevor Swan (*Swan, 1956*), while the theory further developed by James Meade (*Meade, 1961*). Both Solow and Meade were awarded with a Nobel Prize in Economics for their accomplishment (*Ayres and Warr, 2009*). From this point forward the author will be referring to this model as the "*Solow-Swan*" model.

Solow's mainly attempted to solve the stability problem of full-employment by adopting a neoclassical framework, though with respect to the Keynesian growth theory (*D' Agata and Freni, 2003*). In a nutshell, the Solow-Swan model expresses the logarithmic time derivative of output elasticities with respect to capital, labor and time multiplied by their corresponding growth rates. The growth rate for labor is normally taken to be equal to the population growth rate[17]. The growth rate of capital is defined as the rate of savings (thus, investment), less depreciation. Hence, the output Y is a function of K (Capital stock) and L (Labor-employment) (*Ayres and Warr, 2009*).

The model

Actually, the major contribution of the Solow-Swan model was that it was managed to alleviate the constrictions raised by the Harrod-Domar model, by adding two new elements: the rate of capital-labor is variable, hence, there is a perfect substitution between the two inputs; and secondly, the capital has a decreasing marginal productivity (*Reppas, 2002).*

[17] This is the general remark. However, there are many models that account for the growth rate of Labor in more detail e.g. by estimating only the labor force growth rate by a specific age group, economy sector, etc.

According to Solow (1957), the production process is better described with a Cobb-Douglas production function:

$$Y=AK^{\alpha}L^{\alpha-1} \qquad (1)$$

Where,

K=Capital

L=Labor

A=technological progress

α, α-1= elasticities of substitution

Cobb-Douglas form with an exogenous multiplier A(*t*) depending only on time (*A(t) is in fact, an exponential function of time which increases at constant average rate based on past history*). A(*t*) multiplier it is now called Total Factor Productivity (TFP).

An insight of the Critique on the Solow-Swan model:

- One implication of the Solow-Swan model, or any production model, is that Capital and Labor are perfectly substitutable for each other. Adding a third or a fourth factor of production does not change this requirement for mutual substitutability (*Ayres and Warr, 2009*).

- The core assumption that only K and L drive growth was sharply challenged in the early 1950s (*Abramovitz 1952, 1956; Fabricant 1954*).

- The neoclassical paradigm does not allow any role for "real" material flows (except as consequences, but not causes, of economic activity). Economy is considered to be a closed system in which production and consumption are linked only by money flows. (Wages flowing to labor and expenditures flowing to production). The goods and services produced and consumed are supposedly measured in real terms, though in practice they are measured only in monetary terms (*Ayres and Warr, 2009*).

- In the Solow-Swan model, technological progress is not created by capital or labor. Hence, technological progress is exogenous. Some economists have called it “manna from heaven”.

- Long-run growth of the Solow-Swan model considers a growing population coupled with a more efficient labor force. The direct consequence of this approach is that long-run growth rate in these models is ultimately tied to demographic factors , such as growth rate of population, the structure of the labor force and its productivity growth, all exogenously determined. Hence, the only policies that could contribute to long-run growth were those that would increase the growth population or the efficiency of labor force (*Turnovsky, 2003- p. 1*).

1.5.2 The á la Ramsey growth models

Inspired by the seminal article published by Ramsey (1928), several growth models have tried to improve Solow-Swan’s model by making the rate of household’s savings endogenous. In that kind of models, traditionally called “á la Ramsey”, the economic decisions concerning production and savings are taken by a planner choosing over an infinite horizon (*D’ agata and Giusepe, 2003*). The most representative growth models of that category can be found in the early works of Cass (1965) and Koopmans (1965). The assumptions concerning their production functions are the usual neoclassical ones, providing a positive theory of growth like the Harrod-Domar’s and Solow’s models (*D’ agata and Giusepe, 2003*).

1.5.3 Epilogue

The Solow-Swan model was consistent with Smith’s insight that, while population growth might increase the total wealth of a nation, only improvements in productivity could make a nation richer. Yet, unlike Schumpeter, Solow wanted to measure innovation in a way that would be consisted with neoclassical theory hence maintain the equilibrium of the economy (*Beinhocker, 2006*). Actually Solow tried to envision the economy in a dynamic equilibrium – a balanced growth (*Solow, 1956*). Due to that purpose, he treated two key variables as exogenous: the rate of population growth and the rate of technological change. Furthermore, he showed that the rate of savings and the total amount of capital in the economy would automatically be balanced in response to changes in population growth and technology. In that context, markets of capital and labor are adjusted in order to keep everything in a

Pareto optimal equilibrium, even as the economy growths (*Beinhocker, 2006*). By all odds, another substantial contribution of Solow's work was that he actually described back in 1956 what is now broadly known as "*the knowledge economy*". Nevertheless, research interest in these models tapered off around 1970, due to other issues: oil shocks, unemployment, inflation etc.

Beyond the realm of neoclassical theory, what is really important for current dissertation is that the origins of physical production in the neoclassical paradigm remain unexplained. Most economic models utilizing either Cobb-Douglas form, or CES (constant elasticity of substitution) (*Arrow et al., 1961*), and accept the implication of mutual substitution among factors of production. The neoclassical model does not allow any role for real material flows (*Ayres and Warr, 2009*), an issue that will be discussed in detail in the next chapter which addresses economic growth within the context of natural resources scarcity.

1.6 Endogenous Growth Theory

The issue of economic growth intrigued almost all schools of economic thought. Nevertheless, the systematic and extensive engagement with the problem of economic growth intensified after the substantial critique of Keynes (*Keynes, 1936*), with the pioneering, at that time, contributions of Harrod, Domar, Passineti, and so on. In addition, equally important was the contribution of the neoclassical growth model that introduced in the mid-1950s by Solow and Swan. The activation of more and more scholars in the employment of models which attempt to explain the ongoing economic growth, characterizes the whole 1960s. Nonetheless, from the late 1960s until the mid 1980s, an intense stagnation in growth theory is observed (*Evdorides, 2000*).

The waters of this observed stagnation were stirred by the innovative contribution of the theory of the endogenous economic growth. Contrary to the prevailing neoclassical model (Solow, 1956, 1957; Swan, 1956), where the rate of economic growth was defined exogenously and it was dependent on the change rate of labor force and the technical change, in these new growth theories the rate of growth was endogenous, defined within the boarders of the model. The conception of endogenous growth is actually based on an ingenious broader classification of the notion capital, into the general manufactured capital and the innovative conception of the so-called "*Human capital*" (*Evdorides, 2000*). In the context of this new expanded definition, the capital of an economy includes, besides monetary and other material dimensions, the accumulation of knowledge within the human beings. Consequently, when the capital of an economy increases, simultaneously is increasing the productivity of human capital, which in turn causes positive loops that further enforce and increase the aggregate productivity of the economy as a whole.

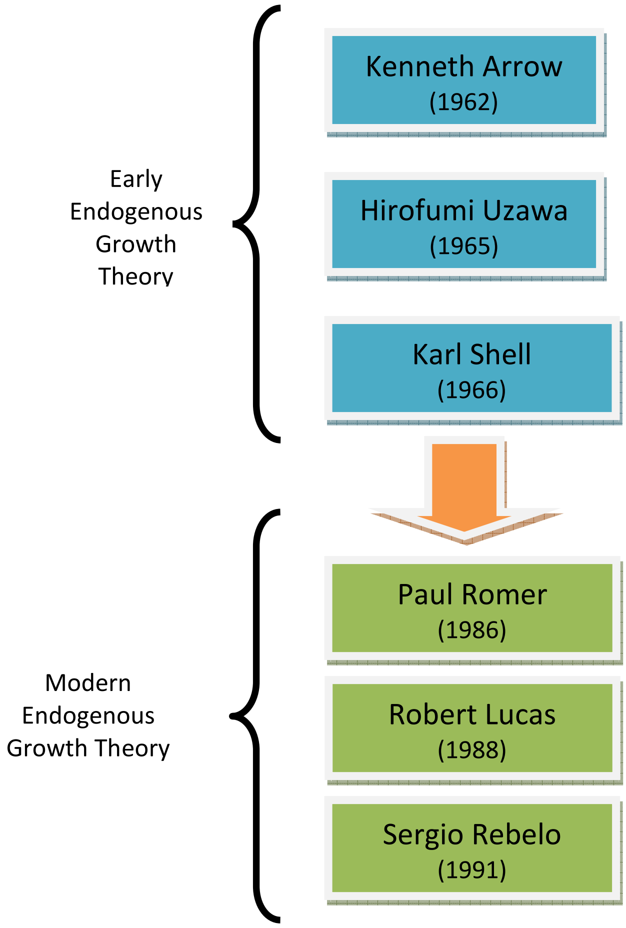

Figure 1.7 *Endogenous Growth Theories.*

In that context, the model of endogenous growth covers a substantial default of Solow's growth model, concerning the properties of the labor production factor. Specifically, the production function that Solow constructed (Solow, 1956, 1957) is based on the quantity of labor and not on the qualitative aspects and attributes that the labor force incorporates; hence, Solow's model actually obscures the properties of human capital that is incorporated within labor force (Reppas, 2002). The labor force, as a production factor, affects positively the growth process in two ways: as a quantity (more workers) and with its qualitative improvements (more knowledge, attributes and craftsmanship increment). As far as the neoclassical growth framework concerned, these two dimensions are determined in an exogenous manner, with population growth (quantitative increment) and with technical change (qualitative change). The exogenous definition hypothesis is based on the assumption that technological progress and knowledge are available to everyone without any cost. Nevertheless, the empirical analysis concerning the, observed at that time, growth trends between developed and developing countries, as well as the continual divergence between poor and wealth countries, contradicted and strongly questioned these assumptions (*Reppas, 2002*).

The following analysis distinguishes the endogenous growth theory in two periods, early and mature. Figure 1.7 pictures the main representatives of the early and mature period of the theory of endogenous growth.

In brief, the introduction to the endogenous theory of growth in modern analysis has passed through many different paths and alternative approaches. Seen from this standpoint, most of the theoretical research in the golden era of neoclassical paradigm mainly concentrated on the effort to make savings and technological progress endogenous (*Pomoni, 2003).* As it was previously mentioned, the "*endogenization*" of savings was the work of a group of young economists – the a la Ramsey models – such as Cass (1965), Uzawa (1965), and Shell (1966). Nevertheless, despite their successful contribution to applied techniques of dynamic optimization, their advance in the analysis of the factors that determine economic growth remained relatively weak (*Pomoni, 2003).*

Yet, what is actually important for our analysis is the technological progress. The effort to endogenize technological progress followed basically two paths (*Pomoni, 2003*): Kaldor's observation (*Kaldor, 1957)* that technological progress is incorporated in new capital goods was further supported by Solow (1960), who developed the assumption that "*technical innovation*" influences technological progress only if it is incorporated into new capital goods, or via substitution of outdated equipment with the latest models (*Solow, 1960-p. 90*).

The second path of technological progress's endogenization is the early contribution of what is now known as the early theory of endogenous growth and it will be presented in the next section.

1.6.1 Early Endogenous growth Theory

The very foundations of endogenous growth theory lie on the consideration of knowledge as a factor of production. If we accept the fact that acquired knowledge becomes an essential factor of production, then its growth (technological progress), becomes an endogenous process (*Pomoni, 2003).* This early stage of endogenous theory of growth is known as the so-called AK approach, with roots back to the Harrod-Domar AK formalism (*Ayres and Warr, 2009*).

The research on endogenous technological progress starts with the seminal paper of Arrow (1962), a fundamental neoclassical contribution to the endogenous growth theory; the well-known Arrow's "*learning by doing model*". According to Arrow's model, the rate of technological progress depends on past experience. In other words, technology is a process of "*learning by doing*", while total output or the investment accumulated at any given time may be considered as an index of such a learning process (*Evdoridis, 1995*). Arrow's model represents the most influential attempt to propose an endogenous mechanism for growth in the neoclassical school. However, there are mainly two basic limitations concerning Arrow's assumptions (*Pomoni, 2003)*: long run growth is only partially endogenous and depends solely on working population dynamics, as in Solow's model; secondly and most importantly, the learning process is considered as the involuntary by-product of the process of accumulation, hence it is not determined by an economic choice.

Closely to Arrow's contribution, the next attempt to endogenous growth theory was formulated by Uzawa (1965). The novelty of Uzawa's model is based on his assumption that besides the sector which produces final goods, there is also another sector which produces knowledge. Moreover, the research sector employs labor in order to produce new ideas which shift the production function, of goods' production sector, upwards. In that context, technological progress depends on the proportion of the labor force employed in the research and education sector (*Pomoni, 2003)*. Specifically, technical progress is a function of the current level of technology and of the number of the persons employed in research and education (*Evdoridis, 1995*). Towards the same direction, we can distinguish other studies (*Phelps, 1966*).

The third major contribution to the early approaches of endogenous theory of growth belongs to Shell. Shell's analysis (*Shell, 1966, 1967*) is closely related to Uzawa's work, in the sense that accumulation of knowledge is depended on the resources allocated to the research sector (*Pomoni, 2003)*. However, the novelty of Shell's work, that distinguishes him from Uzawa's approach, is the observation that accumulated new ideas – knowledge – could be considered as a production factor in their own right (*Pomoni, 2003).* Furthermore, Shell develops a production function in which the stock of knowledge is the third factor of production, alongside with labor and capital, while he considers technology as a public good (*Shell, 1974-p. 79*). This assumption which addresses knowledge as a public good was about to play a decisive role in the next generation of endogenous growth models.

1.6.2 Modern Endogenous Growth Theory

The 1970s were a very difficult period for the neoclassical research dedicated on economic growth. The effort to put more realism within the theoretical context of analysis led to an increase in technical complexity, such as the multi-sectoral models (*Burmeister, 1990*). In the end, this complexity resulted in exactly the opposite results (*Pomoni, 2003)*. However, in the mid 1980s growth theory experienced a remarkable revival and became once again a profoundly active field in macroeconomics. A group of researchers led by the Stanford economist Paul Romer, became significantly dissatisfied with the fact that the actual driver of growth –technology- was exogenous in Solow's model, and to that point re-discovered the Schumpeter's assumption expressed about fifty years ago, that innovation should always be considered as an endogenous factor (*Beinhocker, 2006*). This new growth theory (*Turnovsky, 2003*):

- has an international orientation

- re-conciliates theory with empirical evidence

By setting as starting point the seminal papers of Romer (1986) and Lucas (1988), the growth theory takes a different direction, than the earlier neoclassical view, through an endogenous determination of technological change.

This milestone period for the so-called Neo-AK models (*Ayres and Warr, 2009*) is dominated by Romer's remarkable contribution (*Romer, 1986; 1987; 1990*). Romer located the source that motivates growth, not in the heroism of the entrepreneur[18], but in the very nature of technology itself. What is more, he argued that the more knowledge we accumulate the greater the payoff from the next discovery will be. For Romer, knowledge is what economists refer to as an "*increasing return*" phenomenon (*Beinhocker, 2006*). In that context, Romer (1990) constructed a two-sectors model were the new knowledge produced in one sector is used as an input in the production of the final output. This treatment of knowledge (technology) accumulation is actually the key distinction between the new and the old theories of growth. Romer managed to create a positive feedback loop in his model – a virtuous circle – in which the more society invests in knowledge (technology), the richer it gets and, hence, it has greater payoffs to further investment in knowledge. In that context, Romer assumes that knowledge could be monopolized long enough to be profitable to the discover stage, yet almost immediately becomes a free good accessible to others (*Ayres and Warr, 2009*). Behind Romer's ideas we can trace the early Kaldor's idea, further developed by Shell, that technology is a public good. Nontheless, Romer dealed with success the shortcomings derived by the early observation of Kaldor, by assuming that knowledge is produced privately (*Pomoni, 2003*), yet it almost immediately becomes available as a free good (spillover) to everyone and achieves due to this effect increasing returns – because knowledge begets knowledge – (*Ayres and Warr, 2009).* The result of Romer's model is unbounded, exponential growth (*Beinhocker, 2006*).

A closely related approach has been proposed by Lucas (1988), based on some ideas of Uwaza, focusing on "*social learning*" and the development of "*human capital*" (*Ayres and Warr, 2009).* In a similar manner, Lucas (1988) proposed a two-sector based model, where private capital disaggregated in: Human and non-Human capital. However, Lucas' model is less innovative, compared with that proposed by Romer, on the interpretative level (*Pomoni, 2003*). According to his approach, the spillover is indirect: the more human capital the society possesses, the more productive each individual member of this society will be (*Ayres and Warr, 2009).* Lucas succeeded by adding in Uzawa's model a more microeconomic context; the research sector is being replaced by the notion "*human capital*" and the accumulation of human capital depends linearly on the time each worker spends on study and training (*Pomoni, 2003*).

[18] As Schumpeter suggested

Other contributions to the field of endogenous growth divide capital explicitly into real and human capital (*Rebelo, 1991*). Rebelo uses the simplest endogenous growth – AK model – which is actually a *á la Ramsey* model.

To sum up, Romer, Lucas and Rebelo, among others, completely re-constructed the neoclassical growth theory by shifting the interest of the analysis from the material resources (capital and labor), to the immaterial knowledge, technology and innovation (*Pomoni, 2003*). Modern endogenous theory continues to develop, in a close relation to the neoclassical theory, with the works of Ashion and Howitt (1998) and the "neo-schumpertian" approaches of Barro and Sala-I-Martin (1995). Furthermore, critique on the endogenous growth theory models for the constant returns to scale assumption (*Solow, 1994*), created the "*non scale growth models*" (*Jones, 1995*). But, in the light of empirical evidence, these models are somehow hybrids of the endogenous and neoclassical models (*Ayres and Warr, 2009*).

By all odds, what is really interesting for the following analysis is the total absent of the natural resources as an input in the production process, in the early growth models, and the wide comprehension of natural resources as intermediate goods, instead of primary factors of production, within the vast majority of all the aforementioned approaches. This is an issue that it will be challenged in the next chapter.

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2ND CHAPTER

Perspectives of natural resources scarcity within the context of economic theory of growth.

A historical viewpoint

"…Rising productivity, rather than drawing down humanity's stock of natural resources capital may, in an effective sense, actually augment it and may be able to continue to do so for the indefinite future…"

William Baumol, 1986-p.178

"… The question that confronts us today is whether we are going to discover new resources of energy that can be safely used. No elasticities of some Cobb-Douglas function can help us to answer it….."

Nicholas Georgescu-Roegen, 1979-p.98

2.1 Introduction

The pessimism of the nineteenth century endowed economics with the title "*the dismal science*". As it is already discussed at the first chapter, the classical economists Malthus and Ricardo envisioned models of growth in which the rate of population growth was surpassing the growth of output. Despite the restricted consideration of arable land as the only primary resource input at that time, Malthus and Ricardo managed to realize, at these very early stages of economic science's evolution, that the primary constraint to economic expansion resided in nature itself (*Cleveland, 1991*); irrevocably, natural resources will become increasingly scarce with time, something that will inevitably affect the economic growth process. Specifically, Malthus assumed that scarcity will rise due to constraints in arable land caused by overpopulation, while Ricardo argued about the declining quality of land (diminishing returns), as the production process (and population) expands. Contrary to the pessimism about the forthcoming scarcity endowed by the classical economic school of thought, a wind of optimism blows as the neoclassical school of economic though engages an era of new approaches and methodologies. From the seminal work of Hotelling (1931), and the complete absence of natural resources (*Solow, 1956*), to the updated neoclassical models that include natural resources and technological progress (*Solow, 1974*a*; Stiglitz, 1974*a), a fundamental assumption remains profoundly unchanged; natural resources are not the most essential input of the economic process. The neoclassical model of production assumes that capital and labor are the primary inputs of the production process (*Cleveland, 1991*). Contrary to this viewpoint, the alternative approach of ecological economics highlights the crucial contribution of natural resources in economic growth. The biophysical model of the economic process assumes that capital and labor are intermediate inputs produced ultimately by the actual primary factors of production: low entropy energy and matter (*Cleveland, 1991*). Towards this ongoing debate, the present chapter attempts a brief historical representation of the natural resources scarcity issue within the context of the two opposite schools of economic though: weak versus strong sustainability, neoclassical versus biophysical model of the economic process. Furthermore, it engages the crucial implications of the scarcity dialogue in contemporary empirical analysis such as the so-called decoupling and the rebound effect. The present chapter is structured as follows: a short section briefly summarizes some important definitions, such as natural resources scarcity, natural and man-made capital, reproducible and non-reproducible means, end-means spectrum, and so on. Accordingly, the next section provides a brief historical review of the most important aspects of the neoclassical economics of natural resources and economic growth, and finally, the rest of the chapter ends up with the critical repost of biophysical school of economic thought to the neoclassical theory, and the empirical contributions of the contemporary rebound effect dialogue.

2.2 Perspectives of natural resources scarcity within the economic theory of growth

2.2.1 Introduction

Before reviewing the dialogue that concern the role of natural resources in the economic process, it is essential to provide the definition of some important terminology that will be used in the following sections. This first step of clarifying concepts and notions that will be utilized is very important before focusing on the essential debate that concerns the natural resources scarcity and its implications on economic growth, within the realms of economic science, through mainstream and heretic approaches.

A definition for natural resources

To begin with, the adequate definition of what is actually defined as natural resources and the attributes that determine their scarcity and the potential substitutions among them, remains somehow still debatable, within economic theory. In a nutshell, all natural resources are assets whose utilization (consumption) yield service flows (*Smith and Krutilla, 1979*). Earlier studies apprehended natural resources as raw materials that were "*produced*" by extractive activities and "*consumed*" during the production process. For example, the majority of early neoclassical models were initially directed solely to mineral resources (*Hotelling, 1931*). Following the seminal article of Smith and Krutilla (1979), we adopt the most appropriate definition of natural resources as "*all the original elements (energy carriers and mass) that comprise the earth's natural endowments*". A more detailed analysis concerning further classification and categorization of natural resources will be displayed in the chapters 5-6.

What is scarcity?

The main purpose of the economic science is to provide an optimal solution to the ultimate economic problem: to use the finite means wisely in the service of infinite ends (needs). Herman Daly, in his exceptional ends-means analysis (*Daly, 1980; 1996*), defines low entropy matter-energy as the ultimate means that man utilizes and cannot, by definition, create or replenish. According to Daly, capital stock and labor power are intermediate means. From the ends point of view, besides the ultimate end –let us arbitrary define it as the optimal allocation of means (ultimate and intermediate) for achieving the best possible (optimal) Pareto welfare for all participants – there are the intermediate ends (residence, education, health, well-being, and so on). Daly argues that mainstream economics pay attention only at the middle range of figure 2.1, while absolute limits are absent from their paradigm, as the poles of Figure 2.1 (the ultimate ends-means) are excluded from the focus of mainstream economic analysis.

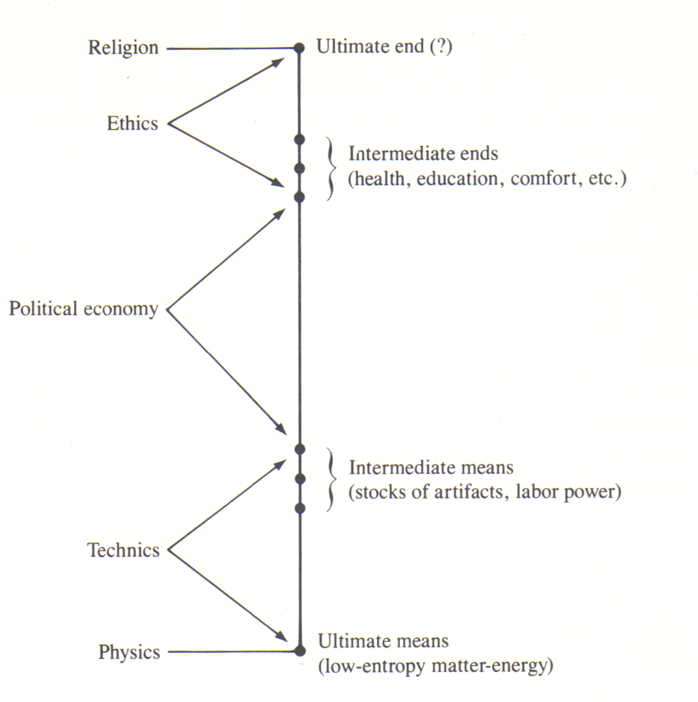


Figure 2.1 *The ends-means spectrum (source: Daly, 1980-p.9)*

The economic problem vanishes if we assume the abundance of all natural resources. If that assumption could hold true, then the term scarcity vanishes as well, since the very source of the scarcity concept lies on the finite nature of the ultimate means. In the real world however, the economic process is a struggle of satisfying all society's competing ends, by rationally allocating the scarce (finite) means. In essence, the substance of the resources scarcity problem is deeply interrelated with the goals that society sets (ends) and the state of technology that converts natural resources (ultimate means) and other intermediate means (capital, labor), into final goods that serve human needs (intermediate ends) (*Smith* *and Krutilla, 1979*). Indeed, the actual moderator of natural resources scarcity lies in the ends-means spectrum. The one who sets the boarders of the ends-means relationship actually defines the importance (or not) of the scarcity.

The neoclassical framework resolves the issue of scarcity in terms of substituting natural resources in the production process. In general, the neoclassical growth theory indeed recognizes that particular resources are finite, yet it still does not recognize any general aggregate scarcity of all natural resources. According to Daly, growth economists' vision is one of continuous growth in intermediary means, a vision that in other words translated as "*infinite means serving infinite ends, hence unbounded economic growth*" (*Daly, 1980, 1996*).

By contrast, the biophysical approach severely questions the potentials for everlasting substitution among resources, while debates the technological change within the limitations and restrictions set by the physical laws of thermodynamics. Furthermore, the biophysical paradigm raises crucial queries concerning the intergenerational equity and scarcity, terms that completely change the context of unbounded economic growth assumption.

The crucial distinction between natural and human-made capital

Another essential step, before analyzing the neoclassical and biophysical approaches, is the distinction of the term "*capital*" into natural and man-made. Capital is traditionally defined as the manufactured means of the production process. In mainstream economics, capital, in its narrowed definition, is considered to be the primary factor of production (together with labor and land). A broader definition of capital is required for our analysis.

Following Costanza and Daly (1992), we distinguish two broad types of man-made capital (Fig. 2.2): manufactured capital, consisting of factories, machinery, tools, buildings, and other physical artifacts; and human capital, consisting of the knowledge accumulation, skills, culture and education, stored in human beings. The engagement of the term "*natural capital*" calls for a more elegant explanation. Natural capital (*Costanza and Daly, 1992*): "*is the stock that yields a flow of valuable goods and/or services into the future*". A stock of trees, a coal deposit or a metal ore deposit, are all examples of natural capital. What is more, natural capital provides substantial services (i.e. ecosystem services) crucial for human survival. Natural capital can be distinguished into two categories (Fig. 2.2): renewable or active and nonrenewable or inactive natural capital. Renewable natural capital is self-maintained and based on solar energy (i.e. ecosystems). Nonrenewable natural capital is more passive (i.e. fossil fuels, mineral deposits). Figure 2.2 elaborates the concept of broaden capital definitions and briefly pictures the basic classifications presented in this section.

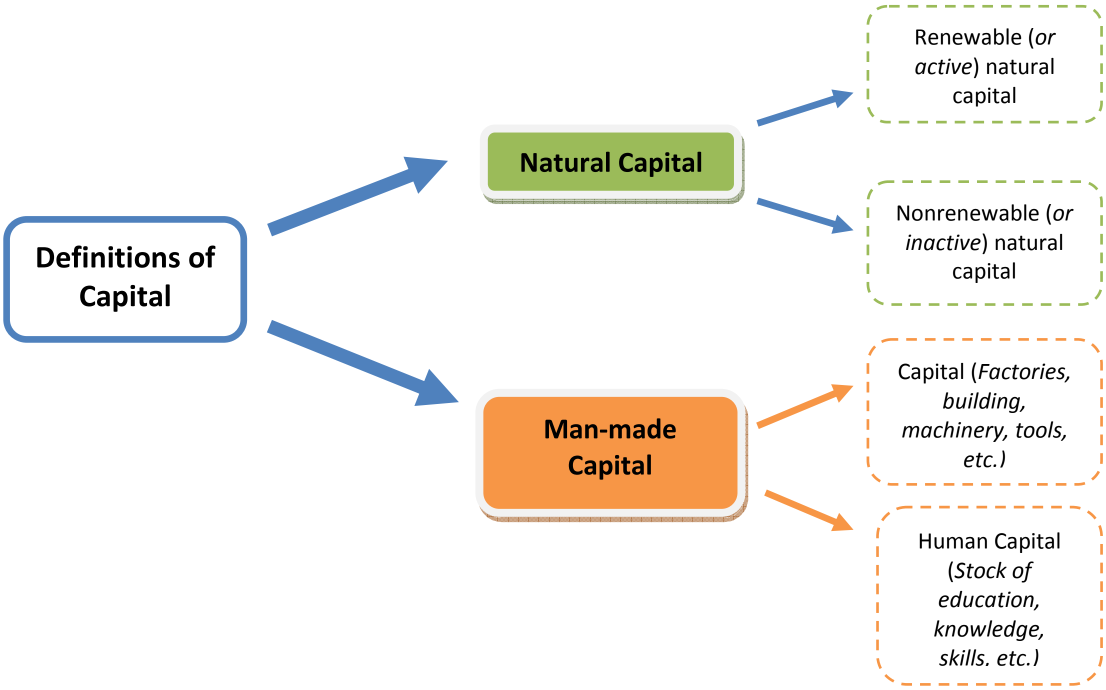


Figure 2.2 *Definitions of capital. Figure has been constructed by the author, according definitions provided by Costanza and Daly (1992-p.38)*

Reproducible and non-reproducible factors of production

The concept of reproducibility (or not) of an input that enters in the economic system is of paramount importance in the economics of production. Following the ends-means conception of Daly (Fig. 2.1) and the essential distinction of capital into man-made and natural (Fig. 2.2), this section integrates these key concepts concerning the natural resources scarcity issue. Primary factors of production are inputs that exist at the beginning of the examined period and are not directly used up in production, whereas intermediate inputs are created during the production process and are used up entirely in production (*Stern, 2004*). Those inputs that can be manufactured within the economic system are called reproducible inputs, whilst those that are not created within the economic system are called non-reproducible factors. Within the realm of neoclassical theory, capital, labor, and land are the primary factors of production, whereas energy and matter are used as intermediate inputs (*Stern, 2011*). However, capital and labor are actually reproducible factors of production, while the natural resources are not. Nevertheless, in the long run, natural resources could be considered as reproducible factors, except for energy (*Stern, 2004*). In any case, the exact determination of what should be defined as primary factor of production remains an open debate between neoclassical and biophysical economics.

The elasticity of substitution

The elasticity of substitution between production factors is an essential term that calls for an accurate definition. Let us use an example: the elasticity of substitution between capital and natural resources indicates by how much one of the inputs must be increased in order to maintain the same level of production, when the use of the other input is decreasing (*Stern, 2011*). Consequently, a unitary elasticity of substitution is cited as "*perfect substitutability*", while a zero elasticity is cited as "*perfect complementarity*" (Figure 2.3). The issue of properly estimating the elasticity of substitution is of paramount importance within neoclassical theory of growth (*Christopoulos, 2000*). In other words, a possible "*perfect substitutability*" between man-made capital and natural resources implies that, as natural resources use approaches zero, the production process –thus, economic growth- can be maintained by increasing (man-made and human) capital utilization toward infinity (*Stern, 2011*).

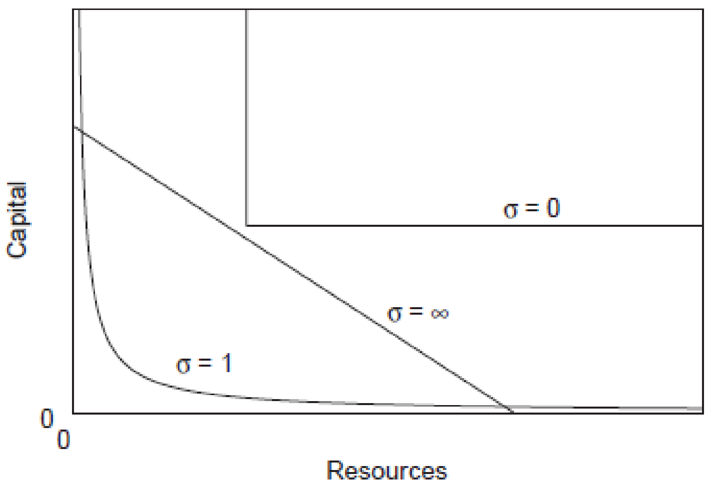


Figure 2.3 *The elasticity of substitution (Source: Stern, 2004-p.41)*

2.2.2 Natural resources scarcity within neoclassical theory of growth

In describing the implications of natural resources and their scarcity on economic growth, within the spectrum of neoclassical theory, is important to distinguish those studies that their main aim is to explain the driving forces of economic growth, from those dealing with scarcity of resources and optimal depletion. We deal with the former category in the next section. Concerning the latter category, following Cleveland (1991), the twin pillars of neoclassical economic model of natural resources scarcity are Hotelling's seminal study that sets the basis for the theory of optimal depletion (*Hotelling, 1931*), and the empirical analysis of Barnett and Morse (1963) that investigates the resources scarcity in the US.

Contrary to the iron law of diminishing returns envisioned by Ricardo and Malthus, during the early era of classical economics, the neoclassical model places natural resources scarcity within the context of two opposite forces: cost-increasing resources depletion and cost-decreasing technological change. The relative strengths of those opposite forces determine the actual context of scarcity, within the neoclassical theory (*Cleveland, 1991*). Henceforth, according to the neoclassical model, the market mechanism resolves the problem of scarcity. The main concept of the aforementioned twin pillars of neoclassical model (*Hotelling, 1931; Barnett and Morse, 1963*) goes as follows: the price of a resource will eventually increase, as it becomes more scarce, due to the increasing extraction cost and/or rental payment to the owner of the resources stock. Yet, this price increment will stimulate the market mechanism to find alternative solutions, for example, exploration of new deposits, research for alternative resources and potential substitutions, technological innovation, recycling, efficiency, and so on. In the neoclassical model, the long run resources scarcity is almost impossible because the rising scarcity itself will stimulate the process to overcome it (*Barnett and Morse, 1963*). Reminding Adam Smith's "*invisible hand*" this socioeconomic automatic mechanism, described by Barnett and Morse as "*self generating*" seems the ultimate driving force in modern growth economics (*Cleveland, 1991*).

Two kinds of studies could be distinguished in the context of neoclassical models (*Smith and Krutilla, 1979*): those depicting the behavior of a firm engaged in extractive activities, and those construct simplified economic growth models. Economic growth models will be discussed in detail in the following sections. In brief, the first category introduced above contains studies that are mainly directed towards analyzing the effects of various factors, concerning the extraction patterns of firms. Accordingly, the structure of market is analyzed by Hotelling (1931) and Stiglitz (1976), the influence of taxes is evaluated by Burness (1976) and Stiglitz (1979), and the issue of uncertainty is analyzed by Heal (1975). Some important assumptions that hold for most of the studies belonging to this category could be summarized as:

- Natural resources are identified as raw materials

- There assumed a fixed stock of resources, at least in most cases

In a nutshell, the neoclassical literature on growth and resources endeavors to trace and evaluate those conditions that permit a continuous economic growth or, at least non-declining consumption. These conditions can be classified in two broad categories (*Stern, 2004, 2011*) which are briefly pictured in Figure 2.4:

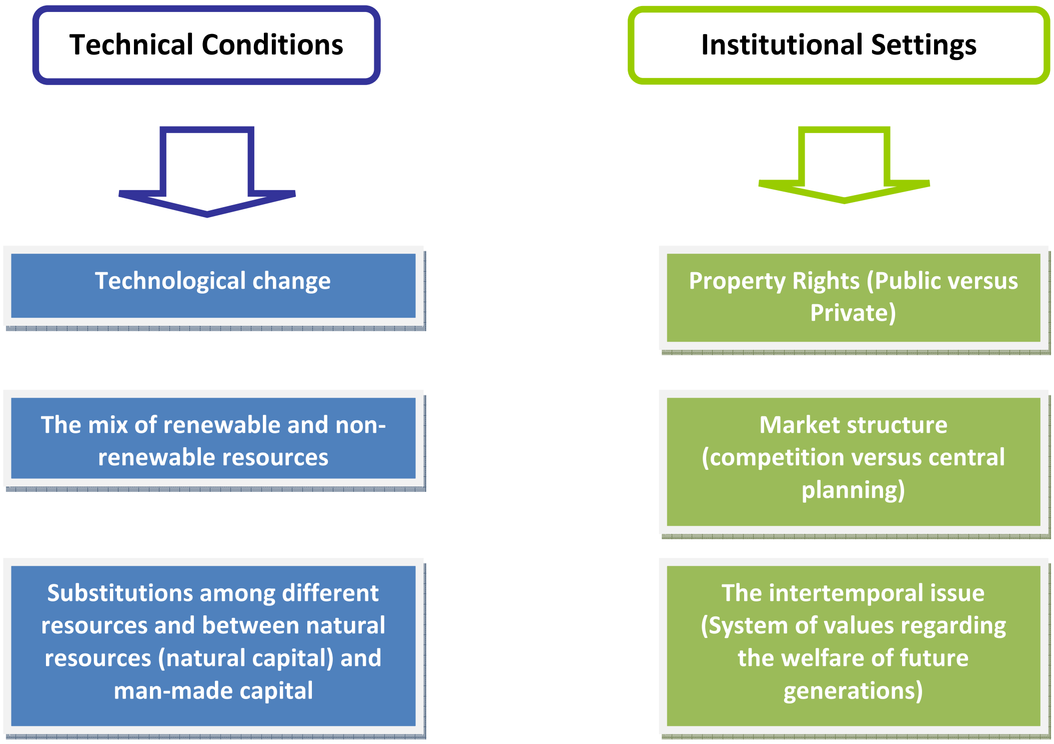


Figure 2.4 *The taxonomy of the neoclassical literature in technical and institutional conditions*

In line with Fig. 2.4, Gopalakrishnan (2000) distinguishes five types of studies, deeply interrelated the one another, according to:

1. **The Intertemporal problem**: The focus of this type of studies mainly concerns to ensure the well-being of future generations through optimal allocation of the natural resources, intertemporal efficiency and intergenerational equity. The seminal study of Hotelling (1931) that introduced the issue of the optimal rate of depletion, has deeply affected since then the vast majority of the relevant literature. Baumol (1968) argues that it may not be possible to determine a precise the social rate of discount because our institutional arrangements are rather too complex, whilst he concludes that "*it made little sense for present generations to consciously forego current consumption to invest in projects designed to benefit future generations, since history suggested that future generations would be surely be richer than present generations*". Furthermore, Arrow and Fisher (1974) investigate the uncertainty of the estimated environmental costs of some economic activities.

2. **The externalities and market failure**: The concept of externalities dates back to the early contribution of Adam Smith, and has been further analyzed by A. Marshall. Alfred C. Pigou formally analyzed how costs and benefits that are not included in market prices affect the people's interrelation with their environment. An externality is a phenomenon that is external to markets and hence does not affect how markets operate, when in fact it should (*Costanza et al., 1997*). The essence of externalities lies on the divergence between private and social costs (*Gopalakrishnan, 2000*). One of the most influential studies on externalities and optimal resources allocation has been published by Roland Coase (1960). The core of the Coasian approach lies in the voluntary negotiations among the affected parts, without market interventions or governmental regulations. Coarse argued that such a voluntary agreement will lead in an efficient resources allocation, as long as the property rights are well defined, the costs of negotiation are negligible, and there is a perfect competition market.

3. **The Property rights, institutions and public choice**: The ownership, the allocation and use of natural resources are strongly interrelated with the property rights and institutions establishment. The early analysis of Hotelling (1931), the private or

public regulation to the dilemma of overfishing problem (*Gordon, 1954*), and the "*political choice externality*" proposed by Buchanan and Stubblebine (1962), could be seen as some indicative examples.

4. **The economics of exhaustible resources:** The dictum: "*the present value of a unit of homogeneous but finite stock of mineral must be identical regardless of when it is extracted*" known as the "*Hotelling Principle or Rule*", has deeply affected the neoclassical economics of exhaustible resources. Towards this direction, Solow (1974b) bases his premises on the Hotelling rule, whilst Barnett and Morse (1963), Stiglitz (1974a), Dasgupta and Heal (1974), Baumol and Qates (1979), and Baumol (1986) point out that technical change and substitutability between exhaustible resources and man-made capital and labor will solve the problem of exhaustible resources' scarcity. We further scrutiny these assumptions in the next section.

5. **The economics of renewable resources:** In addition to the 4th category, the renewable resources are examined as a separate case study since the optimal depletion rate of a renewable resource is very different from the one of the exhaustible-nonrenewable resource. What is more, renewable resources are also a subject to externalities, institutional setting and market structure. Some indicative examples of studies on renewable resources are the effort of Vernon Smith (1968) to provide a unified theory of production from natural resources, Paul Samuelson's (1976) optimal forest management, and Kaufmann and Azary-Lee (1991) who examine the substitution effect in the US industry of forestry.

The next section follows the classification of neoclassical theory of growth and natural resources, as it is proposed by Stern (2011). This next section should be perceived as complementary to this one, since both sections are essential in order to briefly summarize the core of neoclassical theory of natural resources scarcity and economic growth.

The basic Growth model (without natural resources)

If someone wishes to set a chronological point of view in order to review the modern theory of growth (*Barro and Sala i Martin, 2004*), he should set as starting point the seminal article of Ramsey (1928). Following Ramsey, Harrod (1939) and Domar (1946) attempted to integrate the Keynesian analysis within the theory of economic growth. Despite the remarkable contribution of these efforts at their time, very little of this analysis plays important role in today's thinking (*Barro and Sala i Martin, 2004*). However, the pure core of neoclassical theory of growth can be traced in the so-called Solow-Swan growth model (*Solow, 1956; Swan, 1956*). The main important characteristic of these early efforts to explain economic growth through aggregate production functions is that they do not include natural (energy and mass) resources (*Stern, 2011*). Essentially, these early models reflect the basic assumption of neoclassical theory, namely, the recognition of Labor, Capital, and Land, as the primary independent factors of production (*Cleveland, 1991*). In brief, the early Solow's growth model assumes a constant sized labor force that uses manufactured capital in order to produce the output which is measured in monetary terms of GDP. A constant proportion of the output is saved and invested, in order to create capital, whilst a constant proportion of capital is depreciated. This simple closed economy will eventually reach a stationary stage, where economic growth will stop (*Stern, 2011*). Following the notion of "*diminishing returns*" that Ricardo and Malthus engaged in economics, Solow showed in this simple model that as the amount of utilized capital increases, the output increases at a decreasing rate, since there are diminishing returns to capital which lead into the equilibrium of the stationary state. If savings rate is increased, growth will continue until a new equilibrium is reached, and so on (*Ibid*).

The missing element that endorses the endeavor to escape from the stationary state of Mill, which seems irrevocable, is the technological change. Technological change offsets the diminishing returns to capital and, hence, allows the economic process to continue growing. Evidently, according to the neoclassical theory of growth, the main cause of continual economic growth is the technological process (*Cleveland, 1991; Stern, 2004, 2011*). These early growth models do not explain or capture the essential contribution of technological change, consequently are said to have an "*exogenous*" technological change (*Stern, 2011*). Already discussed in the first chapter, the pressing demand to account the contribution of technological progress on economic growth led into the next generation of growth models with "*endogenous*" technological change. From the early AK "*learning by doing*" (*Arrow, 1962*), to the modern endogenous growth models (*Acemoglu, 2009; Romer, 2011*), growth theory has enhanced with new evidence and innovative approaches. Following the classification proposed by Smith and Krutilla (1979), the second type of studies concerning economic growth and natural resources use, mainly attempt to evaluate the welfare implications of different extraction patterns, or the allocation leading to different extraction paths. We attempt an integration of the aforementioned classification with the one proposed by Stern (*Stern, 2004, 2011*) in the following sections.

Growth models with natural resources and no technical change

The early growth models introduced by Solow (*Solow, 1956, 1957*) and Swan (1956) do not include any natural resource as an input in the economic process. Substantial problems arise when more inputs enter into the production process, other than Capital and Labor. The addition of a finite and exhaustible resource in a growth model, crucially questions the potentials for further economic growth while calls for more rigorous analysis, compared to the simple "*non-resource input*" economy of the early models. Following the pressing demand for more realistic approaches, Solow published a study which shows that non-declining consumption, hence sustainability, was achievable in a model with a finite resource, no extraction cost and no depreciation of the capital, when elasticity of substitution between the two inputs is unity (*Solow, 1974a*). Nevertheless, under competition, the same model results in the exhaustion of the resources and consumption falls into zero (*Solow, 1974b*). During the same period, Stiglitz (1974b) by using the same model with Solow showed that a competitive market structure results in the exhaustion of natural resources in the future. However, Stiglitz further argues (*Stiglitz, 1974a,b*) that the firms function in a competitive market offer an intertemporally efficient use of the nonrenewable resource, where intertemporal efficiency means that the present discounted value of the net marginal product will be constant for all dates. Furthermore, Dasgupta and Heal (1974) argued that with any constant discount rate, the optimal growth path eventually leads to the depletion of the resource, hence to the consequent collapse of the economy. The basic Dasgupta and Heal (1974) and Solow (1974a,b) models assume a closed economy with capital accumulation and non-renewable resource depletion. The production function is a Cobb-Douglas function with two inputs: capital and the resource and with no technical progress. An effort to overcome this result can be found in Hartwick's seminal study, known since then as the "*Hartwick rule*" (*Hartwick, 1977*). Hartwick showed that a constant level of consumption could be achieved by reinvesting the resources rents in other forms of capital which in turn can be function as substitutes for finite resources (*Stern, 2011*). The Hartwick rule is further extended by Dixit et al. (1980) for other capital forms, and applied to open economies (*Hartwick, 1995*).

Evidently, with only a few exceptions (*Vousden, 1973; Krautkraemer, 1985*) the literature on natural resources depletion and sustainability has paid little attention to the direct value people might attribute to natural resources, apart from their use in production, as a labor force-production factor. The addition of technological change was the essential key-element that would ensure further economic growth without limitations and restrictions.

Growth models with natural resources and technical change

The crucial need to overcome the restrictions and limitations raised by the use of nonrenewable natural resources led the neoclassical theory of growth to engage a, complementary to the Hartwick rule substitution of capital to resources, concept: the technological change issue. In addition to the potential substitution of the man-made capital for natural resources, technological progress may permit further economic growth, or at least permits a constant consumption, in the context of a finite resource base (*Stern, 2011*). Evidently, Stiglitz (1974b) showed that when the elasticity of substitution between the utilized resource and capital is unity, exogenous technological change allows growth to be occurred, hence to overcome the stationary state. Technological progress could permit further growth even if the elasticity of substitution is less than unity, as long as the rate of technological change, divided by discount rate, is greater than the output elasticity of resources (*Stiglitz, 1974b*). In line with Stiglitz, Dasgupta and Heal (1979) argued that capital accumulation and technological change are the remedies of growth; even in the case of absence of technological change, a positive rate of production and consumption could be maintained if there are adequate potentials of substitution between man-made capital and nonrenewable resources.

Endogenous growth models

As already argued in the 1st Chapter, the crucial need to measure the impact of technological change, led in the development of more advanced endogenous growth models, which incorporated and further developed the neoclassical economic growth framework, in their effort to better understand the relationship between capital, nonrenewable resources, technological change and the economic process (*Aghion et al., 1998; Barbier, 1999; Di Maria and Valente, 2008*).

Virtually all modern economic growth theory assumes that the per capita GDP growth is driven by technological progress, man-made capital investment/accumulation, human capital (knowledge) investment/accumulation, and substitutions between man-made and natural capital (*Romer, 1994; Aghion et al., 1998; Barro and Sala-i-Martin, 2003*). This core assumption of capital and knowledge accumulation over time ensures, for most of the mainstream growth economists, that economic growth is a potentially non-stop process, as long as technology changes (*Ayres et al., 2013*). Furthermore, it is well-known that as the price of resource increases that forces entrepreneurs to invest in research for cheaper substitutes (*Nordhaus et al., 1972*). Evidently, there is a close interrelationship between potentials of substitution and technological change; the technological progress endorses the potentials for further substitution, or resolves problems of accessibility of new resources deposits.

As an epilogue to the previous brief representation of the neoclassical framework of growth theory, we can mainly distinguish two basic pillars on which the neoclassical growth models based on: substitution and technological change. In a nutshell, neoclassical theory argues that the substitution of non-reproducible, nonrenewable natural resources with reproducible (human and manufactured) capital; and continues technological change (triggered by human ingenious and scarcity itself) can, in effect, decouple economic growth from natural resources use. Towards these assumptions, neoclassical economists firmly believe that an *a priori* economic growth is technically feasible. Perhaps the most representative example that clearly illustrates this optimism can be found at the preface of C.E. Ferguson's book:"*…placing reliance on neoclassical economic theory must be a matter of faith…*" (*Ferguson, 1969*). Evidently, concerning economic theory of growth, this faith is based on the complementary pillars of substitutability potentials and technological progress. This optimism lied on these two twin pillars of neoclassical theory of growth, couldn't better be expressed than the conclusions of a distinguished scholar's seminal paper: "*Rising productivity, rather than drawing down humanity's stock of natural resources capital may, in an effective sense, actually augment it and may be able to continue to do so for the indefinite future. Resources which are not reproducible and whose quantities are finite may nevertheless be increased by technological advance in terms of their prospective contribution, and may do so for the indefinite future"* (*Baumol, 1986-p.178*).

2.3 The biophysical critique of neoclassical model. The ecological economics approach

2.3.1 Introduction

"*How is possible for man to produce something material, given the fact that he cannot produce either matter or energy?*" (*Georgescu-Roegen, 1976-p.53*)

The above statement summarizes, within just a few lines, the core of the biophysical critique on the neoclassical model. Evidently, the progress in physics and mechanics endowed economic science with valuable empirical tools and innovative conceptions. While the core of early neoclassical economic theory (i.e. see Warlas and Fisher at the 1st chapter) is essentially based on pure mechanics and rigorous mathematic formulations, the progress in physics (laws of thermodynamics) defined the actual biophysical foundations of the economic system and determined the boarders in which it functions. The pressing demand for the proper integration of the actuality of physical laws with the mechanistic nature of economic theory, led in the creation of new fruitful and innovative branches of economics, such as bio-economics and ecological economics. Hitherto, it is believed that ecological economics are novelties that have been recently – within the last four decades – developed. Despite the fact that this assumption is partially true, yet the first seeds of what is now defined as the "*biophysical approach*" in economics, can be traced in the long past.

From a historical viewpoint, the very first effort to place economics in accordance with natural laws, can be traced in the "*physiocrats*" (*i.e. Quesnay, 1758*), a group of social philosophers appeared in the mid 18th century, in France (*Daly, 1980; Martinez-Alier, 1987*). However, the physiocrats never determined the context by which the laws of physics applied to the economic system (*Costanza et al., 1997*). As already argued in the 1st chapter, Malthus and Ricardo traced and tried to quantify some first limitations concerning the economic process, the population growth and the soil productivity constraints. However, one of the first economists that recognized the critical importance of energy resources in the economic process was W. Stanley Jevons (*Costanza et al., 1997*). With his seminal study "*The coal question*" (*Jevons, 1865*), Jevons raised critical questions concerning the scarcity of coal, as the dominant energy input at that time, and its implications on British economy. The next stop of this historical review belongs to the outstanding contribution of Alfred J. Lotka. Lotka managed to provide the first integration of the early definitions of ecology (*Haeckel, 1870*) with the economic system, in a quantified mathematical way (*Lotka, 1922, 1925*). His influential work intrigued numerous distinguished scholars such as H. Odum, P. Samuelson, and N. Georgescu-Roegen. The well-known "*Lotka's energy principle*" declares that it is vital for a system (i.e. the economic system) to maximize its energy flows, hence use its available energy resources efficiently (*Costanza et al., 1997*). Moreover, Lotka was the first that used the concept biophysical economics (*Cleveland, 1987*), a term which, however, became popular later on by Georgescu-Roegen, in the early 1970s (*Georgescu-Roegen, 1971*). Evidently, the mid 1960s were characterized by an unprecedented and fruitful evolution of alternative and interdisciplinary economic approaches. Essentially, the population issue is brought to the forefront again by Paul Ehrlich, with his seminal book "*The population bomb*" (*Ehrlich, 1968*), while Kenneth Boulding's essay on conceiving earth as a spaceship with limited resources (*Boulding, 1966*), raised critical questions about the natural resources scarcity. Accordingly, the historical book of H. Odum "*Environment, power and society*" (*Odum, 1971*) and the influential "*Limits to growth*" (*Meadows et al., 1972*) cast light in new evidence, concerning the potential constraints on further economic growth (*Røpke, 2004*). About the same period, the early contributions of Herman Daly (1968) and Ayres and Kneese (1969) further elaborated physical laws within the boarders of the economic system, while the groundbreaking work of Nicholas Georgescu-Roegen, "*The entropy law and the Economic process*" (*Georgescu-Roegen, 1971*) was probably the most substantial effort to incorporate the entropy law in the economic process and to ground the economic theory in biophysical reality (*Røpke, 2004*). These remarkable contributions further triggered an innovative wave of theoretical conceptions and empirical applications, such as the "*Steady State Economy*", proposed by H. Daly (1973), the "*emergy*" approach (*Odum, 1971*), the "*exergy*" approach (*Ayres and Warr, 2009*), the qualitative differences and the substitutions among different energy resources types (*Cleveland et al., 1984; Kaufmann, 1992; Stern, 2011*), and so on.

The following analysis attempts to provide a brief representation of the critique of the biophysical school of though on the neoclassical model of growth. For this purpose, we mainly focus into the main conceptual differences exist between the two schools of economic thought. Specifically, the biophysical critique of neoclassical theory is structured in five distinct categories:

- Criticism of mainstream production functions
- Distinction between primary and intermediary means
- The substitution potentials between man-made and natural capital

- Technological change and efficiency

- Hotelling's Rule and the discounting of the future

2.3.2 The flow-funds production functions. Questioning the neoclassical production analysis

There is an enormous variety of models and approaches that endeavour to represent the production process. Beyond the already discussed subset of neoclassical models of economic growth, there are other supersets of production models that we have not dealt with, as it is out of the scopes and limits of the present analysis. Essentially, this pluralism calls for a rigorous classification in order to address the different aspects and assumptions each category deals with. Following Artigues and González-Calvet (2007), production models can be classified in two broad types:

- The models that comprise circular aggregate schemes, built upon the sectoral interdependence that exist in the economic system and analyse the long-term conditions for reproduction and the distribution of the generated surplus. In this type of models belongs the early works of physiocrats, such as Quesnay, and classical economists, such as Marx. The Sraffian proposal (*Sraffa, 1960*) is assumed to be the best developed approach of the general interdependence models.

- The models that do not deal with the mutual influences that co-exist among different sectors but try to understand the internal configuration of the production process, through the direct relationship from raw materials to goods production. These models of partial interdependence can be further divided in two types:

  - *The pursuit and the refinement of optimisation*. This subcategory includes the formations of the so-called neoclassical production functions (*Koopmans, 1951; Solow, 1956; Shephard, 1970; Johansen, 1972*).

  - *The detailed description of the production process*. This category includes the flow-funds approach, established by G-R and a model that considers the production process as a network of tasks (*Scazzieri, 1993*).

We dedicate this section in providing a brief representation of the flow-funds production function, proposed by Georgescu-Roegen (1969, 1971, 1976, and 1979a, b)[1], as a critical challenge of the mainstream neoclassical production functions that based on the Cobb-Douglas prototype (*Solow, 1956; Swan, 1956*). To the author's knowledge there is, unfortunately, no empirical employment of the flow-funds prototype so far, except of one case at the micro-level (*Artigues and González-Calvet, 2007*).

The outstanding analysis of G-R is characterized by the systematic endeavour to adequately describe the economic process, within the context of actuality, as it is defined by physical laws. G-R recognizes the influence of Alfred Marshall, as the only neoclassical economist that realized that biology – not mechanics – is the true Mecca of economics (*Georgescu-Roegen, 1971-p.11)*. Mainstream economics, lacking Marshall's insights for biology, failed to embody fruitful subsequent contributions, such as the studies of Alfred Lotka (1922) who managed to integrate the economic process with ecological and biological processes. We could assume that G-R perhaps owns a part of his first ideas concerning the flows-funds concept, to the Lotka's biological distinction of "*endosomatic*[2]" and "*exosomatic*[3]" instruments.

An initial step of briefly defining the production process is required. The most widely accepted premises, adopted in most cases, concerning the production process can be summarized into 5 propositions (*Artigues and González-Calvet, 2007-p.6*):

1. The production process requires time, hence is a process that evolves through time (i.e. $t \in [0,T_p]$ is the time period of a production process, as Fig. 2.5 depicts). Inputs are essential for starting a production process[4]
2. These inputs are being transformed or processed, through the production process, into one or more outputs.

[1] The complete model of flow-funds production function was first introduced by Georgescu-Roegen in the conference of the International Economic Association, held in Rome, in 1965.

[2] As "*endosomatic*" instruments are defined the instruments that are part of each individual organism, by birth (i.e. feathers, flaps, hands, etc.)

[3] Exosomatic instruments are the tools, machinery, engines, and so on, that operated by humans and could be perceived as an expansion and enforcement of their "*endosomatic*" ones.

[4] Irrevocably, time is continuous, homogenous, and it has only one-way, in the Newtonian sense.

3. At any given time there will always be a finite number of production methods
4. There are finite inputs and outputs, during the specific production process.

Let us now specify the main propositions that define the analytical representation of the production process, based on the analysis of Georgescu-Roegen (1971-p.211-234):

- **Establishing the boundary of the partial process**: The first essential step lies in the establishment of the border that separates a partial process from anything else. As Georgescu-Roegen (1971-p.213) characteristically sets it: "*No analytical boundary, no analytical process".*

- **Defining the analytical coordinates of a partial process:** The next essential step is the accurate definition of all the coordinates that involved within the boarders of the partial process. In this context, every element that crosses the borders from the environment into the process is an input, while any element that goes out the borders of the process is an output.

Accordingly, G-R provides an essential distinction of these coordinates into two important categories: Stocks and Flows; and Funds and Services (Fig 2.5). Specifically:

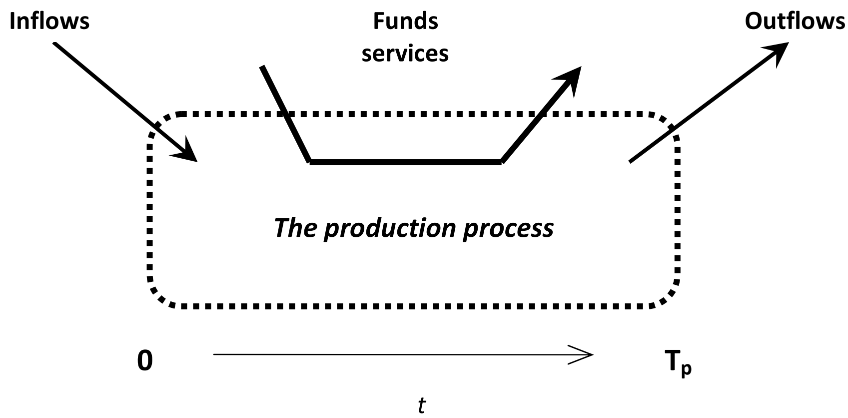


Figure 2.5 *The production process (source: reconstructed by the author from Artigues and González-Calvet, 2007-p.7)*

- **Funds:** The *funds* elements represent the agents of the process. The main characteristic of these coordinates is that they are not consumed – but being used – in the production process; thus the *funds* elements enter and leave the production process, albeit with some scars, without being physically incorporated into the output. G-R distinguishes mainly three different types of funds[5] (Fig. 2.6):
    1. *Labour power (H):* workers and their services in the production process
    2. *Capital (K):* Machinery funds and manufactured equipment; tools; constructions
    3. *Ricardian Land (L):* the area which all production activities take place

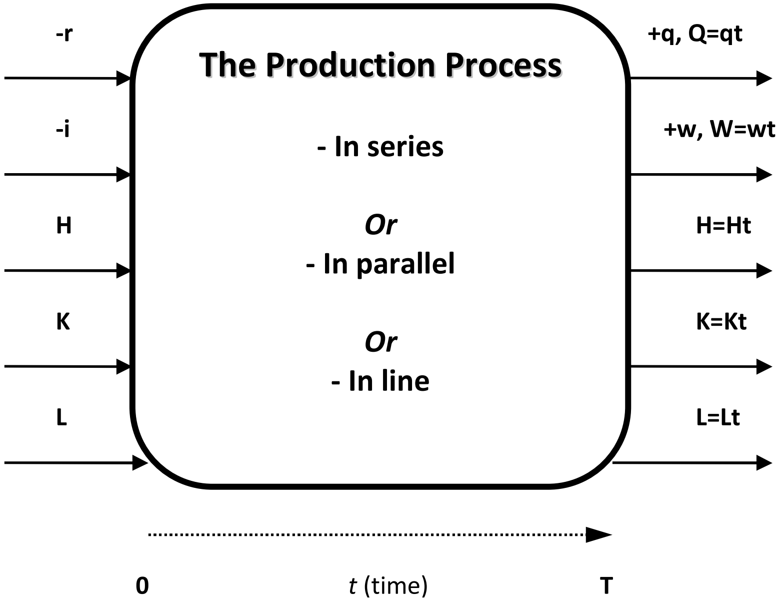
- **Flows:** The *flows* elements are these coordinates that used or acted upon by the agents. G-R distinguishes flows into five categories (*Georgescu-Roegen, 1971, 1976*: Figures 2.5-2.6):
    1. *Inflows from the nature*: Natural resources, energy and matter (R)
    2. *Inflows from other production processes*: semi-final goods, machines and tools (I)
    3. *Inflows for maintenance* (MK)
    4. *Outflows:* final products – useful goods (Q)
    5. *Outflows:* waste and other non-useful by-products, such as emissions, pollution, and so on (W)

It is worth to mention here that the division of the production factors into flows and funds does not necessarily mean that the same element could not be appeared both as a flow and as a fund (*i.e. see Georgescu-Roegen, 1971-p.231*). However, no substitution between flows and funds is possible. The flow-funds production function – actually a set of functions into one function – is represented by the function (*1)* (*Georgescu-Roegen, 1971, 1976, 1979a*):

$$\underset{0}{\overset{T}{Q}}(t) = F\left[\underset{0}{\overset{T}{R}}(t), \underset{0}{\overset{T}{I}}(t), \underset{0}{\overset{T}{M}}(t), \underset{0}{\overset{T}{W}}(t), \underset{0}{\overset{T}{L}}(t), \underset{0}{\overset{T}{K}}(t), \underset{0}{\overset{T}{H}}(t)\right] \quad (1)$$

[5] We mainly use in this classification what G-R described as funds, in 1971. Contemporary analysis includes two other categories, such as population of natural organisms and the process fund, which we intentionally left outside the current analysis for the sake of simplicity (For more see: *Artigues and González-Calvet, 2007-p.8-9)*

Figure 2.6 *The flow-funds production function. A detailed representation (Source: constructed by the author from: Georgescu-Roegen, 1969, 1971, 1976, 1979, 1986)*



Elements / *Flows*	*P_0 (Transforms MS into CM*	*P_1 (Transforms ES into CE*	*P_2 (Produces MK)*	*P_3 (Produces C)*	*P_4 (Recycles and garb-junk)*	*P_5 (maintain the population)*
Controlled Matter (CM)	X_{00}	-	$-X_{02}$	$-X_{03}$	-	-
Controlled Energy (CE)	$-X_{10}$	$-X_{11}$	$-X_{12}$	$-X_{13}$	$-X_{14}$	$-X_{15}$
Maintenance Capital (MK)	$-X_{20}$	$-X_{21}$	X_{22}	$-X_{23}$	$-X_{24}$	$-X_{25}$
Consumer goods (C)	-	-	-	X_{33}	-	$-X_{35}$
Refuse Matter (RM)	-	-	$-X_{42}$	$-X_{43}$	X_{44}	-
Energy in situ (ES)	-	$-e_1$	-	-	-	-
Matter in situ (MS)	$-M_0$	-	-	-	-	-
Recycles and garb-junk (GJ)	w_0	w_1	w_2	w_3	$-w_4$	w_5
Dissipated Energy (DE)	d_0	d_1	d_2	d_3	d_4	d_5
Dissipated Matter (DM)	s_0	s_1	s_2	s_3	s_4	s_5
Refuse (R)	r_0	r_1	r_2	r_3	r_4	r_5
Capital Fund (K_0)	K_0	K_1	K_2	K_3	K_4	K_5
People (H_0)	H_0	H_1	H_2	H_3	H_4	H_5
Ricardian land (L_0)	L_0	L_1	L_2	L_3	L_4	L_5

Flows

- Inflows from nature (-r)
- Inflows from processes (-i)
- Outflows of products (+q)
- Outflows of waste (+w)

Funds

- Labor power (H)
- All capital (K)
- Ricardian land (L)

"There is no substitution between Flow and Fund factors"

q=F (H, K, L) This function shows the scale of the process. Hence, it is not a homogenous function

Q= g(R, I; w) This function is necessarily homogenous of first degree because energy and matter neither be created nor annihilated

By establishing the flow-funds production model, G-R managed to severely criticize the over-simplified way that the neoclassical production functions were trying to capture and represent the complex reality of the actual production process, whilst he formulated concrete arguments concerning the substitutability potentials between flows and funds, hence, between natural and man-made capital. We will further discuss G-R's contribution to the substitution debate, later on.

2.3.3 Defining the spectrum of primary and intermediate means

As it is already discussed, the neoclassical model of scarcity begins with a plausible but arbitrary assumption (*Cleveland, 1991*): capital, labor and land are primary, independent factors of production. Evidently, this perspective is consistent with the standard neoclassical theory which envisions the economic process as an endless cycle, where the production inputs (capital, labor, land, sometimes entrepreneurship) and the production outputs (goods and services) are circulated between households and firms (including the state and banks, in more expanded diagrams). By contrast, the biophysical perspective is based on a different set of assumptions (*Cleveland, 1991*): a different definition of primary factors and intermediate inputs of production. As Daly proposes (*Daly, 1980*), there is a different perspective between neoclassical and biophysical models, concerning the ends-means spectrum (Fig. 2.1). From the biophysical point of view, the law entropy energy-matter flows are the only primary factors of production because they are the only production inputs which cannot be produced within the boarders of the economic system (*Georgescu-Roegen, 1971, 1972; Daly, 1980; Cleveland, 1991*). Entropy, as an irrevocable physical law, makes impossible the physical reproduction of energy and matter through the production process (*Georgescu-Roegen, 1971, 1979b*). In that context, the services provided by capital and labor are intermediate inputs, intermediate means according Daly (1980), which are reproduced within the boarders of the economic system (*Stern, 2004*) and produce, with the fundamental contribution of low-entropy energy-matter flows, output flows thus, goods, services and high entropy waste (*Georgescu-Roegen, 1971*). It should also be denoted that while land is a natural resource, same certain properties of land (i.e. soil fertility) require low entropy energy-matter (*Cleveland, 1991*). Furthermore, it worth adding here that, as far as the factor "land" concerned, the neoclassical model mainly handles it as property (an asset), rather as a physical input (*Daly and Cobb, 1990*), neglecting Ricardo's original definition of land as "*the original and indestructible powers of soil*" (*Cleveland, 1991*). Evidently, the "*forces of nature*" originally concerned by most of the classical economists evade from the neoclassical model (*ibid*).

Technological change, as the main neoclassical argument against aggregate scarcity of natural resources, will be discussed separately. In any case, some of the neoclassical criticism against the biophysical perspective was mainly directed towards criticizing the biophysical models for using only energy-matter as primary factors, ignoring other inputs (*Allesio, 1981; Huettner, 1981*). At the crux of affairs, the biophysical perspective does considers capital, labor and technology, yet as intermediate, interdependent and internally reproduced means, distinguishing them from the low entropy inputs which are the actual primary, independent, external, non-reproducible, ultimate means of the economic process (*Georgescu-Roegen, 1971, 1976, 1979a-c; Daly, 1980; Costanza, 1980; Cleveland et al., 1984; Hall et al., 1986; Cleveland, 1991; Costanza et al., 1997*)

2.3.4 The substitution potentials between man-made and natural capital. Tracing limits to substitution.

We have discussed early on that a key mechanism, by which the neoclassical theory assumes that the economic system manages to overcome the rising scarcity of a resource, is the mechanism of substitution. A scarce commodity can, in effect, be substituted alternatively by another similar commodity, in either production or consumption side (*Solow, 1974a*). However, the biophysical perspective traces some very crucial obstacles and restrictions in the substitution mechanism.

Victor (1994) distinguishes two ways of substitutions: manufactured capital *directly* substitutes natural capital, when manufactured capital provides a service equivalent to that provided by natural capital; manufactured capital *indirectly* substitutes natural capital when more efficient machinery (capital) increase the productivity of natural resources. We examine here the former category, whilst we deal with the latter one in the section that argues about technological progress and efficiency. Stern (*2004, 2011*) provides a brief summary of the potential substitution mechanisms:

- Substitutions can be occurred within a category of similar production inputs (i.e. energy inputs) and between different categories of inputs (i.e. man-made capital for natural resources)

- Substitutions at the micro-level and substitutions at the macro level. Additionally, substitutions that may be possible in a single country are not possible at the global level.

Solow argues that the substitutions take place within a category of inputs, is the most important ones, while he assumes that new substitutes could always be available (*Solow, 1997*). Evidently, as we will discuss in chapter 6, the history of the production process is characterized by constant transitions/substitutions from one energy source to another, from wood to coal, from coal to oil, from oil to natural gas and electricity, and so on. Essentially, these substitutions take place in one category of inputs. Furthermore, it is possible that the elasticity of substitution (see the introduction section) for within-category types of substitution could exceed unity, hence provide evidence for perfect substitutability (*Stern, 2011*).

On the other hand, ecological economists assume that the other-category types of substitution are more essential, concerning the production process. The biophysical perspective is mainly based on the thermodynamic limits to substitution. The first law of thermodynamics implies the mass-balance principle which means that in order to produce a given material output, greater or at least equal material inputs are required (*Ayres and Kneese, 1969*). Therefore, there is a minimum of material requirements for any production process which creates material outputs (*Stern, 1997*). Since humans cannot create energy and matter, then it is irrevocable to violate the first law of thermodynamics, as being the first critical limitation of the substitution mechanism (*Georgescu-Roegen, 1971*). As Georgescu-Roegen implied by the crucial distinction of inputs into flows and funds, the laws of thermodynamics raise substantial restrictions concerning the other-category types of substitution. Expanding this argument to the aforementioned classification of capital (see Fig. 2.2), the substitution of manufactured, man-made capital for natural capital is a physically limited process. The well-known example with the oven and the cake literally illustrates the constraints imposed by the laws of thermodynamics. In Daly's own words: "*since the production function is often explained as a technical recipe, we might say that Solow's recipe calls for making a cake with only the cook and his kitchen*" (*Daly, 1997-p.261*).

Perhaps a great part of neoclassical optimism in substitution potentials between different categories of inputs is dedicated to the early Solow's historical statement: "*if it is very easy to substitute other factors for natural resources, then there is in principle no 'problem'; the world can, in effect, get along without natural resources*" (*Solow, 1974-p.11*). By all odds, Daly's example reveals that it is not possible to have a cake (output) with only the cook (labor) and the oven (manufactured capital); we need a realistic technical recipe that will further include flour, eggs, sugar (matter resources), and electricity, natural gas, or at least woods (energy resources) to provide us with the necessary power to process the rest of the inputs. In addition, Daly (1992) argues that, from a historical point of view, man-made capital and natural capital have been developed as complements, not as substitutes. Further commenting on that, Costanza and Daly (1992) are wondering why there is such a need to manufacture and accumulate manufactured capital, if it is perfect substitute for natural capital, since an equivalent form already exists out there.

Indeed, there are a lot of potential substitutions at the micro-level, or within a single country. However, there is evidence that substitutability potentials are less at the macro-level (*Stern, 2010*). Ecological economists have further argued that some forms of natural capital are irreplaceable and hence cannot be substitutes by manufactured (man-made) capital, at least beyond a certain stock minimum (*Costanza and Daly, 1992; Costanza et al., 1997; Stern, 2004, 2011*). This fear, that excessive substitution of man-made capital for natural resources will cause the natural systems to lose their resilience and collapse, is expressed and analyzed in many studies (*Common and Perrings, 1992; Perrings and Pearce, 1994*).

Towards this substitution/complementary debate, there are neoclassical approaches that try to investigate the functional relationship between man-made capital and energy resources, which conclude that time-series data result in a complementary relation between energy and capital, whilst pooled cross-section data induce substitutability (*Apostolakis, 1990*). Evidently, neoclassical economists argue that the addition of "*smarter*" capital may lead into a more sophisticated manipulation of natural resources, hence a more efficient use of natural resources, by using more "*smart*" (efficient) capital and less resources (*van den Bergh, 1999*). On the other hand, other studies result in complementary conclusions (Nilsen, 2010); whilst many trace serious substitution constraints at the macro level (*Georgescu-Roegen, 1976; Daly, 1991, 1997; Kaufmann and Azary-Lee, 1991*).

Georgescu-Roegen (G-R) firmly believed that one of the greatest fallacies of the neoclassical economic theory lies in the confusion of the distinct role of flows-funds, in the production process. This false comprehension concerning this relationship led, according to G-R, into a fundamental misrepresentation of the relation between man-made and natural capital (*Georgescu-Roegen, 1979a*). By using wittily a Cobb-Douglas production function, in the context of the flow-fund concept though, G-R managed to provide an insightful example that illustrates this fallacy and has also direct implications on the complementary/substitute debate (*Georgescu-Roegen, 1979a, 1979b, 1979c*):

$$Q = K^{a1} L^{a2} R^{a3} \qquad (2)$$

Where, *Q=output per time period; K = capital stock; L = Labor supply per time period; R = flow of natural resources; and* a_1, a_2, a_3 *are fixed parameters of elasticity of substitution, where* $a_1 + a_2 + a_3 = 1$.

From (*2*) it follows that with constant L_0 we can obtain any given Q_0 if R satisfies the condition (*3*), namely:

$$R^{a3} = \frac{Q_0}{K^{a1} L_0^{a2}} \qquad (3)$$

With (*2*), G-R shows that R may be as small as someone wish, provided that K would be large enough. Eventually, function (*3*) tell us that we can obtain a constant Q with an even infinitesimal R, as long as R>0, if we increase properly the stock of capital each year. However, G-R comments that, in actuality, the increase of capital stock requires, inevitably, the depletion of natural resources; hence if $K \rightarrow \infty$ then R will be exhausted by the production of capital. This is the well know “*conjuring trick*” of “*paper and pencil exercises that lacks of any relation to facts*” of Solow and Stiglitz, as exposed by Georgescu-Roegen (1979a, 1979b, 1979c), based on the fundamental discipline: “*no agent can create the material which it works*”.

It goes without saying that there is an irrevocable biophysical interdependence between man-made and natural capital. By all odds, the complementary premise does not preclude the potentials for substitution between them. In a nutshell, the potential for substitution between man-made and natural capital is a multidimensional issue that depends on (*Cleveland and Ruth, 1997-p.207*): the type of substitution (direct versus indirect and marginal versus non-marginal); the boundaries of the economic system (micro-economic versus macro-economic level); the spatial scale (local versus global); and the time scale (short run versus long run). All in all, it seems that, at least with current technological state, the potentials for substitution between manufactured capital and natural capital are less at the macro, global aggregate level (*Cleveland and Ruth, 1997)*.

2.3.5 Limits to technological change and efficiency

"*Technology is an omnipotent "dues ex machine" who will get us out of any growth-induced problems*" (*Daly, 1980-p.5*).

The previous review of the neoclassical theory of growth revealed the critical role of technical (or technological) change (or progress) in the production process. Technological change emerges as a key mechanism of escaping the diminishing returns, something which was broadly recognized by the vast majority of neoclassical economists of the 1950s and the 1960s (*Barro and Sala-i-Martin, 2004*). From the early exogenous (technological change) growth models, to the mid-1980s growth models with endogenous technological change, the technological progress remains a key element of the neoclassical theory of growth. In general, technological changes are occurring in a purposeful manner and only rarely occurred spontaneously (*Stern, 2004*). Research and Development (R&D) activities carried out in universities, institutes and other governmental organizations (i.e. army research), while these activities are funded by governmental agencies or/and private organizations, (i.e R&D sectors of corporations and firms) (*Barro and Sala-i-Martin, 2004*).

Evidently, the endogenous technological change led in the division of capital into manufactured (man-made) and human capital (see figure 2.2), where the term human capital includes all these aspects, skills, attributes, and knowledge that are incorporated within human beings. Furthermore, the knowledge is also embodied, indirectly, in improved capital goods i.e. sophisticated techniques and machineries (*Stern, 2011*). However, there is a substantial difference between accumulated knowledge and the other inputs of production, since knowledge is a non-rival good; the same knowledge, skill, method, or idea, can be used at the same time in various different processes and locations without causing any reduction in the initially accumulated knowledge elsewhere in the economic system (*Barro and Sala-i-Martin, 2004; Stern, 2004, 2011*). In other words, there can be constant (or even increasing) returns to the development of knowledge within the production process, while other inputs experience diminishing returns (*Stern, 2011*).

The neoclassical theory assumes that changes in technology occur when new more efficient techniques are introduced into the production process (*Stern, 2004*). Furthermore, it assumes that, in any given time, there co-exist an infinite number of efficient techniques that are being continuously substituted by new, innovative and sophisticated methods and tools (*Stern, 2011*). Evidently, the optimism that the technological change will manage to overcome any constraints imposed by nature is reflected in the work of many distinguished neoclassical economists (*Barnett and Morse, 1963; Solow, 1974a; Stiglitz, 1974a; Houthakker, 1983; Baumol, 1986; Bower, 1986; Solow, 1997*). This line of thinking, which actually starts with Barnett and Morse (1963), is defined as "*technological optimism*" (*Costanza, 2000*).

Contrary to the "*technological optimism*" lies the "*technological skepticism*" line of thought, assuming that technology may not overcome the constraints imposed by natural resources scarcity, pollution constraints and the thermodynamic laws, that eventually will halt economic growth (*Costanza et al., 1997*). Apparently, technological change does improve machinery, techniques and adds new skills and knowledge in human capital, yet obeys the same thermodynamic restrictions implied by physical laws as there will always be limitations in further energy and material reductions. Thermodynamic limits of further technological change and efficiency improvements have been thoroughly discussed in the work of Georgescu-Roegen (1971, 1976) and Daly (1992). Towards this "*technological skepticism*", it seems that some material processing industries are approaching thermodynamic thresholds (*Chapman and Roberts, 1983*), whilst fossil fuels use and, important for modern life, industries such as plastic production, are also approaching thresholds to further efficiency improvements (*Cleveland and Ruth, 1997*).

Another important aspect which dramatically pictures the restrictions of thermodynamics on further efficiency improvements is the surprisingly high volume of thermal (high entropy) waste as a result of the (low entropy) fossil fuels use for the production of useful work. Evidently, a great amount of the energy (exergy) consumed is lost during the energy conventions[6]. For example, the internal combustion engine, with more than one century of continuous improvements, still performs in extremely low efficiency, (i.e. about 12,6% for urban driving and about 20,6% for highway driving) something which is translated as great (thermal) loses (*Ayres and Warr, 2009*), during the convention process of thermal energy into mechanic and kinetic. Additionally, Figure 2.7 pictures the efficiency of the global electricity generation system; literary, the greatest part of energy consumed is wasted (in thermal form), while only 33% of the total energy input is finally consumed (as electricity) by industrial and other end users (*IEA, 2002*).

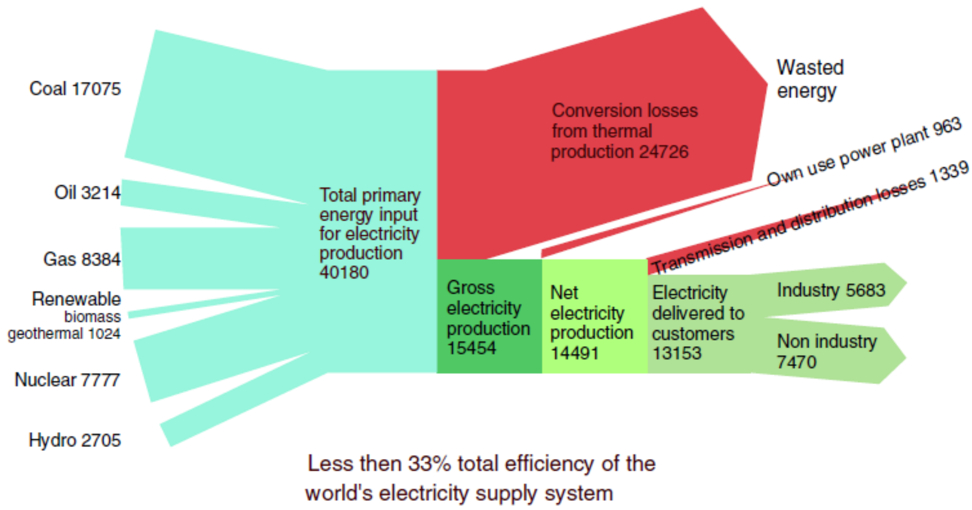


Figure 2.7 *Global Electricity generation (in TWh) (source IEA, 2002)*

Finally, another noteworthy debate, even though it is not directly related with the biophysical context of analysis, seems to be indirectly supportive for the technological skepticism line of thought; it is the so-called "*Rebound effect*". Known also as "*Jevons Paradox*", this peculiar phenomenon was first put forward by Stanley W. Jevons, in his classic work "*The Coal Question*", (*Jevons 1865*): "*it is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth […] the reduction of the consumption of coal, per ton of iron, to less than one third of its former amount, was followed, in Scotland, by a tenfold increase in total consumption, between the years 1830 and 1863, not to speak of the indirect effect of cheap iron in accelerating other coal-consuming branches of industry*". Albeit Jevons was the first one that

[6] More details on that issue, in chapter 6.

raised that important query, according Alcott (2005), some other neoclassical economists, like Hotelling (1931-p.64) and Domar (1962-p. 605), also noted that efficiency, sales, and resource use rise hand in hand. Nevertheless, the contemporary debate of "*rebound effect*" actually (re-) introduced by Brookes (1979) and Khazzoom (1980). Evidently, (*Brookes, 1979, 1990; Khazzoom, 1980, 1987; Saunders, 1992; Schurr, 1990; Brookes, 2000*) state that the increased energy efficiency, at the microeconomic level, albeit leading to a reduction of energy use at this level, actually leads to an increase in energy use, at the national, or macroeconomic level. Saunders (1992) classifies the rebound effect as (Fig 2.8):

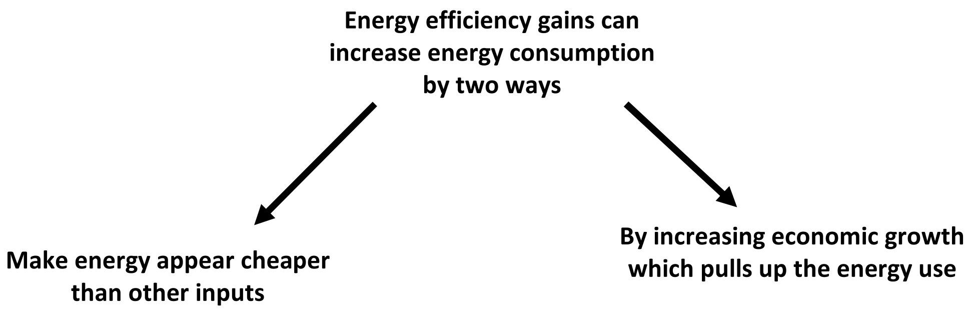
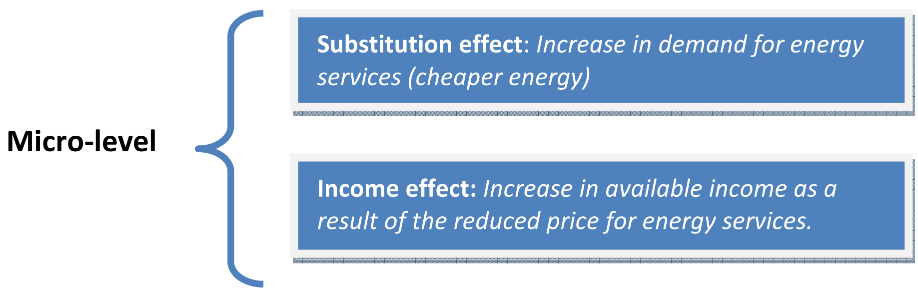


Figure 2.8 *The classification of the rebound effect*

Greening et al. (2000) give a more detailed analysis of the effect's implications at the micro-economic and the macro-economic level (Fig. 2.9):



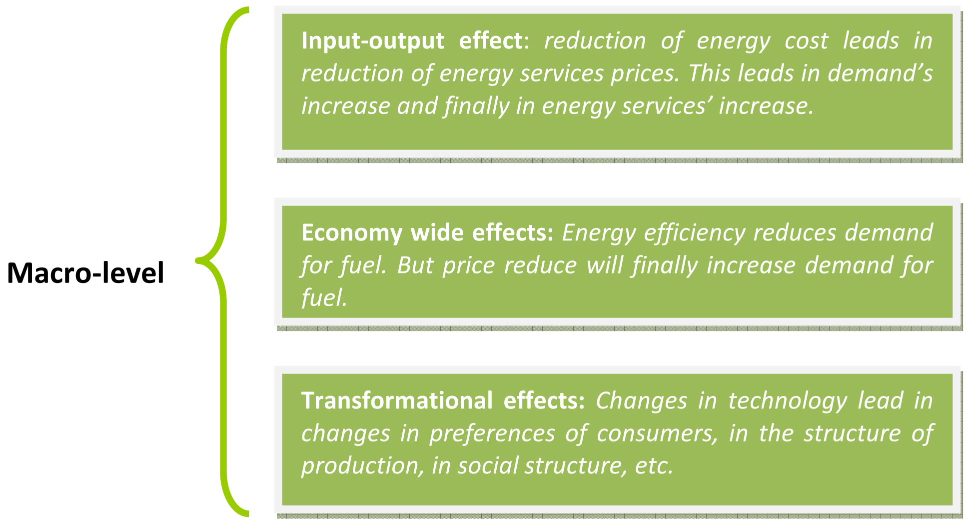


Figure 2.9 *The implications of the rebound effect at the micro- and macro- economic level*

The rebound effect's assumptions have been seriously adopted by various ecological economists (*Pearce, 1998; Wackernagel and Rees, 1997*), whilst Kaufmann (1992; 2004) claims that substitution and technical change have had relatively little effect on the amount of energy used to produce a unit of GDP (E/GDP) in France, Germany, Japan and the UK during the post war period. Further, Kaufmann concludes that most of the changes occurred are related with shifts between the different types of energy used (from lower to higher qualities) and the structure of the production process.

A critical query could stand as an epilogue to that section: besides all the aforementioned arguments and restrictions, will technology follow the right direction? Gutès (1996) argue that if natural resources are not priced correctly, due to market failure, then there are increasing probabilities that there will be insufficient incentives to develop technologies that reduce resources use. By all odd, the self-generated process of technical change that Barnet and Morse (1963) envisioned may not work in the case of market failure.

2.3.6 Hotelling's Rule and the discounting of the future.

"*....we must discard the principle of discounting the future, which has served as the basis for Harold Hotelling's famous study […] our policy toward natural resources in relation to future generations must seek to minimize regrets.*" Georgescu-Roegen (1977-p.375)

Harold Hotelling (1931) developed a model of efficient mineral resource allocation over time that helps us understand how resources are exploited over time and the conditions under which conservation or depletion occur (*Costanza et al., 1997*). His fundamental assumption was that the owner of mineral resources had mainly two options: to extract the resource and put the profits of its utilization in the bank (hence earning an interest rate from these savings), or leave the resource in the ground to gain more value in the future. The owner would choose the first option unless the potential profits that could be earned from mining the resource in the future were increasing in value at a rate faster than the rate of interest (of savings). In a competitive resource owners market, they would all mine more if they could earn more by saving their revenues (according to bank's interest rate), or not mine at all, in the case that the owners could benefit more by leaving the resource unexploited in the ground, for future extraction.

Future expectations are reflected in the expected interest rate and the expected future price of the resource. These expectations are critical concerning the functioning of Hotelling's model. Following these assumptions concerning the expected interest rate and the expected future prices, someone could assume that any species or ecosystem that cannot be managed at a level such that it is generating a flow of services at a rate greater than the rate of interest "*should*" be depleted (*Costanza et al., 1997*). How sure could we be that our prices are fully reflected the externalities and the scarcity (*Bithas, 2011*)? What if a market failure may generates rates of interest which are falsely too high (at present) and hence leading to excessive a biodiversity loss or an exhaustion of a finite resource (*Marglin 1963; Gutès, 1996)*? In other words, by using Hotelling's model premises beyond the field of natural resources, may tell us that it will be efficient to exploit a species to extinction; or totally degrade an ecosystem and the services it provides; or, in the case of nonrenewable natural resources, to totally exploit a nonrenewable finite resource, if their values are not increasing over time, at least as fast as the interest rate of monetary units deposited in a bank account (*Costanza et al., 1997*). By extending Hotelling's argument, we could probably trace some of its implications in the debate that concerns the substitutability potentials between man-made and natural capital. Evidently, a form of natural capital (resource, ecosystem, species, etc) may be more profitable to be transformed into man-made capital (by saving the profits of their exploitation in a bank's account interest rate). In any case, we ought to keep in mind that when Hotelling introduced his model, his main concern was its implementation on raw materials (mineral resources) and not, by any means, on species extinction or ecosystems degradation. In that context, someone should deal with Hotelling's remarkable contribution, in respect to the context of problems and needs of his time, back in 1931.

Hotelling's rule is currently dominating the neoclassical theory of natural resources and economic growth as it indirectly reflects most of its aforementioned key-assumptions such as the substitution potentials between natural capital and man-made capital, future technological achievements, and so on. By all odds, the irreversibility of biodiversity loss (*Fisher and Hanemann, 1985*), the conservation of nonrenewable resources (*Georgescu-Roegen, 1979b; Bishop, 1978*), the setting of a lower limit (safe minimum standards) on the quantity of a resource that must be maintained (*Ciriacy-Wantrup, 1952*), or the definition of the Biological Crucial Levels (*Bithas and Nijkamp, 2006; Bithas and Nijkamp, 2013*) are crucial parameters that ought to be taken into account, whenever we attempt to understand and evaluate the complexity of - CHANS - Coupled Human and Natural Systems (*Liu et al., 2007*).

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3RD CHAPTER

The Dependency of Economy on Resources

Recent empirical evidence; The Material Flow Analysis (MFA)

3. Measuring Resources Use

Recent developments in the established methodologies, that account the flows of natural resources enter the economic system, have made possible the construction of long-run, periodically updated, and publicly accessible databases, available for empirical analysis and comparisons among methods and results. Essentially, this progress in data collection and utilization has enhanced contemporary research with the ability to perform rigorous empirical estimates concerning the link between Resources-Economy. Indeed, nowadays it is possible to scrutinize old theoretical approaches and test their validity through empirical estimates.

The present Chapter summarizes the main resources-waste flows accounting frameworks of the contemporary literature and focuses explicitly on the Material Flow Analysis/Accounting (MFA) methodology. The MFA framework has been officially adopted by the most significant international organizations, such as the United Nations, OECD, The World Bank, and Eurostat. Accordingly, the MFA framework has been selected as the mainstream methodological background of the present dissertation. The 3rd Chapter provides a detailed analysis concerning the estimation of the decoupling effect, through the energy and material intensity frameworks, within the context of MFA. Furthermore, we review and analyze certain modern techniques, proposed by the United Nations and OECD, which classify the estimated decoupling into various categories. In that context, the 3rd Chapter accomplishes two aims: first, it functions as a preparatory chapter which presents and analyzes the basic methodological attributes of MFA framework, and second, provides a brief literature review of some of the most contemporary studies evaluating the decoupling effect and the energy/material intensity of the economic process.

On the other hand, Chapter 4 challenges some certain properties of the MFA decoupling estimates. While the present dissertation adopts the methodological properties of MFA, it aspires to reveal certain properties that may obscure the actual potential for decoupling economic growth from resources use. In that sense, the 4th Chapter functions as complementary to the present one, as it uses MFA properties in order to delineate the alternative methodological framework that the present dissertation applies and investigates, through its empirical estimates presented in Chapters 5-6. In any case, the proposed methodological contribution should be perceived as an alternative and complementary framework to the one presented in this Chapter.

3.1 Introduction

A brief overview of human history on earth reveals the great dependency of human civilization's creation, preservation and evolution, on natural resources use. Following humanity from the first historical steps of the fire discovery to the dawn of the first industrial revolution, and until the present post industrial era, the amount of materials extracted and used is continuously growing by several orders of magnitude. Since the time of Paleolithic hunter-gatherers, the preservation of human existence, like all the other living organisms, depended on low entropy material and energy consumption (Fig. 3.1). Continuous and uninterrupted flux of material and energy flows remains an essential input for the function of human social[1] (*Fischer-Kowalski, 1998; Fischer-Kowalski and Huttler, 1999; Fischer-Kowalski, 2011*) and industrial[2] "*metabolism*" (*Ayres, 1989; Baccini & Brunner, 1991; Ayres and Simonis, 1994*) (Fig. 3.1).

In that sense, an attempt to account the quantities of energy-material flows entering in the "*exosomatic metabolism*" is of paramount importance for evaluating the performance of coupled human and natural systems (Fig. 3.1-3.3).

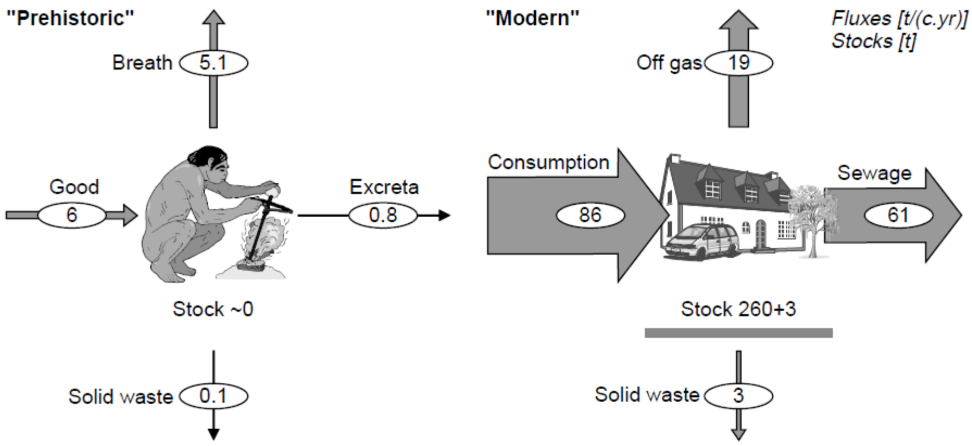

Figure 3.1 *A comparison between different magnitudes of endosomatic "prehistoric" and exosomatic "modern social/industrial" metabolism (Source: Brunner and Rechberger, 2004-p.35).*

[1] Or societal, according to the relevant literature

[2] Or alternatively, metabolism of the anthroposphere

The endosomatic[3] metabolism is a subset and, hence, consisting of a part of the more complex superset of exosomatic metabolism. Under these definitions, the preservation and the evolution of human societies require a continuous and uninterrupted energy and material flow. These low entropy flows create, after being consumed through exosomatic and endosomatic metabolism process, an output flow generally called waste (dispatched energy and material or high entropy) (Fig. 3.3). Figure 3.2 briefly captures the concept of exosomatic-endosomatic metabolism, as it represents the links between the exosomatic and endosomatic metabolism with population and economic growth. Flows of biomass are directly linked with human nutrition, hence, population growth. Flows of nonrenewable metal ores, minerals, fossil fuels, etc, are directly linked with exosomatic metabolism of society and industry, hence economic growth. Both endosomatic and exosomatic metabolism are indirectly linked with economic growth and population growth, respectively. Finally, population growth is indirectly linked with economic growth and vice-versa. Population growth is a key element usually neglected when it comes for energy-material intensity estimates. However, despite the fact that human population increases at a much slower pace, than material use and the global economy does, human beings still remain the essential driving force behind endosomatic and exosomatic metabolism.

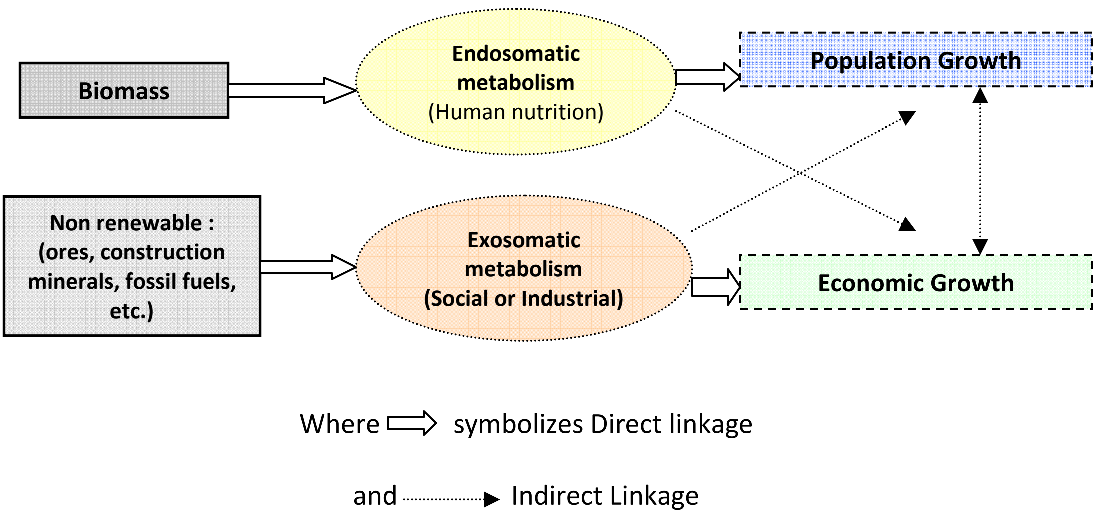

Figure 3.2 *Metabolism links with population and economic growth.*

[3] "Endosomatic" metabolism of human beings in pre-industrial period was mainly based in renewable biomass. On the other hand, the industrial societies are dominated by "exosomatic" metabolism and mineral resources use. (Krausmann, 2011. Working Paper, p. 75) (See also Fig. 3.1).

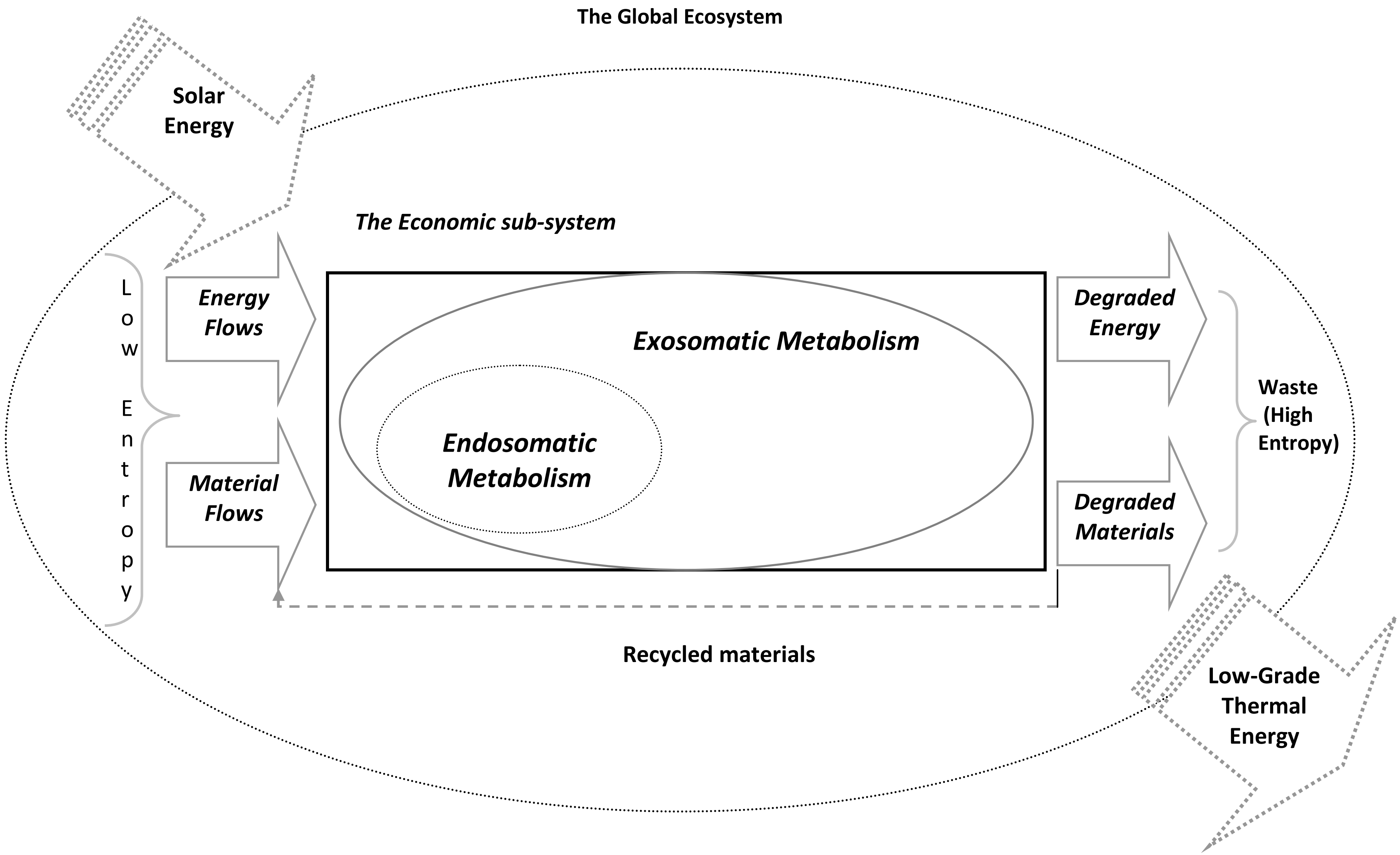

Figure 3.3 *The endosomatic and exosomatic metabolism systems as parts of the global ecosystem (Based on a modification on Hall et al., 1986 made by the author)*

3.2 A brief review of the most important measuring frameworks and indicators

Evidently, during the last 20 years there was an increasing interest on the proper and detailed quantitative assessment of the interrelations and interactions occurred between coupled-human natural systems. In order to evaluate this intricate relationship between socio-economic systems and natural ecosystems, there have been developed various measuring frameworks, accounting concepts and relevant indicators. This section aspires to give a brief glance of the most important methodologies and indicators.

Resource use accounting frameworks

In line with Giljum et al. (2011), we mainly distinguish five different methodologies that have been developed in order to trace, account and evaluate the main five aggregate natural resources categories (Fig 3.4): biotic and abiotic material resources; air; water; and land use.

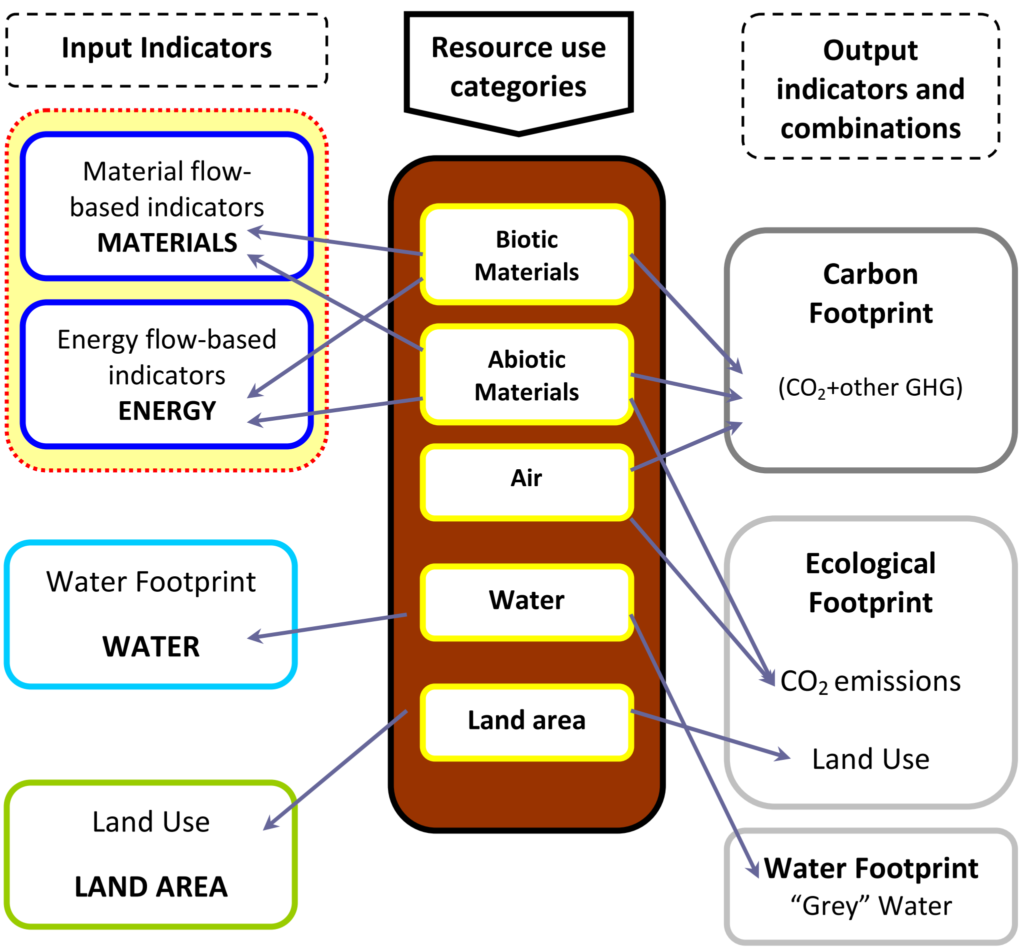

Figure 3.4 *Core resource use measurement methodologies and indicators derived from the core resource categories (Source: reconstructed by the author, based on Giljum et al., 2011-page 302.)*

The main resources use accounting systems are (Fig 3.4):

- **Material Flow Accounting and Analysis (MFA)**: MFA accounts for various material flows on the basis of mass balance calculations (kg or tones), during a defined period of time, usually one year. Further, MFA accounts the domestic extraction of material resources and the physical trade balance (imports and exports) of a national economy. Since, the MFA methodology is the basis of the present thesis, a more detailed analysis is provided to the following sections of this chapter.

- **Energy Flow Accounting and Analysis (EFA):** Actually, this distinct category is a subset of MFA. In the present study we utilize this category as a special part of the broader MFA framework; we essentially examine the energy carrier materials separately from the non-energy (non-fuel) materials. Nevertheless, the essential diversification between MFA and EFA is that, concerning the latter, the material flows are converted into energy equivalents (joules, Btu's, mtoe, etc.), reflecting the full amount of energy that could potentially be derived by their combustion[4].

- **Air Quality and Emissions accounts:** Air quality is a key variable in many environmental problems, such as climate change and Green House Gases (GHGs), air pollution, and so on. In that broad context, emissions quantification and accounting is of paramount importance for establishing and evaluating methodologies such as the Ecological Footprint and the Carbon Footprint.

- **Water resources accounts:** The comprehension of human activities' impact on the water cycle and the hydrological system calls for more coherent and accurate measurement techniques of water resources consumption, waste water and reuse. The concept of Water Footprint is among the most representative models on water accounting (*Aldeya et al., 2012*)

- **Land cover and Land use accounts:** The most common way of land accounting is through satellite images. The main aim of land accounting is to trace and classify the changes among different land cover types, across a region or a country, over time. The way this

[4] For more details in energy transformations see Chapter 6.

change occurs and the process that drives this change is among the most crucial parameters that the land accounting examines.

Major Accounting indicators

Using the classification made by *Giljum et al. (2011)* we distinguish the major indicators, used in resources accounting, in **input** and **output** oriented indicators (Fig 3.3):

- **Input Indicators**

  MFA (and EFA): The indicators derived from MFA (and EFA) comprise resources consumption, international trade (imports, exports), as well as productivity and material (and energy) intensity indicators, expressed in mass (and energy) units related to GDP. Among the most popular indicators of this category are:

  - Total Materials Requirement (TMR)

  - Domestic Material Consumption (DMC)

  - Direct Material Input (DMI)[5]

  - Domestic Energy Consumption (DEC)

  - MIPS (Material input per Service unit (MIPS)

  - DMC/GDP (material input per unit of GDP)

  - DEC/GDP (energy input per unit of GDP)

  ***Water Footprint indicators*:** These indicators account water input in production and consumption process, usually in the unit of liters. More specifically, there are three main water accounting indicators (*Aldeya et al., 2012*):

  - "Virtual" Water (*the water that directly and indirectly embodied in internationally traded products*)

  -"Blue" Water (*surface and ground water used directly in agriculture, industry and households*)

  - "Green" Water (*rainfall water used directly to grow crops*)

  Land accounts: Indicators on actual land cover and land use, expressed in ha or in m^2

[5] Direct Material Input (DMI) indicator sums up all inputs from domestic extraction and foreign trade. However Domestic Material Consumption is a better measurement of materials consumed domestically, since it excludes material exports. In other words, DMC=DMI – exports (*Schandl and Schulz, 2002*).

- **Output Indicators**

Carbon Footprint: Assesses the greenhouse gas emissions (CO_2, the so-called the F-gases, and other GHGs), through the complete supply chain of foods and services consumed in a region or a country, usually measured in kg, or in kg of CO_2 equivalents (*Bruckner et al., 2010*).

Water Footprint indicators: A quite recent approach concerning the Water Footprint methodology is the effort to trace the waste accumulation water as an output of the production process (*Aldeya et al., 2012*):

- "Grey" Water (The waste water assimilation)

Ecological Footprint: Actually this methodology combines both resources inputs and generated outputs (emissions) and briefly defined as the total biologically productive land and water areas required to produce the resources consumed by a specific population, and simultaneously to assimilate the waste produced through this consumption (*Wackerangel et al., 1999; GFN Standards Committee, 2009*).

3.3 The Material Flow Analysis (MFA)

From the early attempt of *Ayres and Kneese (1969)* to measure material and energy flows, by virtue of the mass balance principle, and the early Leontief's work on input-output analysis trough matrices[6] (*Leontief, 1982*), until the recent Material Flow Analysis[7] (hereinafter MFA) (*EUROSTAT, 2001; EEA, 2012*), various indicators have been developed in order to monitor and assess the metabolic performance of global (*Krausmann et al., 2009; UNEP, 2011b; Dittrich et al., 2012*) and national economies (*Bringezu et al., 2003; OECD, 2004; Krausmann et al., 2011; Gierlinger and Krausmann, 2011*). The substantial research has be done so far, reflects the crucial need for an accurate recording of the energy-material flows entering, and being processed by, the societal and industrial "*metabolism*". MFA has approached a high level of maturity and methodological accuracy, bringing out a wide range of publicly accessible material flow databases available for empirical analysis and

[6] Mainly used for forecasting purposes rather than historical analysis of material intensity trends

[7] Or Material Flows Accounting, as referred in the relevant literature in some cases

comparisons among methods and results (*Brunner and Rechberger, 2004; Fischer-Kowalski et al., 2011*).

The Material Flow Analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time (*Brunner and Rechberger, 2004*). By incorporating the mass balance principle, MFA quantifies and monitors all inputs, stocks, and outputs of the economic processes. In that context, MFA provides an essential accounting framework that measures and quantifies the exchanging flows between human and natural systems, hence traces the relevant interrelations and interconnections between coupled human and natural systems. MFA provides substantial information about the amounts of natural resources entering in the socio-economic system. The use of natural resources is traced, estimated and reported with standardized accounting methods which permit the development of long run time-series data for almost all countries as well as for the global economy. In that context, MFA has been developed in accordance with standards that permitted its integration to national and international prototypes such as NAMEA (*Eurostat 2008*), and SEEA of *United Nations et al. (2003)*. As a result, MFA is adopted by statistical offices in many countries and international organizations such as the European Union, United Nations, IMF, OECD and The World Bank (*Eurostat, 2001; UNEP, 2011b; European Commission et al., 2012*), while indicators and estimates based on MFA are today an officially integral part of international environmental-economic accounting and reporting tools (*EEA, 2012*). Evidently, MFA framework, as an interdisciplinary application, has gained ground in many diverse fields such as economics, resources management, environmental and waste management, and so on. The fields that MFA is employed can be summarized in (*Brunner and Rechberger, 2004*):

- Environmental Management and Engineering
- Industrial Ecology
- Resources Management
- Waste Management
- Anthropogenic Metabolism (see the Social/Industrial metabolism concept)

MFA has been designed to cover a broad spectrum of mainly direct material flows. Direct use refers to the actual resources use along the production process of all products as well as the direct use of resources during their consumption. Nevertheless, an effort to trace and evaluate the indirect material flows (all materials that are extracted or moved, but do not enter the economy), within MFA, is currently the aim of several projects (*Fisher-Kowalski et al., 2011*). In MFA, these indirect flows are also referred as "*hidden flows*". However, estimates based on MFA cannot yet capture the full environmental change induced by hidden material flows (environmental impacts during the extraction, the processing of raw materials and the wastes-emissions discharged to the environment). Furthermore, ecological services, such as sink and as the absorption services, water use, land use, which indirectly support the economy, are not yet directly accounted by the MFA's databases.

Why these residuals (hidden flows) are so important in MFA? The material consumption literacy argues about the new methods of metal ores and minerals potential utilization and recycling, but only briefly deals with the residuals of extraction procedure which are useless rubbles, wastes not capable of recycling or further use. *Meadows et al. (2002)* describe in Limits to Growth 30 years update:

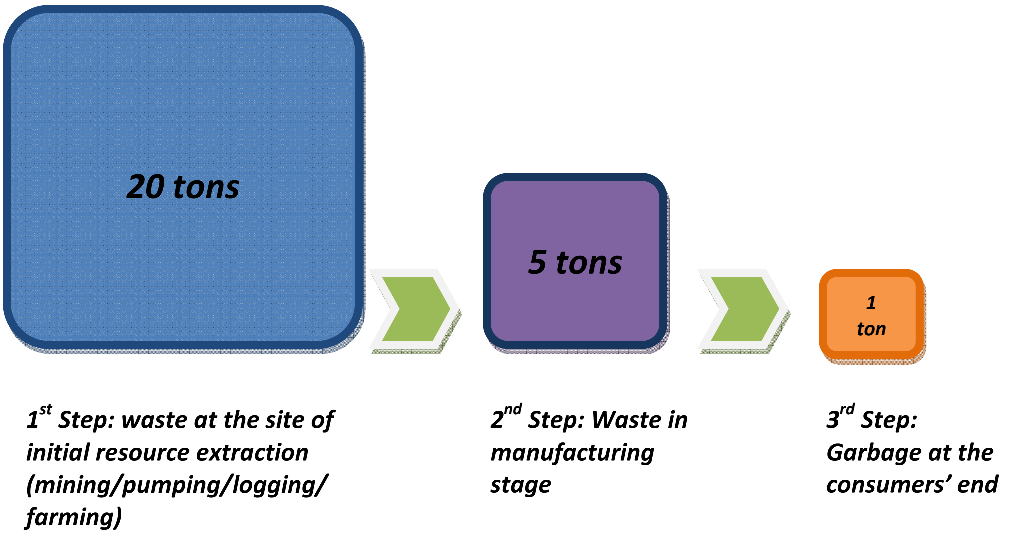

Figure 3.5 *A graphical representation of hidden flows during the production process*

Figure 3.5 depicts that for a ton of garbage at the consumer's final stage, 25 tons of waste were produced during extraction and manufacturing procedure. Obviously the consumers' recycling process mostly deals with the 3rd step, the least problematic end of materials stream (*Meadows et al., 1972*). If we consider this stream as a whole and embed it in final material consumption, we may dramatically change the prospect of dematerialization and hence, most of the assumed decoupling in material consumption. Recent reports of World Resource Institute (*WRI, 2001*) comprehend the importance of these hidden material flows from mining, earth moving, erosion etc., which together count for as much as 75% (*WRI, 2001*) of the total material flows that the industrial economies use. Hence, these hidden material flows do not enter the economy as a traded commodity, consequently, are being systematically ignored, as it is very difficult to be traced and properly accounted.

Albeit this material flows mainly consist of useless mass, unable to be used in economic production, we cannot avoid the great environmental pressure and degradation lurks behind these changes. As a result, MFA reveals only a part of the comprehensive link of the economy and the environment. In that sense, the term "*material flows*" is used, within MFA, to define the direct use of natural resources. Hitherto, statistics based on MFA concern three main material flows:

- **Biotic materials:** (*Agricultural biomass, forestry, fishery, cattle*)
- **Abiotic materials:** *Construction minerals, Ores-industrial (non-metallic) minerals*
- **Fossil[8] energy carriers:** (*coal, oil, natural gas, peat*)[9]

Utilized Indicators

MFA dataset established the ground for robust and comparable empirical estimates of the link between direct use of resources - material flows- and economic development. In the present analysis, the main variables-concepts are the following:

- **Domestic Material Consumption (DMC)**: the net flow of materials (plus energy vectors) used in a national economy. DMC accounted in kg/yr (or, 1000 tons/year,

[8] Nevertheless, a part of fossil fuels (oil and coal) is highly considered as biotic resource, as well. In any case, here we use the distinction made by the relevant literature (*Giljum et al., 2011*)

[9] The notion "*material flows*" used within MFA framework to denote all natural resources and energy carrier materials enter in the economic process. Nevertheless, energy vectors are also investigated distinctly with the assessment of Domestic Energy Consumption and the relevant energy intensity through the estimation of DEC/GDP ratio (Chapter 6).

etc.) as Domestic Extraction – exports + imports. Alternatively DMC= DMI – exports, since DMI= DE + imports (*Shandl and Schulz, 2002*).

- **Domestic Energy Consumption (DEC)**: the exclusive use of energy carriers in a national economy. DEC is accounted as Domestic energy production/extraction – energy exports + energy imports.

- **Total Material Supply (TMS)** reflects the total flow of materials (and energy vectors) at the global level, where the distinction between domestic and no domestic consumption is irrelevant since at the global aggregate level all materials are consumed "*domestically*" within earth's system.

In addition, the so-called social or industrial metabolism of an economy is being estimated by the **DMC per capita** and the **DEC per capita** indicators, respectively. In that sense, the per capita consumption of natural resources performed by a national, or the global economy, gives a sheer depiction of the magnitude that social (or industrial) metabolism has on crucial issues such as natural resources scarcity, natural resources allocation, and climate change.

The link between the economy and the flow of material is evaluated through the Material Intensity and the Energy Intensity indicators:

Material Intensity (MI)

- **DMC/GDP** ratio for total material flows (+ energy vectors) (at the national level).

- **TMS/GDP** ratio for total material flows (+ energy vectors) (at the global aggregate level).

Energy Intensity (EI)

- **DEC/GDP** ratio for total energy consumption (at the national level).
- **TPES/GDP** ratio for Total Primary Energy Supply of a national or global economy.

The **DMC/GDP** and **TMS/GDP** ratios indicate the so-called **Material Intensity (MI)** of the economy. Similarly, the **DEC/GDP** and the **TPES/GDP** indicate the so-called **Energy Intensity (EI)** of the economy. Further, some supplementary indicators, supported by MFA, are the so-called social-industrial metabolism rates. The per capita material flow (the per capita direct use of resources) measured as DMC per capita, emerges as the most broadly used.

While the estimation of MI and EI allows a comparison between the different trajectories that the individual national economies display, it has limited ability to give a precise measure concerning the magnitude of the decoupling effect. In order to verify whether the observed decoupling is relative or absolute, a second level of analysis is essential: among the most prevailing methods of assessing and classifying the magnitude of decoupling effect is the estimation of the Decoupling Index (DI), proposed by *UNEP (2011b)*, and the Decoupling Factor (DF), proposed by *OECD (2002)*.

DI evaluates the sensitivity of GDP to the changes in *Natural Resources* use (NR), or *Environmental Pressure* (EP), defined as the elasticity of GDP to the natural resources inputs:

$$DI = \frac{\left((NRorEP)_t - (NRorEP)_{t-1}\right)/(NRorEP)_{t-1}}{\left(GDP_t - GDP_{t-1}\right)/GDP_{t-1}} = \frac{\Delta\left((NRorEP)\right)}{\Delta\left(GDP\right)} \quad (1)$$

DI (*1*) is interpreted as follows (*UNEP, 2011b*):

- DI>1: there is coupling between the two examined variables.
- DI=1 is the turning point between coupling and relative decoupling.

- 0<DI<1: relative decoupling is taking place.
- DI=0 indicates that the economy is growing while resource consumption remains constant. This is the turning point between relative and absolute decoupling.
- DI<0: the relationship can be described as absolute decoupling.

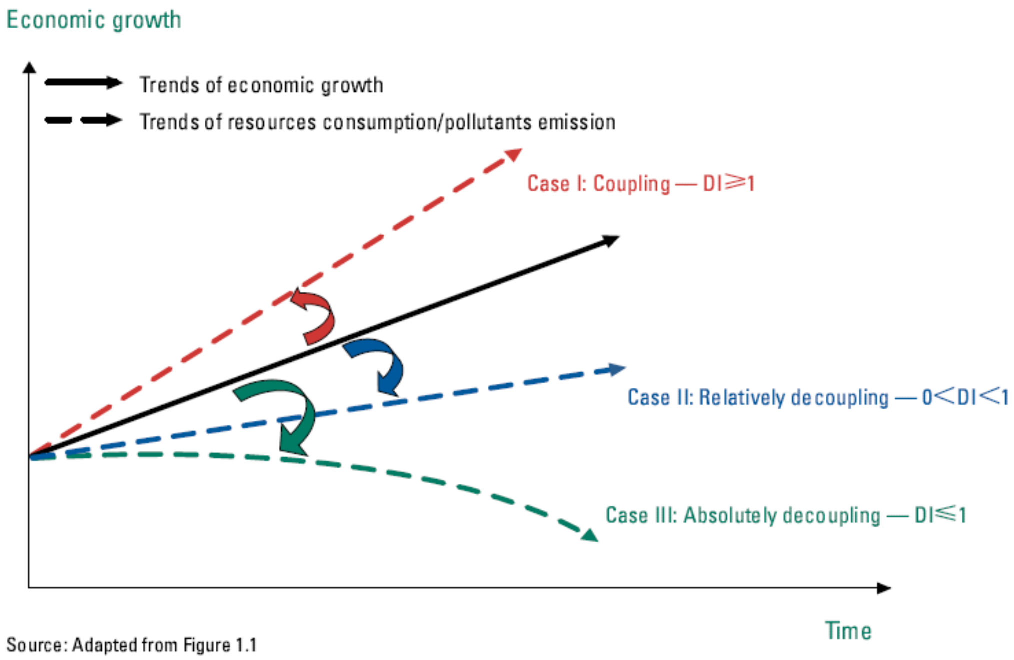

Figure 3.6 *Estimation of Decoupling Index (Source: UNEP, 2011-p. 111)*

The Decoupling Factor (*OECD, 2002*) is estimated as:

$$DF = 1 - \frac{(EPorRI / GDP)_{end-of-period}}{(EPorRI / GDP)_{start-of-period}} \quad (2)$$

Where (*2*), EP= *Environmental pressure* and RI=*Resources Inputs*. DF is zero or negative in the absence of decoupling and has a maximum value of 1, when the examined environmental pressure (or the specific natural resource use) reaches zero.

3.4 Reviewing the Decoupling and the Dematerialization estimates within the context of MFA

From the early attempts to estimate material intensity (*Malenbaum, 1978; Tilton, 1977*) to the latest empirical analysis of contemporary literature (*Krausmann et al., 2009; UNEP, 2011b; Schandl and West, 2012*), empirical evidence asserts that the global aggregate material use has increased at a slower pace than the global economy – namely GDP growth-during the last century (*Fischer-Kowalski, 2011*). This is the so-called decoupling of economic growth from material resources inputs which is alternatively called the "*dematerialization*" of economic process (*Wernick et al., 1996*). Dematerialization is defined as the relative or absolute reduction in the quantity of materials required to serve economic growth (*Wernick et al., 1997*).

Relevant literature distinguishes the decoupling effect into two distinct categories: relative decoupling and absolute decoupling. Relative decoupling means that the growth rate of the resource used is lower than the rate of economic growth (GDP) while, absolute decoupling is defined as the decline in resource use irrespective of the economic growth rate (*UNEP 2011b, p. 5*). Relative decoupling seems to be fairly common in the relevant literature (*UNEP, 2011a, 2011b*). Although most of the relevant literature concludes that there is a trend towards a relative decoupling (*Bringezu et al., 2004*), a few recent studies do exist that provide empirical evidence for absolute decoupling trends in some post-industrial economies, such as the United Kingdom (*Goodall, 2011*) and Japan (*Krausmann et al., 2011*). In that sense, many argue that a transition from the materially intensive industrialization era to a post-industrial dematerialization regime could be feasible, at least for the so-called "*developed*" economies (*Brooks and Andrews, 1974; Malenbaum, 1978; Hawken et al., 1999; Behrens et al., 2007*). These historical dematerialization trends may well raise optimism over further decoupling potentials in the future, something which is reflected in the concluding remarks of numerous studies implying that dematerialization could be seen as an important factor promoting sustainability (*Weizsaecker et al., 1997; Hekkert, 2000; Giljum et al., 2005; Ausubel and Waggoner, 2008; Allwood et al., 2011*). , while there are a few studies providing empirical evidence for absolute material decoupling as well (*De Bruyn, 2002; Goodall, 2011; Krausmann et al., 2011*).

Furthermore, decoupling could be distinguished in two distinct effects (*Bringezu et al., 2003; UNEP, 2011b – p. 5*):

- *Resource decoupling (reducing the rate of use of natural resources per unit of economic output)*

- *Impacts decoupling (reducing negative environmental impacts per unit of economic output)*

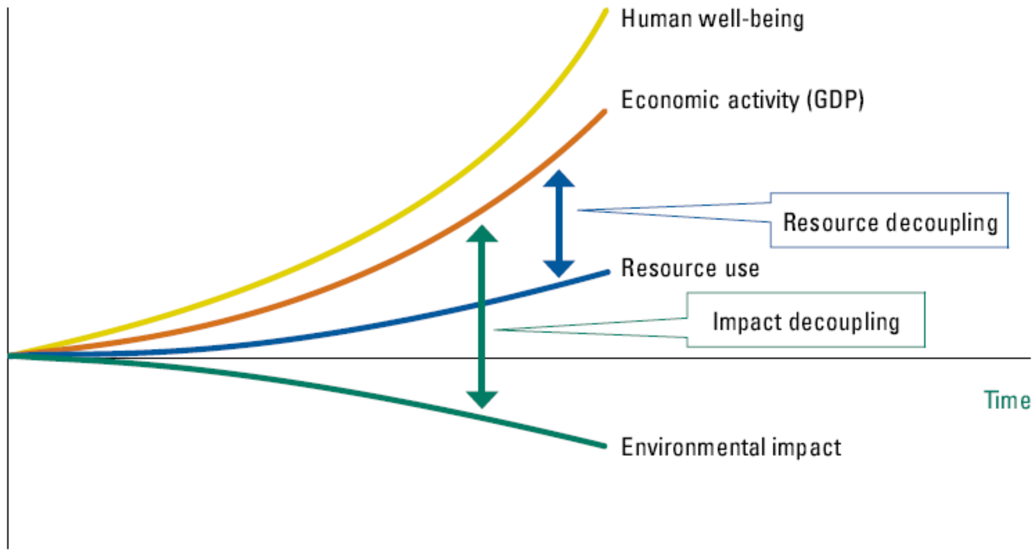

Figure 3.7 *The two aspects of Decoupling (Source: UNEP, 2011b-p.xiii)*

In the present dissertation, we firmly examine the "*resource decoupling*"; nevertheless, our empirical results may also provide indirect implications concerning the "*impacts decoupling*" category as well.

Three principal driving forces behind the dematerialization of the economy are recognized (De Bruyn 2002):

- *structural change of production towards services;*
- *technological advances which make more efficient use of resources;*
- *Substitutions among resources with a notable shift towards "lighter" inputs.*

In addition to these factors, new evidence from the contemporary literature also indicates international trade and the outsourcing of heavy industry, of the developed economies to the developing ones, as potential determinants of the extensive decoupling trends in developed countries (*Schipper et al., 1992; Giljum 2004; Giljum and Eisenmenger 2004; Munõz et al. 2009; Schandl and West 2012*).

Concerning the so-called structural change hypothesis, it is asserted by relevant literature that during the early phases of industrialization, the structural change of economic growth (GDP) increases material resources use. However, when the country enters in the post-industrial phase, material resources use starts declining (*Kander, 2005*) something which eventually leads from the material intensive industry to the "*immaterial*" services (*Hawken et al., 1999; Wölfl, 2005*). In that sense, it is assumed that in the post-industrialization phase, the service sector is acquiring an increasing share in the economy (*Panayotou, 1997; Panayotou et al., 2000; Stern, 2004*).

Concerning the technological progress and material substitution, *Bernardini and Galli (1993)* attempted to establish a theoretical framework suggesting that continuous research in material technology and substitutions among different material types could bring about substantial gains and, in turn, dematerialization of economic process. Due to technological progress, material substitution, and structural changes of GDP, it is argued that a transition to a post-industrial dematerialization era of economic production may be feasible (*Behrens et al., 2007; Brooks and Andrews, 1974; Hawken et al., 1999*). In that context, many studies acknowledge dematerialization as a potential factor towards achieving long-term sustainability (*Ausubel and Waggoner, 2008; Hekkert, 2000; Giljum et al., 2005; Weizsacker et al., 1997*).

Towards this objective, four major strategies are being proposed in relevant literature for achieving less material inputs and consequently sustainability in the long run (*Allwood et al., 2011*):

- *Longer lasting products,*

- *Modularization and remanufacturing,*

- *re-use,*

- *designing products with less materials.*

On the contrary, a large part of the relevant literature is devoted to repartees entailing various conclusions as to the potentials dematerialization trends have. Taking into account the rapidly developing countries, many suggest that the growth in large developing economies such as China and India triggers material intensity further, despite the achievements of technological progress, something which may finally push the global system to the unsustainable boundaries of resource availability (*Schandl and Eisenmerger, 2006*). In addition to this argument, new evidence from the contemporary literature also indicates that the international trade and the outsourcing of heavy industry to the emerging developing countries may proved to be a crucial parameter that substantially explains (besides technological advance and material substitution) the extensive decoupling trends in the vast majority of the developed countries (*Schandl and West 2012*). As far as the assumption of GDP reconstruction towards services concerned, some early studies (*Trainer, 1999; Vogely, 1976; Wernick et al., 1996*) have already supported the idea that if a trend away from manufacturing is truly occurring, it would not necessarily lead to less material use, since the service sector generates its own material requirements. In that context, many question the potentials a service economy has for bringing about dematerialization (*Auty, 1985; Cleveland and Ruth, 1999; Herman et al., 1990; Røpke, 2001*), while others claim that the slowdown in material intensity may be a fallacy in terms of real production (*Herring, 2006; Jackson, 2009; Kander, 2005; Lawn, 2001; Trainer, 2001*).

Tilton (1986) argues that, in order to better understand the observed decline in MI, two are the main determinants that the focus should concentrate on: demand-side consumer needs which increase intensity; and supply-side technology which mitigates intensity.

As far as the demand side is concerned, further support to "*pessimism*" over the future potentials of decoupling of economic growth from materials use, offer the consumption trends of the western lifestyle, a lifestyle being adopted by more and more developing countries, , such as China and India, which entails substantial material requirements (*Reisch and Røpke, 2004; Røpke, 2001; Wernick et al., 1996; Schandl and Eisenmerger 2006*). Specifically, *Weisz et al. (2006)* imply that the quest of today's developing countries for a higher standard of living would undoubtedly cause an increase in tomorrow's resources demand. In that context, others assert that the declining global MI trends seem to have stabilized after 2000, already reflecting the rapid industrialization of Asia (*Schandl and West 2010*).

As far as supply-side technology is concerned, *Lawn (2001)* makes an explicit reference to the thermodynamic limits that technological progress faces when it comes to the use of natural resources. Furthermore, some studies suggest that dematerialization is occurring rather spontaneously (*Larson et al., 1986*), while others assert that what appears as dematerialization, may finally proved to be a trans-materialization[10] instead (*Labys and Waddell, 1989*).

Trainer (2001), in an extremely critical paper against dematerialization potentials, distinguishes mainly four major reasons explaining why the dematerialization thesis is misleading and probably is based on a "*myth*":

- **The dubious significance of GDP**. GDP remarkable increment actually reflects a great turnover in sectors with little or no real effect on real living standards, welfare and quality of life, since much economic activity is more a speculation within the financial sector. The financial illusion of decoupling will be further discussed later on, since the main argument of the Chapter 4 deals with the abstract nature of GDP, as an inappropriate index for accounting the actual economic output.

- **Changes in the forms of energy (and mass) used**. The shift from lower (e.g. coal) to higher quality resources of energy (e.g. oil and natural gas) has resulted in a more efficient energy consumption ways. Nevertheless, Trainer argues that the fossil fuel bill is being increasingly subsidized by an accelerating decline in the ecological "*account*'. To put it differently, energy cost (hence, intensity trends), would be much higher if the current volume of production was being carried out in a more ecologically and environmentally sustainable ways.

- **The increasing importation of goods that were once manufactured domestically.** International trade and embodied resources use in imports, as well as the reallocation of heavy industries and other energy intensive activities to the

[10] A shift from one material form to another

developing countries, are among the determinant factors of energy and material intensity declines observed in the developed countries.

- **Garbage is increasing.** Besides the increasing per capita energy and material consumption trends, another impressive argument against the dematerialization is the dramatic increase of the per capita "*waste*" that modern economies produce.

Finally, *Ayres et al. (2004)*, in a more radical manner, conclude that evidence points to the fact that dematerialization cannot be achieved except by an end to economic growth, a view that is further supported by some recent studies (*Heinberg, 2011; Jackson, 2009; Martenson, 2011*).

3.5 A snapshot: reviewing the most significant recent publications on MFA

Recent scientific studies and reports identify decoupling trends, based on the standard MI indicator (DMC/GDP) and various Energy Intensity (EI) indicators (i.e. DEC/GDP), for all the cases with long run available data. Table 3.1 presents a representative review of some of the most significant recent scientific publications and decoupling reports, from international independent organizations and distinguished scholars on the field of MFA, for the global level and various other countries. The different economic levels that covered by the review of Table 3.1 will be evaluated in detail, through the proposed decoupling framework, in the empirical part of the present dissertation (Chapters 5-6).

Evidently, relative decoupling is the predominant trend in most cases, except of the Japanese economy which performs an absolute decoupling in recent years. Yet, as we will reveal in our empirical estimates, the argument of absolute decoupling performance, seems to be valid for Germany, and the United Kingdom, besides the aforementioned case of Japan.

Table 3.1 The most significant recent (after 2001) publications on MFA, for the Global economy and various countries.

References	Country	Decoupling Indicators	Time-period	Major Findings
Chen and Qiao 2001	China USA	DMI per capita TMR per capita GDP/TMR GDP/DMI	1990-1996 (China) 1990-1994 (USA)	Relative decoupling (USA) Relative decoupling (China)
Eurostat 2001	EU- 15 USA Japan	DMC per capita TMR per capita DMI per capita GDP/TMR GDP/DMI	1980-1997	Relative Decoupling
OECD 2002	OECD countries	DMI/GDP	1980-1997	Relative Decoupling (EU 15) Absolute Decoupling (Japan)
Bringezu et al. 2004	International comparison among countries	DMI per capita TMR per capita GDP per capita	1960-2000 (*Varied among countries*)	Relative Decoupling for most of the cases

		DMI per capita/GDP per capita TMR per capita/GDP per capita		
Haberl et al. 2006	European Union USA	DEC per capita DEC/GDP	1970-2001	Relative Decoupling
Schandl and Eisenmenger 2006	Global Economy	DE per capita DE/GDP	1999	-
Behrens et al. 2007	Global Economy	Global used resource Extrcation per capita DEU/GDP	1980-2002	Relative Decoupling
Xu and Zhang 2007	China	GDP/DMI GDP/TMR DMC/GDP	1990-2002	Relative Decoupling
Hashimoto et al. 2008	Japan	DMI/GDP	1980-2002	Absolute Decoupling

		GDP/DMI		
WRI 2008	USA	DMC per capita DMI per capita TMR per capita DMC/GDP	1975-2000	Relative Decoupling
OECD 2008	Global Economy OECD	DMC per capita DMC/GDP	1980-2005	Relative Decoupling
SERI et al. 2009	Global Economy	Resource Use/GDP	1980-2005	Relative Decoupling
Krausmann et al. 2009	Global Economy	TMS per capita TPES per capita TMS/GDP TPES/GDP	1900-2009	Relative Decoupling
Warr et al. 2010	USA	Exergy/GDP	1900-2000	Smooth Decoupling

	Japan Austria United Kingdom	Useful Work/GDP		
Gierlinger and Krausmann 2011	USA	DMC per capita TPES per capita DMC/GDP Biomass/GDP Minerals and Fossils/GDP	1870-2005	Relative Decoupling
Krausmann et al. 2011	Japan	DMC per capita TPES per capita DMC/GDP TPES/GDP	1878-2005	Absolute Decoupling
UNEP 2011a	Asia and Pacific (China and India)	DMC per capita DMC/GDP TPES per capita TPES/GDP	1970-2005	Relative Decoupling

		DEC per capita DEC/GDP		
UNEP 2011b	Global Germany South Africa China Japan	DMC per capita TPES per capita DMC/GDP TPES/GDP DI	Global (1900-2005) China (1990-2008) Japan (1990-2008)	Relative Decoupling (*Global & China*) Absolute Decoupling (*Japan*)
Singh et al. 2012	India	DMC per capita DMC/GDP dissagregated DMC intensity	1961-2008	Relative Decoupling
OECD 2012	OECD member countries	DMC/GDP	1980-2007	Relative Decoupling
Eurostat 2012	EU-27	DMC per capita GDP per capita GDP/DMC	2000-2009	Increased resource productivity (Relative Decoupling)

Schandl and West 2012	China Australia Japan	DE DMC DE per capita DMC per capita DMC/GDP	1970-2005	China (Relative Decoupling) Australia (Stability) Japan (Strong Decoupling)
UNEP 2013	Global Economy China India Japan	DMC per capita DMC/GDP	1970-2005	Relative Decoupling (World) Relative Decoupling (China) Relative Decoupling (India) Strong Decoupling (Japan)

Notes

DE=Domestic Extraction

DMI= Direct Material Inputs

TMR= Total Material Requirement

DEU=Domestic Extraction Used

DMC=Domestic Material Consumption

DEC=Domestic Energy Consumption

TMS=Total Material Supply

TPES=Total Primary Energy Supply

DI= Decoupling Index

GDP=Gross Domestic Product

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4TH CHAPTER

Methodology

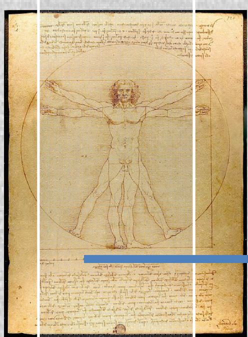
Establishing the concept of Biophysical Human Scale (BHS) and its implications on the Human Scale of Production (HSP)

"…as we have learned from Aristotle, Leonardo da Vinci, Herbert Spencer and Edward Chamberlin […] humans cannot operate at the size of an ant…"

(Georgescu-Roegen, 1983-p.27)

"…Man is the measure of all things…"

Protagoras (490-420 BC)



4. The revival of a historical argument. The Decoupling Effect and the optimism over natural resources scarcity

Contemporary literature salient to the decoupling of economic growth from material consumption asserts empirical evidence for a transition into an era of dematerialized economic production (*Goodall, 2011; Herman et al., 1990; Hawken et al., 1999; Wölfl, 2005*). Evidently, global material and energy intensity has been following a downward trend since the 1950's marking the initiation of a relative decoupling period (*Dittrich et al., 2012; Krausmann et al., 2009; UNEP, 2011*). Technological progress does allow for the more efficient use of energy and material resources. The production process is reengineered; goods and services are redesigned; and substitutions by means of lighter materials have resulted in the production of lighter goods. Technological efficiency, coupled with a general shift of developed countries towards a growing service sector, may raise optimism as to further dematerialization of the economic process.

Yet, the queries remain crucial: Is current economic growth actually delinked from natural resources inputs? Is the production process actually becoming less dependent on energy and material resources? What will be the prospects of future material and energy decoupling trends? And, ultimately, to what extent is the scarcity of energy and material resources related to sustainability conditions (*Bithas, 2008; Bithas and Nijkamp, 2008; Howarth, 2007; Kallis, 2011; van den Bergh, 2011; van den Bergh and Kallis, 2012*).

Empirical estimates of dematerialization and decoupling could be seen as the empirical aftermath of the, old but still relevant, contradictory approaches of Solow and Georgescu-Roegen, on the necessity of natural resources in the economic production and the relevant constraints on growth (*2nd Chapter*). Solow's early work with aggregate Cobb-Douglas production functions (*Solow, 1956, 1957*) reflects the "*animus*" of neoclassical theory: resources are not so important since the energy-material flows could be substituted almost perfectly by manmade capital (Daly, 1997). As a result of the substitutability of other factors for natural resources, Solow suggests that "*the world can, in effect, get along without natural resources*" (*Solow, 1974- p.11*), an approach that is further corroborated in later studies (*Solow, 1978; Baumol and Qates, 1979; Baumol, 1986, Solow, 1997*). On the other hand, the subsequent work of Georgescu-Roegen (1971, 1976), reflected on a flow-fund production function, verifies constraints implied by the physiology of the economic process: "*no agent can create the materials on which it works*". Georgescu-Roegen criticized Solow for analyzing the "*garden of Eden*" rather than the real world properties of economic production: "*there are no material factors other than natural resources*" (*Georgescu-Roegen, 1975, p.361*). Daly reshapes the argument through the well-known paradigm of the "*oven and the cake*": "*we might say that Solow's recipe calls for making a cake with only the cook and the kitchen*" (Daly, 1997, p.261).

The core of this scientific debate has been revived through the contemporary dialogue on the potential dematerialization of the economic production. To some extent, the optimism over further decoupling economic growth from energy and material inputs may reflect the optimism over further substitution of natural resources with manmade capital in an "*immaterial*" service economy. Recent studies assess empirically material intensity of economies by means of the methodological principles of the economy-wide Material Flow Analysis (MFA). The principal indicators utilized are based on the prototype "*Resources Use (energy and mass)/Gross Domestic Product (DEC or DMC)/GDP)*" ratio, which is employed in some of the most cited macroeconomic indicators[1] measuring the decoupling effect (*Krausmann et al. 2009; Krausmann et al. 2011; UNEP 2011*). Assessments based on MFA ratios seem to verify that material and energy intensity decline. Specifically, the Energy Intensity (EI) and Material Intensity (MI) trends indicate, after the WWII, *that one unit of GDP has been produced with gradually decreasing energy and material inputs* (*Nilsson, 1993; Kaufmann, 2004; Krausmann et al., 2009*). These trends establish the so-called decoupling effect between economic growth and energy-material use, for the global economy (*Krausmann et al., 2009*) and the majority of national economies (*Nilsson, 1993; Dincer, 1997; Zhang, 2003; Haberl et al., 2006; Kuskova et al., 2008; Schandl and West, 2010, 2012*). Be that as it may, such a trend may raise optimism over the future potentials of further economic growth dematerialization (*Schandl and Turner, 2009*).

The present Chapter aspires to trace the indirect revival of the timely argument on natural resources scarcity and economic growth, in the decoupling estimates of the relevant literature and to propose a new methodological framework. We assert that decoupling estimates on the basis of the (DEC or DMC)/GDP ratio systematically neglect certain physical properties of the economic process, crucial for the proper the evaluation of decoupling and its prospects. The physical dimensions of production are among these properties (*Daly, 2013-p.21*). Real-world economic production can only be envisioned as a Human Scale

[1] As it is presented in the 3rd chapter

Production (HSP) and, hence, a production that is formed and conducted by human needs. The GDP aggregates heterogeneous goods in abstract monetary units; however, this homogenization conceals some properties of the HSP (*Daly, 1997; Gowdy, 1997*). Towards these objectives, the present chapter stands as the theoretical basis of the proposed framework of the decoupling evaluation, whilst chapters 5-6, provide the empirical evaluation of our theoretical context.

4.1 The concept of the Biophysical Human Scale (BHS).

What is defined as the "*Human Scale (HS)*"? Broadly speaking, the HS notion is used for defining the interaction of human beings with their environments based on their physical dimensions, capabilities and limitations. From the infinite universe (macro-cosmos) containing a plethora of stars, planets, suns, galaxies, to the smallest micro-cosmos of particles, atoms, protons, neutrons and electrons, there are numerous different scales of measuring and quantifying the physical dimensions of objects and entities. Similarly, there are timescales much greater than human lifespan (extremely long run geological and cosmological time scales), or much shorter (atomic and sub-atomic events)[2]. In that broad context, Human Scale (HS) is defined as that abstract measuring unit which has as an explicit reference point the human beings and their biophysical properties. A human being has certain average physical dimensions (height, weight) that vary within a relatively certain space which is not expected to change drastically[3]. What is more, a human being has certain given biological characteristics, such as constant body temperature, a varied but limited lifespan, and numerous other attributes based on his sensory and mental capabilities.

For the purposes of the present study, it is essential to restrict the HS notion to the physical dimensions that human beings are embodied in. And since a human being is a living organism with certain biological characteristics, we perceive the physical dimensions of human beings as the **Biophysical Human Scale (BHS)**. The scientific field of anthropometrics,

[2] Source: Wikipedia http://en.wikipedia.org/wiki/Human_scale (Accessed December 2014)

[3] Nevertheless, according to Herman et al. (1990-p: 334) it would be extremely interesting to calculate the significance that the increasing average height and weight of humans has for materialization. Evidently, from the view of anthropology, this average "*enlargement*" of human beings will probably cause the direct increase for more food and textiles, as well as further pressure for larger vehicles and dwellings. Besides the obvious importance of these assumptions, present study will assume, for the sake of simplicity, that the average HS remains constant through time.

dealing with human scale measurements, broadly accepts the verity that the biophysical characteristics of human beings are predictable and objectively measurable. Furthermore, ergonomics is the applied science of object and equipment design that obeys to the average biophysical characteristics and, hence, to the relevant limitations and constraints imposed by BHS. From an "*anthropocentric*" point of view, every aspect of man-made production systems, every man-made object, infrastructure and building ought to serve the human needs. Irrevocably, such an anthropocentric creation, as human systems are, has to obey the restrictions and limitations that the BHS possesses.

The preservation of the biological characteristics that the human beings entail, hence the maintenance of BHS, requires a minimum of 2.000 kilocalories/per capita/per day (*Morris, 2011*). A healthy and productive adult for example, needs 2.500 Kcal/day, thus 10,5 MJ/day, or 11.000 Btu/day (*Ayres and Warr, 2009*), in order to maintain his biological existence and his productive activities. It is more than obvious that in the contemporary complex human societies, food, as a direct energy capture is not the only essential input. Modern man requires at least a minimum standard consumption level of a bunch of goods, other than food and water, such as a shelter (residence) accompanied with the relevant accommodations (sewage, tap water, electricity, equipment, furniture, etc.), transportation, and further access to product markets. From the hunter-gatherers to the first communities established after the agricultural revolution, and from the early agrarian societies to the industrialized and the post-industrial advanced economies, the basis of the prerequisites for the maintenance of BHS and the consumption patterns of the endosomatic and the exosomatic (social/industrial) metabolism have been dramatically changed; though, there is something that has remained relatively unchanged through these transitions: the entity lies behind our analysis, the biophysical properties and the physical dimensions of human beings, the irrevocably constant BHS.

The endosomatic metabolism of early human societies has been enhanced with the exosomatic social and industrial metabolism of modern human systems. However, despite these long run transitions and the multiple needs they have created, requiring more natural resources inputs, the core of this consumption pattern has remained relatively unchanged, at least as a biological entity (BHS).

4.2 A brief demographic history and implications for BHS

The humans, in their present form (Homo sapiens), appeared on Earth less than 300,000 years ago. Table 4.1 shows that, initially, population growth was extremely slow until about 10.000 BC (0,0045%). Humans lived as hunter-gatherers, until the farming and animal husbandry development, firstly in the Middle East, between 10.000 and 7.000 BC. The population historian Carlo Cipolla (1962, p.18) called the development of farming the "*first great economic revolution*". By 5.000 BC, farming had spread[4] to nearly all of the rest of the world. During that extraordinary event, the population growth rate rose more than ten-fold between 10.000 BC and 3.000 BC (Table 4.1: 0,066%). The discovery and the further development of farming led to the establishment of permanent settlements and caused the gradual reduction of nomadic tribes. These permanent settlements soon led to the first true urban areas (e.g. Jericho and Babylon).

Table 4.1 *Global population growth rate for 300.000 BC – 2010 AC*

Year	*Population (Millions)*	*Growth Rate (Annual %)*	*Year*	*Population (Millions)*	*Growth Rate (Annual %)*
−300000	1	-	1300	360	−0.03
−25000	3	0.0031	1400	350	0.19
−10000	4	0.0045	1500	425	0.25
−5000	5	0.034	1600	545	0.0
−4000	7	0.069	1650	545	0.23
−3000	14	0.066	1700	610	0.33
−2000	27	0.061	1750	720	0.45
−1000	50	0.14	1800	900	0.58
−500	100	0.14	1850	1,200	0.40
−200	150	0.06	1900	1,625	0.83
1	170	0.06	1920	1,813	0.92
200	190	0.0	1940	2,213	1.28
400	190	0.03	1950	2,516	1.82
600	200	0.05	1960	3,019	2.02
800	220	0.09	1970	3,693	1.87
1000	265	0.19	1980	4,450	1.81
1100	320	0.12	1990[2]	5,284	1.70
1200	360	0.0	2000[3]	6,057	1.30
			2010[4]	6,909	1.18

[1] Except for 1990, 2000, and 2010, all data is from Michael Kremer (1993), Table 1, p. 683.
[2] The World Bank (1992), *World Development Report 1992*, Washington, DC: World Bank.
[3] Human Development Report 2002 (2002), New York: UNDP, TABLE 5, p. 165.
[4] United Nations, Department of Economic and Social Affairs; www.unpopulation.org.

[4] Or had been independently invented in other places, rather than transferred there.

However, the most remarkable population growth rate is observed after 1750. Evidently the first industrial revolution and the gradual use of fossil fuels (initially coal), together with the unparalleled technological progress (i.e. internal combustion engine), caused a tremendous population growth. In fact, global population not only rose dramatically, but continued to accelerate throughout the nearly two-hundred year period, just as global economic growth did (Table 4.2). It took about 100 years, from 1820 to 1929, to double the world's population from about 1 billion to 2 billion. But, it took only 60 years to nearly triple world population from about 2.5 billion people in 1950 to more than 7 billion in 2014[5] (Table 4.2).

Table 4.2 *World population and GDP per capita annual growth rates (0-2003)*

Year	World Population (millions)	GDP Per Capita (billions 1990 $)	Period	Population (Annual % growth rates)	GDP Per Capita (Annual % growth rates)
0	231	445			
1000	267	436	0–1000	0.01	0.00
1500	425	565	1000–1500	0.10	0.05
1820	1,068	651	1500–1820	0.29	0.04
1870	1,260	895	1820–1870	0.33	0.64
1913	1,772	1,539	1870–1913	0.79	1.64
1929	2,047	1,806	1913–1929	0.90	1.00
1950	2,512	2,138	1929–1950	0.97	0.80
1973	3,896	4,123	1950–1973	1.91	2.86
2003	6,852	6,432	1973–2003	1.50	1.41

Source: Angus Maddison (2006), **Historical Statistics for the World Economy: 1–2003 AD**, Statistical Appendix; this document was downloaded on August 19, 2006 from the website (http://ggdc.net/maddison/) maintained by the Groningen Growth & Development Centre at the University of Groningen, Netherlands. Growth Rates are from Angus Maddison (2003), **The World Economy: Historical Statistics**, Paris: OECD, Table 8b.

Population growth, especially human being as an entity, is a parameter usually neglected when it comes for decoupling estimates, within the current literature. A first simple relationship, but not rigorously specified, between GDP growth, income (GDP per capita), human population growth and material intensity, could be traced in Malenbaum's early studies (*Malenbaum, 1977, 1978*). Recent studies in material consumption recognize population density as a largely neglected but important variable in material intensity dialogue (*Weisz et al., 2006*). Others claim that both economic and population growth tend to draw new materials into the economic system, hence implying an increasing coupling among materials usage, population and economic growth (*Wernick et al., 1996; Steinberger et al., 2010*). Krausmann et al. (2009) plainly conclude that population growth was indeed a major driver behind economic growth during 20th century, because per capita material

[5] Data on population growth in 2014 derived from the updated Total Economy Database, retrieved in March 2014.

consumption has multiplied. This assumption is further empirically supported by Madisson (2003) in his material consumption per capita estimates. Indeed, population growth plays a very important role in economic growth trends. However, this crucial interrelation between demographics and the economic growth is obscured by the vast majority of the studies in the relevant decoupling and dematerialization literature. The present research aspires to transfer the decoupling dialogue one step forward; since population growth does play a key role in the resources consumption, may we focus our efforts in understanding the energy-material requirements of a single human being entity and how these affect the economic production?

4.3 The Decoupling Effect; the physical dimensionality of economic goods and the Human Scale of Production (HSP)

Contemporary human societies utilize a plethora of goods and services in order to satisfy the today's numerous and continuously multiplied human needs. Buildings and apartments are scaled to the physical capabilities of humans (BHS). Means of transportation, furniture, clothes and tools, even the food quantity required for a healthy daily endosomatic metabolism, all these goods ought to be scaled in such a manner that must be compatible with BHS. In a nutshell, the main assumption of this section is that there is a lower boundary regarding how small could be the produced goods, in order to be compatible with the properties of BHS.

4.3.1 Defining the Human Scale Production (HSP)

No good, product or service can be envisioned and properly designed without taking into account the limitations and constraints imposed by BHS, otherwise it won't be functional for human needs. The irrevocable biophysical dimensions of human beings (BHS) result in demand for goods with certain physical properties, characteristics and dimensions. In addition, the physical dimensions of goods necessitate the substantial input of energy and material flows during their production process. Just like the smallest particle of matter which cannot be divided into smaller parts, human being (Homo sapiens), as a biological organism, is an entity that has a biophysical scale almost unchanged throughout the Darwinian journey of evolution. In other words, the Biophysical Human Scale (BHS) is an absolute "*unit*". BHS sets the required dimensions that a good ought to entail and not vice versa. The unvaried of BHS sets a very crucial questioning in energy and material consumption. Behind the phenomenal simplicity of this syllogism hides a very crucial inquiry: for how long can we possibly assume that our economic growth engine will continue to grow, to serve the growing needs of an increasing population, in account with natural resources scarcity and limitations asserted by this scarcity? Dematerialization has a downscale limit and it's not rational to assume that a reality with zero or less than a crucial level of energy and material consumption is feasible, at least for today's complex exosomatic metabolism of the economic system. A safe minimum energy and material consumption will always be crucial for life conservation, and furthermore, for the conservation of current exosomatic consumption status of developed and developing nations.

The "*cause*" of goods' physical dimensionality is the nature of the needs of human beings. Human beings are the "*causa-efficient*" – the reason – of the economic process. Goods should have certain physical properties in order to be able to satisfy human needs and preferences, hence, the human needs determine the properties that goods-production ought to have in the actual world. Physical dimensions are among the most eloquent and relevant properties of goods. The nature of human needs irrevocably define good's physical dimensionality. Human needs determine the actual physical size that goods should have and set thresholds on the potentials for "*shrinking*" that size: a matchbox sized car or an apartment of $2m^2$ would never be functional and operable by human beings. The implications and limitations imposed by the actual physical dimensions that goods embody set the actual boundaries of the economic process. Inevitably, the economic process, the actual economic production, is a procedure which takes place within the realm of human needs. The human needs, as the essential outcome of BHS, endow goods with certain physical dimensions. These physical dimensions ought to be scaled to BHS. Consequently, the economic process should be scaled to BHS in order to serve properly the actual human needs. In that sense, the real world's economic production should be envisioned as the production process that functions in respect to the human scale. Hence, the economic process that functions in respect to the fundamental limits and restrictions imposed by BHS is irrevocably a **Human Scale Production** (*hereinafter HSP*), therefore the actual production process which is performed in such a way as to serve the actual human needs, compatible to the BHS. The use of a simple equation could give a better illustration of the HSP concept:

We define as: $$BHS = f\int_{y_1}^{y_2} \sum \left(x_1 + x_2 + \ldots + x_n\right) dx \qquad (1)$$

Where, *$x, n, y_1, y_2 > 0$*

x_i= the biophysical properties of human beings (BHS) which attributed to HSP[6]*.*

n= the number of the relative characteristics that consist the BHS (e.g. weight, height, muscle power, average food consumption, physical capabilities, etc).

$[y_1, y_2]$= the closed space in which the BHS takes values. Hence, BHS cannot be valid for values lower than y_1 and beyond y_2. Hence, the majority of goods[7]*, in order to serve the BHS, should obtain certain properties which take values within the $[y_1, y_2]$.*

Consequently, by using (*1*) we derive: $$HSP = f \int_{Y_1}^{\infty} \sum (BHS)\, dx \qquad (2)$$

With $[Y_1, \infty)$, where Y_1 is defined as the aggregation of y_1 of each individual BHS consist of the sum of human beings of an economic system (i.e. a region, a country, the global level).

HSP $\rightarrow \infty$ mainly for two reasons:

a) The infinite nature of human needs that are only sutured temporarily.

b) Due to the infinite human needs, the HSP could increase in future infinitely as population (hence BHS) can grow infinitely, given the fact that there is an infinite flux of natural resources flows (or a possible total substitution of natural capital with man-made capital).

---

[6] We assume that the x_i biophysical properties of human beings, such as their height; weight; daily demand for certain calories; heating; daily demand for potable water, and so on, can be homogenized to a common measuring unit. In practice, however, this remains a hard task since each x_i takes values from different S_i, so this aggregation remains strictly theoretical.

[7] It goes without saying, that in the real world production, this general assumption holds true only partially; i.e. many constructions and buildings are huge for aesthetic or other (than serving BHS) purposes. Further, it is rather an ambitious task, an effort to directly quantify the immaterial services so as to fit within BHS concept. By all odds, this is only a brief equation which tries to briefly depict the argument of HSP by simple logical equations and by no means reflect accurately the real nature of BHS.

Hence, while Y_1 reflects the limitations and restrictions imposed by the *aggregate BHS (namely, the downscaling limit of dematerialization process)*, the theoretical upper ∞ limit reflects a hypothetical ideal situation, where there are no limitations and restrictions imposed by the aggregate natural resources scarcity (*namely, the upper limit of materialization process*).

HSP, as a function of BHS characteristics, takes values in $[Y_1, \infty)$. Albeit, HSP could hypothetically tend to infinity (given that there is no natural resources scarcity issue), there always would be an *average lower bound* (per person) regarding how small goods could be (y_1), which is not possible to be violated. Additionally, there also would be an *average aggregate lower bound* (in view of population level) regarding the *crucial aggregate minimum natural resources input* that remains essential in order to serve the average minimum needs of a population (Y_1). The former lower boundary (y_1) is irrevocably shaped and defined by the BHS, while the latter boundary (Y_1) is defined by the HSP, as it is defined by the aggregate BHS. On the other hand, the upper boundary is mainly defined by the technological level, thus, the substitution of natural capital with man-made capital; the natural resources scarcity and availability (energy and mass); the key role that the population growth plays in the above assumptions. Nevertheless, the argument that the HSP could tend to infinity (→∞) is yet an issue strongly debated, since the aggregate scarcity of natural resources remains a hot issue within the realm of economic science and still strongly questioned among scientists (*see 2nd Chapter*).

A second simple example that better illustrates the HSP concept is presented in Figure 4.1:

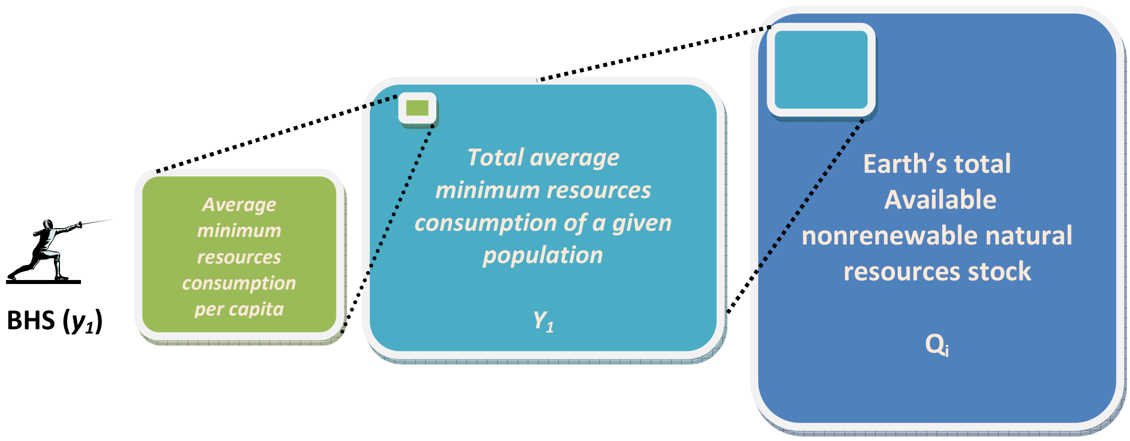


Figure 4.1 *Simple diagrammatical representations of BHS and HSP concepts.*

Q_i is briefly defined as the total sum of earth's available (*n*) non-renewable natural resources (q_i), given the restrictions implied by the entropy law, a constant technological level (efficiency), and a constant demand for natural resources (the consumption rate).

$$Q = \sum_{i}^{n} (q_1 + q_2 ... + q_n) \qquad (3)$$

Hence the HSP is defined as:

$$BHS \leq HSP \leq Q \qquad (4)$$

Where, Q could → to ∞ according to the premises we may accept as potential for natural resources availability.

However, according the analysis of the 3rd chapter, we assume that is not possible[8] for Q→∞, hence, we re-write (*3*), according (*4*) assumption as:

$$HSP = f \int_{Y_1}^{Q} \sum (BHS)\, dx \qquad (5)$$

With,

Y_1 = *defined as the lower boundary of dematerialization (decoupling)*

Q = *defined as the upper boundary of materialization (coupling)*

In a nutshell, despite the simplified and sometimes crude assumptions that this section aspired to present, the effort to trace the lower bound, of the so-called dematerialization of the production process and the decoupling of economic growth from natural resources, reveals the essential and largely neglected role of BHS within the context of economic growth. It goes without saying that, tracing and defining more accurately the BHS requires remarkable and extensive effort, though the rationality of BHS and HSP concepts is not

[8] At least with current technological level

disposable. The following section aspires to incorporate the HSP concept within the MFA methodology and the decoupling estimates.

4.3.2 Integrating Decoupling debate and HSP concept. The proposed framework for MFA

The main assumption of the present dissertation is that the satisfaction of human needs and preferences requires "*real world*" goods which, inevitably, have certain physical dimensions. These physical dimensions are the result of BHS. In turn, the shaping of these physical dimensions requires a substantial quantity of energy and mass flows (resources input). The cause behind the physical dimensionality of economic production is human necessity. In the real world, the outcome of the economic process has certain physical dimensions (*Lawn, 2001*) determined by "*human scale*" (BHS). The human being is the ultimate entity of the economic process and, therefore, the outcome of the production process should be envisioned at the human scale (HSP).

The "*human scale*" concept is widely used by the social and environmental sciences (*Gibson et al., 2007; Folke et al., 1996*), while certain economic approaches use the term "*human scale*" to analyze economic development (*Cruz et al., 2009; Max-Neef, 1991, 1992*). Yet, the human scale, and its implications, is a notion largely neglected by studies of dematerialization and decoupling. At least indirectly, the present research aims at reflecting the human scale impacts on the decoupling estimates. For this reason, this section aspires to incorporate the concept of HSP within the mainstream decoupling indicators of the MFA framework.

The production process should be envisioned as a material-physical process which, by means of the contribution of fund elements (which are the agents of the process, thus: machinery and labor[9]), transforms input flows (low-entropy energy and mass), into output flows (goods and high entropy "waste") (*Georgescu-Roegen, 1971, 1979, 1984*). In that sense, the estimation of decoupling of growth (GDP) from matter and energy becomes synonymous with the estimation of the decoupling of the production process from natural resources requirements. In that context, the existing empirical assessments of GDP decoupling from material and energy inputs are based on the **DMC/GDP** and **DEC/GDP** ratios, respectively. In several cases, the indicators that measure energy and/or material intensity change properly (i.e. TPES/GDP, in the case that instead DEC, the Total Primary Energy Supply is used, or

[9] In his detailed analysis, Georgescu-Roegen adds Ricardian Land as an Agent, too.

DMI/GDP, in case that the Direct Material Input index is used, instead of DMC) (See Chapter 3 for abbreviations). In any case, the link between growth and natural resources use is evaluated by ***"Domestic (energy and mass) resources consumption"* (in physical quantities)/GDP (in monetary values) ratio**, which defines the prototype of all indicators utilized for evaluating Material (MI) and Energy (EI) Intensity of the economy, within the MFA framework. Intensity evaluation indicators, while defer on what the nominator measures in each case study, however they are all based on the aggregate GDP as the dominant denominator measuring the economic system's performance. In effect, decoupling trends evaluated through the historical trajectories of *Natural Resources flows* (NRf), where NRf (could be defined as DMC *or* DEC *or* TPES *or* DMI *or* TMS, etc.) /GDP indicators, are estimated for the global and several national economies (*Eurostat 2001; 2002; Bringezu et al. 2003; Eurostat 2009; EEA 2012*). The *Natural Resources flows (NRf)/GDP* ratio is the prevailing prototype/indicator for measuring natural resources contribution to GDP, where GDP remains the standard utilized denominator that measures economic activity.

As we have already reviewed in Chapter 3 (Table 3.1), the vast majority of empirical estimates indicate a relative decoupling in the natural resources requirements for the production of one unit of GDP. Furthermore, implicit and explicit projection of these estimates into the future may indicate substantial potential for further decoupling of the economic production from natural resources flows (*Ausubel and Waggoner, 2008; Bernardini and Galli, 1993; Goodall, 2011; Schandl and Turner, 2009*). As these estimates of decoupling are arithmetically valid, optimism over the potentials of decoupling is also valid to the degree that decoupling is evaluated at the level of the aggregate monetary GDP. Indeed, one additional monetary unit could be "*created*" by gradually decreasing natural resources inputs. Under the influence of technological advance and substitution among resources forms, shift of advanced economies to service sector, and changes of relative prices of goods, estimates taking place at the aggregate GDP level support that additional monetary units can be "*created*" by a decreasing amount of resources marking a decoupling of economic process from resources use.

Indeed, one unit of monetary value could be created by gradually decreasing energy and material inputs. The GDP index is the abstraction of the aggregate economic production of goods. The GDP homogenizes heterogeneous "*goods and services*" by aggregating their monetary values. The monetary value-based GDP conceals the very fact that growth concerns the production of goods with a physical hypostasis (*Daly, 2013, p.21*), while almost all aspects of services have an indirect "*physical dimensionality*" due to the fact that certain goods providing them carry, as physical objects, physical dimensions (*Lawn, 2001*). Monetary values at the aggregate level of GDP fail to take into account the physical dimensionality of the economic production which determines the potentials for decoupling. The physical dimensionality of production is of paramount importance when tracing projections concerning the future potentials of decoupling economic growth from natural resources inputs. The limits of the potential reduction of natural resources inputs may be revealed once the dimensionality of goods is estimated, even if indirectly so. We argue that these decoupling estimates conceal important aspects of the link between economy and resources, resulting in an "*illusion*" for a dematerialization of the economic production. The main reason is that the aggregate monetary-based GDP, being the sum of numerous monetary-based constitutes, obscures the actual link between the economic process and resources determined by the physical properties of production. GDP reflects the aggregation of the monetary value of all goods produced through the economic process. Hence, GDP is a monetary amalgam that homogenizes the whole production in monetary terms. As GDP stands at the highest level of monetary abstraction, is deprived by any correspondence to the physical properties of individual goods which determine the actual material requirements of the economy. Tracing the linkage between economy and resources use, at the level of aggregate GDP, fails to account for those physical characteristics of goods that determine the actual resources requirements (HSP). The overwhelming effects of monetary factors render aggregate GDP an inappropriate monetary level for evaluating the resources necessities of the economic process. The present analysis proposes the "*per capita GDP*" as a more appropriate level for analyzing the resources requirement of the actual economic output for human beings; welfare-utility.

Regrettably, economic analysis has no solid variable at its disposal that encompasses the actual physical dimensionality of the production process and, hence, to incorporate BHS in the real world of HSP. In that context, we propose the use of the **Natural Resources flows (NRf)**$_{\mathbf{(DMC\ \mathit{or}\ DEC\ \mathit{or}\ TPES\ \mathit{or}\ TMS\ \mathit{or}\ DMI,\ etc.)}}$**/[GDP** $_{\mathbf{per\ Capita}}$**]** indicator as the appropriate framework/prototype that provides an indirect accounting unit of the physical dimensionality that the aggregate GDP incorporates. The use of the **NRf/[GDP** $_{\mathbf{per\ Capita}}$**]** indicator can be seen as an approximation that takes into account the physical dimensionality of production with an indirect relevance to the BHS. The GDP per capita index downscale the GDP, from the aggregate abstract level, to the welfare-utility level. In other words, the GDP per capita, while being still an abstraction, is carried out more precisely at the human level of BHS. In that context, the **NRf/[GDP $_{\text{per Capita}}$]** indicator should be perceived as the estimation of *the resources input required for the creation of a per capita unit of welfare-utility*. The level of the aggregate monetary value of GDP lacks any reference to the physical properties of the goods that compose it. Economies with equal GDP and DMC or DEC, but different populations, have equal MI and EI, respectively, according to the standard MFA framework, although they may differ substantially in their actual characteristics - and hence in the resources requirements - of the goods produced. The different structures of these economies are the result of the very fact that these economies aim to satisfy the needs of different populations (hence, different BHS) and therefore, ceteris paribus, different sets of goods, with different physical properties (hence, different HSP), are produced for that purpose. Henceforth, the present analysis asserts that the estimation of the Resources Intensity (RI) of the economy should take into account the implications imposed by the physical characteristics of goods-production. The implications and limitations imposed by the actual physical dimensions of goods on the RI are thoroughly masked once the RI of the economy is estimated at the level of aggregate monetary GDP.

In synopsis, the inherent merits of the proposed decoupling evaluation framework can be briefly summarized in the following four cornerstones (Figure 4.2):

- Evaluates the *structure and "physiology"*[10] of the economic system, under the influence of ***demographic basis***.
- **Downscales the aggregate monetary GDP** to a more appropriate level of analysis, with more traceable physical properties of actual goods, the **per capita welfare-utility level** (GDP per capita).
- Traces the resources requirement of a "***tangible and traceable set***" of goods, thus the "***bundle (basket) of goods***" consumed by the average representative citizen.

[10] We use the term "physiology" here, since we conceive the "*economic system*" as part of the Coupled Human and Natural Systems (CHANS) approach. Hence, the economic system has its own physiology, as a component of CHANS and a sub-system of the biosphere.

- Estimates the resources intensity of the economic process at the level of **economic welfare** and **economic utility** of the average human being. The economic system should always be envisioned as an engine producing human welfare and prosperity.
- Evaluates the economic system as an integral component of the Coupled Human Natural Systems (CHANS).

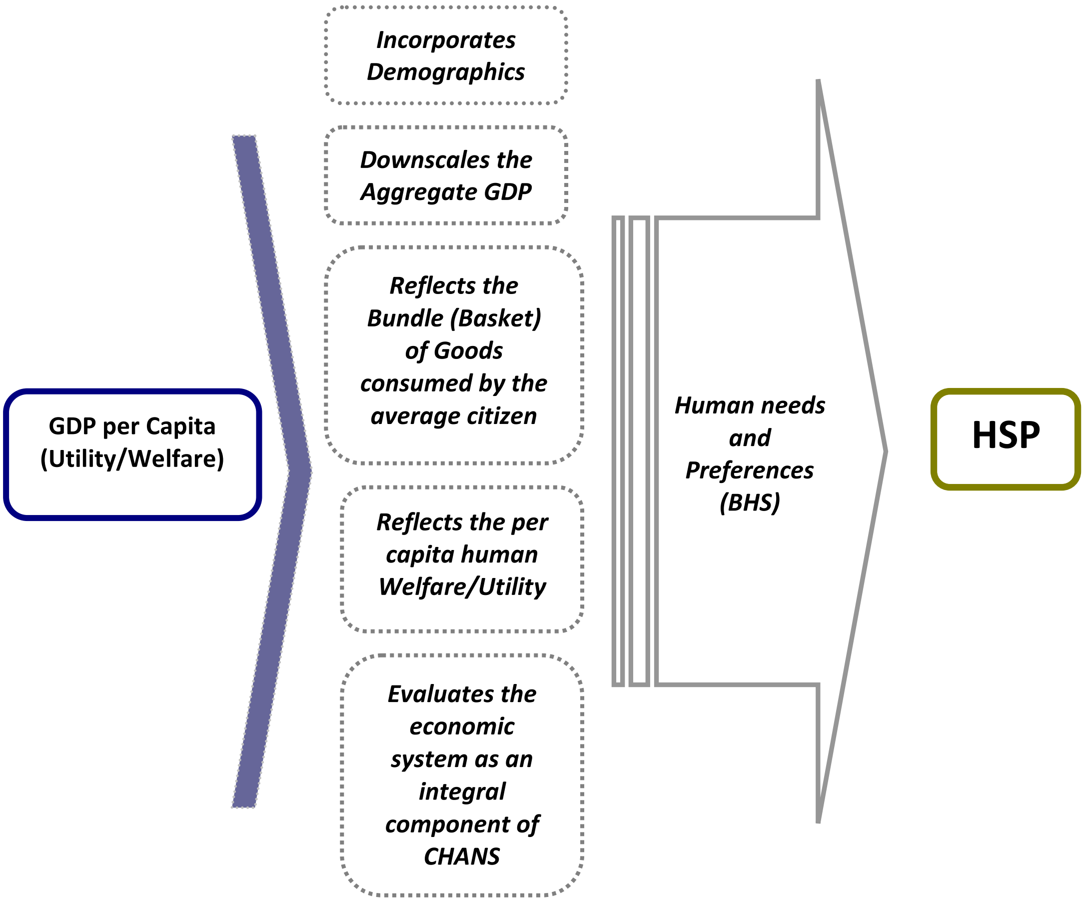


Figure 4.2 *The cornerstones of the proposed framework*

In terms of pure economic science, GDP per capita stands among the most widely utilized indicators that measure the performance of the economic system, as it evaluates the economic welfare created by the economic process[11]. In contrast, the aggregate GDP does

[11] Recently, many contemporary welfare measuring methodologies have been established in order to replace the simple GDP per capita index, such as the Human Development Index (HDI), the Genuine Progress Index (GPI), and other well-being measurement techniques like the Gini index. Despite the fact that contemporary research in welfare measurement proposes various new approaches, we firmly test our theory under the mainstream framework of GDP per capita=Welfare-Utility.

not offer an even indirect assessment of economic welfare, while fails to accurately reflect the demographic basis of an economy. Let us better illustrate this argument with a simple example: does a national economy of 1 billion US$ GDP perform better than another national economy of 2 billion US$ GDP? This question cannot be answered persuasively unless the relevant demographic bases are taken into account and the GDP per capita variables are compared. Consequently, we propose that the evaluation of the RI of an economy ought to take place at the per capita level of production, this being an operational variable that indicates the structure of the economic system better than GDP.

Beyond this aspect, the use of GDP per capita captures within the RI estimates explicitly the effects of an important driving force of the economic process: demographic dynamics. Demographic dynamics result in important implications for the resources requirements of the production process. The population level determines the structure of the production and the shares of different economic sectors. In this respect, the population level is among those crucial factors that determine the production of "*basic goods*". These basic goods (dwelling, accommodation, transportation, food, infrastructures, etc) are embodied in extensive physical dimensions whose production requires substantial resources inputs. In contrast, "*service-like*" goods are "*embodied*" in "*lean*" material structure with marginal necessities in material inputs. A higher population results, ceteris paribus, in a relatively higher production of basic goods, implying a relatively stronger link between production and resources inputs. As a result, demographic structure and dynamics co-determine the RI of the economy. Evidently, the economic process is an integral component of coupled human-natural systems and therefore neglecting its setting within demographic dynamics would result in imperfect evaluation of the RI. **NRf/[GDP $_{\text{per Capita}}$] indicator** attempts to place the economic process within the coupled human-natural system (CHANS).

What is more, the variable GDP per capita brings within the picture of RI evaluation the "*cause*" of economic process, human beings (BHS). The needs of human beings entail the production of goods with certain properties that are relevant to RI. The resources requirements for the production of one unit of per capita GDP introduces into the analysis, even indirectly, the impacts imposed by the physical dimensionality that actual goods carry (Due to the BHS implications). In particular, the RI of the monetary value of per capita GDP estimates the resources requirements of the "bundle (basket) of goods" consumed by the average human being. This bundle of goods offers a far better approximation of the properties of real-world goods in comparison to the aggregate – therefore, dimensionless - GDP. By downscaling aggregate GDP to the level of "per capita GDP", we are able to investigate the resources requirement for a "*tangible*" economic entity: the bundle (basket) of goods consumed by the "*representative*" citizen. The "*per capita GDP*" refers, ceteris paribus, to a more "*actual*" monetary entity whose physical properties can be traced, even indirectly. The present analysis emphasizes on the physical dimensions of goods, being the physical properties with substantial implications for the RI of goods and hence of the economy.

Although both indexes reflect pure monetary values, the "*per capita GDP*" denotes this monetary value in relation to an actual entity, human beings, which eventually are the "*reason*" behind the production process (HSP). On the other hand, aggregate GDP is an extreme abstraction of monetary values of numerous goods and services; this monetary amalgam is being deprived by any correspondence to the physical properties of the production process and hence, to the HSP. We argue that the proposed framework amalgamates to some extent those economic and physical properties of the production process that determine certain aspects of decoupling and dematerialization. In that sense, the real interest of the analysis can be found in the discrete evolutionary patterns the **NRf/[GDP $_{\text{per Capita}}$]** and **NRf/GDP** indicators followed through the economic history of the period analyzed. The quantitative comparison between the two ratios is irrelevant and unimportant as they form different accounting units. The difference in the magnitude of the two indicators is deprived of any meaningful interpretation since they form distinct algebraic structure. The proposed indicator is sensitive to the absolute scale of population and therefore international comparisons cannot be performed unless the ratio is indexed to a base year. Nevertheless, by scaling both indicators their comparison is possible. In that context, the indexing of all indicators into a base year (base year=100) is adopted throughout the empirical estimates of the present dissertation.

In a nutshell, the present analysis explicitly focuses on the historical path followed by *the resources inputs required for the "formation" of a unit of GDP*; and on its comparison to the historical path of *the resources inputs necessary for the production of a unit of GDP per capita*. The former indicator envisages an autonomous economic system without any actual relevance on the nexus of nature-human interactions. On the contrary, the latter indicator investigates the link between resources and the production, once the production process is envisaged as taking place at the human scale (BHS), hence, envisages the economy as an integral part of coupled human-natural systems (CHANS) (*McConnell et al., 2011*).

Furthermore, an additional merit of the proposed framework is that it aspires to enhance the decoupling literature and the MFA with empirical evidence from other scientific dialogues. Specifically, the literature concerning *Environmental Kuznets Curves (EKCs)* mainly investigates (*Panayotou, 1992; 1997*) the relationship between income (GDP per Capita) and environmental pressure (aggregated pollution i.e. CO2 measured in tons), while a recent meta analysis study of the literature concerning the causal relationship between energy consumption and economic growth (*Kalimeris et al., 2014, see also the 7th Chapter*), has revealed several studies exploring *the causality between aggregate energy consumption and GDP per capita (income)*, instead of GDP (*Soytas and Sari, 2003; Lee, 2006; Soytas and Sari, 2006; Huang et al., 2008*).

Nevertheless, a direct investigation of the relationship between energy-material flows and GDP per capita, within the RI estimates, is an issue that has been widely neglected by the relevant literature.

In any case, the present thesis does not aspire to come up with an explanation of (de)coupling trends and the factors that determine the link between Resources-Economy. Its scope is the development and the employment of an alternative indicator for evaluating this link, an indicator that considers the economic process as an integrated part of coupled human natural systems. A similar framework was recently used to estimate the decoupling of GDP per capita from energy inputs (*Brown et al., 2011; Bithas and Kalimeris, 2013*). Empirical estimation of the NRf/[$GDP_{per\ Capita}$] indicator sheds light on certain aspects of the link between economy and resources. Missing elements obscured by NRf/GDP are revealed and evaluated.

By all odds, the NRf/[$GDP_{per\ Capita}$] shares with NRf/GDP all those intrinsic drawbacks arising from the appropriateness of GDP as a reliable measure of the economic process. It goes without saying, that criticisms concerning the so-called environmental externalities hit both the standard and the proposed framework (*van den Bergh, 2010; Bithas, 2011; Daly, 2013; Costanza et al., 2014; IHDP, 2014*).

4.3.3 The proposed Material Intensity indicators

Material Intensity (MI)

- **DMC $_{non\text{-}fuel}$/[GDP $_{per\ Capita}$]** ratio for pure mass –material- flows (at the national level).
- **DMC/[GDP $_{per\ Capita}$]** ratio for total material flows (+ energy vectors in quantities i.e. tons) (at the national level).
- **TMS/[GDP $_{per\ Capita}$]** ratio for total material flows (+ energy vectors) (at the global aggregate level).
- **DMI/[GDP $_{per\ Capita}$]** ratio, for Direct Material Input (DMI)

4.3.4 The proposed Energy Intensity indicators

Energy Intensity (EI)

- **DEC/[GDP $_{per\ Capita}$]** ratio for total energy consumption (at the national level).
- **TPES/[GDP $_{per\ Capita}$]** ratio for Total Primary Energy Supply of a national or global economy.
- **TPEC/[GDP $_{per\ Capita}$]** ratio for Total Primary Energy Consumption of a national or global economy.

4.3.5 The Divergence framework

In addition to the decoupling classifications provided by UNEP (Decoupling Index) and OECD (Decoupling Factor), presented in Chapter 3, we implement a new methodology that aspires to further reveal the divergence between the standard and the proposed Material-Energy Intensity framework.

The *Divergence* between the *standard Resources Intensity –GDP–* (*SRI*) and the *proposed Resources Intensity –GDP* $_{per\ capita}$*– frameworks* (*PRI*), at time *t,* is defined as the difference of their indexed values to a base year of each case study:

Indexed (Base year t_0=100) SRI_t = (SRI_t-SRI_{t_0})/SRI_{t_0} (Similar process is followed for PRI)

Divergence $_t$ = indexed PRI $_t$ – indexed SRI $_t$

Where *t=one decade*

The relative contribution of *SRI* and *PRI* to their divergence is estimated as the percent contribution of their differences from 100, to the Divergence *100:

- Relative contribution of SRI $_t$ = Indexed SRI $_t$/Divergence $_t$ * 100%
- Relative contribution of PRI $_t$ = Indexed PRI $_t$ Divergence $_t$ * 100%.

Where *t=one decade*

The Divergence and the % contribution to Divergence are evaluated for all the long run examined energy-mass intensity cases, in the Chapters 5-6. The implementation of the divergence framework aspires to provide an innovative depiction of the substantial differences between the empirical results of the standard and the proposed decoupling frameworks. Further details will be given in the relevant sections of chapters 5-6.

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5TH CHAPTER

Integrated evaluation of the material intensity of the economy

The case of non-fuel materials

" ... The robber, the only robber, of energy and matter is matter itself (...) matter is thus continuously displaced, altered and scattered to the four corners of the world, becoming less and less available for our own purposes ..."

Georgescu-Roegen, 1979

5.1 Introduction

The 5th Chapter investigates explicitly the mass (non-fuel materials) intensity of the economic process by estimating and comparing the mainstream material intensity framework with the proposed methodology presented in the 4th Chapter. Since the mass resources serve different purposes than the energy resources, we examine their link to the economic process separately. The energy intensity is explicitly evaluated in the 6th Chapter. The present chapter begins with a brief historical review in material resources utilization by humans, classifies the different material resources, and estimates the intensity of 9 primary metals, cement, plastic materials, and fertilizers. Furthermore, it estimates the non-fuel material (mass) intensity of the global economy, the USA and Japan. In addition, the two appendices, at the end of the 5th Chapter, estimate the total material intensity (including the energy carrier materials), at a continental and various national levels.

5.2 Why material resources are so essential? The dawn of Anthropocene

Inevitably, all organisms inhabit the earth use materials, directly and indirectly. Modern human societies utilize material flows through the essential, for the preservation of life, endosomatic metabolism and the essential, for the complex human systems preservation, exosomatic (social/industrial) metabolism[1]. The earth's crust provides all these essential material resources. The Lithosphere is the earth's outermost shell of rock, the rigid outer layer of our planet. It is composed by the crust and the uppermost lithospheric part of mantle, being about 100-120 km thick (*McNeil, 2000; Wikipedia, 2014*[2]). The uppermost part of the Lithosphere that chemically reacts to the atmosphere, hydrosphere, and biosphere, is called the Pedosphere. Consequently, the Pedosphere is the soil, the earth's skin, which could be perceived as a membrane between the lithosphere and the atmosphere. What makes Pedosphere so exceptional is that it constitutes the main interaction "*area*" between air (atmosphere), biosphere (the sum of all ecosystems and living organisms, including human systems), lithosphere (in brief the mineral stock), and hydrosphere (underground, surface, and over the surface waters). In a nutshell, Pedosphere is this exceptional area where the miracle of what is called life takes place.

[1] See 3rd and 4th Chapter for the terms "endosomatic and exosomatic metabolism"

[2] Wikipedia http://en.wikipedia.org/wiki/Lithosphere

In general, we can distinguish two main sources of material flows, those derived from lithosphere (minerals, ores, fossils) and biomass creation taking place in the Pedosphere area, through the complex process of global photosynthesis (a "*gift*" of solar radiation that reaches the earth's surface – thus the Pedosphere –). As we have already predefined in chapter 3, human societies are characterized by "*endosomatic*" and "*exosomatic*" metabolism. Besides the obvious endosomatic (biomass-food consumption), human societies also "*consume*"[3] substantial quantities of many other material forms.

One of the most controversial achievements of Mankind was the ability to change the earth's surface. Human action has altered the surface of the planet biologically, chemically, and physically (*McNeil, 2000*). The Human kind became, for the first time in the history of its existence on earth, a significant geological agent that has already changed the biosphere so substantially, that many distinguished scientists recognize the time period in which we live as a new geologic epoch, the so-called Anthropocene (*Steffen et al., 2011; Barnosky et al., 2012; Gowdy and Krall, 2013*). The social (or industrial) metabolism of the human systems has approached the state of being comparable in magnitude with the major geological agents of natural systems (*Brunner and Rechberger, 2004; Harberl et al., 2007*).

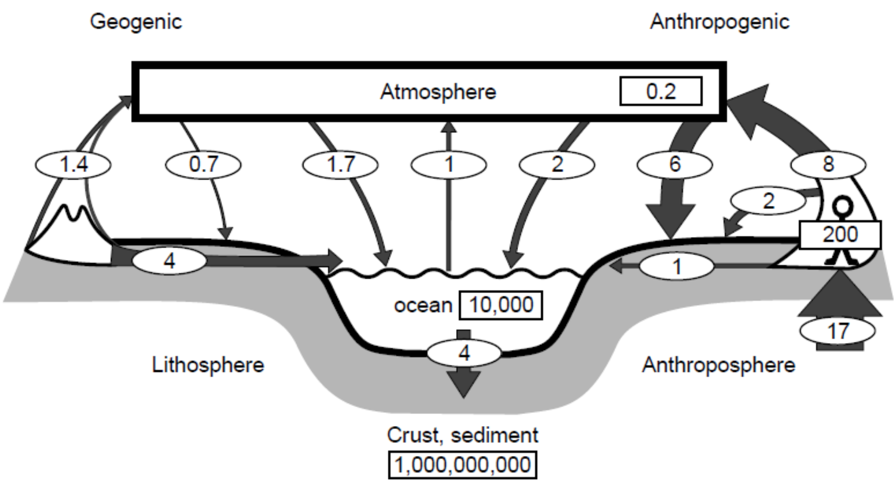


Figure 5.0 *The example of Global cadmium flows (kt/yr) in the 1980's (Source: Brunner and Rechberger, 2004-p.23)*

[3] The use of the word "*consume*" does not imply that humans consume materials per se, but it refers to the services provided by the use of material goods.

The excessive augmentation of the per capita human consumption has tremendous impacts on natural systems. Anthropogenic flows have surpassed the geogenic (natural) flows, concerning various chemical elements and material types. Brunner and Rechberger (2004) provide a representative example about how global man-made flows of cadmium (Cd) from the lithosphere to the anthroposphere, are 3-4 times larger than the geogenic flows (erosion, volcanoes, etc) (see *Figure 5.0*). Accordingly, Table 5.1 gives a more dramatic depiction of the consequences of human activities functioning as geological agents. Specifically, the average annual transportation of rock and soil is estimated between 40-45 billion tons for human activities (*Table 5.1*), when the wind erosion counts for 1 billion tons, and the only natural agent which has stronger impacts on global materials transport, other than humans, is the water, with 53 billion tons annually (*Hooke, 1994; McNeill, 2000*).

Table 5.1 *Earth movers. The Average world annual transport of Rock and Soil*

Natural Forces	Billion tons per year
Wind Erosion	1,0
Glaciers	4,3
Mountain building	14
Oceanic Volcanoes	30
Human activities	40-45
Water	53

Data Source: Hooke, 1994. The table is derived from McNeil, 2000-p. 30. (reconstructed by the author)

5.3 The saga of the historical use of materials in retrospect

Christian Tomsen (1836) divided material use evolution into three distinct eras: Stone, Bronze, and Iron ages. Nevertheless, this sequence is not valid for all civilizations, since some societies had a pure copper era (i.e. Ancient Egypt), while others moved directly from Stone to Iron Age without any intermediary stage. Smil (2014) provides a very detailed analysis of the historical evolution in materials use, classifying it in four[4] distinguished time periods:

- ***Materials in Prehistory:*** For millions of years, stones were used as the main material forming the Paleolithic tools. Perhaps the most notable innovation 164.000 years ago was the ability to modify stone's properties by using thermal energy – fire heating – (*Brown et al., 2009*). Apparently, prehistoric societies managed to perform their exosomatic metabolism without using any metal materials.

- *Ancient and Medieval Materials:* The first evidence for smelting metals is coming from the complex civilizations evolved in Middle East, Mediterranean, and East Asia. Ore mining and metal smelting began with copper and followed by iron ores, establishing iron as the dominant metal of ancient Greece and the posterior Roman Empire. Besides copper and iron, other metals such as zinc, lead, mercury, silver and gold, were mastered by the ancient metallurgists. However, it should be denoted that wood remained the main fuel material, during the process of smelting.

- *Materials in the early modern era (1500-1800):* The early modern material era was characterized by increasing population, urbanization, and the first steps towards what was going to be the industrialization process. All these processes, together with the discovery of the so-called New World, stimulated vast changes in material consumption trends. However, besides the remarkable material (especially silver and gold) flows from the New World's colonies to Europe, wood remained indispensable: from house building and means of transportation construction, to the provision of heating, iron smelting and so on, wood remained the most essential (serving as both a fuel and construction) material flow through the entire human history on earth, at least until 1800.

- *Modern material civilization. The 20th century miracle:* The modern material era, the miracle of the 20th century concerning the magnitude of the material flows used in the human systems, started in England, were coal finally substituted the wood as the dominant fuel material. The unparalleled structural changes this transition set off, first occurred in the United Kingdom and then progressively expanded in Western Europe and North America

[4] Actually Smil (2014) provides five distinct eras; however we decided to merge the last two periods into one, for simplicity's sake.

were mainly based on two facts: the dawn of the fossil fuels era and the massive extraction and consumption of construction minerals and metal ores. According to Smil (2014), many historians of industrialization focus on the increasing consumption of fossil fuels and metal ores, neglecting the unprecedented enormous quantities of construction materials (stones, soil, sand and glass) that had to be moved, incorporated in bricks and concrete, in order to built the essential infrastructure of the modern economies (roads, railways, ports, mines, factories, settlements, buildings, etc.)

Modern material era created an expanding process of new needs creation, followed back by the invention of new materials, such as asphalt roads (after 1900, due to the increasing use of cars), cement production and steel production, paper, silicon and of course plastics, perhaps the most essential material of the twentieth century which replaced wood, metals, zinc, tin and glass, in many household, transportation and industrial goods (*Storm and Rasmussen, 2011*). Finally, the unparalleled progress in chemical engineering led to the invention of numerous other innovative materials such as polyamides and polycarbonates, as well as the synthetic fertilizers. In any case, this section only serves introductory purposes and does not aspire to give an exhaustive representation of the progress occurred in the materials use.

5.4 Natural Resources Classification.

Natural resources can be initially classified in two broad categories: first, according their organic or non-organic origin can be classified in biotic and abiotic resources:

- **Biotic natural resources**. Biotic natural resources are those resources being obtained from living (and decomposed) organisms, such as trees and their products, agricultural crops, cattle, fishery, etc. In the context of current category, fossil fuels, such as oil and coal[5], are classified as biotic natural resources due to the fact that they were derived from organic matter[6].

[5] Coal and its other forms (charcoal, lignite, etc) are believed to have formed from prehistoric land plants and trees, while the most prevailing theory on petroleum's origin is that of the plankton. Source: Edx On-line course: Energy 101- Energy 101: Energy Technology and Policy. University of Austin, Texas, by Dr. Webber)

[6] Natural gas is not considered as biotic natural resources. Nevertheless there are forms of "*biotic*" gas, such as the bio-gas produced from organic matter (manure, biomass).

- **A-biotic natural resources**. A-biotic natural resources are those obtained from non-living sources. The ores, the industrial and the construction minerals are representative examples of a-biotic natural resources. What is more, air, land and water, are considered as a-biotic natural resources, as well. The potential origin of a-biotic resources into biotic natural resources (i.e. the biotic origin of soil or the potential biotic origin of some ores and minerals in the extremely long-run period, etc.) remains out of the scopes of this introductory essay.

Secondly, natural resources can be distinguished according their rate of replenishment. In that sense, natural resources can be classified into renewable and non-renewable ones:

▪ **Renewable natural resources**. Renewable resources are those physical or biotic resources that are used by people and can be replenished in a timely manner. For example, forests, fish stocks, water, and agricultural crops can be replenished over time, with forests taking a longer time than fish or water, and agricultural crops replenished over a short time period. In the context of energy production, we define as renewable energy this amount of produced energy that derives from the utilization of renewable sources of energy, such as solar, geothermal, wind, tidal, water (gravital) energy, biofuels derived from biomass, and wood fuel.

Renewable resources can be further sub-divided into two additional categories (*Μπίθας, 2012-p.231*):

- *Plentiful (non-exhaustible) renewable natural resources*. This sub-category includes those natural resources that are plentiful and continuously available; they are not affected by human consumption. To mention some indicative examples, as non-exhaustible renewable natural resources are considered the sunlight (solar energy), the wind, geothermal, and tidal energy.

- *Limited (exhaustible) renewable natural resources*. This sub-category includes those natural resources that are limited and can be depleted by excessive human use, but also can be replenished or reproduced relatively quickly. Examples include animal life (fish, cattle, etc.), agricultural crops and generally what is called biomass, lakes, rivers and underground waters, forests, etc.

- **Non-renewable natural resources**. Non-renewable resources are those limited in amount that cannot be replenished in a timely manner and are essentially irreplaceable once extracted. For example, minerals and fossils fuels are formed over very long geologic periods. Since their rate of formation is very slow[7], they cannot be replenished once they get depleted. Examples of non-renewable natural resources are crude oil, coal, natural gas, ores and industrial minerals.

5.5 The special case of non-fuel materials decoupling

5.5.1 Introduction. Why non-fuel materials?

The last one hundred years were characterized by remarkable increases in both economic growth trends and demographic dynamics. Evidently, the global population, quadrupled from the beginning of the 20th century, is currently estimated to more than 7 billion persons (*The Total Economy Database, 2014*). Economic growth (expressed in terms of GDP growth) grew more than 20-fold while materials use per capita doubled from 4.6 (1900) to 10.3 (2009) t/cap/yr (*Krausmann et al., 2009*). During the same period (1900-2009), the global aggregate materials use increased 8-fold, something which is translated into 60 billion tons (Gt/yr) of total materials consumption per year (*ibid*).

As already discussed in Chapter 4, there is a crucial downscaling dematerialization limit, concerning the biophysical properties of the Biophysical Human Scale (BHS). In that context, it is essential for our analysis to distinguish the material resources into those utilized as energy (power) providers and to those shaping the material body of goods (non-fuel/non-energy mass). Mass inputs accomplish a distinct operation in the production process, shaping the material substance of goods (the material scaffolding of goods), and therefore they function differently from energy inputs which are "*consumed*" during the production process. Disaggregating natural resources in such a manner offers a solid basis for investigating specific aspects of the Resources-Economy (R-E) link. Mass – non-fuel – resources offer a well-defined field of application, as mass resources are related to certain physical properties of production which determine its Material Intensity (MI).

[7] In an extremely long-run geological period, fossil fuels and minerals could be presumed as renewable resources as well. However, this distinction into renewable and non-renewable resources remains essential, according to the average human life span as a reference point.

Geologists classify elements as geochemically abundant and geochemically scarce; the first category includes 12 elements (including aluminium; iron; magnesium) which account for 99.23% of the mass of the Earth's continental crust, whilst the second category includes more than 90 other elements that account for just 0.77% of the crystal mass (*Ayres, 2007-p.119*). It is broadly assumed that certain metals may be exhausted for practical (human) purposes within a few decades (*ibid*). Copper and lead are representative examples of the aforementioned assumption. *Ayres et al. (2003)* give a detailed analysis about the increasing amounts of energy that would be required in order to mine lower and lower grades of pure metal. There is a boarder line (Figure 5.1), called "*the mineralogical barrier*" (*Skinner, 1976*), which implies that after the exhaustion of the mineralized (copper i.e.) reserves, the mining of earth's crustal rock (i.e. for copper) would increase energy requirements per ton by a factor of hundreds or even thousands (*Ayres et al., 2003*). Clearly, what is referred as geochemically scarcity is actually more an energy resources scarcity and that may lead in a progressively more and more energy intensive extraction process, in the future. Evidently, the extraction of iron ore, copper, bauxite (aluminium) and nickel is now rising faster than world GDP (*Jackson, 2009*), underling the crucial consequences that a potential approach of the mineralogical barrier may have in economic growth.

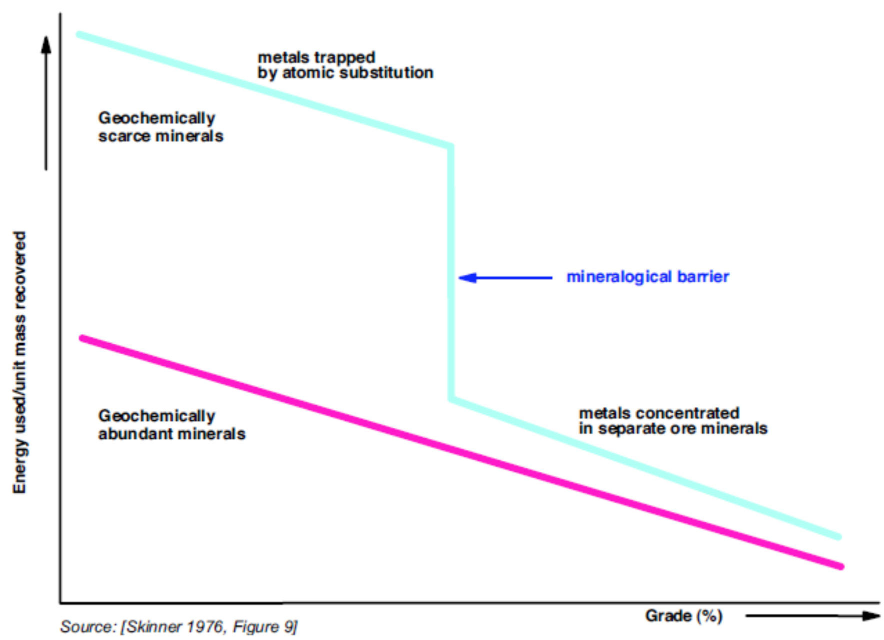


Figure 5.1 *The mineralogical barrier (Source: Ayres, 2007)*

The complex interrelationship between materials extraction and energy use calls for a more detailed investigation. The present chapter evaluates explicitly the MI of the non-fuel material flows, while the chapter 6 estimates the Energy Intensity (EI), separately[8].

5.5.2 Data

All data on 9 primary metals extraction and cement production are drawn from Goldewijk (2001) and the **History Database of the Global Environment (HYDE)**. The HYDE database has been developed under the authority of the Netherlands Environmental.

Data on GDP and population are drawn from Maddison (2008)

5.5.3 9 Primary metals production (extraction) Intensity for 1890-1990.

In this section we investigate the decoupling effect for 9 basic metal ores at the global level. We assume that, at the aggregate global level, the total production of a specific primary metal is equal to its total consumption, as the international trade is zero. Nevertheless, that is not absolutely true, due to the uncounted wastage between the quantity produced and the quantity that actually consumed in the economic process. In any case, due to the lack of more reliable data at the global aggregate level, we utilized the historical HYDE Database in order to perform the 9 basic metal intensity estimates presented in this section. Specifically, in figures 5.2-5.10 we estimate the global production/GDP ratios and the global production/[$GDP_{per\ capita}$] ratios for Aluminium; Copper; Crude steel; Pig iron; Lead; Magnesium, Nickel; Tin; and Zinc, respectively.

Aluminium

Aluminium (extracted from bauxite) is considered as a substantial metal ore in modern industrial production, manufacturing and daily-life applications.

[8] Nevertheless, the Appendixes at the end of the present chapter evaluate the MI of total DMC (including energy resources as well), in line with the relevant decoupling literature which mainly investigates MI without the distinction into fuel and non-fuel material resources.

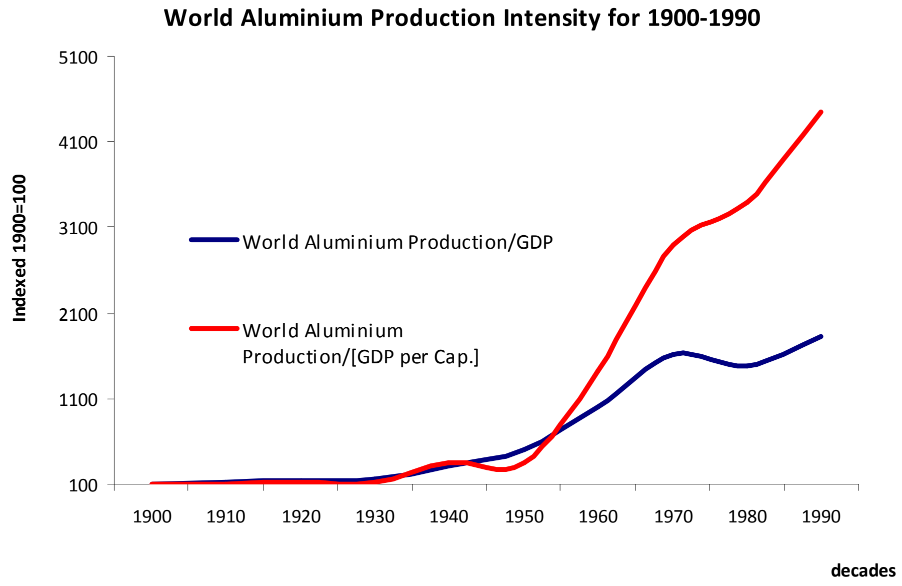


Figure 5.2 *The World Aluminium Production Intensity for 1900-1990 (Indexed 1900=100)*

Furthermore, it is an important substitute of iron, tin and even copper. *World aluminium production/GDP* ratio is presented in Figure 5.2 (indexed 1900=100). Estimated ratio depicts only a short dematerialization period (1970-1980), to continue rising again until 1990. This short decoupling period could be the result of the massive deceleration of global economic production caused by the two oil crises of 1972 and 1979, respectively. No evidence of decoupling world aluminium production from economic growth can be traced. On the other hand, concerning the *World aluminium production/[GDP $_{per\ capita}$]* ratio (Fig 5.2, indexed 1900=100), there is no empirical evidence of decoupling effect throughout the examined period, except for the WWII period. The *World aluminium production/[GDP $_{per\ capita}$]* ratio supports a dramatically increasing coupling between aluminium production and GDP per capita growth during 1950-1990, underling the importance of aluminium in modern industrial production.

Copper

Copper was among the most important metal ores, utilized mainly for telecommunication networks (wire cables), until 1980, when the optical glass fibbers began to replace the copper wires. The remarkable contribution of copper as an irreplaceable raw material in the construction of telecommunication networks could be traced in the estimation of *world copper production/GDP* ratio and, especially, at the evolutionary path of the *world copper production/[GDP $_{per\ capita}$]* ratio, both presented in Figure 5.3 (all indexed 1890=100).

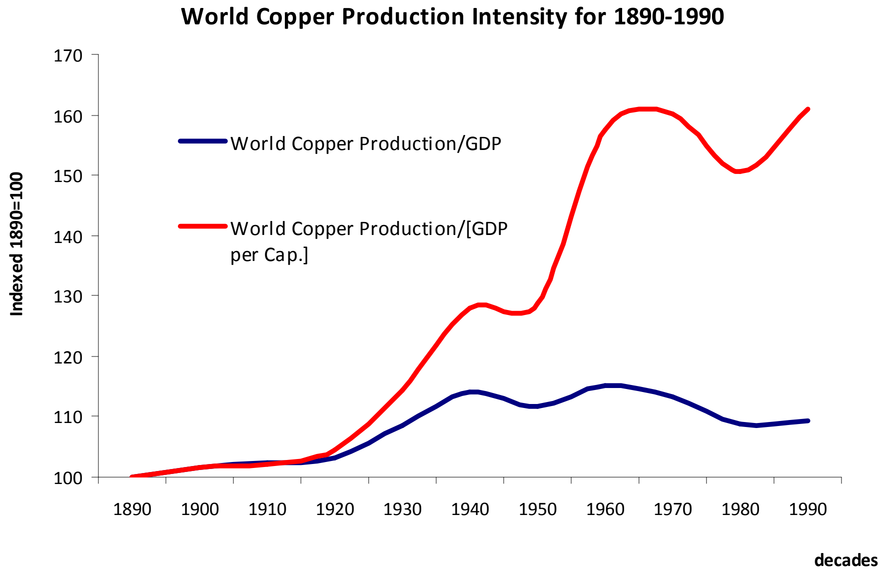


Figure 5.3 *The World Copper Production Intensity for 1890-1990 (Indexed 1890=100)*

Both the *world copper production/GDP* and *world copper production/[GDP $_{per\ capita}$]* ratios depict a long coupling period lasting until the WWII brake in 1940-1950. After the WWII the *world copper production/GDP* ratio remains relatively stable, while the *world copper production/[GDP $_{per\ capita}$]* shows a dramatic increment which last until late 1960's, when a continuous decline is occurred. This decoupling trend, presented by both indicators during 1970-1980, may be partially explained by substitutions with other material types; a number of plastic products have replaced the old copper pipes in urban water networks; furthermore, the telecommunications industry is gradually replacing copper wires worldwide with fibber optic cables, while the invention and the wide use of cell-phones and satellite telephone technology has allowed many areas of the world to have telecommunications without the need to install "*copper telephone wires*" (*USGS, 2005*[9]). However, copper still plays a significant role in many applications (*Kaufmann and Drury, 1987*), since its production in terms of absolute quantities is still increasing at the global aggregate level (*Jackson, 2009*). Towards this argument, the *world copper production/[GDP $_{per\ capita}$]* ratio, contrary to the relative stability of the *world copper production/GDP ratio*, presents a dramatic coupling trend between world copper production and per capita GDP growth, after 1980. Nevertheless, despite the fact that the utilized database is updated until 1990, recent

[9] Available at: http://pubs.usgs.gov/of/2005/1294/ Accessed in June 2012

studies verify that indeed the world copper production (thus, its consumption) is increasing more rapidly than the world GDP (*Jackson, 2009-p. 75*).

Crude steel and pig iron

About 98% of iron ore is used to make steel (*USGS, 2005*). In Figures 5.4 and 5.5 we estimate the indexed (1890=100) *world crude steel production/GDP* and *world crude steel production/[GDP $_{per\ Capita}$]*, and the *world pig iron production/GDP* and *world pig iron production/[GDP $_{per\ Capita}$]* ratios, respectively. A continuous period of coupling can be identified for all estimated indicators, until late 1960s. This coupling trend is far more intensive in the proposed indicators' trajectories. The different evolution of the two ratios observed during 1960-1980 can be probably explained by recycling; though there is no substitute for iron, iron ores are not the only materials from which iron and steel products are made. Very little scrap iron is recycled, but large quantities of scrap steel are recycled. (*USGS, 2005*). Some steel is produced from the recycling of scrap iron, though the total amount is considered to be insignificant.

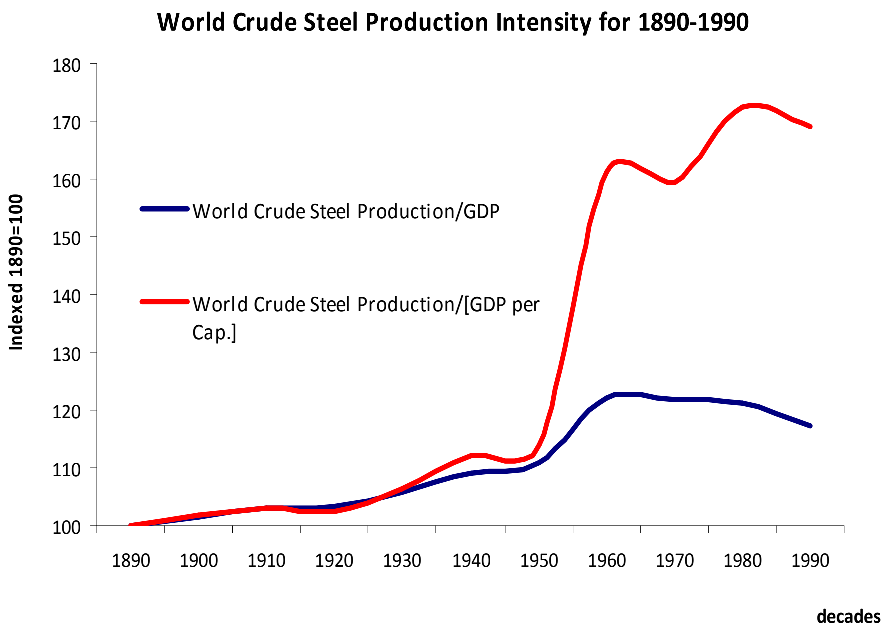


Figure 5.4 *The World Crude Steel Production Intensity for 1890-1990 (Indexed 1890=100)*

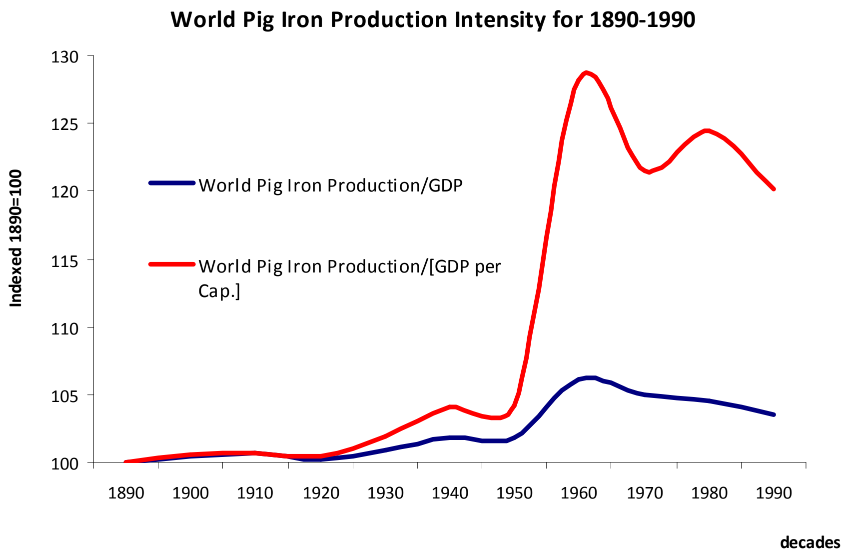


Figure 5.5 *The World Pig Iron Production Intensity for 1890-1990 (Indexed 1890=100)*

As far as the crude steel production concerned, no clear evidence of decoupling from GDP per capita can be traced. However, the evolution of pig iron production gives a smooth relative decoupling trend during 1960-1990. The steel recycling impact can be trace in the way the two ratios evolved; while the pig iron production seems to decouple from GDP per capita, steel production gives further smooth coupling trends, probably attributed to steel recycling.

Lead and Zinc

Lead and zinc are usually derived from ores containing significant amounts of both metals; hence, there is a high correlation between the two ores extraction trends (*Cleveland and Ruth, 1998*). The majority of the lead element consumed annually is used to make batteries for cars, trucks and other vehicles, as well as wheel weights, soldering, bearings etc. Lead is used in electronics and communications, ammunition, television glass, crystal glass production, construction, and protective coatings.

Zinc ore is applied in thin layers to iron and steel products that need to be protected from rusting. This process is called galvanizing. Galvanizing is done in a number of ways. Generally, the metal is dipped in molten zinc. It can also be done by electroplating or by painting on a layer of zinc compound. More than half of the zinc consumed is used for galvanizing (*USGS, 2005*). The second largest use of zinc is as an alloy, while making brass and bronze accounts for another portion of zinc consumption. The remaining zinc consumption is for making paint, chemicals, agricultural applications, in the rubber industry, in TV screens, fluorescent lights and for dry cell batteries.

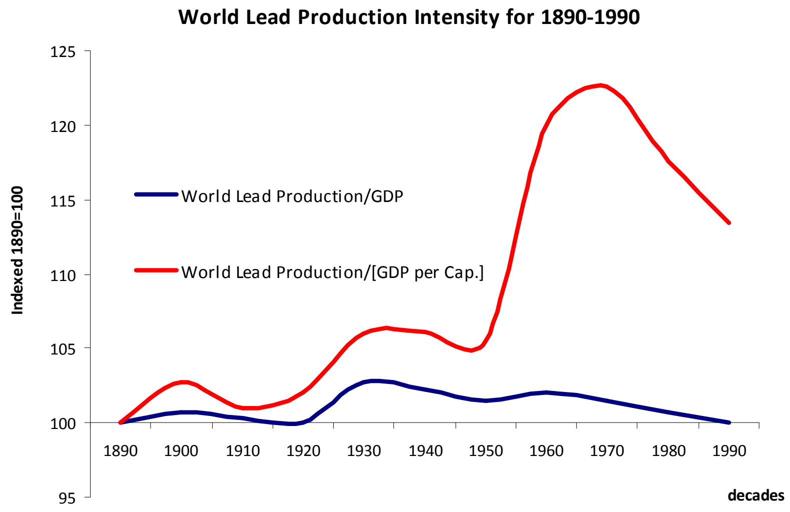


Figure 5.6 *The World Lead Production Intensity for 1890-1990 (Indexed 1890=100)*

In Figure 5.6 we estimate the Lead production/GDP ratio and the Lead production/[GDP $_{per\ capita}$]. After a massive coupling period in 1920-1930, the Lead production/GDP ratio presents two sharp dematerialization periods; 1930-1950 and 1960-1990. Mainly two explanations can be conceived for this result: for the first period the most probable reason was the economic recession of 1929 and WWII; for the second period, massive substitution of Lead for other materials mainly because of its hazardous effects in human health. More specifically, Plastics, aluminium, tin, and iron are replacing the use of lead in construction materials, containers, packaging, etc. Tin and other metals are being used to replace Lead in some applications where it could poison people (Lead is a toxic material), such as in potable water pipeline systems, while lead used to be added to gasoline (to eliminate "knock" in car engines), until the discovery of the environmental and health damage caused by its usage, and the incompatibility of lead with catalytic converters found on virtually all US automobiles since 1975, this practice began to wane in the 1980s (*Powell, 2001*).

In contradiction with previous results, the Lead production/[GDP $_{per\ capita}$] ratio shows a period of constant coupling between lead production and GDP per capita, until 1970, when a dematerialization trend occurred in 1970-1990, probably due to human health threats that were detected as a result of lead ore utilization. Most regulations against lead usage took place after 1970, the consequences of which can be detected at the declining trends of both MI indicators, in Figure 5.6.

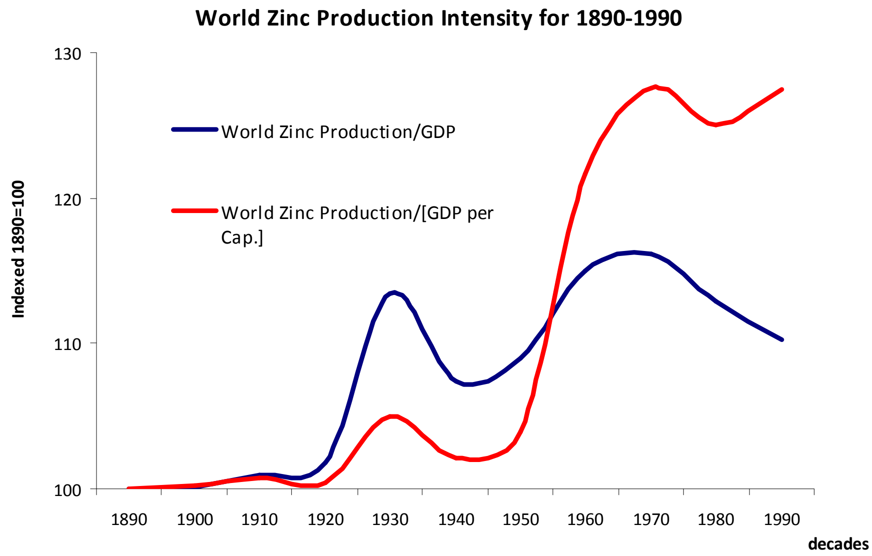


Figure 5.7 *The World Zinc Production Intensity for 1890-1990 (Indexed 1890=100)*

World Zinc production/GDP ratio and world Zinc production/[GDP $_{\text{per capita}}$] are estimated in Figure 5.7. The world Zinc production/GDP ratio depicts mainly four breaking points: massive coupling in 1920-1930; a short decoupling period in 1930-1940; a smooth coupling period during 1940-1970; finally a decoupling period is observed during 1970-1990. A period of relative decoupling from economic growth seems to initiating in 1970 for zinc production. Substitution of zinc for aluminium and plastics may further shed light in the effort to interpret the observed decoupling trend.

Furthermore, the estimate of the world Zinc production/[GDP $_{\text{per capita}}$] (Fig. 4.7) illustrates a substantially different pattern of evolution; besides some smooth fluctuations in 1930-1940 and 1970-1990, which cannot support a severe decoupling trend, no evidence of strong decoupling of zinc production from per capita economic growth can been identified.

Magnesium

As a metal, magnesium's principal use is as an alloying additive to aluminium with these aluminium-magnesium alloys being used mainly for beverage cans. Figure 5.8 estimates the world magnesium production/GDP and the world magnesium production/[GDP $_{\text{per capita}}$] ratios. Magnesium production is coupled with economic growth until 1960, when a period of smooth deceleration occurred until 1980, when the coupling trend appears again. One explanation for this pattern in 1960-1980 would probably be the deceleration previously observed in Aluminium production/GDP ratio (Fig. 5.2).

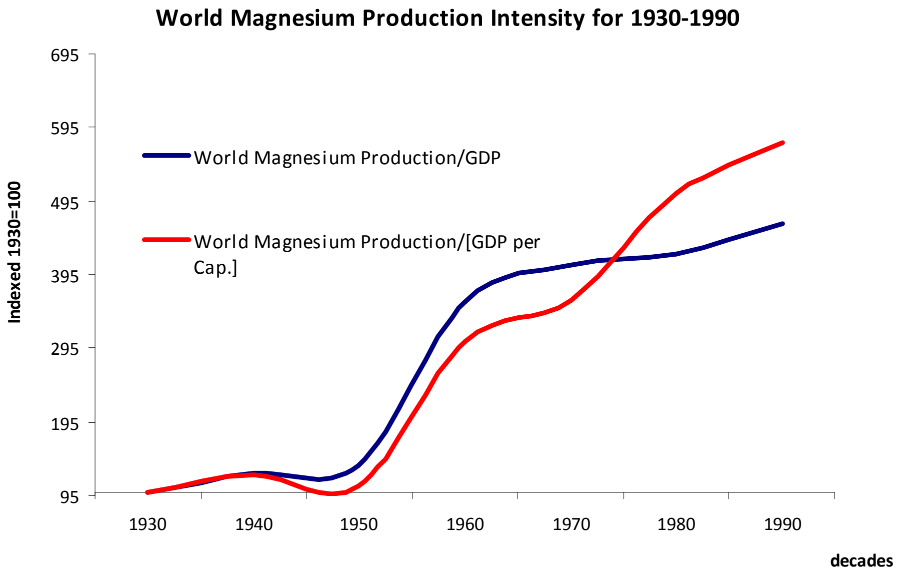


Figure 5.8 *The World Magnesium Production Intensity for 1930-1990 (Indexed 1930=100)*

Since magnesium's principle use is strongly connect to aluminium processing (acting as complementary goods), results of this relationship can be trace in the magnesium production/GDP ratio as well.

As far as the world magnesium production/[GDP $_{\text{per capita}}$] ratio concerned, only one short relative decoupling period can be identified, during WWII. No evidence for decoupling is observed after 1950.

Nickel

Nickel is a vital alloying constituent of stainless steel. Furthermore, it plays key role in the chemical and aerospace industries. World Nickel production/GDP and world Nickel production/[GDP $_{\text{per capita}}$] ratios are estimated in Figure 5.9 (indexed 1960=100). World Nickel production/GDP ratio presents a massive coupling period in 1950-1960. Following the trends of crude steel production/GDP ratio, the way the World Nickel production/GDP ratio evolves after 1960 reflects the substantial relationship existing between steel and nickel production. Furthermore, another way to explain this relative decoupling period after 1970 is the recycling; during steel recycling procedure, a substantial quantity of nickel (57%) initially used to make steel stainless, is being rebounded as well (*Reck et al., 2008*).

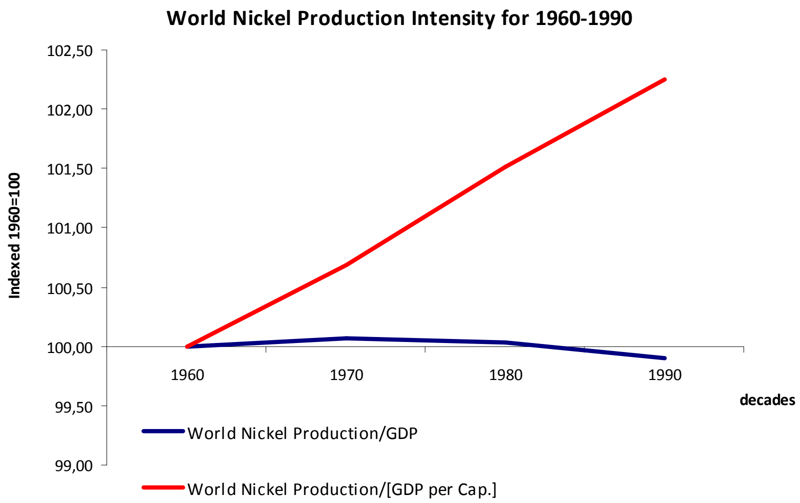


Figure 5.9 *The World Nickel Production Intensity for 1960-1990 (Indexed 1960=100)*

On the contrary, the world Nickel production/[GDP $_{\text{per capita}}$] indicates a non stop coupling relationship. This mainly reflects the importance of nickel production as a substantial component of modern industry. This linear coupling trend reflects to some extend, the importance of nickel material flows in serving the growing needs of a growing population for specific economic goods (e.g. cell phones), whose demand grows exponentially.

Tin

The main use of tin is to coat the so-called "*tin*" cans. Since tin does not oxidize in air or water, it is applied to the surface of flat-rolled steel to make tin plate, which is then fabricated to produce "tin" cans. This use accounts for about one-fourth of the tin consumed annually (*USGS, 2005*). It is also used in alloys, construction, transportation and other various industrial applications (e.g. window glass is made by pouring molten glass onto molten tin). World tin production/GDP and tin production/[GDP $_{\text{per capita}}$] ratios are estimated in Figure 5.10. Three main stages can be traced for World tin production/GDP ratio: a continuous coupling period in 1910-1940; a massive dematerialization trend in 1940-1950; finally, a smooth relative decoupling period in 1950-1990. Two explanations can be conceived for the last two stages: first, WWII consequences in economic production during 1940-1950 and, secondly, continuous substitution of tin by plastic.

We can distinguish two main decoupling periods for tin production/[GDP $_{per\ capita}$] ratio (Fig. 5.10): during 1940-1950, due to WWII, and 1960-1990. Albeit the two ratios present a substantial difference in the way they evolve during 1950-1960, they generally present the same result; a strong evidence for relative decoupling of tin production from economic growth and per capita economic growth, can be traced for the period 1960-1990.

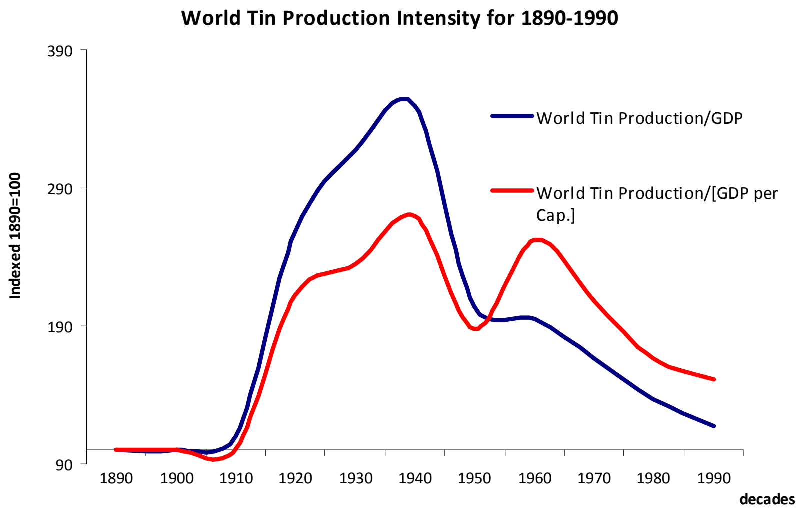


Figure 5.10 *The World Tin Production Intensity for 1890-1990 (Indexed 1890=100)*

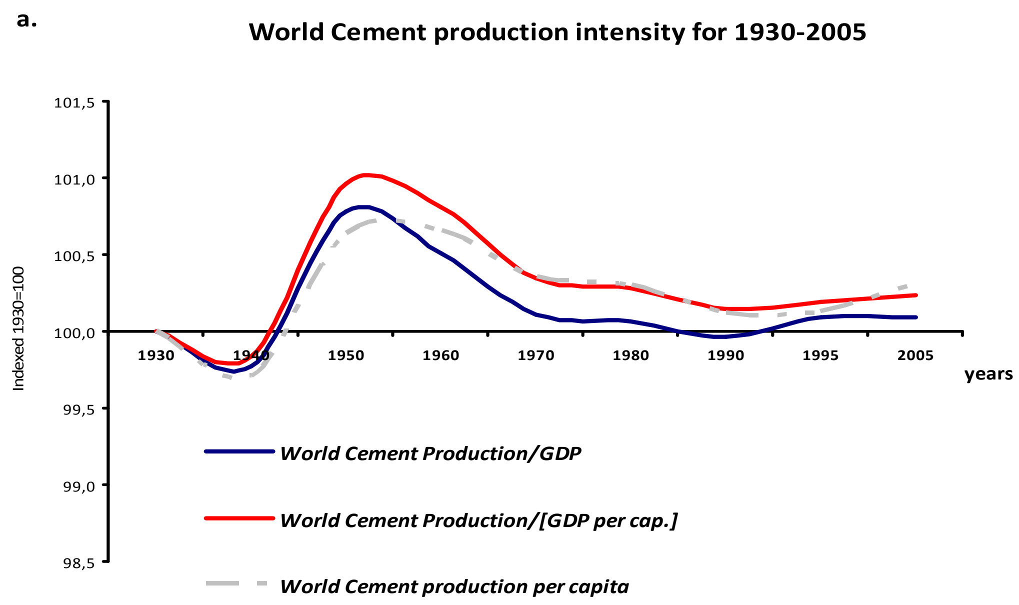
5.5.4 Global Cement production and decoupling

Cement is definitely the most substantial component of the global infrastructure, building and housing construction. Therefore, it is the dominant material of the construction industry. Cement is made out of limestone, shell, clay (mined out of a quarry close to the plant), which mixed with gypsum and ground to a fine powder to produce final grade of cement. The technology of cement production is a continuous and, thus, a highly energy and material intensive process. It is estimated that there are around 1500 integrated cement production plants in the world (*Lasserre, 2007*). Data used in this section are derived from HYDE database[10] and Lasserre (2007).

In this section we estimate the world Cement Production/GDP and world Cement Production/[GDP $_{per\ capita}$] ratios. Figure 5.11.a presents the estimates of the decoupling effect between cement usage and economic growth. The only period of relative decoupling is

[10] Data available here: http://themasites.pbl.nl/tridion/en/themasites/hyde/productiondata/cement/index-2.html Accessed in June 2012

observed during the period between the economic recessions of early '30s until the end of World War II, in late '40s.



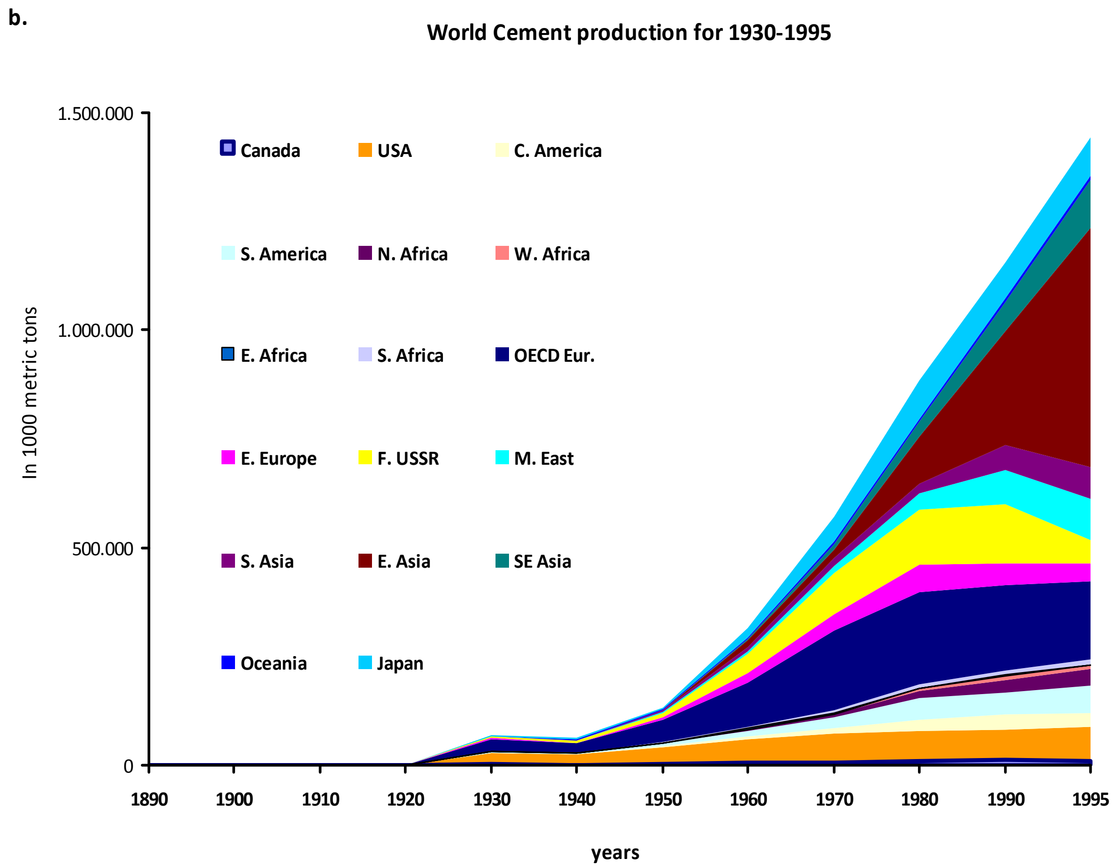


Figure 5.11 *a). World Cement Production Intensity (indexed 1930=100), for 1930-2005; b). World Cement production (in 1000 metric tons) per region, for 1930-1995*

After this period of relative dematerialization the ratio rises sharply again, signalling a period of constant coupling, until late '80s, when a stabilization seems to be occurring. Obviously, the observed dematerialization trend in 1930-1940 was a consequence of the economic recession and the devastating consequences of the WWII, a conclusion that is further supported by Krausmann et al. (2009).

The world Cement Production/[GDP $_{per\ capita}$] ratio (Fig. 5.11.a) presents a similar trend with the world Cement Production/GDP, albeit it gives a less intensive decoupling period between early '30s and mid '40s and then it rises more sharply, without signs of any stabilization in its trend. World cement demand was 2.283 million Tons in 2005, with China accounting for 1.064 million tons (47% of total demand for cement). China will increase its demand by more than 250 millions tons during next years, an increment that is higher than the total yearly European demand (*Lasserre, 2007*). Bearing in mind the future cement demand projections for developing countries, as well as the estimated ratios of Figure 5.11.a and the increasing cement production trends per world region depicted in Figure 5.11.b, future prospects of potential decoupling of cement production from economic growth does not seem to be a feasible option.

5.5.5 Global plastic materials production and decoupling

The invention of plastics as a petroleum by-product was meant to play a decisive role in the material substitution and consumption trends. Initially, plastics had been widely accepted as a packaging material. However, the flexibility, the functionality and the easy-use of this material found a broad range of applications, setting the base of a wide-spread expansion in every material aspect of modern life; from medical supplies and laptops, until toys, clothes and cell-phones, almost every product that modern society consumes contains a substantial quantity of plastics materials. The world's annual consumption of plastic materials has increased from around 5 million tonnes, back in the 1950s, to more than 300 million tons today (*Brydson, 1999; BASF, 2007*). Consequently, we produce and use 60 times more plastic than we did 60 years ago. A clear evident of material substitution for plastic is the fact that the automotive industry is now a major user of plastic with the weight of plastics being used per car increasing year by year (*Brydson, 1999*). Data on world plastic materials production were drawn from Brydson (1999) and BASF (2007).

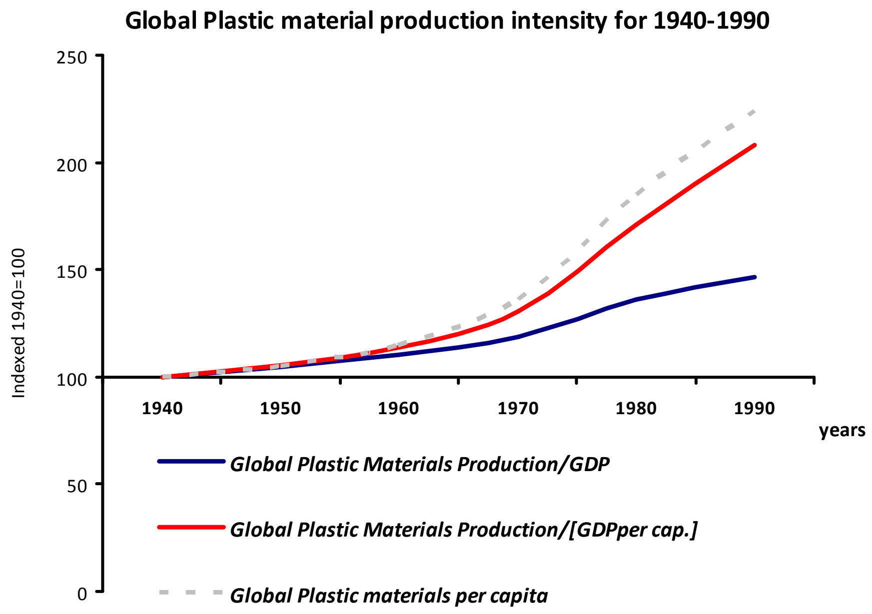


Figure 5.12 *Global plastic materials production intensity (indexed 1940=100), for 1940-1990*

The importance of plastic materials for modern production and further materials substitution highlights the need to include them in present analysis, even though plastics could be considered as a fuel-origin material according with the initial separation we made, since it is mainly produced by petroleum (fuel materials). However, since plastic materials serve as material scaffolding and not as a source of power, we include this section which estimates the plastic materials required to produce a unit of GDP, in other words, the (de)coupling of plastics materials from economic growth. Figure 5.12 presents schematically the world Plastic Materials Production/GDP and the world Plastic Materials Production/[GDP $_{\text{per capita}}$] ratios (indexed 1940=100). Both MI indicators depict a continuous coupling between plastic materials and economic growth during 1940-2008. No evidence of relative decoupling can be identified.

Further projections in plastic materials production, according to BASF chemical company (2007), estimate that the 208 million tons of 2006 will reach the 328 million tons production, probably in 2015. These projections may further reduce any prospect of plastics materials decoupling potentials in the future, while might cause further substitution of many other materials with plastic. Notably though, the production of plastic materials – being competitive to petroleum's main utilization as an energy carrier resource – may be affected in the future by oil's availability. In any case, plastic materials remain the dominant material component of modern societies.

5.5.6 Global synthetic (and total) fertilizers consumption and decoupling

This section employs the non-fuel material intensity analysis on fertilizers[11], a special group of non-fuel materials that plays a decisive role in plant and crop growth, an essential process for food production. According to the International Fertilizer Industry Association (see footnote 11), fertilizers are classified into organic (natural fertilizers i.e. manure) and mineral/synthetic (manufactured fertilizers).

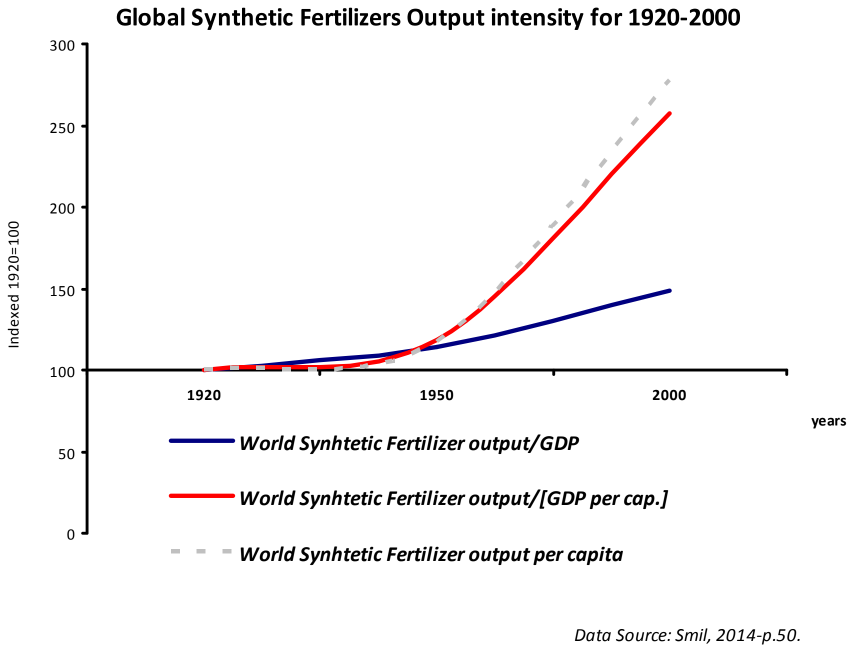
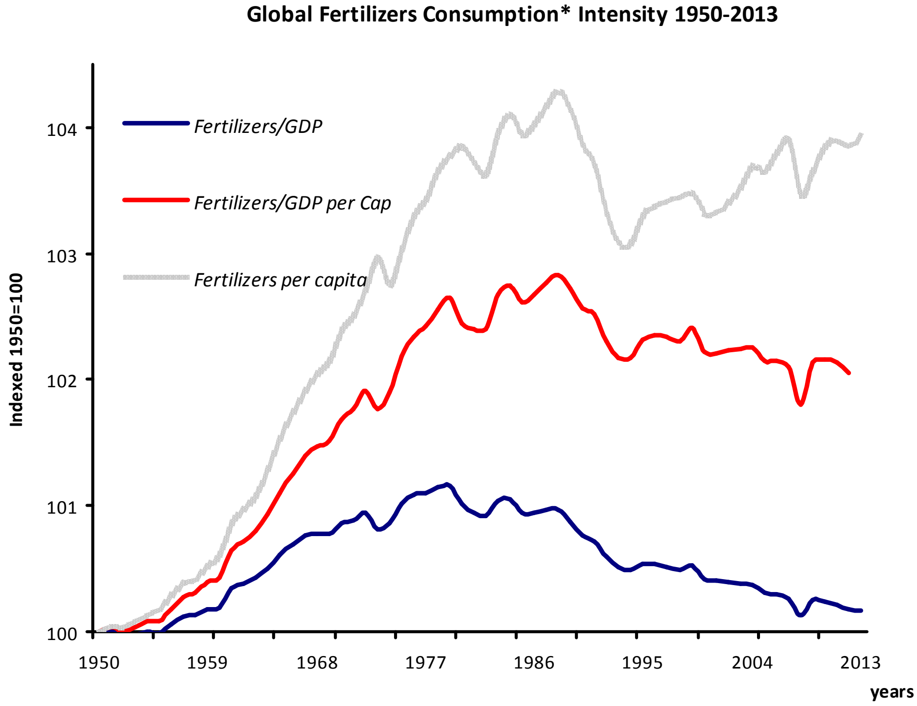


Figure 5.13 *World Synthetic Fertilizers production intensity, indexed 1920=100, for 1920-2000*

Figure 5.13 depicts the synthetic fertilizers intensity for 1920-2000, while the Figure 5.14 presents the global fertilizers' consumption (natural and synthetic) intensity for 1950-2013. Figure 5.13 illustrates the great importance of synthetic/manufactured fertilizers into food production, as the fertilizers intensity results in strong coupling trends among synthetic

[11] "*Fertilizers are any solid, liquid or gaseous substances containing one or more plant nutrients in known amount, that is applied to the soil, directly on the plant (foliage) or added to aqueous solutions (as in fertigation) to maintain soil fertility, improve crop development, yield and/or crop quality*" Source: International Fertilizer Industry Association, http://www.fertilizer.org/AboutFertilizers)

fertilizers output, GDP and GDP per capita. What is more, the per capita use of fertilizers increases dramatically throughout the examined period. On the other hand, Figure 5.14 pictures, after 1985, a more moderate intensity for total fertilizers consumption. Nevertheless, the proposed framework results in relatively stable fertilizers intensity during 1990-2013, contrary to the standard MI indicator which depicts a smooth decoupling trend, whilst, the per capita consumption of fertilizers increases again after 1990.



**Data Source: Compiled by Earth Policy Institute with 1950-1961 fertilizer data compiled by Worldwatch Institute from U.N. Food and Agriculture Organization, Fertilizer Yearbook (Rome: various years); with 1962-2010 fertilizer data from International Fertilizer Industry Association (IFA), IFADATA, electronic database, at www.fertilizer.org/ifa/ifadata/search, downloaded 17 December 2013; with 2011-2013 fertilizer data from Patrick Heffer and Michel Prud'homme, Fertilizer Outlook 2013-2017, public summary report (Paris: IFA, June 2013), p. 3.Data for GDP and population derived from The Total Economy Database (Retrieved in January 2014)*

Figure 5.14 *Global Fertilizers consumption intensity, indexed 1950=100, for 1950-2013*

5.6 Long run estimates of the non-fuel materials intensity. The cases of the global economy, the USA and Japan

5.6.1 Estimating global non-fuel materials intensity for 1900-2009

On the global aggregate level, total net trade is zero, hence total materials extracted DE (Domestic Extraction) equals the total amount of resources used DMC (Domestic Material Consumption). Consequently, at the global level, the terms DE and DMC are synonyms. The relevant literature mainly uses the term DMC to denote the "*sum*" of all the world's nationals DMCs (*Krausmann et al. 2009*). However, we adopt for the purposes of current analysis, the term Total Material Supply (where, TMS = world aggregate DE = world aggregate DMC) to define the global aggregate DE=DMC. In addition, since we refer to the global aggregate level, we assume that total material supply (without the so-called hidden flows – see Chapter 3) equals to the total materials consumption. The reason for this assumption is the effort to overcome the complexity that the term DMC may cause at the global level, specifically the term domestic. By all odds, where we use the term TMS, is equivalent to the use of the term DMC, at the global level (as in *Krausmann et al., 2009*).

Data

Global non-fuel materials consist of non-fuel biomass, ores-industrial minerals, and construction minerals. With the exception of data on global wood-fuel biomass, (*Krausmann, 2012*), all other data are drawn from Krausmann et al. (2009). It is assumed that data on non-fuel biomass is the only fuel/energy part of the total biomass. Since the constructors of the databases provided us the wood-fuel data, as the only traceable fuel (energy) part of biomass, we assumed that by excluding wood-fuel we approximate the total non-fuel biomass. It goes without saying that this is a crude estimation of non-fuel (non-energy) biomass, yet that was the only available data we had[12]. Unavoidably, the present chapter's estimates fail to incorporate the use of timber extraction and other agricultural by-products as well as the so-called bio-fuels production. Consequently, according to the databases

[12] During the review process of an article submitted to the journal of Industrial Ecology, an anonymous reviewer questioned our estimation of the non-fuel materials. Obviously we estimate an approximation of the non-fuel materials. I give a short part of our answer here: "*We could devote a lot of time in discussing about the mass aspects of fossil fuels, that are not captured, as well, in our non-fuel estimates, (i.e. plastic materials do produced by petroleum and indeed are materials broadly used in modern economies), yet this is not the issue of our study*".

employed, it is quite likely that the real fuel-biomass quantity has been underestimated to some extent. In any case, the author did not aspire to make any additional assumption concerning the bio-fuels proportion in total biomass, besides the data kindly provided by the constructors of the utilized databases. Furthermore, we have adjusted the provided data so as to create a continuous time-series dataset without gaps. To do so, we assumed that the rate of change of the total biomass is equal to the rate of change of the non-fuel biomass. Professor Krausmann provided us data for the wood fuel consumption for: 1900; 1910; 1920; 1930; 1950; In order to create a year to year dataset we assumed a 1.7 % rate of change for 1901-1909 period; a 1% rate of change for 1911-1919; a 1.5 % rate of change for 1921-1929; a 1% rate of change for 1931-1949; and a 0.25% rate of change for 1951-1960, respectively. The period 1961-2009 has been fully provided by Prof. Krausmann.

All data are available online[13] at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm. Data on GDP and population are drawn from Maddison (2008). Materials are measured in thousand metric tons[14] (1000 t/yr). Economic growth is expressed in terms of GDP in million 1990 International Geary-Khamis[15] dollars per year (million 1990$/yr). Population is expressed in million persons per year.

The World non-fuel total and per capita consumption, and MI $_{non\text{-}fuel}$, for 1900-2009

Total non-fuel Materials Supply (hereinafter TMS $_{non\text{-}fuel}$) consists of the aggregate: ores-industrial minerals; construction minerals; non-fuel biomass. Figure 5.15 presents the absolute quantities per year (1000t/yr) for these three non-fuel material resources. Evidently, non-fuel biomass remains an essential resource at the global level, albeit construction minerals take the lion's share in the late 1990's.

[13] Data on wood fuel biomass are unpublished and kindly provided after personal communication.

[14] Metric ton is the unit of mass equaling 1000 kilograms, equivalent to 2204.62 pounds (*Cleveland and Morris, 2009-p.326*).

[15] 1990 international Geary-Khamis dollars are purchasing power parities (PPPs) used in evaluating output. They are calculated based on a specific method devised to define international prices. Information on the computation of the PPPs in Geary-Khamis dollars is available at http://unstats.un.org/unsd/methods/icp/ipc7_htm.htm.

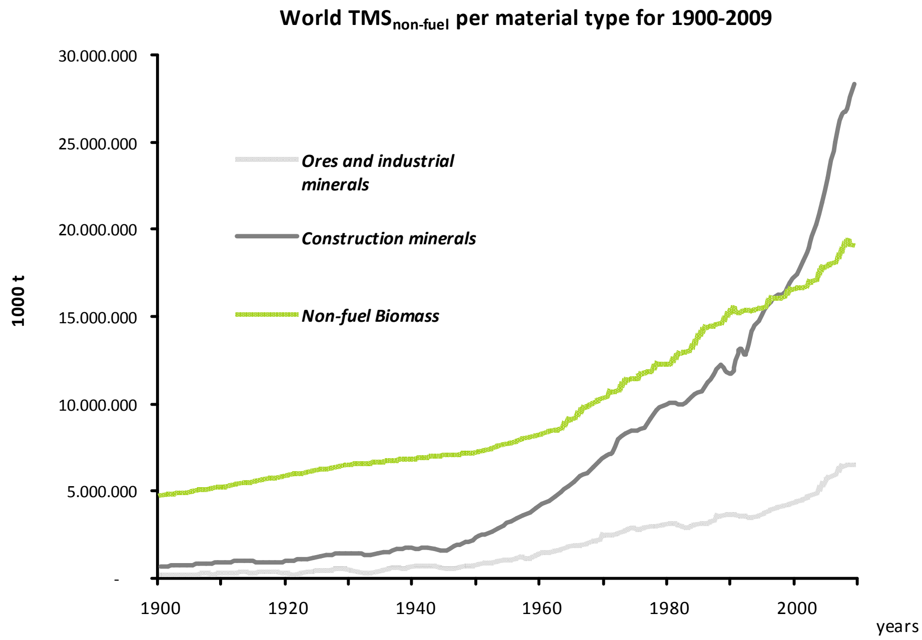


Figure 5.15 *World TMS $_{non-fuel}$ per material type, in 1000t/yr, for 1900-2009*

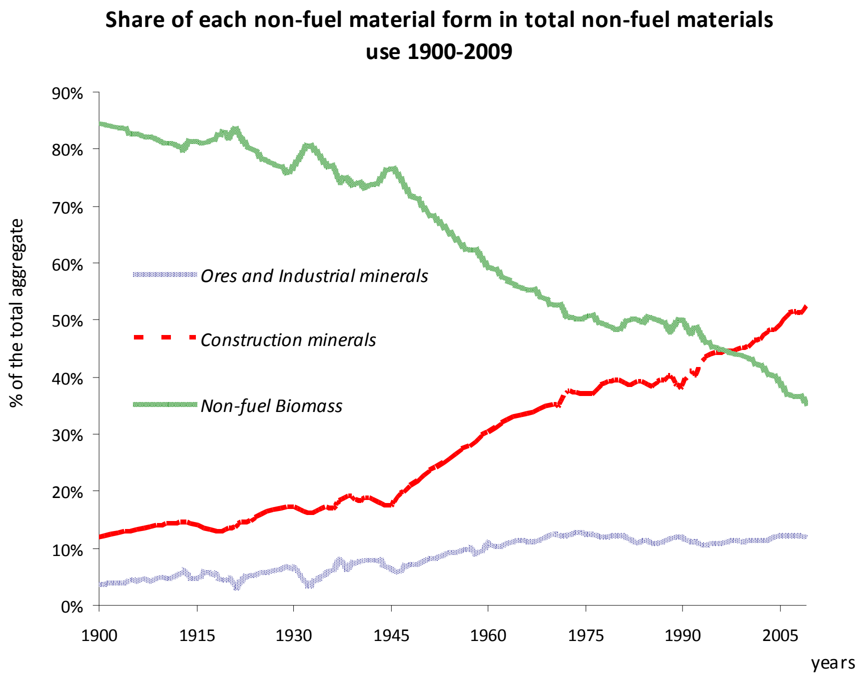


Figure 5.16 *Percentage share (%) of each material type in TMS $_{non-fuel}$*

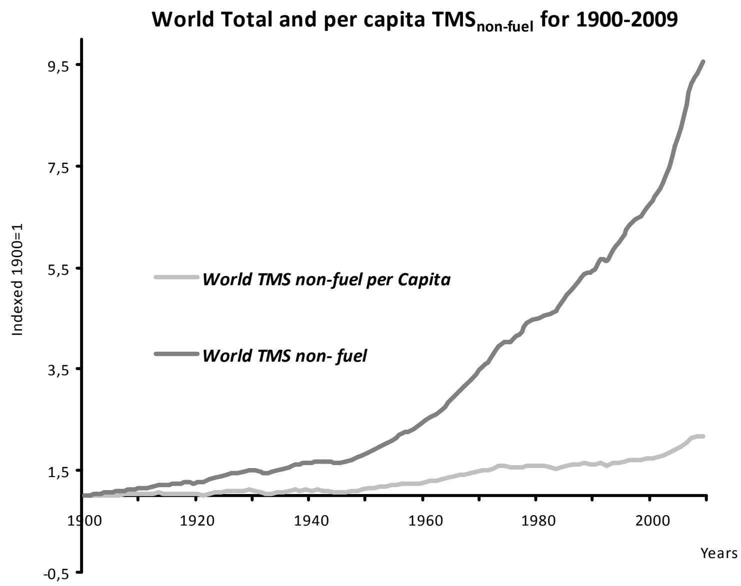


Figure 5.17 *World total and per capita TMS non-fuel, for 1900-2009 (indexed 1900=1)*

Accordingly, Figure 5.16 shows the percentage contribution of each non-fuel material type in TMS $_{non\text{-}fuel}$, and Table 4.2 illustrates the changes (%) in the composition of TMS $_{non\text{-}fuel}$ for selected years and historical periods. Non-fuel biomass presents a continuous declining trend, while the ores-industrial and construction minerals increase their share over time. Figure 5.17 depicts the indexed (1900=1) world total and per capita TMS $_{non\text{-}fuel.}$ The comparison between the tremendous increment of TMS $_{non\text{-}fuel}$ and the more moderate augmentation of per capita TMS $_{non\text{-}fuel}$, reveals the magnitude of non-fuel material resources in the per capita consumption; after 1950, the increment of the per capita consumption accompanied by a disproportionate increase of total consumption. In other words, the population growth rate is far lower that the TMS $_{non\text{-}fuel}$ rate of growth.

Finally, Figure 5.18 shows the evolutionary paths of world TMS $_{non\text{-}fuel}$/GDP and global TMS $_{non\text{-}fuel}$/[GDP $_{per\ Capita}$] ratios, both indexed (1900=100). The world TMS $_{non\text{-}fuel}$/GDP estimation depicts the “standard” evaluation of $MI_{non\text{-}fuel}$ which is clearly characterized by a macro decoupling trend. Specifically, standard $MI_{non\text{-}fuel}$ decreases constantly in the 1900-1920 period. The next period, 1921-1950, is characterized by mixed trends, with three short intervals of relative stabilization: the early economic recession period (1921-1930); the pre-war and early WWII period (1931-1941); and, lastly, the post-WWII period (1945-1950). The year 1950 is a milestone as it marks the beginning of a steady long-term decrease in MI non-energy, lasting up until 2000. Finally, relative stabilization is also observed during 2001-2009.

Table 5.2 *Changes in the composition of world $TMS_{non\text{-}fuel}$ for selected years (expressed in % of the global $TMS_{non\text{-}fuel}$)*

Selected Years	Ores-industrial Minerals	Construction Minerals	Non-energy Biomass
1900	3.7%	11.8%	84.5%
1913*	5.8%	14.4%	79.8%
1921	3.1%	13.6%	83.3%
1929±	7.1%	17.1%	75.8%
1932	3.6%	16.1%	80.3%
1940†	7.8%	18.3%	73.9%
1945	6.3%	17.3%	76.4%
1950	7.7%	22.8%	69.4%
1960	10.6%	30.3%	59.1%
1973ŧ	12.5%	37.1%	50.4%
1980	12.3%	39.4%	48.3%
1985	11.4%	38.2%	50.4%
1997‡	11.3%	44.6%	44.1%
2000	11.5%	47.5%	41%
2009	12.1%	52.5%	35.4%

*Outbreak of WWI (1913-1918)

±The Great Depression (1929-1933)

† Outbreak of WWII (1940-1945)

ŧ First oil crisis

‡Construction minerals take the lion's share of the global $TMS_{non\text{-}fuel}$

On the other hand, the world $TMS_{non\text{-}fuel}$/[$GDP_{per\ Capita}$] evolves in stark contrast to the $TMS_{non\text{-}fuel}$/GDP (Figure 4.18), as the first half of the 20th century is characterized by a fluctuating stability with an increasing macro-coupling trend that prevails in the second half. More specifically, the $TMS_{non\text{-}fuel}$/[$GDP_{per\ Capita}$] ratio remains relatively stable during 1900-1920. From that point on, relative fluctuations are detected in three respective periods: 1921-1930; 1931-1941; and 1945-1950. The year 1950 proves a milestone for $MI_{non\text{-}fuel}$ estimated by $TMS_{non\text{-}fuel}$/[$GDP_{per\ Capita}$] which exhibits a protracted period of increase in $MI_{non\text{-}fuel}$ until 2009. Special focus should be placed on the 2001-2009 period which is characterized by a strong increase in the $MI_{non\text{-}fuel}$ trend, as it is estimated by $TMS_{non\text{-}fuel}$/[$GDP_{per\ Capita}$].

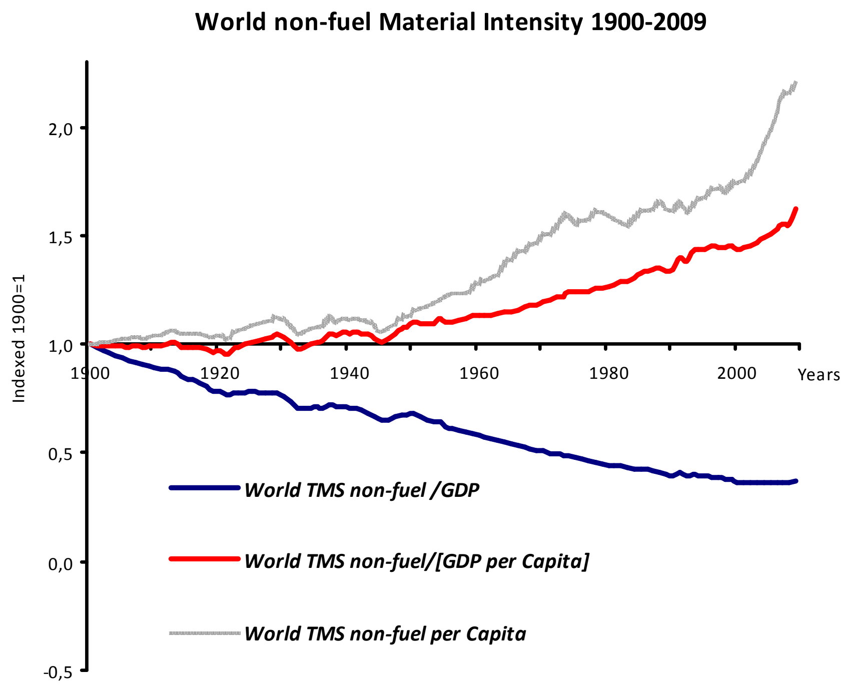


Figure 5.18 *World non-fuel Material Intensity, for 1900-2009 (indexed 1900=1)*

Evidently, the TMS $_{non\text{-}fuel}$/[GDP $_{per\ Capita}$] ratio pictures a markedly different evolutionary path throughout recent economic history in comparison to the "standard" TMS $_{non\text{-}fuel}$/GDP ratio. Furthermore, a comparison with the per capita TMS $_{non\text{-}fuel}$ trends (Fig 5.18), reveals the better approximation of the actual "*industrial metabolism*" (per capita TMS $_{non\text{-}fuel}$) by TMS $_{non\text{-}fuel}$/[GDP $_{per\ Capita}$] ratio's evolutionary path. *The TMS $_{non\text{-}fuel}$/[GDP $_{per\ Capita}$] ratio indicates clearly that the welfare (GDP per Capita) cannot increases unless mass inputs also increase at a disproportionate rate.*

Estimating the divergence between the standard World TMS$_{non\text{-}fuel}$/GDP and the proposed World TMS$_{non\text{-}fuel}$ /[GDP $_{per\ Capita}$]

In this section we apply the methodology concerning the divergence estimation, presented in detail by the 4th Chapter. Since both MI indicators are indexed into a base year=100, their divergence would be the difference of each indexed value from the base year, thus the value 100. According to function (*1*):

$$Divergence_t = |(100 - {}_{\text{indexed value of}}\ TMS/[GDP_{\text{per Capita}}]t)| - |(100 - {}_{\text{indexed value of}}\ TMS/GDP)_t| \qquad (1)$$

Figure 5.19 pictures the divergence trend. Furthermore, we estimate the percentage (%) contribution of each MI indicator to the observed divergence. This percentage contribution is estimated according to function (*2*):

$$\text{Contribution to Divergence}_t = \frac{(100 - MI_t)}{Divergence_t} * 100\ \% \qquad (2)$$

The same function, properly modified, is used for estimating the contribution to divergence of the proposed MI indicator, respectively. Figure 5.20 depicts the percentage contribution of each MI indicator to their divergence. We intentionally kept the negative values for the $TMS_{non\text{-}fuel}/GDP$ in order to depict the difference between the two indicators. Evidently, while initially the $TMS_{non\text{-}fuel}/GDP$ indicator contributes to the greatest part of the occurred divergence, however, there is a gradual convergence (in absolute values) between the two indicators' contribution to divergence, in recent decades (Fig 5.20).

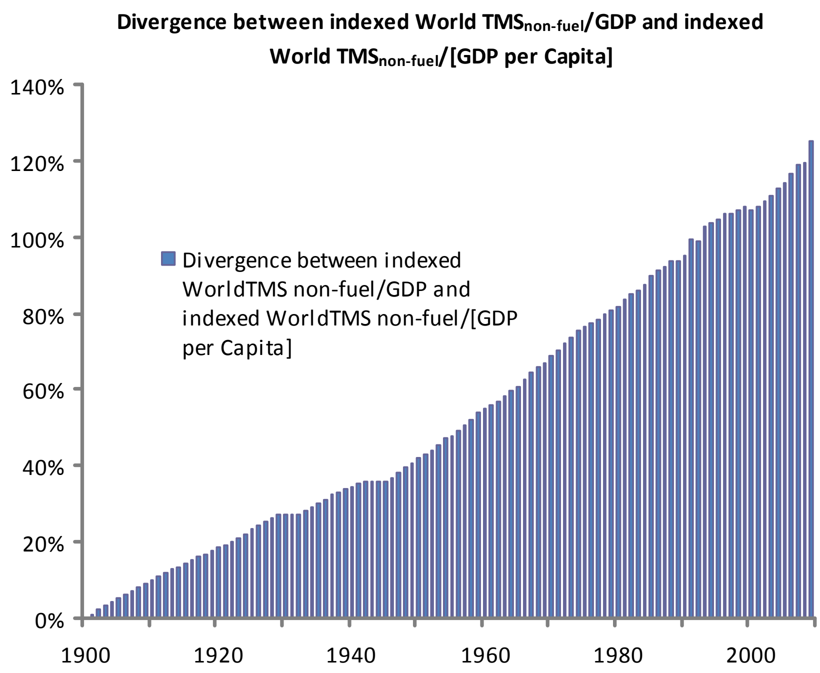


Figure 5.19 *The divergence between indexed TMS $_{non\text{-}fuel}$/GDP and TMS $_{non\text{-}fuel}$/[GDP $_{per\ Capita}$], for 1870-2005*

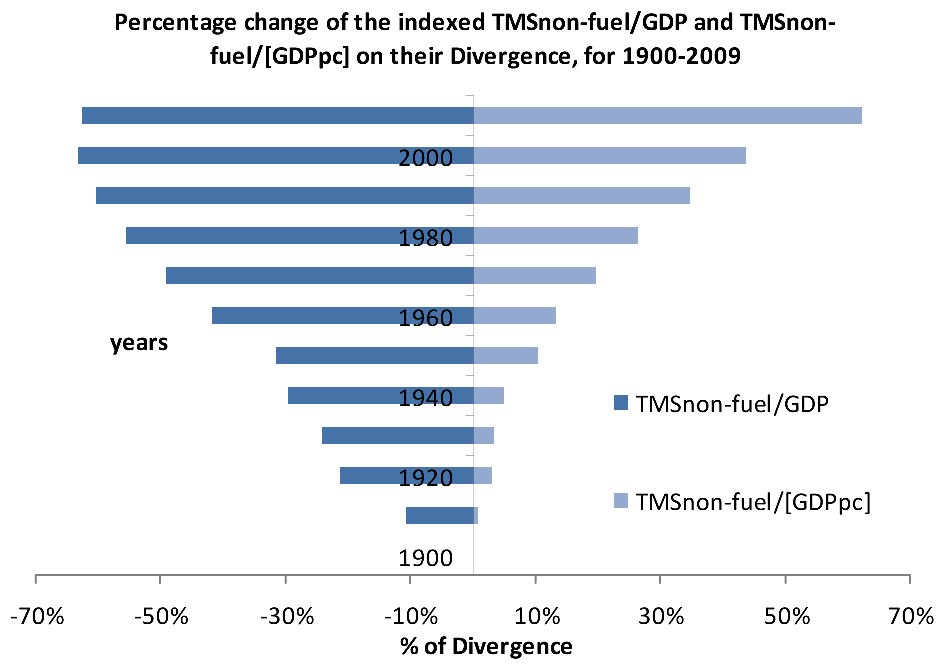


Figure 5.20 *The percentage (%) contribution of each indicator to their divergence, for 1870-2005*

The World non-fuel materials Decoupling Ratio (DR) and Decoupling Factor (DF), for 1900-2009

It is essential to introduce another level of empirical analysis, besides the MI estimation, by plotting the two indexed indicators on the same graph, and their divergence. This section estimates the proposed by OECD (2002) Decoupling Ratio (*3*) and the, derived from the former ratio, Decoupling Factor (*4*). A detailed analysis of these indicators can be found in the 3rd chapter. The Decoupling ratio is the ratio of the value of the decoupling indicator at the end and the start of a given time period and defined as follows (*OECD, 2002-p.19*):

$$Decoupling\_Ratio = \frac{(EP/DF)_{end-of-period}}{(EP/DF)_{start-of-period}} \qquad (3)$$

Where, EP=Environmental Pressure =TMS $_{non\text{-}fuel}$*, in current example; and DF= Driving Force = GDP and GDP per Capita, respectively.*

The Decoupling Ratio is estimated in Fig 5.21.a. If the ratio is less than 1, decoupling has occurred during the examined period. Since Decoupling ratio does not indicate whether decoupling was absolute or relative, OECD (2002) proposes a next level of analysis, the Decoupling Factor which is defined as (*OECD, 2002-p.20*):

$$\text{Decoupling Factor (DF)} = 1 - \text{Decoupling Ratio} \qquad (4)$$

The DF, estimated in Fig. 5.21b, is zero or negative in the absence of decoupling and has a maximum value of 1, when TMS non-fuel reaches zero. According Figure 5.21, the proposed MI indicator is, after 1920, evolves within the area that defined as "*absence of decoupling*" (where, DF<0) according OECD (2002), contrary to the mainstream MI indicator (where, DF>0) which performs a sheer decoupling pattern.

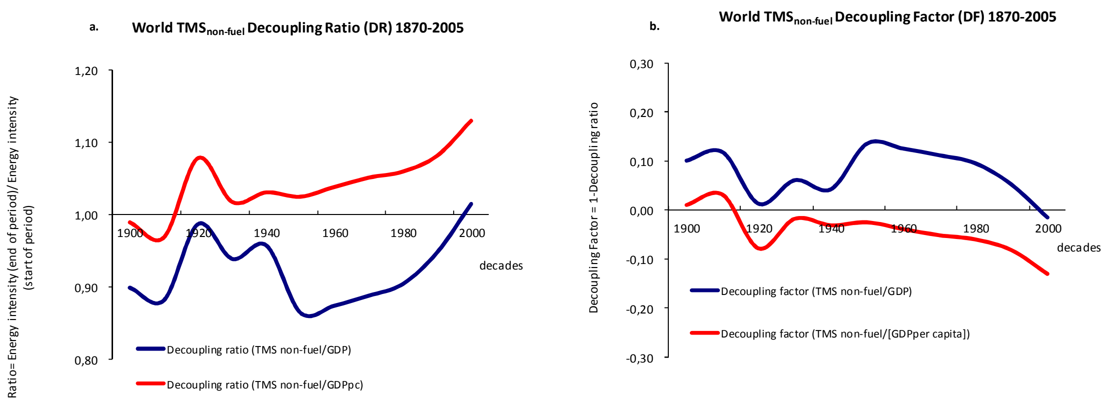


Figure 5.21 *a). The World Decoupling Ratio; and b).The World Decoupling Factor, during 1900-2009*

The World non-fuel materials Decoupling Index (DI), for 1900-2009

The Decoupling Index (DI) has been proposed by UNEP (2011) report, as framework for evaluating whether the occurring decoupling trend is relative or absolute. The methodology concerning the estimation and the interpretation of DI can be found in Chapter 3.

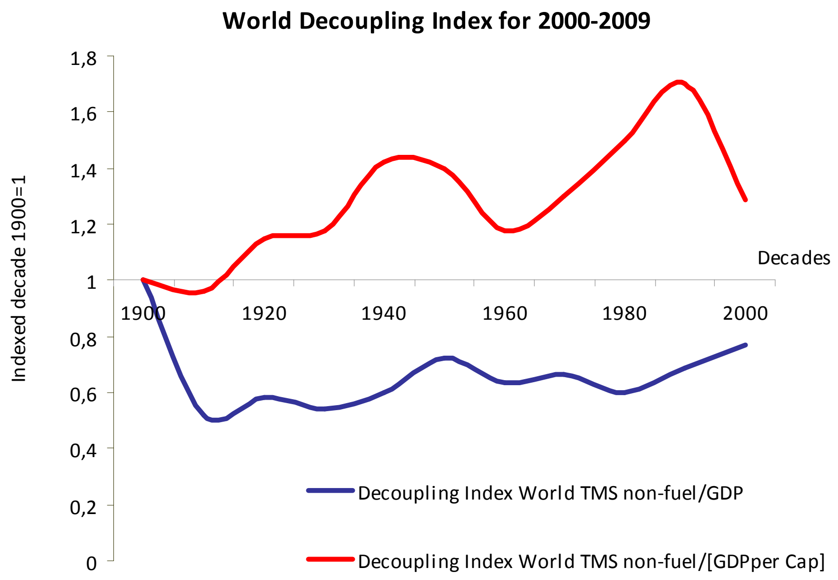


Figure 5.22 *The estimation of the world Decoupling Index of the non-fuel material intensity, for 1900-2009 (decade values, indexed 1900=1)*

The estimated DI (Fig 5.22) of the proposed $TMS_{non\text{-}fuel}/[GDP_{per\ Capita}]$ results in a general coupling pattern (DI>1, expect 1900-1920 period), intensified in two periods: 1920-1940; and 1950-1990. On the other hand, the estimated DI of the standard $TMS_{non\text{-}fuel}/GDP$ pictures a general relative decoupling pattern (1>DI>0). In any case, there is no evidence of absolute decoupling in both examined cases (Where absolute decoupling is defined for values of DI<0).

Disaggregating World non-fuel materials: estimating $MI_{non\text{-}fuel}$ for ores-industrial minerals; construction minerals; and non-fuel biomass

Next, the $MI_{non\text{-}fuel}$ for each category of materials is estimated: ores-industrial minerals; construction minerals; non-fuel biomass. The interest of this analysis lies in decoupling trends in relation to the trends of the composition of total materials at the global level. Table 5.2 reviews the trends in the composition of global non-fuel materials for 1900-2009. Figure 5.23 estimates material intensity through the standard and the proposed decoupling ratios for each individual material form, all indexed (1900=100): $TMS_{ores\text{-}indust.}/GDP$ and $TMS_{ores\text{-}indust}/[GDP_{per\ Capita}]$ (a); $TMS_{construction}/GDP$ and $TMS_{construction}/[GDP_{per\ Capita}]$ (b); $TMS_{biomass}/GDP$ and $TMS_{biomass}/[GDP_{per\ Capita}]$ (c) ratios, respectively.

- Ores and Industrial Minerals

Figure 5.23.a reveals three marked decoupling periods for the "$TMS_{ores\text{-}indust}/GDP$" ratio: 1913-1921 (WWI); 1929-1932 (The Great Depression); and 1941-1946 (WWII). From 1946 onwards, the standard $MI_{ores\text{-}indust.}$ ratio gradually follows an increasing path up until 1970 when it peaks at the highest point of the whole period under examination and subsequently decreases gradually, for most of the period 1971-1994. From 1995 to 2009 (the end of the period examined), the "$TMS_{ores\text{-}indust}/GDP$" ratio appears to have been stabilized, with signs of a possible increase at the end of the period. On the other hand, the "$TMS_{ores\text{-}indust}/[GDP_{per\ Capita}]$" ratio (Figure 5.23.a) follows a rather different evolutionary pattern characterized by a macro-coupling trend. More specifically, over 1900-1946 it presents similarities with the "$TMS_{ores\text{-}indus.}/GDP$" evolution. The period 1947-1974 shows a sharp increase in the proposed $MI_{ores\text{-}indust}$. During 1975-1994, smooth fluctuations are observed, followed by another sharp increase during 1995-2009. Evidently, according to the "$TMS_{ores\text{-}indust}/[GDP_{per\ Capita}]$" as depicted in Figure 5.23.a, a strong macro-coupling for ores and industrial minerals inputs can be identified for most of 1947-2009 period. Comparing the trends of the share of ores and industrial minerals in the world $TMS_{non\text{-}fuel}$, as depicted in Table 5.2, with the $MI_{non\text{-}fuel}$ trends of Figure 5.23.a, it emerges that most of the decoupling periods are characterized by a substantial reduction in the shares of ores and industrial minerals.

- Construction Minerals

The standard (de)coupling ratio "$TMS_{construction}/GDP$" ratio (figure 5.23.b) indicates three short dematerialization periods: 1913-1919; 1929-1933; and 1939-1945. From 1945 to 1960, proposed $MI_{construction}$ increases sharply. After 1960, a period of relative stability lasts up to 1980. Smooth fluctuations, with short periods of decline, occur in 1981-2000, while a sharp increase characterizes 2001-2009. On the other hand, the "$TMS_{construction}/[GDP_{per\ Capita}]$" ratio (Figure 5.23.b) undergoes a strong macro-coupling evolution. For the period 1946-2009, Figure 5.23.b depicts a constant increase in standard $MI_{construction}$ which is briefly interrupted in 1990 and again in 1992. The period 1995-2000 shows a slowdown in the rate of standard $MI_{construction}$ which increases sharply during 2001-2009. As a result, for 1946-2009, the "$TMS_{construction}/[GDP_{per\ Capita}]$" ratio depicts a sheer macro-coupling relationship between construction minerals and per capita GDP. This coupling trend is far stronger than the one estimated through the "$TMS_{construction}/GDP$" ratio. It should be noted that, during the coupling period (1946-2009), construction minerals drastically increase their share in world TMS $_{non-energy}$.

- Non-fuel Biomass

Figure 5.23.c present the "*TMS* $_{biomass}$*/GDP*" and "*TMS* $_{biomass}$*/[GDP* $_{per\ Capita}$*]*" ratios, respectively. The former ratio results in MI $_{biomass}$ reduction during 1900-2009, divided into two macro-decoupling periods: 1900-1950 and 1951-2009. The "*TMS* $_{biomass}$*/[GDP*$_{per\ Capita}$*]*" ratio results in a more moderate decoupling trend, with periods of relative stability in 1900-1950, 1970-1980 and 1985-1995, as well as periods of relative decoupling (1950-1969 and 1995-2006). It should also be noted that biomass, according to Table 5.2, remains a substantial material input during times of war and recession. After 1950, massive industrial production and infrastructure building led to the decrement in the relative use of biomass. However, the two oil shocks of 1973 and 1979 increased the biomass share for a short period (1980-1985). Nevertheless, the "*TMS*$_{biomass}$*/GDP*" ratio presents a stronger reduction in biomass intensity of the economy compared to the "*TMS*$_{biomass}$*/[GDP*$_{per\ Capita}$*]*".

All figures 5.23a-c also include the indexed trajectory of each mass type's per capita consumption (the grey line of dots). Evidently the per capita mass consumption follows a similar evolutionary pattern with the respective trends of the proposed MI evaluation framework, for all the material types examined.

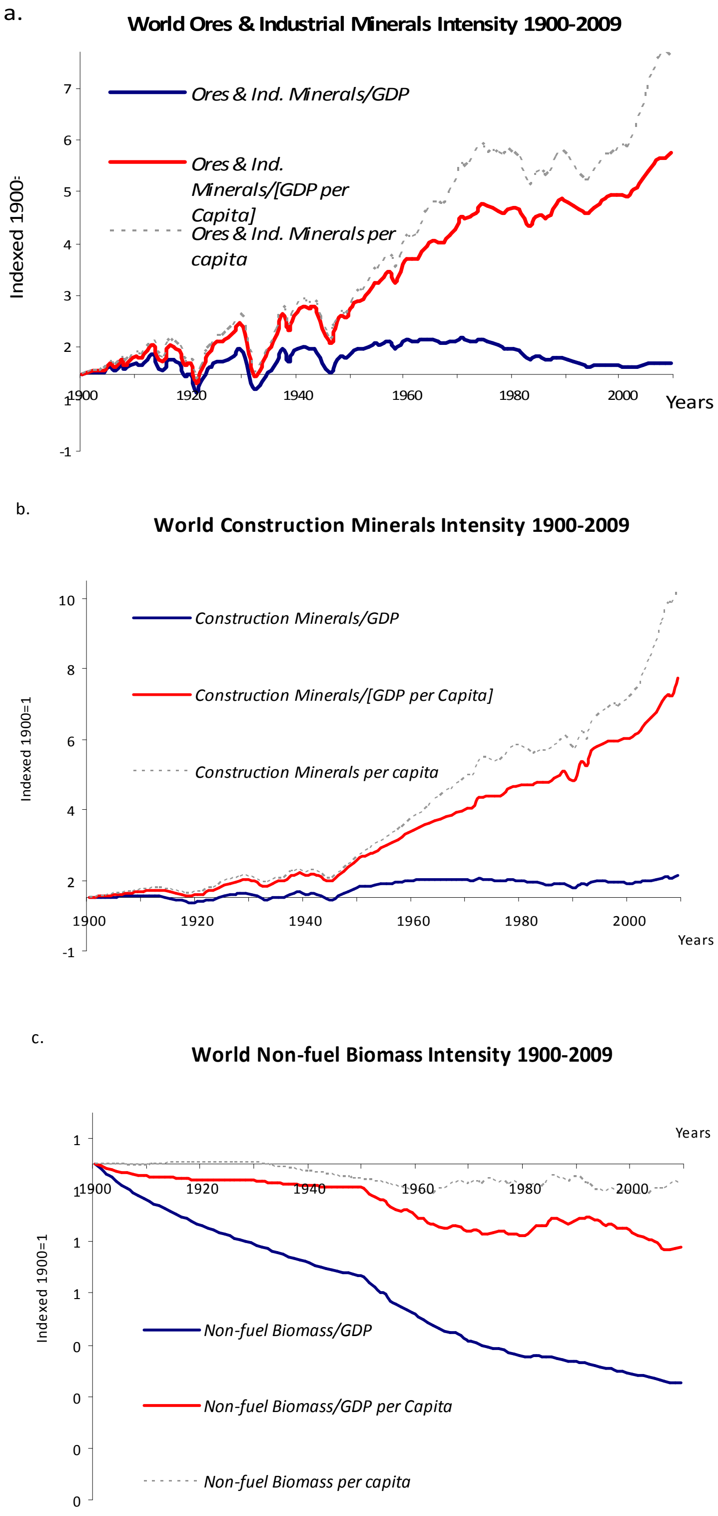


Figure 5.23 *Disaggregated world TMS $_{non\text{-}fuel}$. (a) TMS $_{ores\text{-}indust.}$/GDP ratio and TMS $_{ores\text{-}indust}$/[GDP$_{per\ Capita}$] ratio; (b) TMS $_{construction}$/GDP ratio and TMS $_{construction}$/[GDP$_{per\ Capita}$] ratio; (c) TMS $_{biomass}$/GDP ratio and TMS $_{biomass}$/[GDP$_{per\ Capita}$] ratio, all estimated for the period 1900-2009 and indexed as 1900=100.*

World renewable and non-renewable non-fuel material consumption for 1900-2009

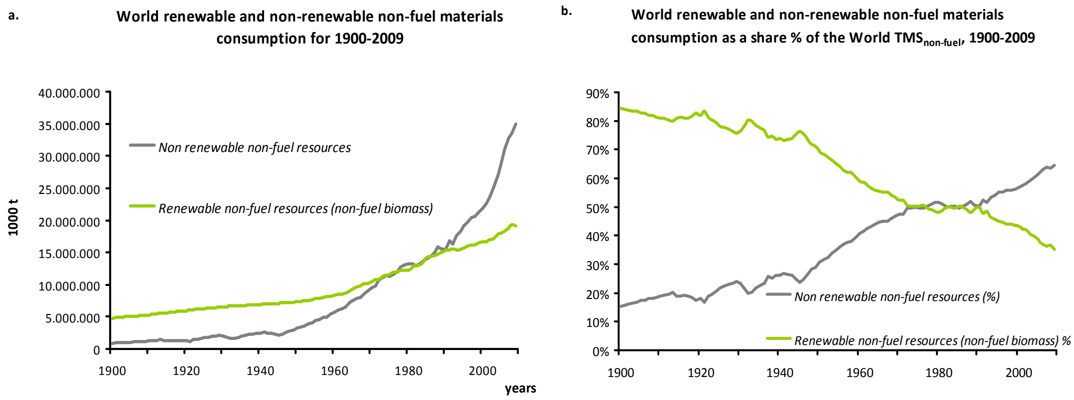


Figure 5.24 *a) World renewable and non-renewable non-fuel materials consumption (in 1000t/yr); b) World renewable and non-renewable non-fuel materials consumption as a percentage (%) share of world TMS $_{non\text{-}fuel}$, for 1900-2009.*

This section attempts to distinguish TMS $_{non\text{-}fuel}$ consumption in two categories: renewable and non-renewable non-fuel materials, where renewable non-fuel materials is the aggregation of all biomass categories, except its fuel aspects; and non-renewable non-fuel materials consist of the aggregation of ores; industrial and construction minerals. Figure 5.24_a presents the world renewable and non-renewable non-fuel materials. Evidently, in mid 1970s the non-renewable non-fuel resources consumption increases dramatically and become the dominant resources type, while the renewable non-fuel biomass increases, yet by a slower rate. Figure 5.24_b depicts the percentage contribution of each non-fuel material category to the TMS $_{non\text{-}fuel.}$ Figure 5.24_b reveals the remarkable decline that has been occurred in non-fuel biomass's contribution since 1900; apparently, from the 84.5% of TMS $_{non\text{-}fuel}$ in 1900, non-fuel biomass contributes in only the 35.4%, in 2009. On the contrary, the non-renewable non-fuel materials increase their share from 15.5%, in 1900, to 64.6%, in 2009, taking the lion's share after 1987 (Fig 5.24).

5.6.2 Estimating US non-fuel material intensity for 1870-2005

Data

Data on the US non-fuel DMC are drawn from Gierlinger and Krausmann (2011) and personal communication (*Gierlinger, 2012*) for data on the United States' wood fuel biomass. Non-fuel DMC data for the USA are estimated as the aggregate of non-fuel biomass; ores; non-metallic (construction) minerals. For data source see previous section (global level).

The US total and per capita non-fuel material consumption and the estimation of MI $_{non-fuel}$, for 1870-2005[16]

The USA is considered to be a typical example of a highly developed nation and is among the world's largest consumers of material flows (*Gierlinger and Krausmann 2011*). Figure 5.25 shows the composition of the USA's DMC non-fuel in absolute quantities per year (1000t/yr). Non-metallic minerals are by far the dominant non-fuel material type followed by non-fuel biomass, which remains an essential non-fuel material, and metal ores which present a decline after 2000.

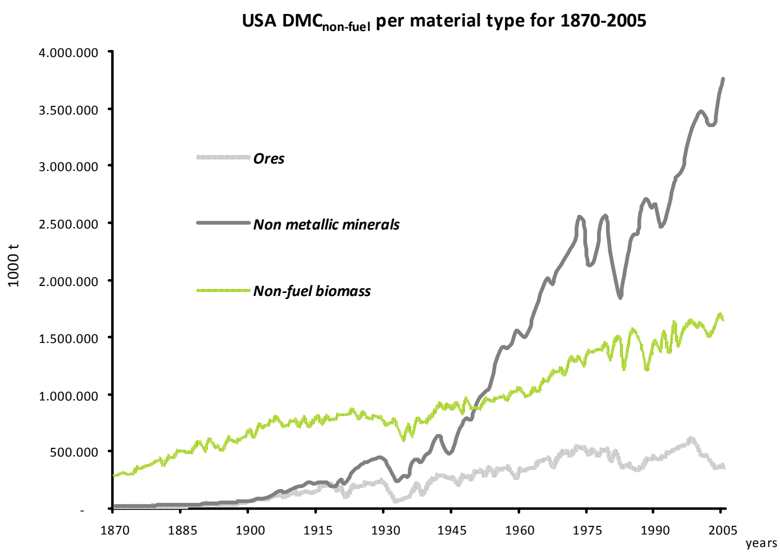


Figure 5.25 *The composition of the US DMC $_{non-fuel}$ in absolute quantities (1000t/yr), for 1870-2005*

[16] Including variations derived from "*other products*" category in the estimation of DMC $_{non-fuel}$, as given by the Gierlinger and Krausmann (2011) database.

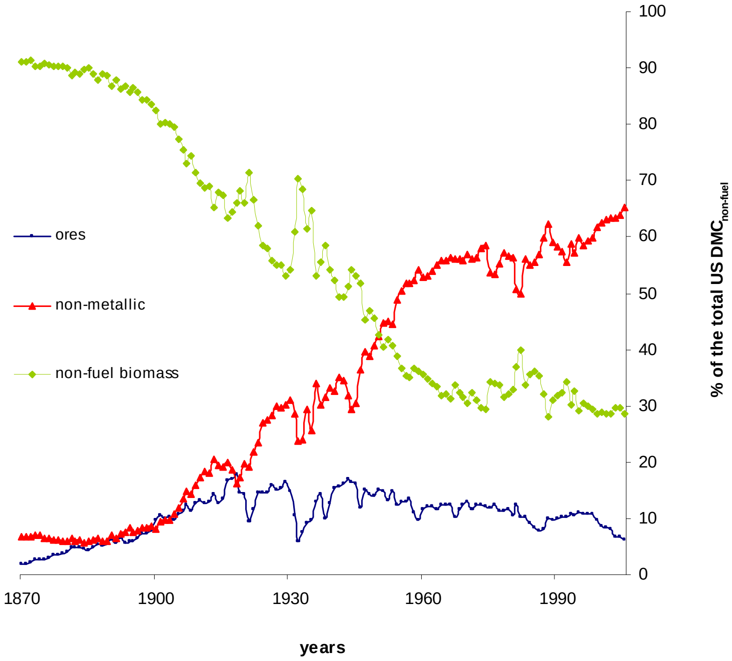


Figure 5.26 *Changes in the composition of the US DMC $_{non-fuel}$ (%), during 1870-2005*

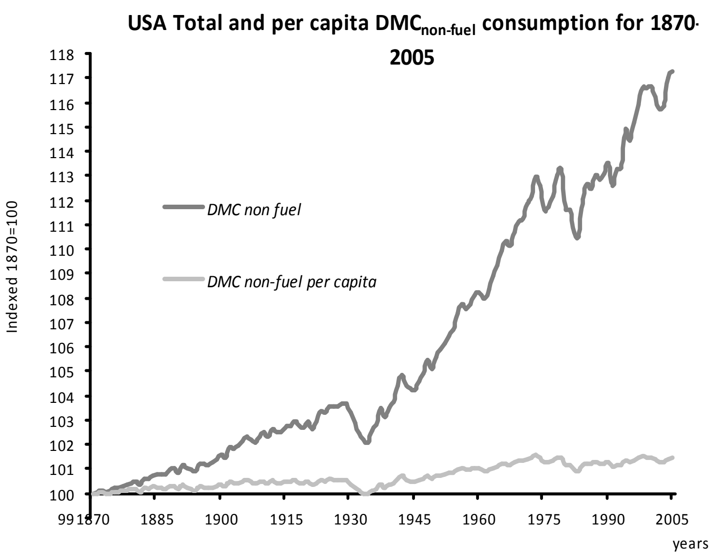


Figure 5.27 *USA Total and per capita DMC $_{non-fuel}$ consumption, indexed (1870=100), for 1870-2005*

Figure 5.26 depicts the percentage contribution of each non-fuel material type in total US DMC $_{non-fuel}$. The share of non-fuel biomass is constantly declining, while substituted by non-metallic minerals whose share increase continuously. Metal ores share indicates a sharp decrement after 2000. Figure 5.27 depicts the total US DMC $_{non-fuel}$ trends compared to the per capita DMC $_{non-fuel.}$ All ratios are indexed (1870=100). Apparently, the divergence between the total and the per capita non-fuel materials consumption is profound. While the per capita DMC $_{non\text{-}fuel}$ increases after WWII, the total DMC $_{non\text{-}fuel}$ increases, during the same period, far more intensively. In other words, every increment at the per capita consumption level per year is requiring a disproportional input of gradually more and more non-fuel material resources.

Finally, Figure 5.28 presents the $DMC_{non\text{-}fuel}$/GDP and $DMC_{non\text{-}fuel}$/[$GDP_{per\ Capita}$] ratios for 1870-2005 (indexed 1870=100). The $DMC_{non\text{-}fuel}$/GDP ratio depicts a sheer dematerialization of the US economy. In contrast, the $DMC_{non\text{-}fuel}$/[$GDP_{per\ Capita}$]ratio indicates a prevailing coupling trend for 1870-1976, with only a brief decoupling period during WWII. After 1976, the $DMC_{non\text{-}fuel}$/[$GDP_{per\ Capita}$] ratio indicates a decoupling trend that intensifies during 1976-1985. Finally, the period 1986-2005 indicates a relative stability for the proposed framework. What is more, the $DMC_{non\text{-}fuel}$/[$GDP_{per\ Capita}$] depicts substantial similarities with the DMC $_{non\text{-}fuel}$ per capita (social/industrial metabolism) index, revealing the close relationship between the two indexes.

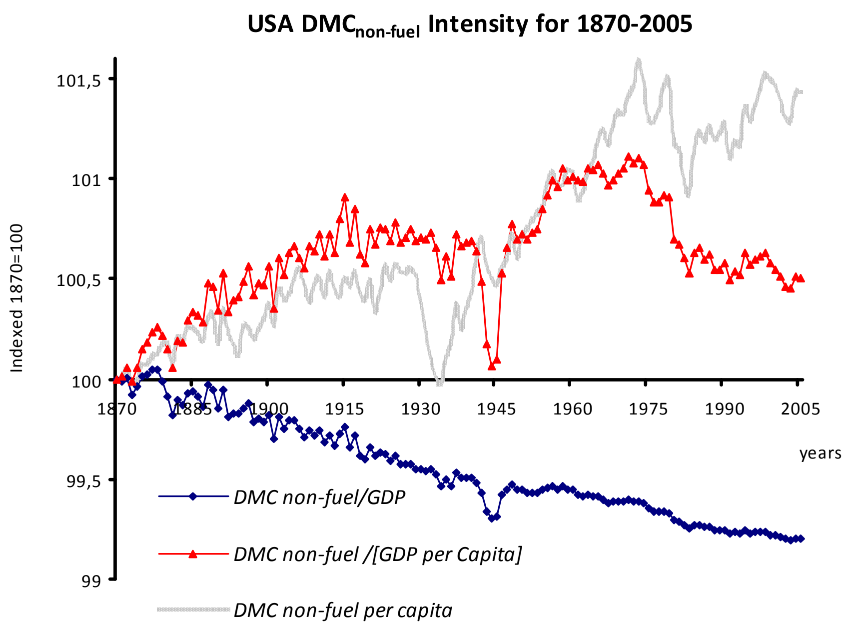


Figure 5.28 *MI for USA in 1870-2005. $DMC_{non\text{-}fuel}$/GDP and DMC $_{non\text{-}fuel}$ /[$GDP_{per\ Capita}$] ratio indexed (1870=100); where $DMC_{non\text{-}fuel}$ is the US aggregate domestic non-fuel materials consumption: ores; non metallic minerals; non-fuel biomass.*

Estimating the divergence between the US $DMC_{non\text{-}fuel}$/GDP and the US $DMC_{non\text{-}fuel}$ /[GDP $_{per\ Capita}$]. Measuring the percentage contribution of each indicator to divergence

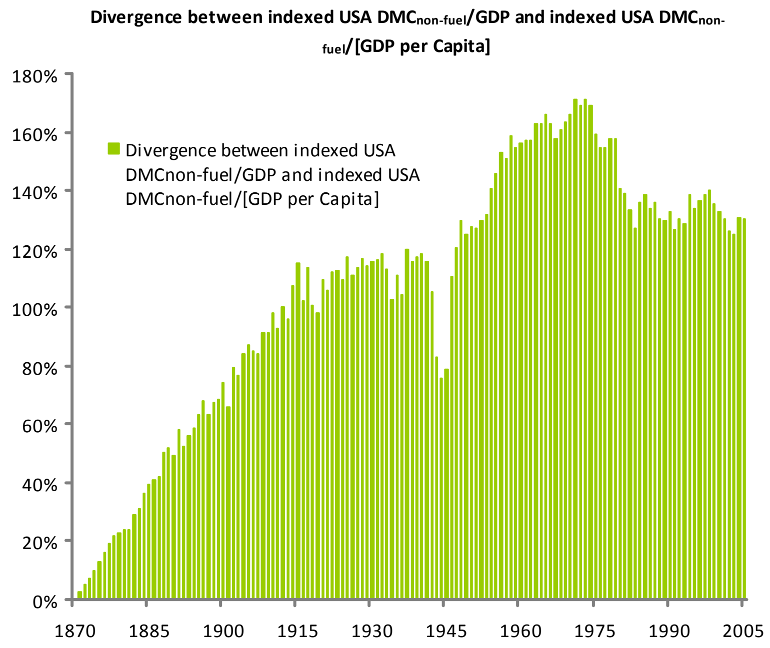


Figure 5.29 *Divergence between the indexed US $DMC_{non\text{-}fuel}$/GDP and DMC $_{non\text{-}fuel}$ /[$GDP_{per\ Capita}$] ratios*

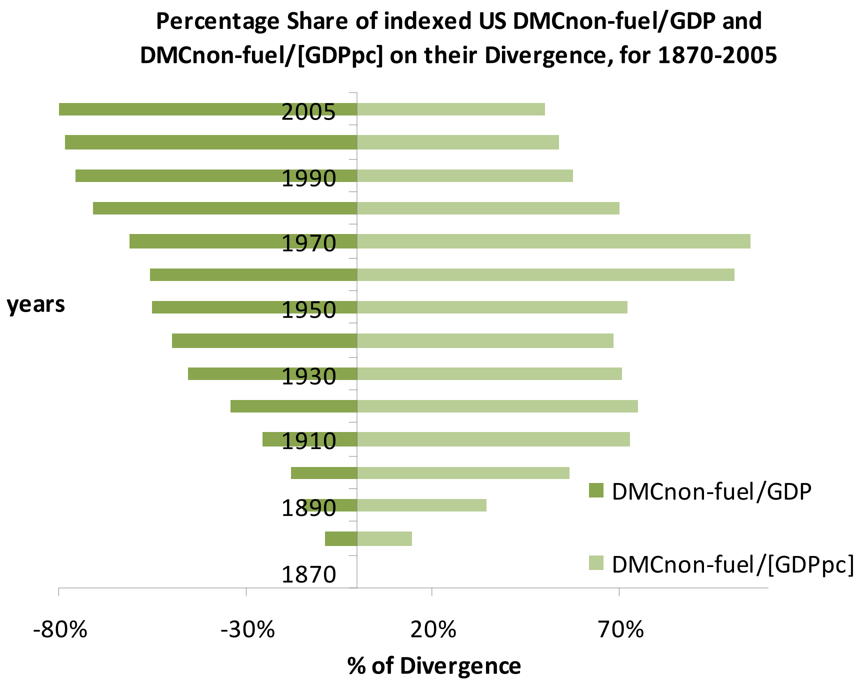


Figure 5.30 *The percentage (%) contribution of each indicator to their divergence, for 1870-2005*

Figure 5.29 estimates the divergence between $DMC_{non\text{-}fuel}$/GDP and the US $DMC_{non\text{-}fuel}$ /[$GDP_{per\ Capita}$] MI indicators. Since both indicators are indexed into a base year (1870=100), their divergence is estimated as the difference of each indicator's value from the base year (base year=100). Accordingly, Figure 5.30 depicts the percentage contribution of each MI indicator to their divergence. As a result, the greatest part of divergence, until 1970s, is contributed by the increment of the proposed MI indicator, whilst after 1980, the standard MI indicator's declining trend is stronger that the relative stability of $DMC_{non\text{-}fuel}$ /[$GDP_{per\ Capita}$].

The US non-fuel materials Decoupling Ratio (DR) and Decoupling Factor (DF), for 1870-2005

The Decoupling Ratio (DR) is estimated in Figure 5.31a. For DR values greater than 1, there is a coupling relationship. Accordingly, the Decoupling Factor (Fig. 5.31b) signals the absence of decoupling effect for values DF≤0. The proposed MI framework results in a general coupling pattern (DF<0), except two decoupling periods in 1910-1930 and 1970-1990, respectively (where DF>0). On the other hand, the standard MI framework follows a general decoupling pattern (DF>0). The next section estimates the Decoupling Index (DI), a helpful framework for classifying the observed decoupling into relative and absolute, according to UNEP (2011).

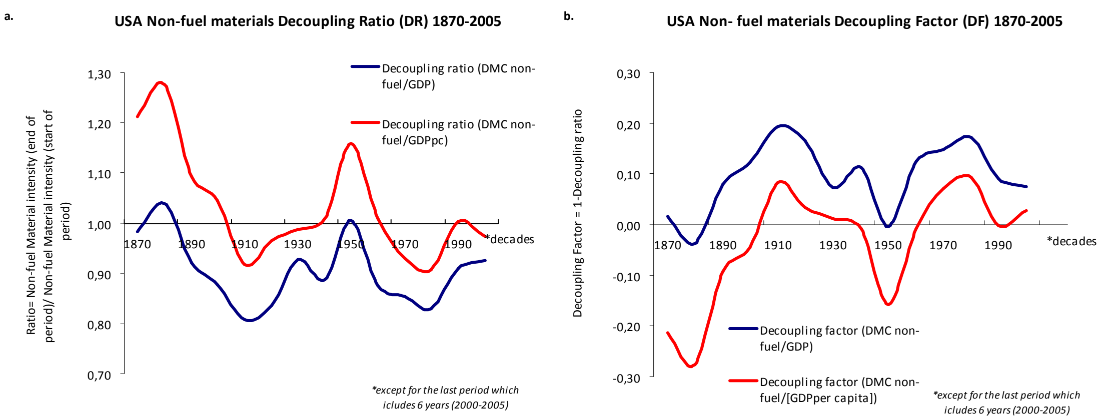


Figure 5.31 *a. The US non-fuel materials Decoupling Ratio (DR), and b. The US non-fuel material Decoupling Factor (DF), for 1870-2005*

The US non-fuel materials Decoupling Index (DI), for 1870-2005

This section estimates the Decoupling Index of the US non-fuel MI for both the standard and the proposed framework. The standard MI indicator shows a general relative decoupling trend, with the exception of WWII period (absolute decoupling: DI≤-4); 1950-1960 (coupling period: DI>0); and 1980s (an almost absolute decoupling period: DI=0). On the other hand, the proposed MI indicator results in a general coupling trend, with the exception of a short relative decoupling period, during WWII, and an almost absolute decoupling pattern – similar with the one depicted by the standard indicator in Figure 5.32, during 1980s (DI=0). Evidently, the estimation of DI clearly captures the dissimilar evolutionary patterns of the two MI indicators, underlining the different conclusions concerning the MI of the US economy.

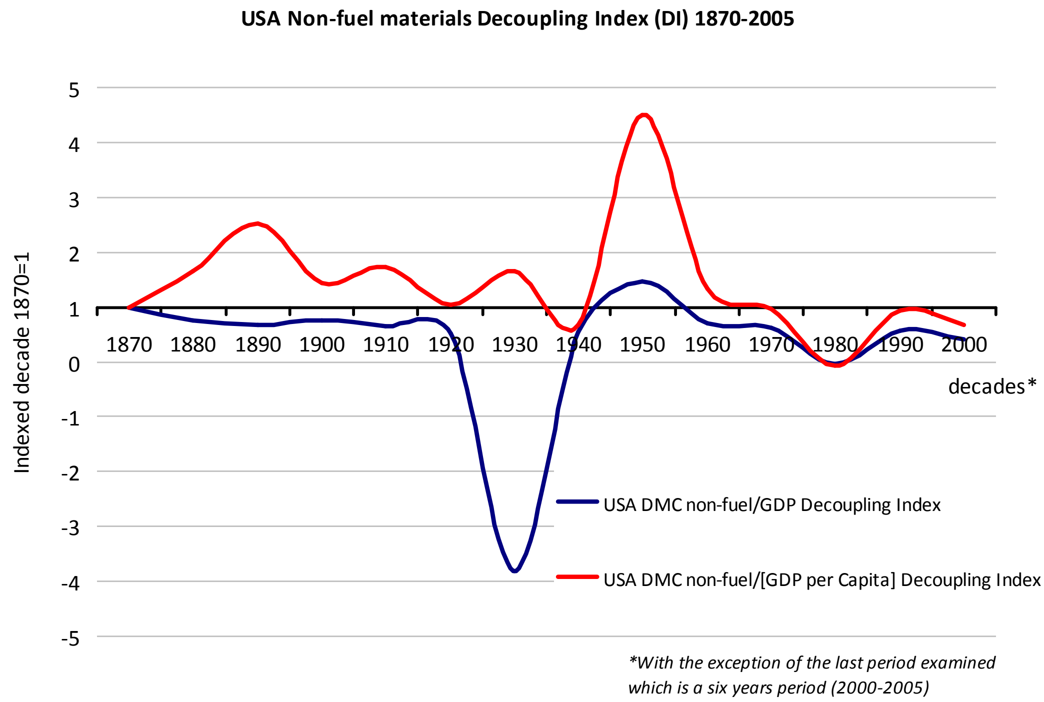


Figure 5.32 *The US non-fuel materials Decoupling Index (DI) indexed (1870=1), for 1870-2005*

Disaggregating US non-fuel materials: estimating decoupling for ores; non-metallic (construction) minerals; and non-fuel biomass, for 1870-2005[17]

[17] In this section only the three major non-fuel material types have been estimated. In order for estimates to capture only the non-fuel materials in DMC, we have excluded all energy carrier material (or any fuel materials whatsoever). What is more, $DMC_{non\text{-}fuel}$ estimates also exclude the "*other products*" category entered in the available databases for estimating total DMC, due to the fact that it is impossible to break down with any precision the "*other products*" category into energy and non-fuel materials. More details about "*other products*" in Gierlinger and Krausmann (2011).

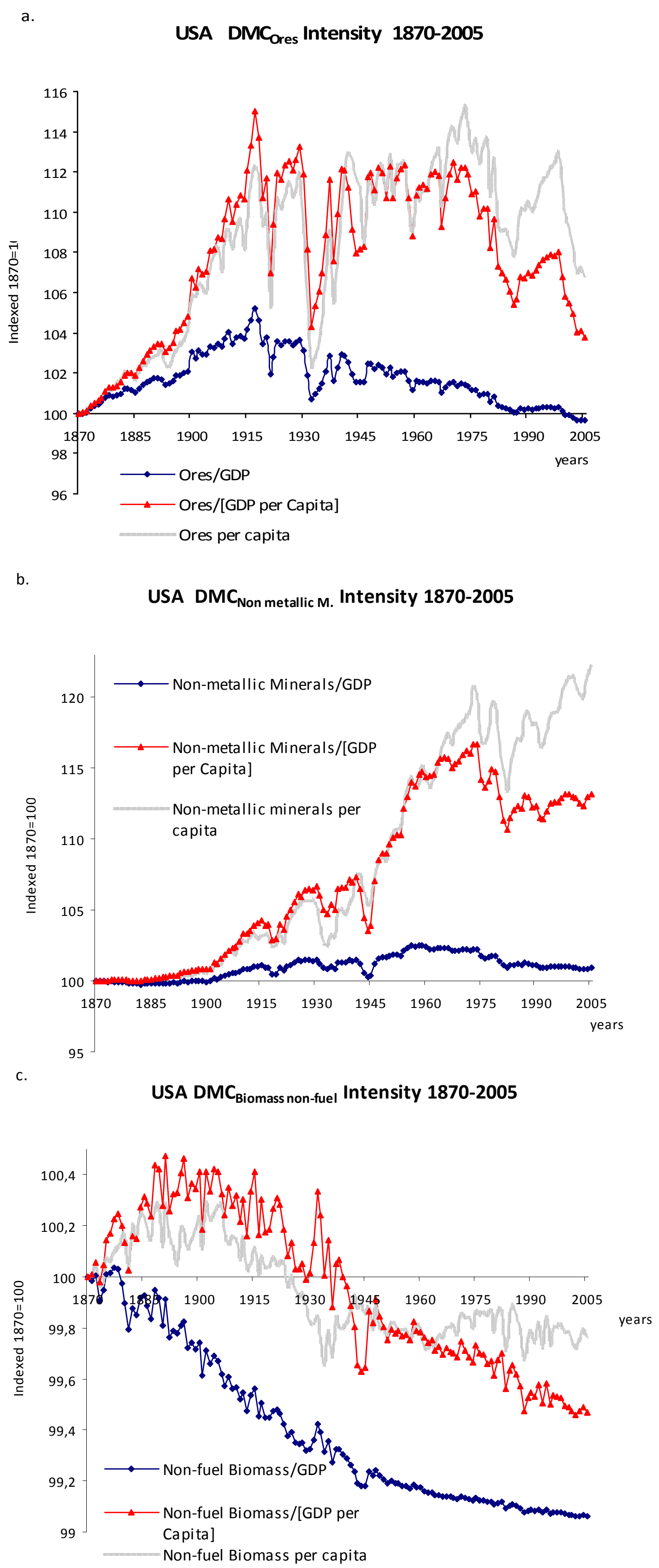


Figure 5.33 *(a) DMC_{ores}/GDP and DMC_{ores}/[$GDP_{per\ Capita}$]; (b) $DMC_{non\ metallic\ min}$/GDP and $DMC_{non\ metallic\ min}$/[$GDP_{per\ Capita}$]; (c) $DMC_{biomass}$/GDP and $DMC_{biomass}$/[$GDP_{per\ Capita}$], where $DMC_{non\text{-}fuel}$ refers only to the*

aggregate domestic non-energy material type consumption in the USA, for the period 1870-2005 and indexed as 1870=100.

As figure 5.33 shows, estimates based on the "*standard*" $DMC_{non\text{-}fuel}/GDP$ ratio depict a more intensive decoupling when compared to the estimates based on $DMC_{non\text{-}fuel}/[GDP_{per\ Capita}]$, for all categories of resources. Furthermore, the proposed framework depicts similar evolutionary paths with the relevant per capita trends, a clue that may reflect the better approximation that the proposed framework performs, of the actual material intensity, as evaluated by the social/industrial metabolism.

The disaggregated $MI_{non\text{-}fuel}$ should be interpreted by taking into account the trends in the composition of the total $DMC_{non\text{-}fuel}$ in the USA, as presented in Figure 5.26. A general pattern can be identified for the (de)coupling trends of the individual material categories: *the MI non-fuel is increasing for those materials whose relative use is increasing while decoupling is evident mainly for those materials whose use is shrinking.* This observation may have important implications concerning the validity (or not) of the decoupling effect.

The US renewable and non-renewable material consumption for 1870-2005

The United States, as a highly developed economy, has completed the transition from agrarian stage of development to the industrial economy, with the domination of the non-renewable resources consumption, as Figure 5.34a shows. The transition has been accomplished after WWII, with the renewable resources contribution resulting in a constant declining trend since then (Fig. 5.34b).

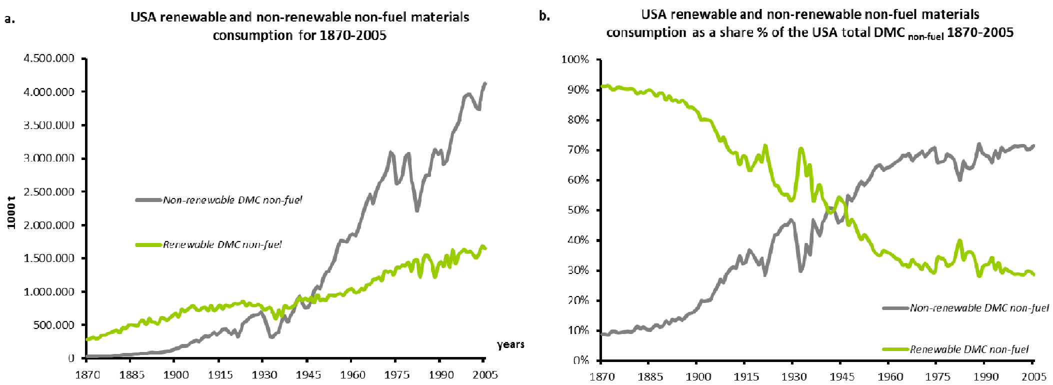


Figure 5.34 *a). The US renewable and non-renewable non-fuel materials (in 1000t/yr), and b) The percentage (%) contribution of renewable and non-renewable resources to the total US DMC* $_{non\text{-}fuel}$ *, for 1870-2005*

5.6.3 Estimating Japanese non-fuel material intensity for 1878-2005

This section attempts to shed light on the MI of Japan, an advanced post-industrial economy and a significant material importer (*Krausmann et al., 2011*). Furthermore, Japan is considered by the relevant literature as among the few countries that may perform an absolute dematerialization (*Krausmann et al., 2011*), hence comprises an appealing case study for further investigation.

Data

Data on Japan's non-fuel DMC are drawn from Krausmann et al. (2011) and personal communication (*Krausmann, 2012*) for data on Japanese wood fuel biomass. Non-fuel DMC data for Japan are estimated as the aggregate of non-fuel biomass; ores; non-metallic (construction) minerals[18]. For data sources see previous data sections (global level).

The Japanese total and per capita non-fuel material consumption and the estimation of MI $_{non\text{-}fuel}$, for 1878-2005

Figure 5.35 pictures the composition of the Japanese non-fuel DMC in absolute quantities, namely in 1000/yr. Contrary to the results at the global level and for the US economy, the Japanese DMC $_{non\text{-}fuel}$ analysis depicts a unique, so far, peculiarity: in early 1990's the absolute quantities of the three main non-fuel material categories, namely ores; non-metallic minerals; non-fuel biomass, perform a gradual decline.

Moreover, Figure 5.36 reveals a long lasting stability, after the late 1970s, concerning the shares (%) of each non-fuel material category in total Japanese non-fuel DMC. Non-metallic minerals are the predominant non-fuel material input of the Japanese economy, while non-fuel biomass and ores depict a small percentage share of the total DMC $_{non\text{-}fuel}$.

[18] Including variations derived from "*other products*" category as given by Krausmann et al. (2011) database.

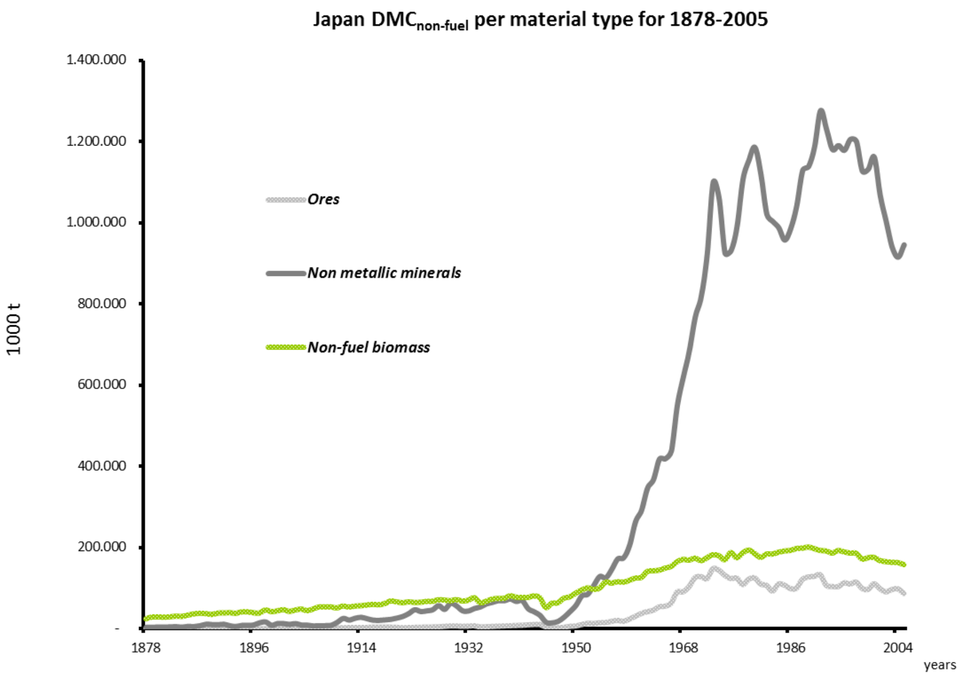


Figure 5.35 *The composition of Japanese DMC $_{non-fuel}$ in absolute quantities (1000t/yr), for 1878-2005*

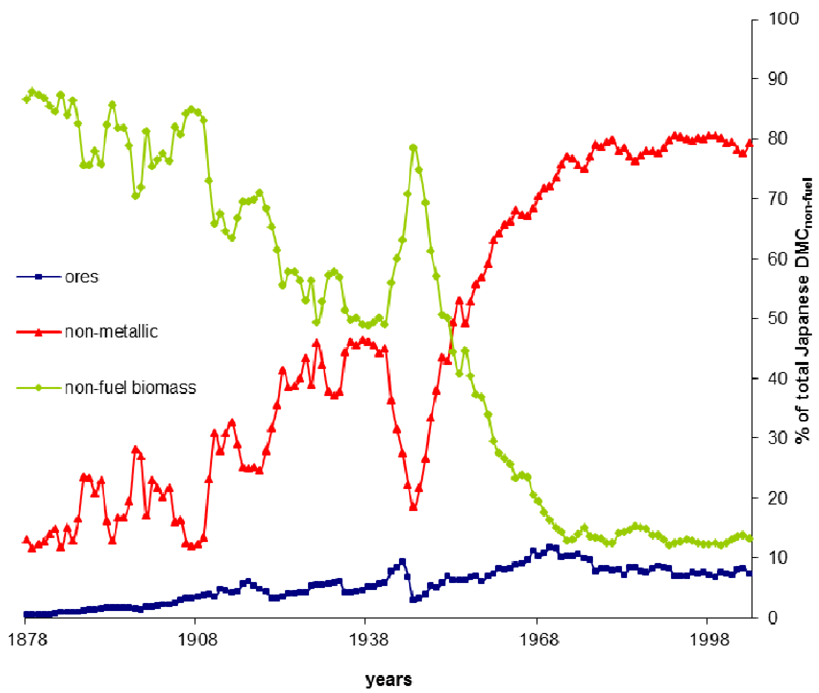


Figure 5.36 *Changes in the composition of the Japanese DMC $_{non-fuel}$ (%) during 1878-2005*

The previous analysis is further endorsed by the Figure 5.37. Both total and per capita Japanese DMC $_{non\text{-}fuel}$ exhibits a sheer decrement after 1990. Transparently, Figures 5.35-5.37 support the main argument of contemporary literature that Japan is among the most representative countries that a potential absolute dematerialization is occurring.

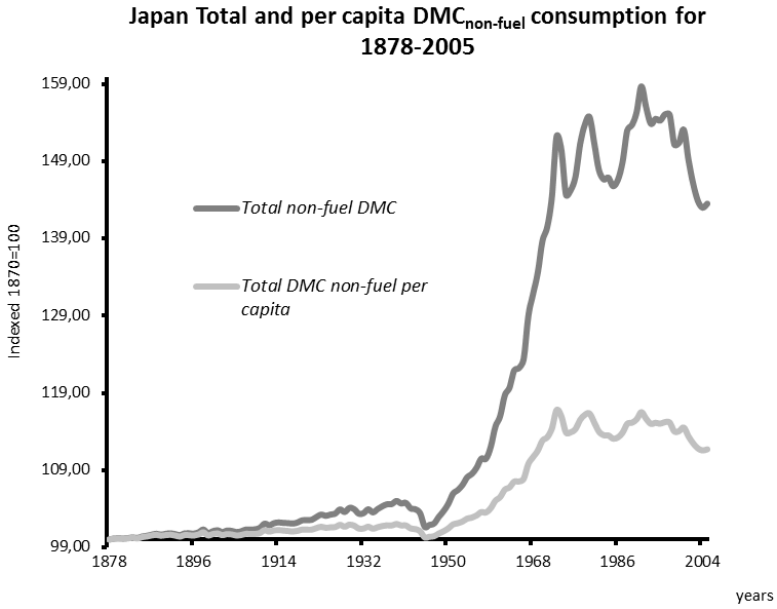


Figure 5.37 *Japan's total and per capita DMC $_{non\text{-}fuel}$, indexed to 1878=100, for 1878-2005*

In order to further test this statement we perform the evaluation of the MI $_{non\text{-}fuel}$ of the Japanese economy. Figure 5.38 compares the evolutionary pattern of DMC $_{non\text{-}fuel}$/GDP; and DMC $_{non\text{-}fuel}$/[GDP$_{per\ Capita}$] (indexed 1878=100), for the Japanese economy for the period 1878-2005. The two indicators follow different evolutionary patterns for 1878-1930. Around 1930, a period of decoupling is initiated which intensifies during WWII, a devastating period for the Japanese economy, as essentially reflected by both indicators. The postwar period 1945-1951 is characterized by strong coupling trends depicted by both the standard and the proposed MI $_{non\text{-}fuel}$ indicators. Next, for 1952-1973, DMC $_{non\text{-}fuel}$/GDP indicates a relative stability in the MI $_{non\text{-}fuel}$ of the economy, while DMC $_{non\text{-}fuel}$/[GDP$_{per\ Capita}$] results in strong macro-coupling trends. However, *Starting with 1974, the recent economic history of Japan has been characterized by clear dematerialization and decoupling of growth from non-fuel materials use.* This de-linkage is depicted by both the MI $_{non\text{-}fuel}$ indicators (Fig. 5.38).

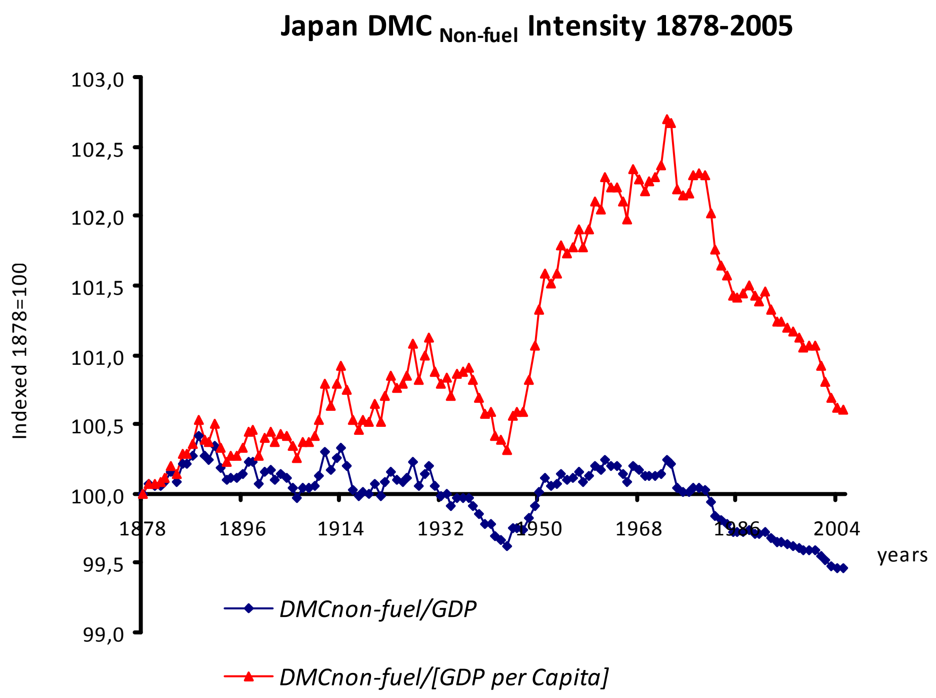


Figure 5.38 *Estimating MI for Japan in 1878-2005. $DMC_{non\text{-}fuel}$/GDP and DMC $_{non\text{-}fuel}$/[$GDP_{per\ Capita}$] ratio (indexed 1878=100), where $DMC_{non\text{-}fuel}$ is the Japanese aggregate domestic non-fuel materials consumption: ores; non metallic minerals; non-fuel biomass.*

Estimating the divergence between the standard Japanese $DMC_{non\text{-}fuel}$/GDP and the proposed $DMC_{non\text{-}fuel}$ /[GDP $_{per\ Capita}$]. Measuring the percentage contribution of each indicator to divergence

The figure 5.39 estimates the divergence between the two indexed MI indicators, while Figure 5.40 depicts the percentage (%) contribution of each indicator to their divergence. The proposed MI framework indeed contributes the greatest part of the observed divergence between the two indicators during the examined period. Indeed, the increment (as well as the decrement) trend of the proposed MI indicator is by far more intensive compared to the, mainly declining, trends depicted for the mainstream MI framework (Fig. 5.40). However, after the early 1980s, both indicators are declining and their divergence is gradually decreasing.

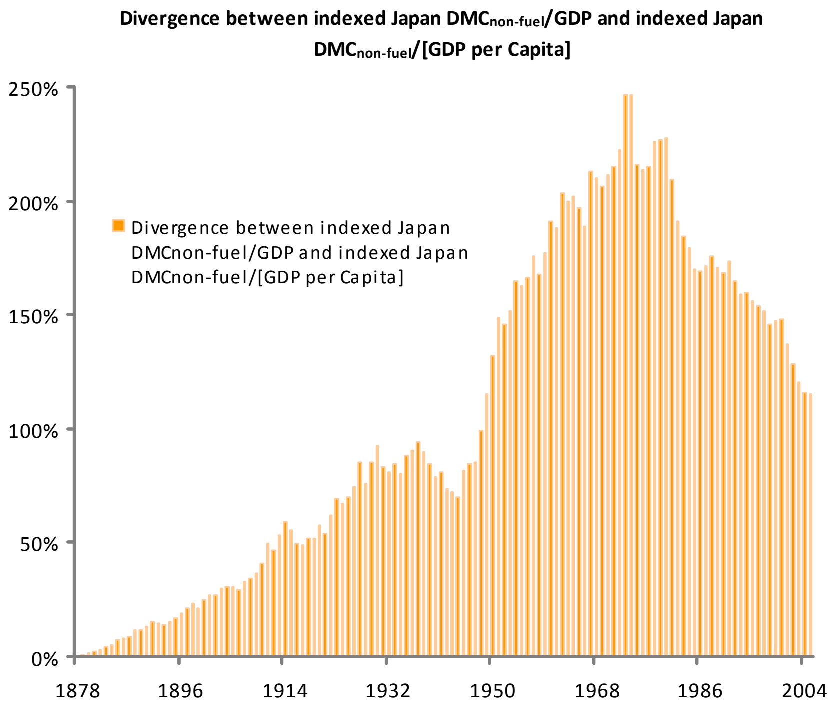


Figure 5.39 *Divergence between the indexed Japanese $DMC_{non-fuel}/GDP$ and $DMC_{non-fuel}/[GDP_{per\ Capita}]$ ratios for 1878-2005*

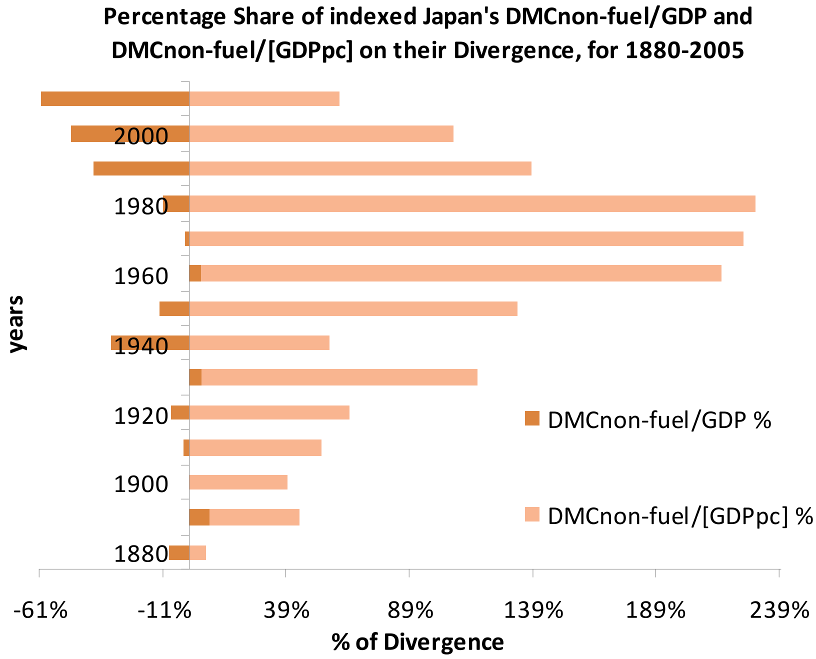


Figure 5.40 *The percentage (%) contribution of each indicator to their divergence, for 1878-2005*

The Japanese non-fuel materials Decoupling Ratio (DR) and Decoupling Factor (DF), for 1878-2005

Accordingly we estimate the DR and the DF, proposed by OECD (2002). Contrary to the respective trends concerning the global level and the USA case, the Japanese case study reveals almost similar evolutionary patterns for both the standard and the proposed indicator. Specifically, there observed only two coupling periods (DR>0 or DF<0, respectively), a short one (1920s) and a stronger one (1950-1970); on the other hand, the early period examined (1880-1910) and the greatest part of 1970-2005 is characterized by a strong decoupling trend (DR<0 or DF>0, respectively).

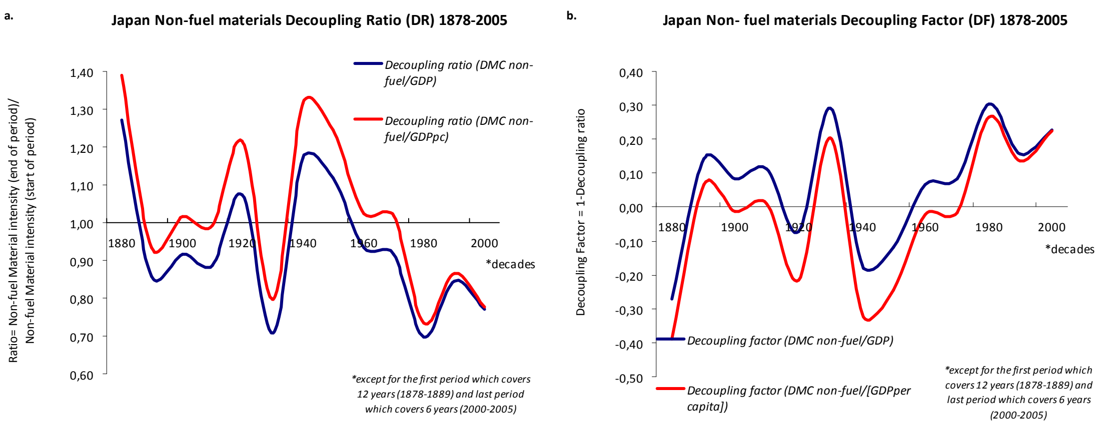


Figure 5.41 a. *The Japanese non-fuel materials Decoupling Ratio, and* ***b.*** *The Japanese non-fuel materials Decoupling Index (DI), for 1878-2005*

The Japanese non-fuel materials Decoupling Index (DI), for 1878-2005

The estimation of the Decoupling Index (DI) is an essential process which helps to evaluate the magnitude of the observed decoupling trend (Fig. 5.42). The indexed (1880=1) DI estimates that concern the standard MI framework reveal two coupling periods, during 1880-1900 and 1950-1970, (DI≥1), while depicts two major absolute decoupling periods during WWII and 1970-2005 (DI≤0). The estimated DI, concerning the proposed alternative MI framework, reveals a general coupling trend during 1880-1930 and 1950-1970 (DI>1) and two strong absolute decoupling periods during WWII (we have excluded an extreme DI value = -37) and 1970-2005, where both DI trends follow similar trajectories towards a strong absolute decoupling. Evidently, the estimates of the DI for both the standard and the proposed framework reveal a similar absolute decoupling trend for both indicators, during 1970-2005. Indeed, the declining total and per capita non-fuel material consumption depicted in Fig. 5.37, as well as the similar declining non-fuel MI estimated for both indicators in Fig 5.38, is further confirmed with the estimations of DF and DI. It seems that the Japanese economy indeed performs in an absolute decoupling stage.

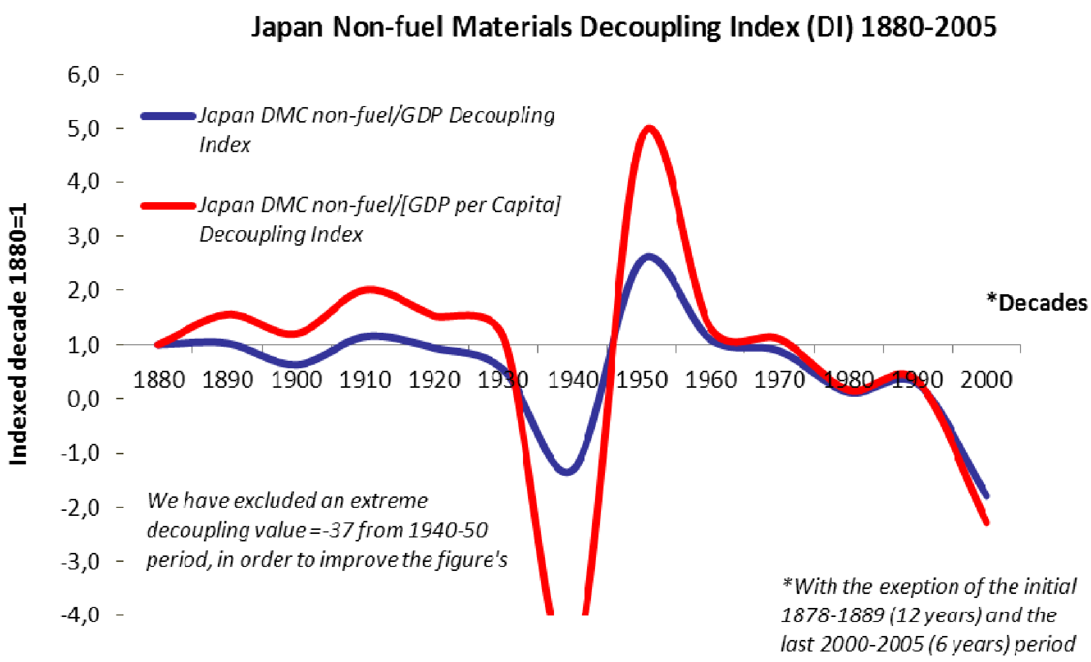


Figure 5.42 *The Japanese non-fuel materials Decoupling Index, indexed (1880=1), for 1880-2005*

Disaggregating Japanese non-fuel materials: estimating decoupling for ores; non-metallic (construction) minerals; and non-fuel biomass, for 1878-2005[19]

Figure 5.43 depicts the estimates for the $DMC_{non\text{-}fuel}/GDP$ ratio and for $DMC_{non\text{-}fuel}/[GDP_{per\ Capita}]$ for all non-fuel material categories, indexed (1878=100). Both $MI_{non\text{-}fuel}$ ratios evolve along similar paths for ores (Fig. 5.43.a1) and non-metallic minerals (Fig. 5.43.b1) for the period 1878-1945. In 1946-1974, the $DMC_{ores}/[GDP_{per\ Capita}]$ and the $DMC_{non\text{-}metallic\ m.}/[GDP_{per\ Capita}]$ present a strong coupling trend, compared to the moderate coupling depicted in the

[19] In this section we estimate only the three major non-fuel material types. $DMC_{non\text{-}fuel}$ estimates also exclude the "*other products*" category (see note 13 for more details). For more information about this material category see Krausmann et al. (2011).

DMC $_{ores}$/GDP and DMC $_{non\text{-}metallic\ m.}$/GDP ratios. *It is worth mentioning that the more recent period of 1975-2005 is characterized by strong decoupling trends for both indicators*, as presented in Figures 5.43.a1-b1. The "*$DMC_{Biomass}$/GDP*" and "*$DMC_{Biomass}$/[$GDP_{per\ Capita}$]*" ratios (Fig. 5.43.c1) present substantial differences for 1878-1930: the former depicts a declining pattern but the latter presents a rather fluctuating stability with a smooth declining trend. After 1930, both ratios move along similar evolutionary paths, up until the end of the period examined in 2005.

The per capita consumption trends are presented separately in Figures 5.43.a2-c2, since it was not possible to include them in a single diagram per material type (with the exception of non-fuel biomass), due to the significant scale differences in the indexed values.

The disaggregated DMC non-fuel further supports the conclusions of the non-fuel MI, the Decoupling Factor and the Decoupling index: Evidently, the Japanese economy exhibits a general declining consumption trend concerning the non-fuel materials. What is more, this decline is further confirmed in both the total aggregate and the per capita level of analysis. The disaggregated MI further endorses the already observed results since both ores; non-metallic minerals; and non-fuel biomass intensities depict decoupling trends after 1974, while simultaneously their per capita consumption trends indeed decline in absolute quantities.

The case of Japan calls for more in depth analysis, since the observed absolute decoupling may be the result of various interrelated dynamic parameters such as population decline, outsourcing of "*heavy-industry*" sectors in developing countries, and international trade, to name indicatively just a few. In any case, a progressive effort to explain the declining MI trends of the Japanese economy is characterizes the contemporary literature (*UNEP, 2013)*.

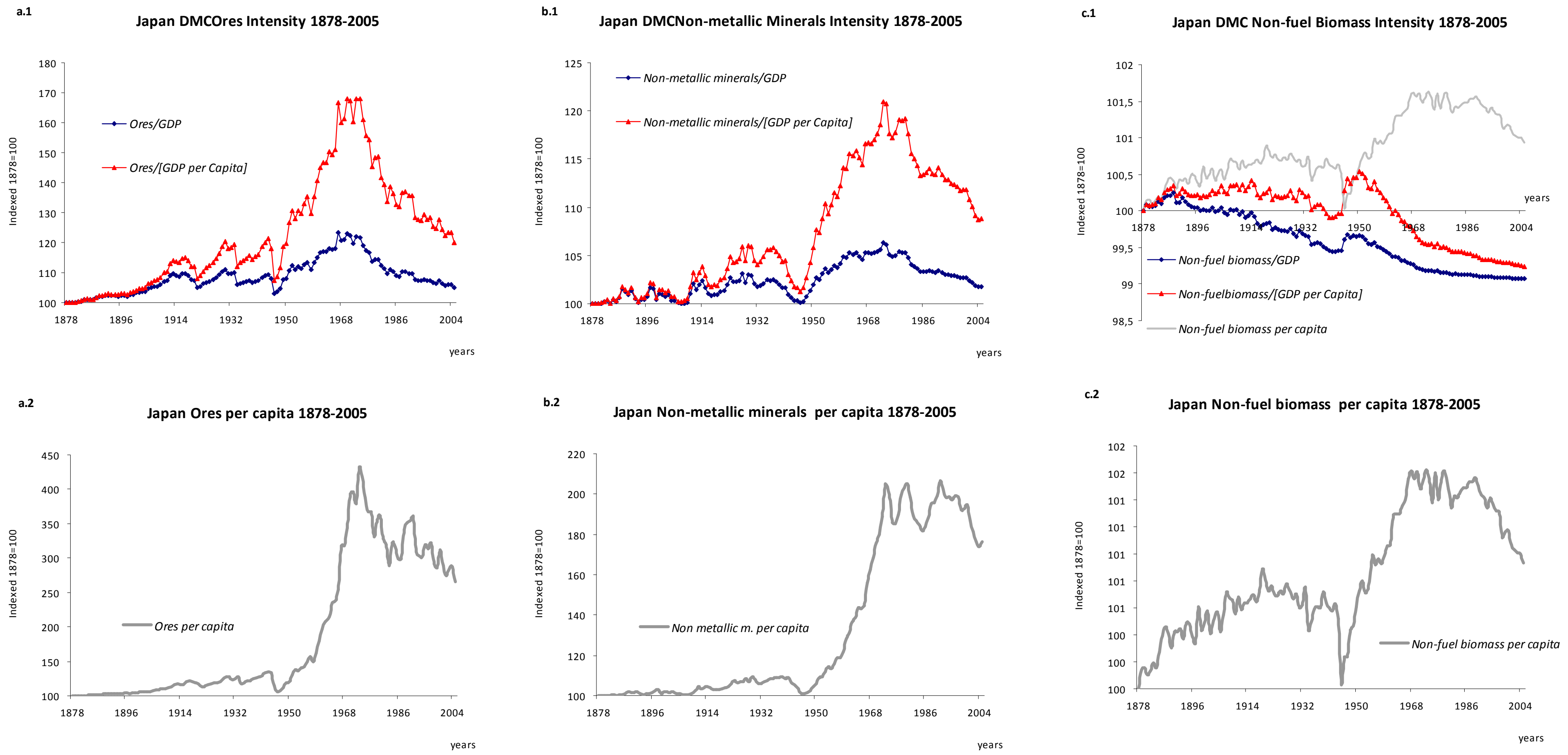


Figure 5.43 *(a1) DMC_{ores}/GDP and DMC_{ores}/[$GDP_{per\ Capita}$]; (a2) per capita ores consumption; (b1) $DMC_{non\ metallic\ min}$/GDP and $DMC_{non\ metallic\ min}$/[$GDP_{per\ Capita}$]; (b2) per capita non-metallic minerals consumption; (c1) $DMC_{biomass}$/GDP and $DMC_{biomass}$/[$GDP_{per\ Capita}$]; (c2) per capita non-fuel biomass consumption, where $DMC_{non\text{-}fuel}$ refers only to the aggregate domestic non-energy material type consumption in Japan, for the period 1878-2005 and indexed as 1878=100.*

The Japanese renewable and non-renewable material consumption for 1878-2005

The Japanese economy has accomplished the transition from the agrarian to the industrial economy, as a highly developed and technologically advanced nation that enters into a post-industrial period (Fig. 5.44). The non-renewable resources consumption is prevailing after the WWII showing a dramatic increase until early 1990s (Fig. 5.44a). From 1990 and onwards, the absolute non-renewable materials consumption decreases rapidly, while the renewable non-fuel biomass decreases as well, albeit with a far smoother rate. Indeed, the synthesis of the non-fuel DMC in Japan seems to be stabilized between the relative shares of renewable and non-renewable non-fuel resources, after mid-1970s.

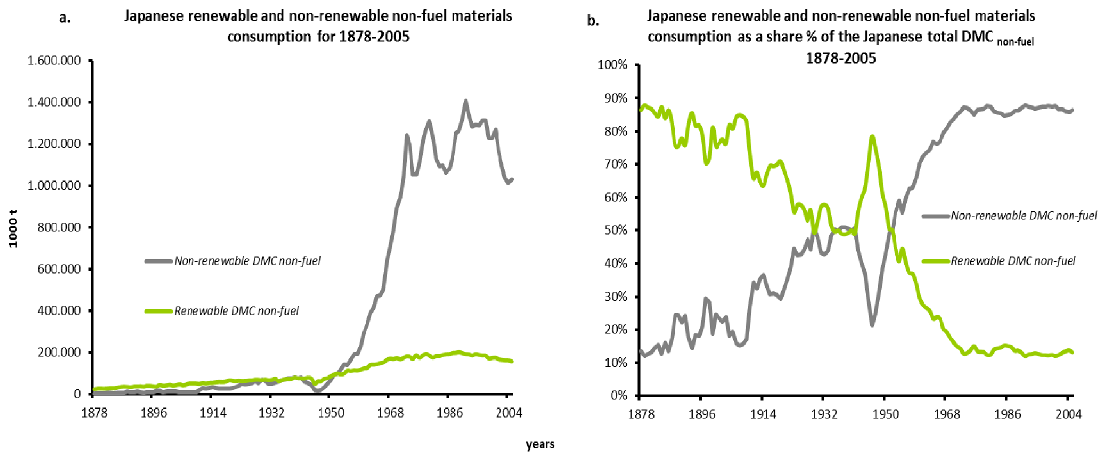


Figure 5.44 *a). The Japanese renewable and non-renewable non-fuel materials (in 1000t/yr), and b) The percentage (%) contribution of renewable and non-renewable resources to the total Japanese DMC $_{non\text{-}fuel}$ for 1878-2005*

5.7 Discussion and concluding remarks

It goes without saying that trends in the materials use are deeply affected by the potential substitutions among different material types. A brief research concerning the substitution issue reveals the potentials this process entails, for endorsing dematerialization (*USGS, 2005*): aluminum can be used instead of copper for wires, refrigeration tubing, and electrical equipment. On the contrary, copper can replace aluminum in electrical applications. Magnesium, titanium and steel can be used in vehicles and other forms of ground and air transportation, instead of aluminum. There are several materials that could be used in place of nickel, but generally, these substitutes are far more expensive than nickel and, in most cases, less effective. In some cases, aluminum, plastics, or coated steel, could be used in place of stainless steel. Titanium can be used instead of nickel, in order to make some super alloys. In the food packaging industry, plastics, paper, aluminum and glass can be used instead of metal "*tin cans*", making good packaging alternatives. There are a number of alternative materials that are used in place of zinc. For example, aluminum and plastics can be used in place of galvanized steel (plastic trash cans are rapidly replacing the old galvanized cans of earlier generations). A number of elements can replace zinc in its electronics and paint applications. Cadmium and aluminum alloy coatings can be used in place of zinc to protect steel from corrosion.

Recycling stands as a critical process that can be further endorse the dematerialization potentials of the economic process. As far as the recycling potentials concerned, aluminum can be recycled by melting cans and other products providing an important source of metal in many developed countries. In that context, 57% of discarded nickel is recycled within the nickel and stainless steel industries (*Reck et al., 2008*), while scarp steel's overall recycling rate of more than 67%, being far higher than that of any other recycled material. Furthermore, recycled copper, predominantly from scrap metal, supplies approximately one-third of the United States' annual copper needs, while recycling of new scrap, old scrap and other zinc-using products produces about 400,000 tons of zinc in the United States (*USGS, 2005*). Evidently, recycling remains a crucial parameter concerning the material intensity trends of the economic process.

Regarding the declining trends in non-fuel material intensity, it seems that the main driving forces behind these trends are (*De Bruyn 2002*): substitutions among different material types; introduction of new lighter materials (i.e. plastics); recycling; and other economic factors such as outsourcing; international trade; and structural changes of the production process towards "*soft goods*" and service sector, in most developed economies (*Munõz et al. 2009; Schandl and West, 2012*). Nevertheless, it is commonly asserted that substitutions among materials may lead to a "*transmaterialization*[20]" instead of "dematerialization" (*Labys, 2002*). If this "*transmaterialization*" is viewed under the prism of BHS concept, gives

[20] According Labys (2002): "*Transmaterialization implies a recurring industrial transformation in the way that economic societies use materials, a process that has occurred regularly or cyclically throughout history. Instead of a once and for all decline in the intensity of use of certain materials, transmaterialization suggests that materials demand instead experiences phases in which old, lower quality materials linked to mature industries undergo replacement by higher quality or technologically more advanced materials.*"

a more realistic apprehension of real world's materially based economic production and, hence, may further confine the potentials to decouple materials use from economic growth. What is more, new materials may appear to be lighter, though not necessarily smaller, due to the irrevocable human scale that defines the dimensionality of economic goods (BHS) and, consequently, the human scale of the production process (HSP).

As far as the material recycling is concerned, this practice indeed offers an indirect dematerialization (indirect because recycling does not reduce material consumption per se, but reduces the extraction of raw materials and consequently reduces the hidden flows of extraction's waste). However, there are many counterarguments concerning the expansion of recycling process in various material types, due to expensive collection costs and fluctuating quality of the waste materials (*Smil, 2014*). In addition, a UN report (*UNEP, 2011b*) examines 60 metals and metalloids and concludes that more than the 50% of metal materials have recovery rates of less than 1%, only five elements have a recovery rate between 1-25%, while 18 common and relatively common metals have recycling rates above 50%, but rarely above 60% (*Smil, 2014, p. 113*).

From a thermodynamic point of view, recycling is irrevocably an entropic process; materials can never be recycled with 100% efficiency, since there will always be looses. Furthermore, the recycling process requires the use of low entropy energy (exergy). In that context, the problem of perpetual recycling could be resolved only in the case of an infinite energy input would have been available for human purposes. In line with these comments, it is not broadly known, but Georgescu-Roegen (G-R) proposed a "*fourth law of thermodynamics*" or "*Law of matter entropy*", in order to emphasize the crucial role of matter in the production process (*Georgescu-Roegen, 1979, 1982*). G-R argued that the entropy law is also valid for materials, besides energy. The main clue of his argument was that as materials are progressively dissipating and the quality of resources is generally declining, the matter scarcity may become, in the end, more crucial than the energy scarcity. The 4th law of thermodynamics has been severely criticized by many distinguished scholars (*Ruth, 1995; Ayres, 1997; Cleveland and Ruth, 1997*). Indicatively, Ayres and Miller (1980) conclude that, in theory, energy is the only resource that could ultimately limit economic growth. Despite the theoretical flaws of G-R's 4th law proposal, the main message that carries out is essential, as the matter matters as well in the production process.

The 5th chapter has concentrated mainly in the analysis and comparison, between the different frameworks implemented in the non-fuel material intensity estimation, at the global level, the USA and Japan. Evidently, OECD countries are consuming over 50% of the world's commercial energy and material resources, but count less than a quarter of world's population (*Podobnik, 1999*). Due to this context, another interesting aspect is that the growth of industrialized countries is mainly supported by a shift from domestic to foreign material resources extraction, thus, imports and international trade (*Bringezu et al., 2004*). It is common ground, between scientists and practitioners that the emergence of new developing countries, especially the contribution of highly developing ones (Such as China, India, Brazil, etc) in the material consumption share, is expected to escalate dramatically the demand for materials, in the near future (*Schandl and West, 2012*). Specifically, in the most recent past newly industrialized developing countries like China, India, Mexico and Brazil have started to build their infrastructures. Least developed countries are more than willing to follow the same trends of industrial/social metabolism of these developing countries.

On the contrary, developed countries seem to have stabilized their per capita material consumption after a century of industrialization and excessive material consumption. Yet, an inconvenient truth, which is not fully explored so far by the relevant literature, lies on the operation and maintenance of the enormous, complex and old infrastructure of the developed countries. A report of the US civil engineering society is revealing: the maintenance of this giant infrastructure of tunnels, bridges, highways, railways, airports, ports, and so on will be extremely costly and will demand, in the near future, more energy and material usage (*ASCE, 2009*). Specifically, the most recent ASCE report (ASCE, 2013) estimates that more that 3.6 trillion US$ will be required for the maintenance of the US's public infrastructure, until 2020. Translating these amounts, from monetary units into actual material and energy requirements, may reveal a potential pressing demand for material and energy resources from highly development nation's, like USA, in the near future.

According to the Resource Efficiency Atlas of the Wuppertal institute for climate, environment and energy (*WI, 2011*), the future trends in global material consumption, in three crucial sectors can be represented in Figure 5.45 (in billion tons for oil and resource extraction, in billion items for cars), if we assume no technological efficiency progress. These projections dramatically highlight the insatiable demand for energy and material consumption. The worldwide car fleet is an indicative example of a product (car) which embodies hundreds of different material types and consumes low-entropy energy (exergy) in order to provide mechanical and kinetic work, during its life cycle.

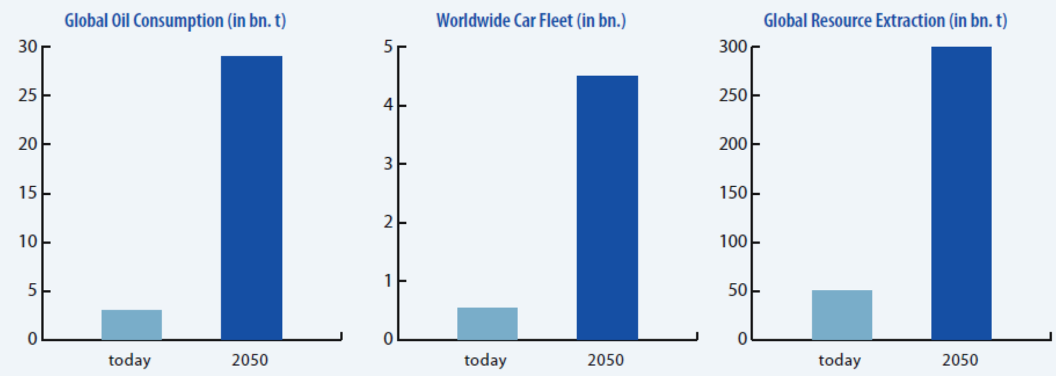


Figure 2: Worldwide demand for raw materials in 2050 without increasing efficiency levels (Source: Hennicke 2006)

Figure 5.45 *A projection of worldwide demand for raw materials in 2050, without increasing efficiency levels (reproduced from the secondary source: Wuppertal Institute, 2011)*

The next chapter aspires to cast light on certain definitions and concepts that concern the role of energy resources in the production process and to estimate the energy intensity by utilizing both the standard and the proposed energy intensity framework. Finally, we choose to close this chapter with two appendices. Appendix A provides a brief DMC intensity estimation at the continental level, whilst Appendix B estimates the DMC intensity of selected developed and developing countries, for the period 1980-2008.

Appendices

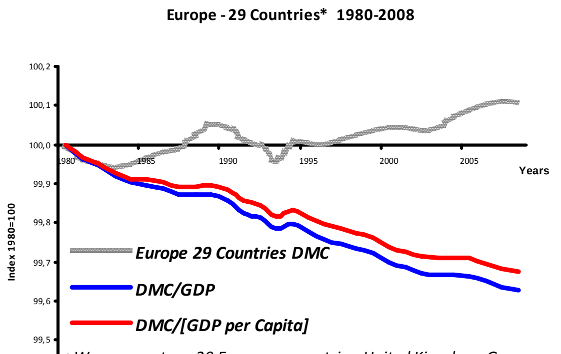
Data Sources

All data utilized in both appendices retrieved from the following sources: Data on DMC are drawn from the on-line database provided by Dittrich and SERI (2014). Global Material Flows Database., available at: http://www.materialflows.net/data/datadownload/

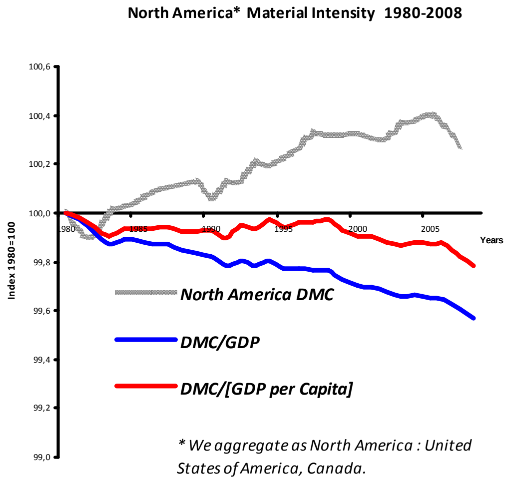
Data on GDP and population are drawn from ***The Conference Board Total Economy Database™*** 2014 (Retrieved in July 2014 - available online at: http://www.conference-board.org/). GDP is estimated in million 1990 International Geary-Khamis dollars per year (million 1990$/yr). Population is expressed in thousand persons per year (1000 per/yr).

Appendix A.

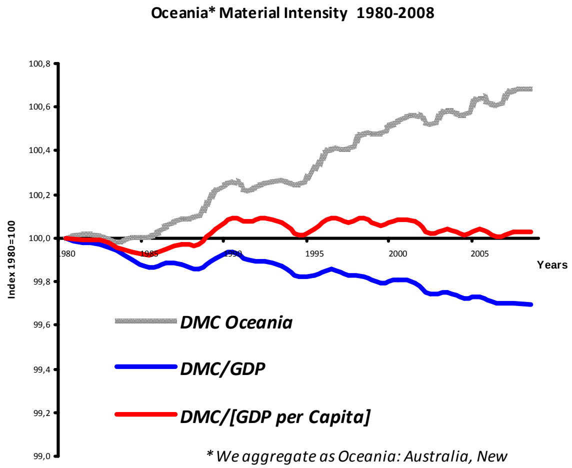
Figure A.1 *Continental Material intensity for 1980-2008 (indexed 1980=100)*



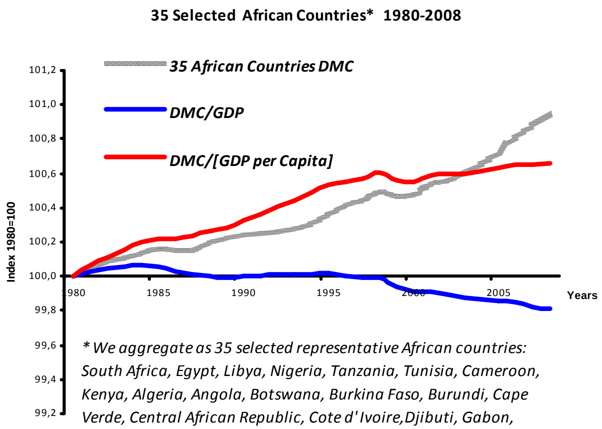
** We aggregate as 29 European countries: United Kingdom, Germany, Austria, France, Italy, Switzerland, Belgium, The Netherlands, Denmark, Sweden, Norway, Finland, Ireland, Greece, Spain, Portugal, Malta, Croatia, Romania, Bulgaria, Czech Republic, Poland, Bosnia and Herzegovina, Servia and Montenegro, Slovenia, Slovakia, Cyprus, Hungary, Lithuania, Czechoslovakia (1980-1992), Yugoslavia (1980-1991).*



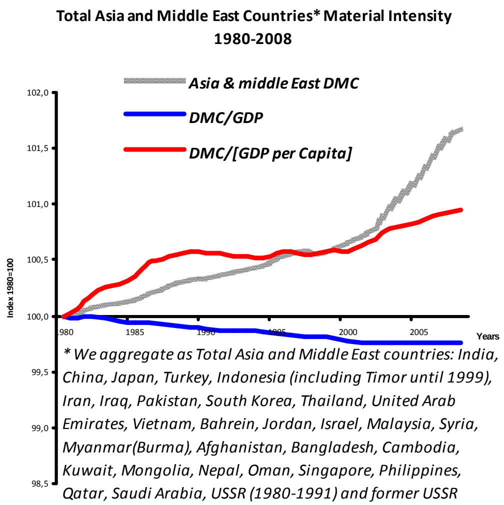
** We aggregate as North America : United States of America, Canada.*



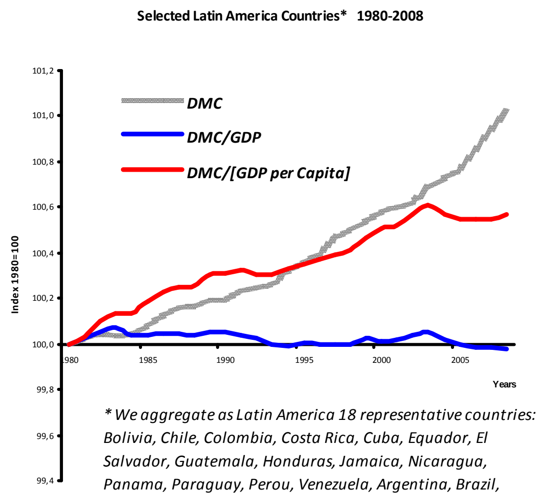
** We aggregate as Oceania: Australia, New Zealand.*



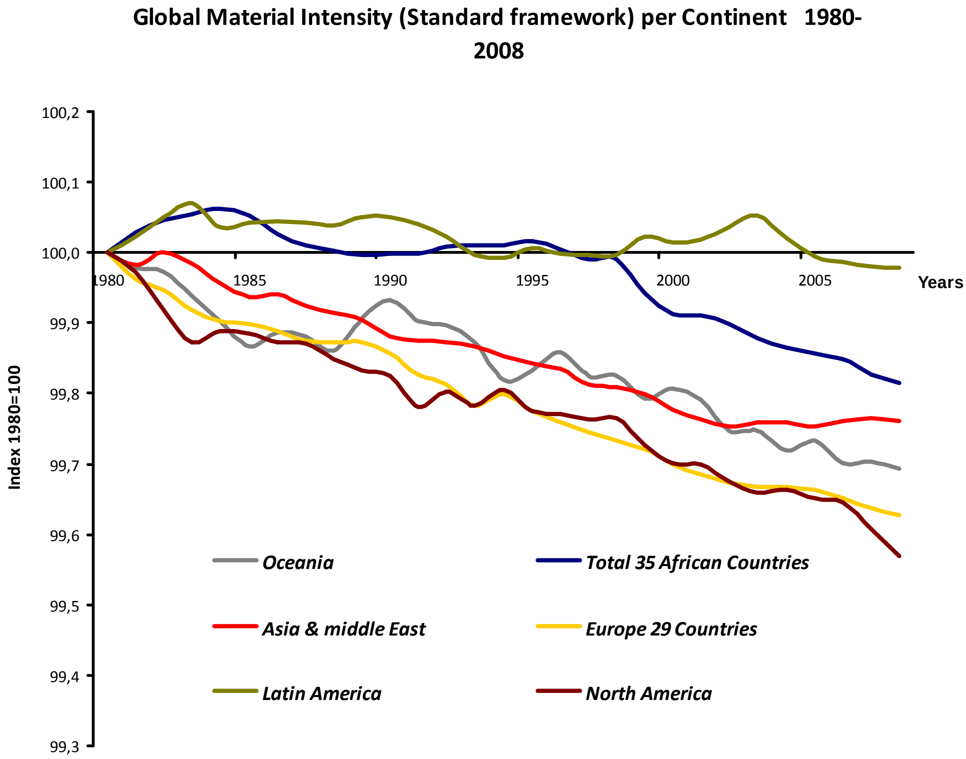
** We aggregate as 35 selected representative African countries: South Africa, Egypt, Libya, Nigeria, Tanzania, Tunisia, Cameroon, Kenya, Algeria, Angola, Botswana, Burkina Faso, Burundi, Cape Verde, Central African Republic, Cote d'Ivoire,Djibuti, Gabon, Gambia, Ghana, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Republic of Congo, Rwanda, Senegal, Somalia, Uganda, Zambia, Zimbabwe.*



** We aggregate as Total Asia and Middle East countries: India, China, Japan, Turkey, Indonesia (including Timor until 1999), Iran, Iraq, Pakistan, South Korea, Thailand, United Arab Emirates, Vietnam, Bahrein, Jordan, Israel, Malaysia, Syria, Myanmar(Burma), Afghanistan, Bangladesh, Cambodia, Kuwait, Mongolia, Nepal, Oman, Singapore, Philippines, Qatar, Saudi Arabia, USSR (1980-1991) and former USSR countries (1992-2008) .*



** We aggregate as Latin America 18 representative countries: Bolivia, Chile, Colombia, Costa Rica, Cuba, Equador, El Salvador, Guatemala, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Perou, Venezuela, Argentina, Brazil, Mexico.*



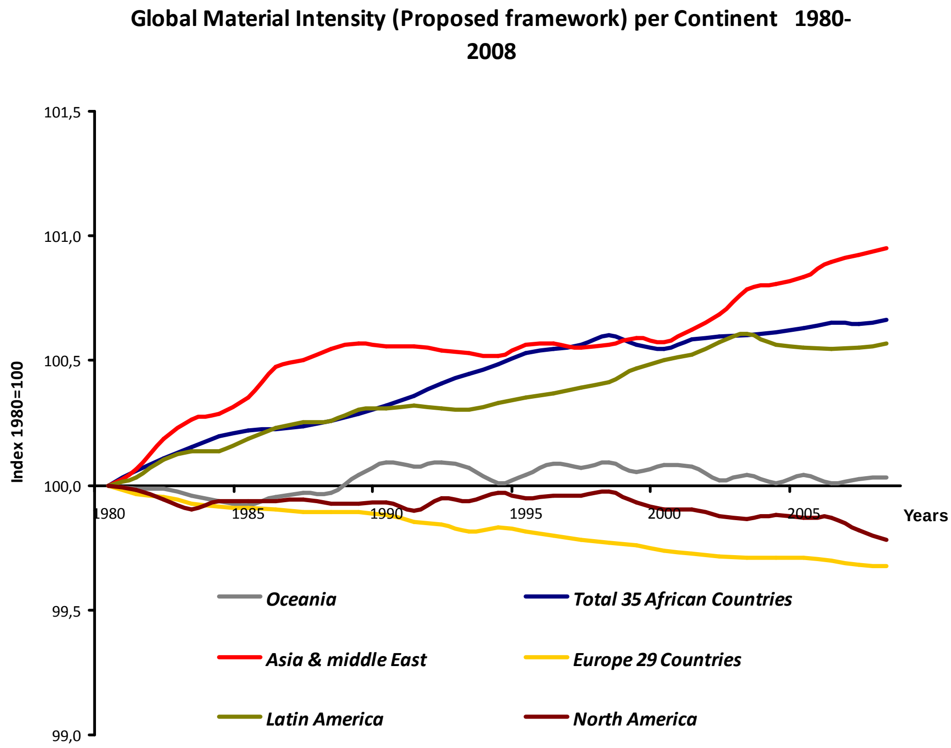
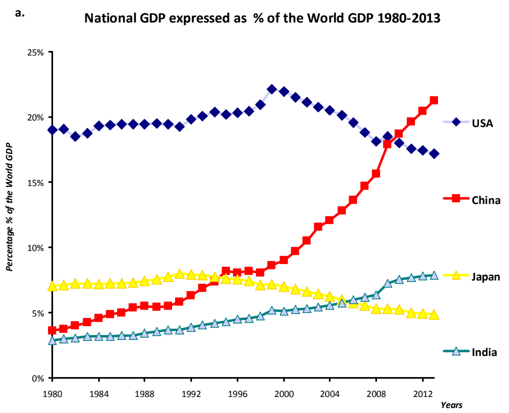
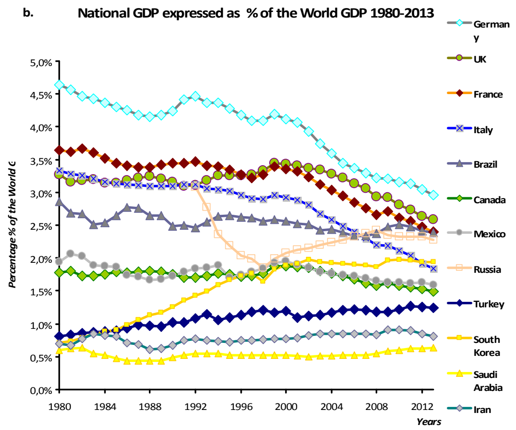


Figure A.2 *Comparing the continental MI of Fig. A.1, in common diagrams*

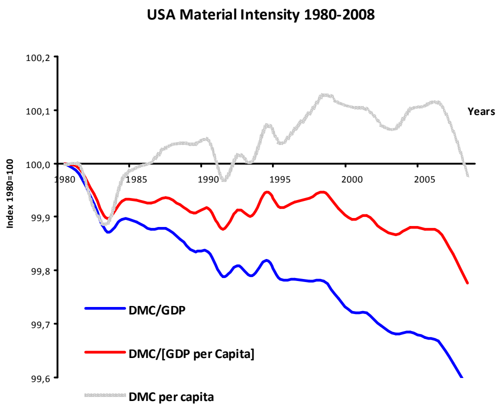
Appendix B. Investigating the proposed MI framework in 19 country case-studies for 1980-2009

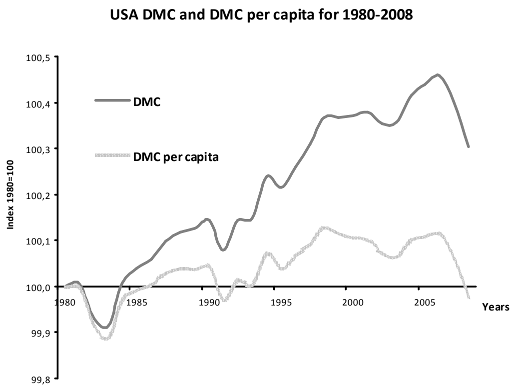
B.1 National GDPs expressed as % of the World GDP (expressed in PPP Geary-Khamis 1990 international US$)



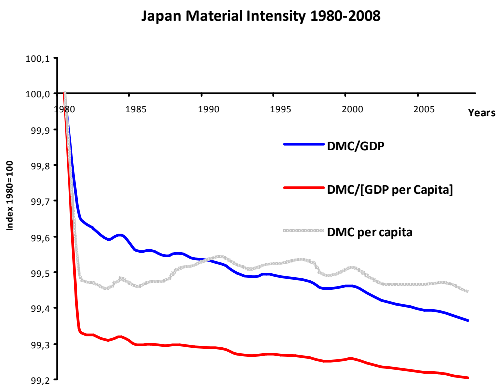


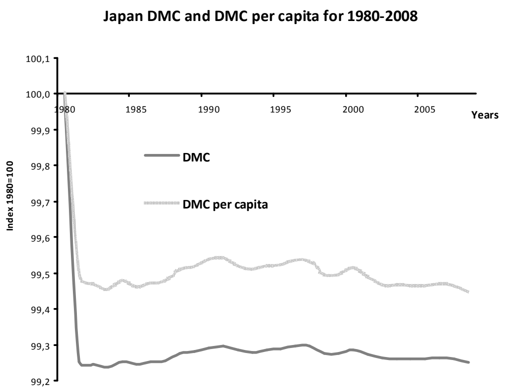
B.2 USA Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



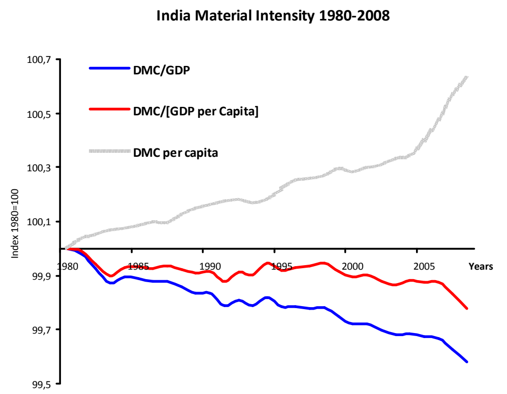


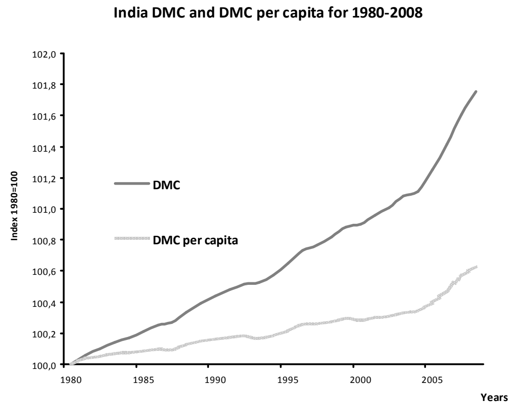
B.3 Japanese Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



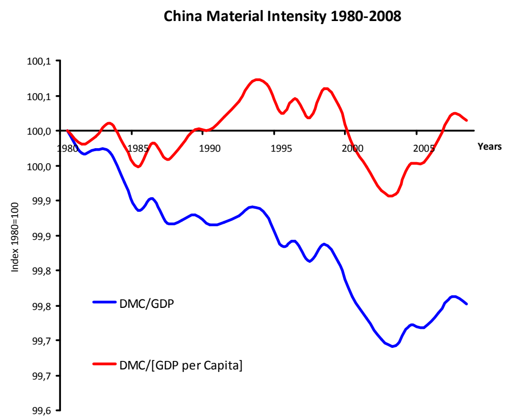


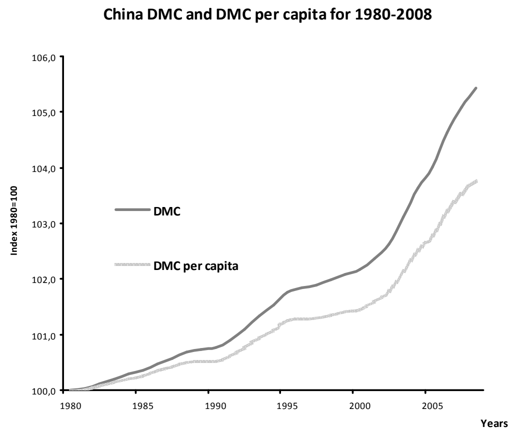
B.4 Indian Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



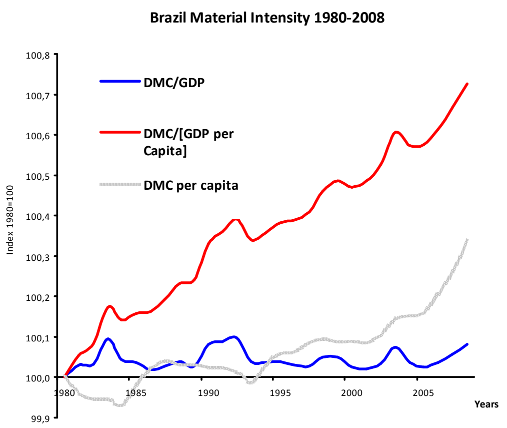


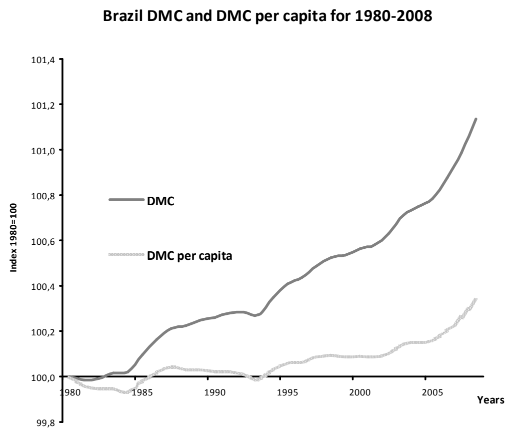
B.5 China's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



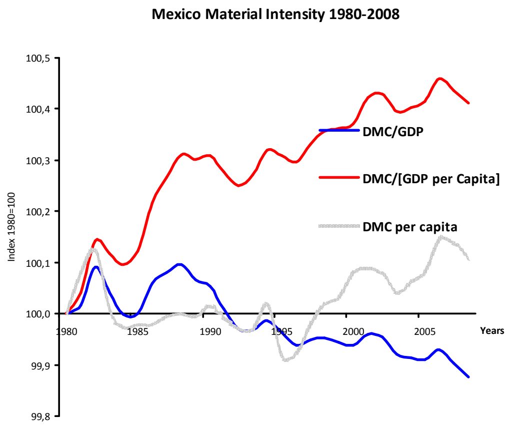


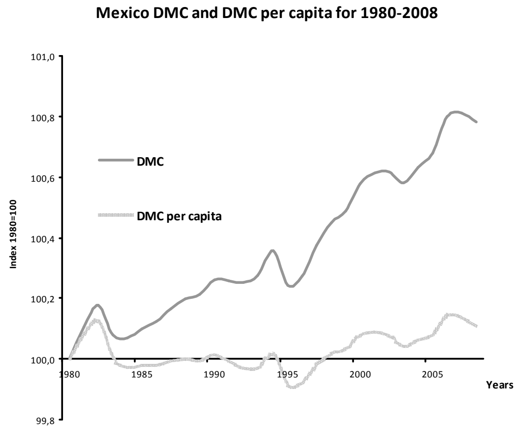
B.6 Brazil's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



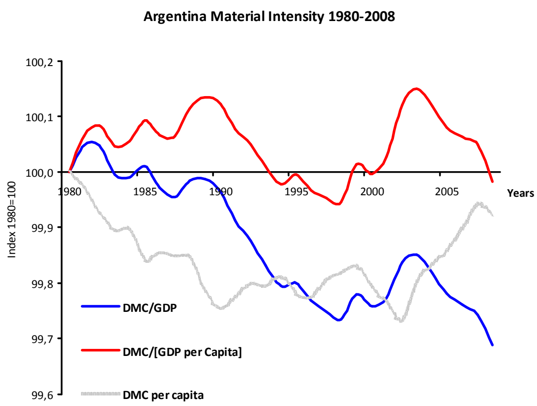


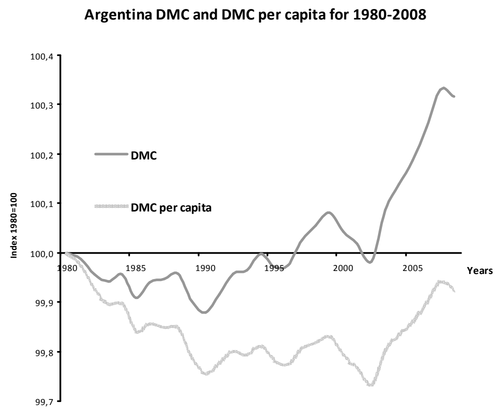
B.7 Mexico's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



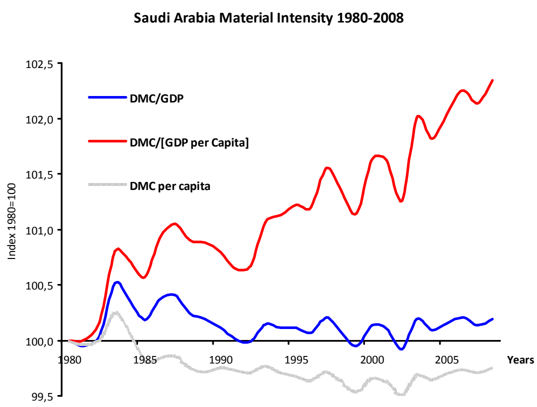


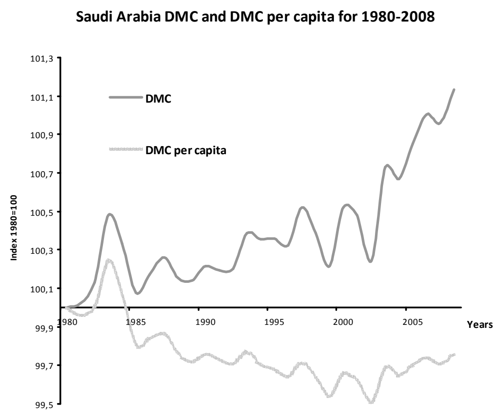
B.8 Argentina's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



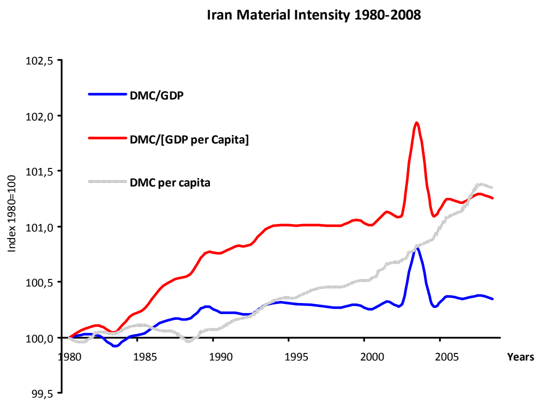


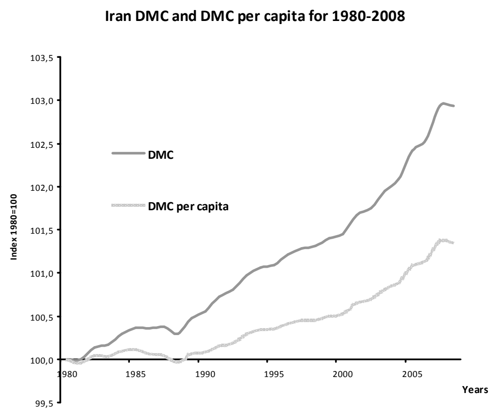
B.9 Saudi Arabia's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



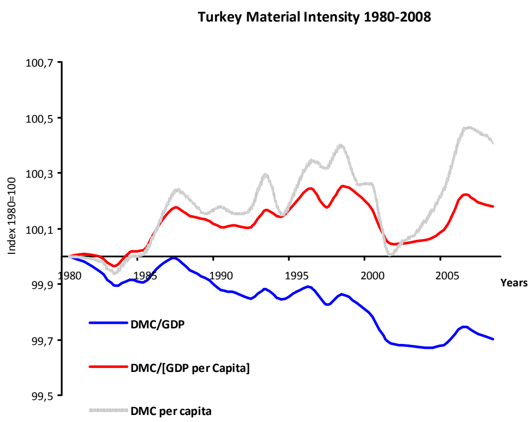


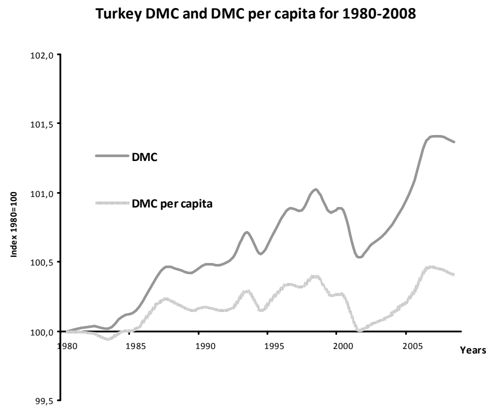
B.10 Iran's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



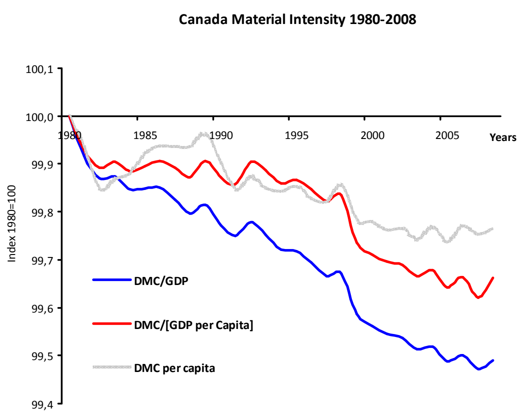


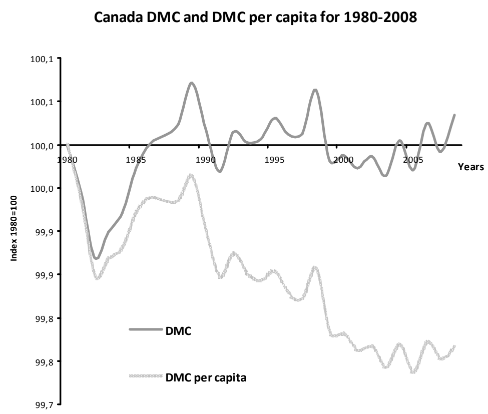
B.11 Turkey's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



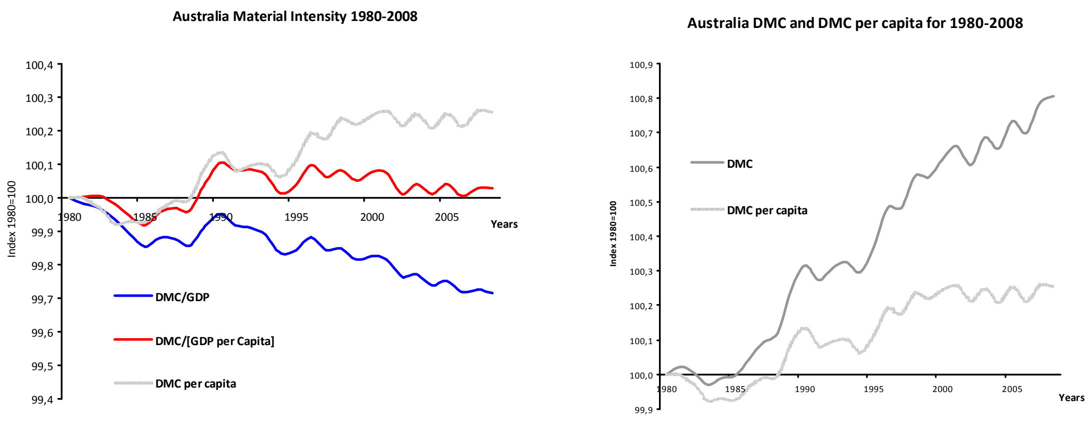


B.12 Canada's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)

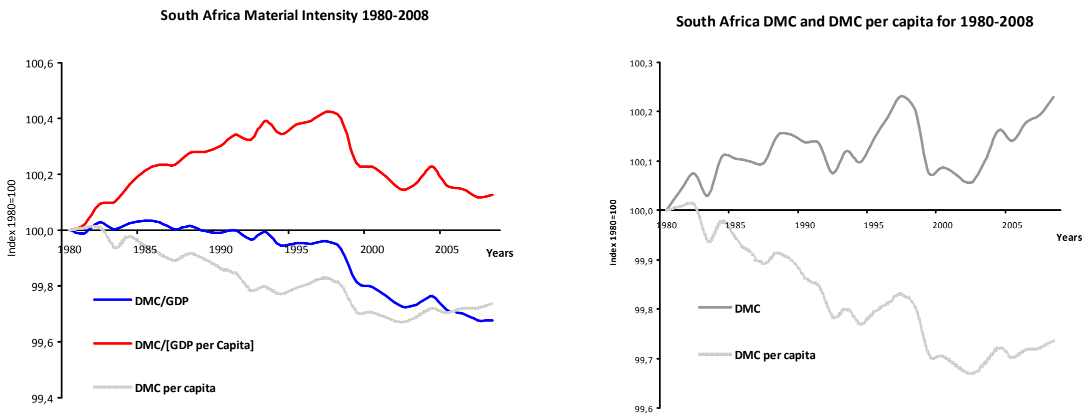




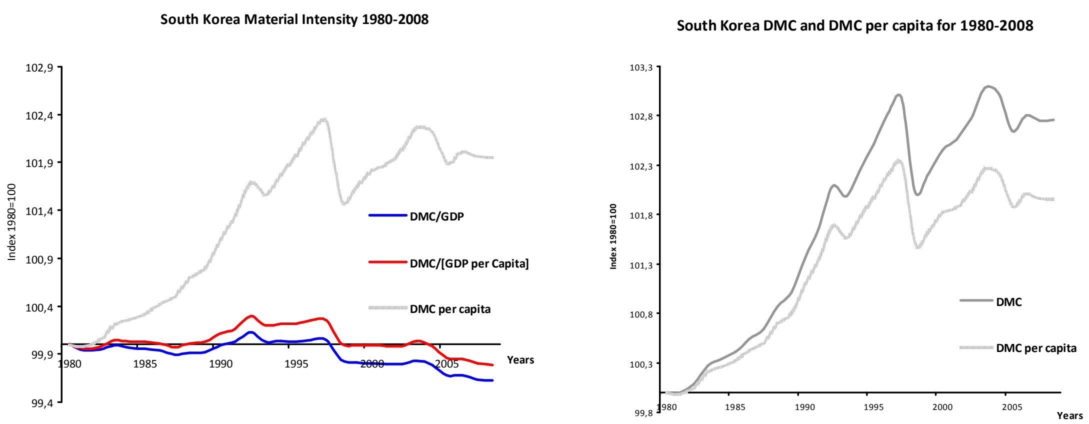
B.13 Australia's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



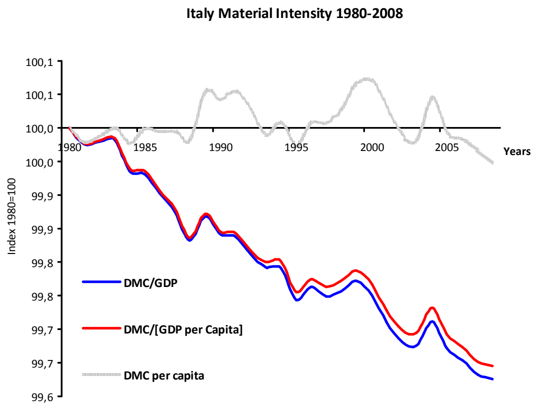
B.14 South Africa's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)

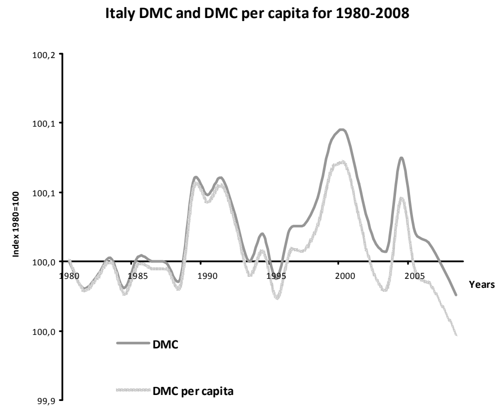


B.15 South Korea's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)

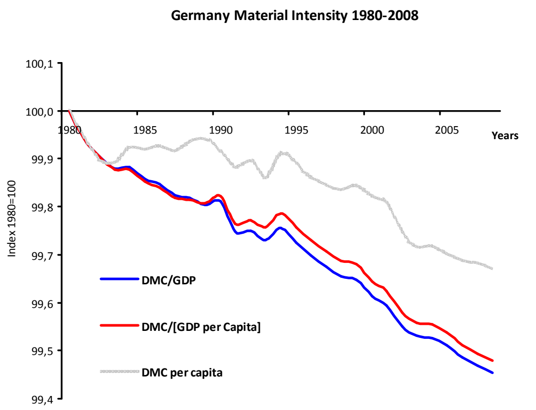


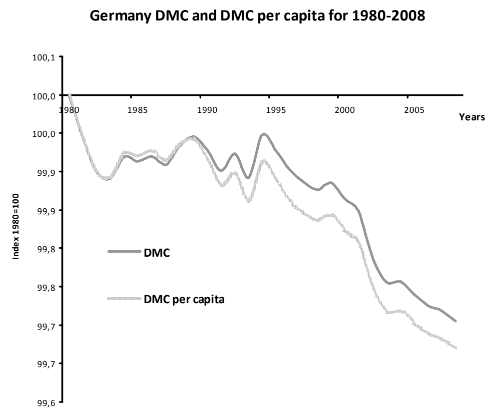
B.16 Italy's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



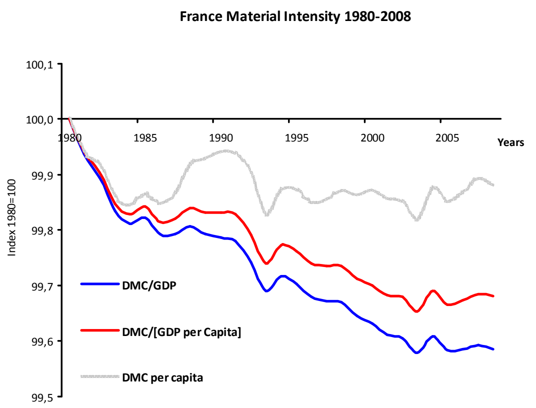


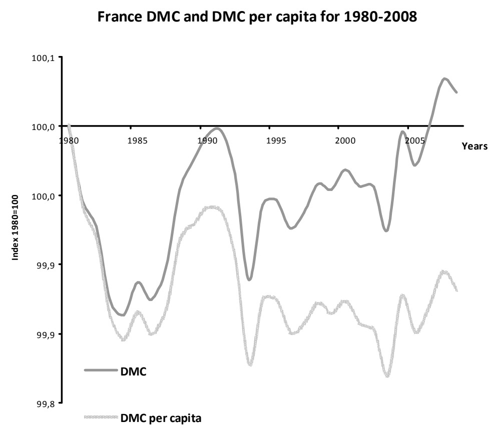
B.17 Germany's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



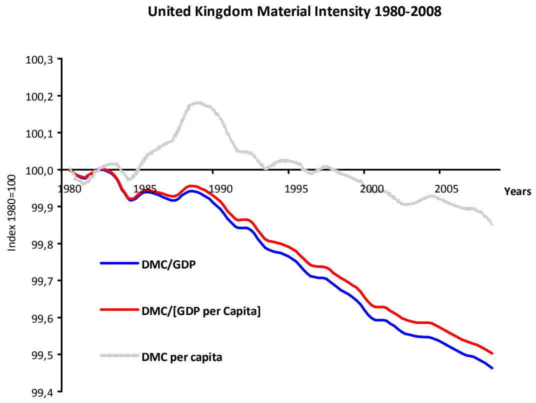


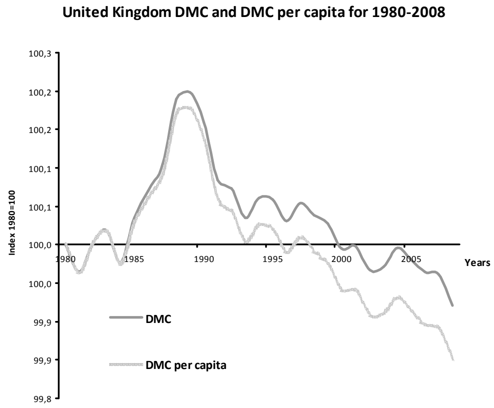
B.18 France's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)



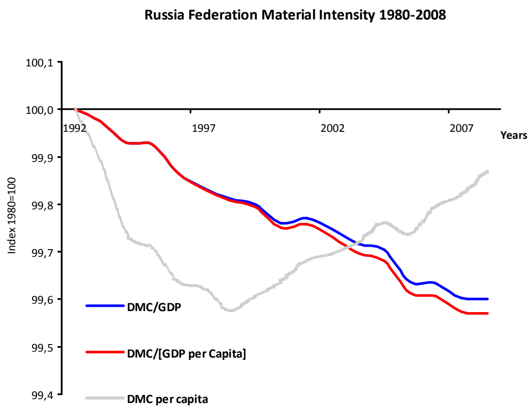


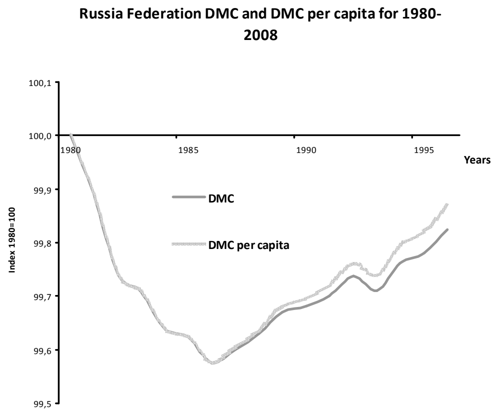
B.19 UK's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)





B.20 Russia's Material Intensity and total DMC and DMC per capita consumption, for 1980-2008 (all values indexed 1980=100)





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6TH CHAPTER

Integrated evaluation of the energy intensity of the economy

The case of energy resources

"There is good reason to doubt that past GDP growth per capita is entirely explained by capital accumulation or non-specific knowledge accumulation, as most growth theorists seem to believe […] it is obvious that neither labor nor capital can function without inputs of energy"

Robert Ayres , Van den Bergh, J. C., Lindenberger, D., and Warr, B. (2013-p. 80-81)

6.1 Introduction

The 6th Chapter estimates explicitly the Energy Intensity of various economic levels by using the standard EI methodology, based on aggregate GDP, and the proposed methodological framework of the 4th Chapter, based on economic welfare-utility (per capita GDP). The energy resources are evaluated separately from the mass (non-energy) resources (Chapter 5), since the energy carrier materials serve different purposes, as they provide the essential power for processing the mass inputs, during the production process. With the combined empirical estimates of Chapters 5 and 6, the present dissertation aspires to provide an integrated analysis of the energy-mass flows enter into the global economic system and to reveal obscured aspects of the resources-economy link. The 6th Chapter begins with a brief historical review of the energy use by humans, provides essential definitions concerning the energy types and energy measurement techniques, and ends up with the empirical estimates of energy intensity for the global economy and various representative economies.

6.2 A brief History of Energy use in human societies

Energy has been among the most fundamental elements of human survival, maintenance and evolution. Sun is the ultimate source of energy. Almost all organisms rely, directly or indirectly, on solar energy for their survival and maintenance. Life on earth would be impossible without the photosynthetic conversion of solar energy into plant biomass (*Smil, 1994*). The sun provides approximately 1366 watts per square meter per second ($W/m^2/sec$), hence, about 170.000 terawatts (TW/sec) on Earth (*Ruddiman, 2001*). Energy flow through most food chains begins with this captured and converted solar energy from plants, through the sophisticated process of photosynthesis. A part of this energy is used by organisms, during their endosomatic metabolism, at each level of the food chain, while a great proportion is lost as heat and a small portion is passed down the food chain as one organism digest another[1].

The mastery of fire and agriculture. The organic (agrarian) economy

[1] Energy Literacy. Essential principles and fundamental concepts for energy education. U.S. Department of Energy. Available on-line at: http://www1.eere.energy.gov/education/pdfs/energy_literacy_2.0_low_res.pdf (Accessed September 2014)

The very first milestone of mankind, concerning the utilization of energy, was the mastery of fire. The utilization of fire for cooking and heating using wood as fuel dates back at least 400.000-500.000 years (*Bowman et al. 2009*). Besides these obvious functions, fire created light, hence improved protection and safety in the human settlements and greatly extended the range of habitation (*Goudsblom, 1992*; *Fouquet, 2011*). The burning of wood and other forms of biomass eventually led to the discovery of ovens proved to be useful, besides cooking, for making pottery, and the refining of metals from ore[2]. Early humans lived mostly in a nomadic way following the change of seasons and the periodical plan growth. The next milestone of mankind was the Agricultural Revolution (*Heinberg, 2011*). The introduction of agriculture increased the amount of available food and consequently resulted in the first permanent human settlements, which caused a substantial increment of human population. Water and wind power were the next essential steps in the evolution of human conquest on energy resources utilization. The watermill was invented about 2.500 years ago. Together with the windmill[3], humans managed to master the water and air power serving their needs for crushing grain (wheat, etc) for flour production, bruise olives for olive oil production, tanning leather, smelting iron, sawing wood, and so on (*Reynolds, 1983*). However, despite the improvements in energy use and the exploitation of several energy resources, the rapid growth of population in Europe about a thousand years ago – as a result of this progress – led to dramatic pressures on land availability for cultivation, while forests were being encroached upon to provide more land (*Fouquet, 2011*).

This first era of mankind from the early fire discovery to the agricultural (and farming) revolution, and the quest for new energy resources can be briefly described as the **Organic Energy Economy** (*Fouquet, 2011*). This solar-based energy system was intimately based in intensive land use and biomass consumption. This pre-industrial socio-metabolic regime was dominated by the so-called "*somatic energy regime*", (*McNeill, 2000*) or, in terms of social ecology, an era where "*endosomatic metabolism*" and biomass consumption were the predominant elements of this "*agrarian metabolic regime"* (*Krausmann, 2011*). Evidently, an organic energy economy was limited to consume energy at the rate at which direct and

[2] Ibid.

[3] The wind wheel of the Greek engineer Heron of Alexandria in the first century AD is the earliest known instance of using a wind-driven wheel to power a machine (Source: Wikipedia available at: http://en.wikipedia.org/wiki/Windmill) Accessed October 2014.

indirect solar energy can be converted in to useful goods and services. Due to this, factors like land constraints and population growth imposed crucial restrictions to further economic growth and gradually forced towards a transition to a new energy regime; the era of fossil fuels (*Fouquet, 2011*).

The transition to Fossil Fuels economy

The remarkable turning point, the milestone that determined the transition from the organic economy to the fossil fuels economy, the invention that settled the era called "*The Industrial Revolution*", was the steam engine. The unique process that steam engine brought forward was the conversion of chemical energy (heat) into mechanical energy (motion) (*McNeill, 2000*). The biomass energy stocks accumulated in earth's crust for over hundreds of millions of years were now available to serve human needs, for the first time in mankind history in such an extensive manner; the dawn of fossil fuels' predomination was about to begin. While the early steam engine mainly used for pumping out the water from coal mines, soon became – thanks to the efficiency improvements made by James Watt, Scottish inventor and mechanical engineer- , a valuable tool which proliferated human muscle and animal power for extracting more coal, drove the manufacturing industry, moved ships and trains, and set the basis for today's complex and energy intensive human systems.

During the 18th century many industries had substituted wood-fuels with coal, while heating services made the transition from organic to fossil fuels by the beginning of the 19th century[4]. Specifically, during 1650-1740 the real prices of wood-fuel increased substantially, something which encouraged the progressive substitution of wood-fuel with coal (*Fouquet, 2009*). The timing of this substitution was very essential, given the fact that during the second half of the 17th century the cutting of forest trees had to be regulated, even restricted, in England and in Europe, in general (*Georgescu-Roegen, 1983*). In that context, *Wrigley (1988)* suggests that, by 1800, had the British economy been dependent on wood-fuel, a surface area equivalent to the whole Britain would be needed to be coppiced every year in order to supply the energy demand of the economy. On the other hand, wind and water power service provided only the one-tenth of the total power of British economy, in 1800 (*Fouquet, 2008*). By 1900, the steam engines provided the two-thirds of all power services; the expansion of the railway network provided more than 90% of the goods

[4] Three quarters of the energy requirements of British economy were used for heating services (households, buildings, industry). (*Fouquet, 2008*)

transportation on land, while steam ships were carrying about the 80% of all freight cargos at sea (*ibid*).

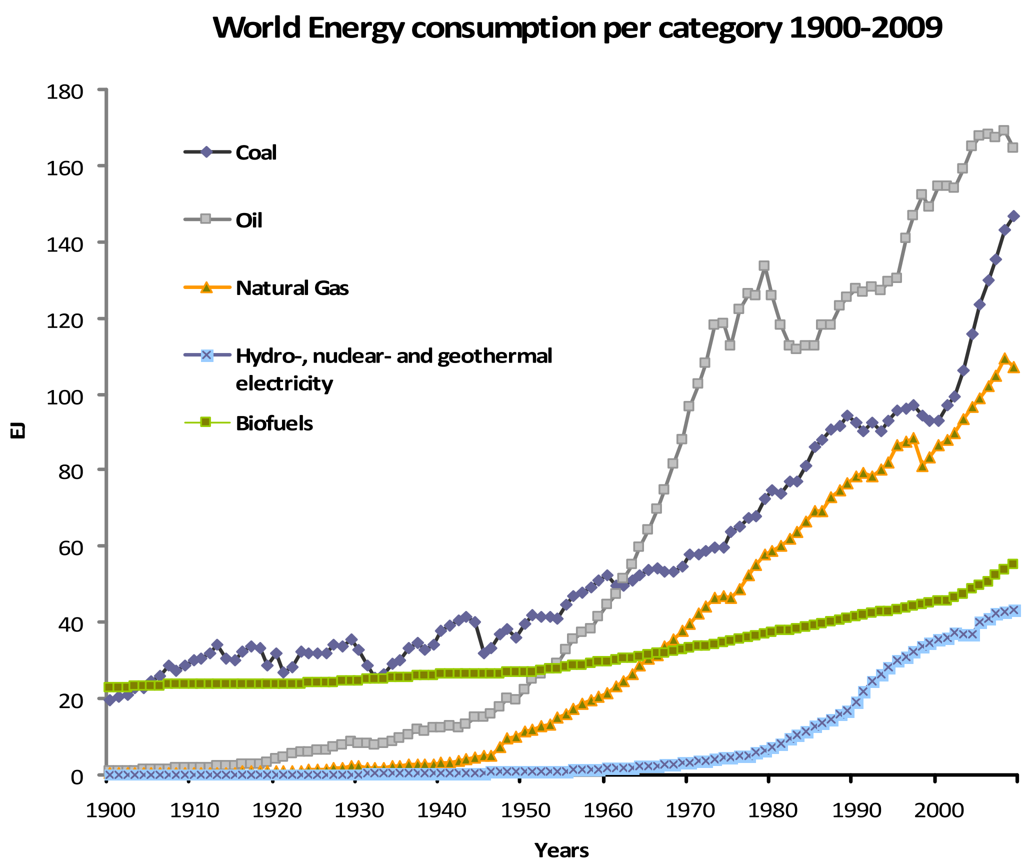


Figure 6.1 *The Global Energy Consumption, per energy type, for 1900-2009. (Data Source: Krausmann et al. 2009)*

However, the growing demand for coal in the 19th century raised concerns about the potential scarcity of coal and its consequences on the production process (*Jevons, 1865*). Nevertheless, the new technological improvements and production techniques managed to achieve constant coal supply, while simultaneously kept prices low (*Fouquet, 2009*). Furthermore, the introduction of new energy resources, such as petroleum and by-products, enhanced the energy mix. Another major invention that essentially promoted the use of refined oil was the internal combustion engine. While the process of refining crude oil discovered by James Young, in the 1850s, and Edwin Drake managed to successfully drill oil through deep rock, in 1859, the oil age actually initiated with the invention and development of internal combustion engines in Germany, after 1880 (*McNeill, 2000*). Nevertheless, the peak of oil production occurred in the US in late 1960's, and the increased concerns about security in constant energy supply caused by the oil shocks of 1973 and 1979, led in the rapid increase of natural gas use. Evidently, after 1970s the natural gas consumption increases dramatically (Fig. 6.1). The Figure 6.1 clearly depicts the predomination of fossil fuels in global energy consumption trends. Specifically, coal consumption overcomes biomass consumption from the very first years of the 20th century, while oil consumption takes the lion's share from coal, in the early 1960s. Natural gas consumption increases dramatically after the WWII, while hydroelectricity, nuclear and geothermal electricity constantly increases from the early 1970s. Finally, the bio-fuel consumption, remarkably though, steadily increases throughout 1900-2000, with a further acceleration of increment trends occurring in early 2000s (Fig.6.1).

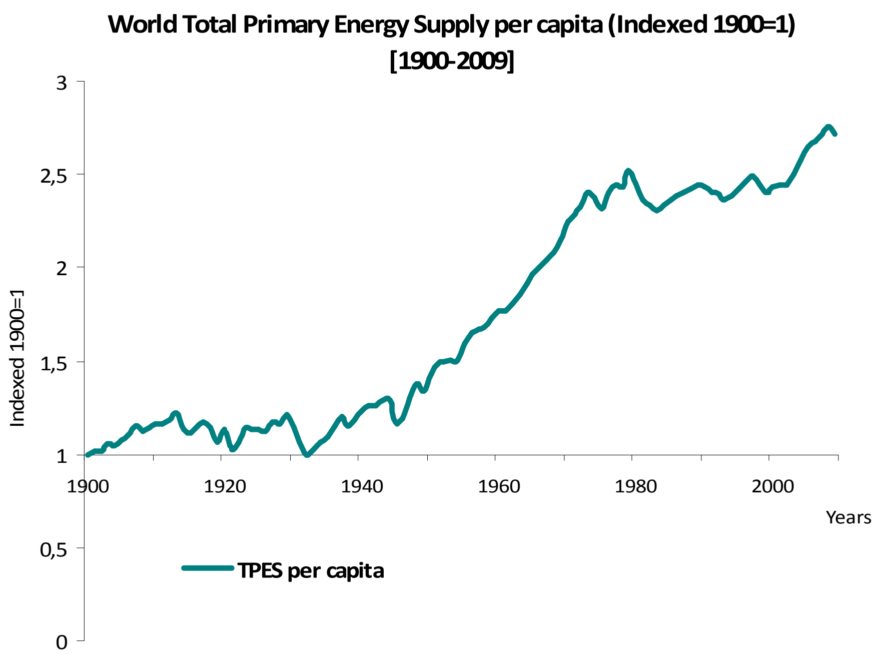


Figure 6.2 *The World per capita Primary Energy Consumption, for 1900-2009. (Indexed 1900=1)*

Figure 6.2 displays the social/industrial metabolism of the world primary energy consumption, for 1900-2009. Clearly, the trajectory of the per capita primary energy consumption ratio results in an extraordinary and unparalleled per capita energy use increase after the WWII. Evidently, this trend gives signs of stabilization during 1980-2000; however, during 2000-2009, a further acceleration is occurring again.

The Industrial Revolution ended the "*(endo) somatic energy regime*" (*or Agrarian regime according Table 5.1*), gradually replacing it with a far more complex energy era that could be named as the "*exosomatic energy regime*" (*McNeill, 2000*) (or Industrial Regime), which is characterized by the extensive use of mineral resources. Table 6.1 briefly illustrates the remarkable evolution of the per capita energy and material consumption, the population density and other variables that indicate the extraordinary industrial metabolism magnitude, compared to the pre-industrial energy regimes of mankind. Evidently, the per capita energy-material consumption of the Industrial regime appears to be 3-5 times greater than the respective one in the agrarian regime. Accordingly, the population density is ten times greater, while the energy-material use density has increased about 30 times (Table 6.1).

Table 6.1 *Historical metabolic profile of socio-metabolic regimes. (All data derived from Krausmann, 2011, -p. 87, available at: http://www.uni-klu.ac.at/socec/downloads/WP131FK_webversion.pdf*

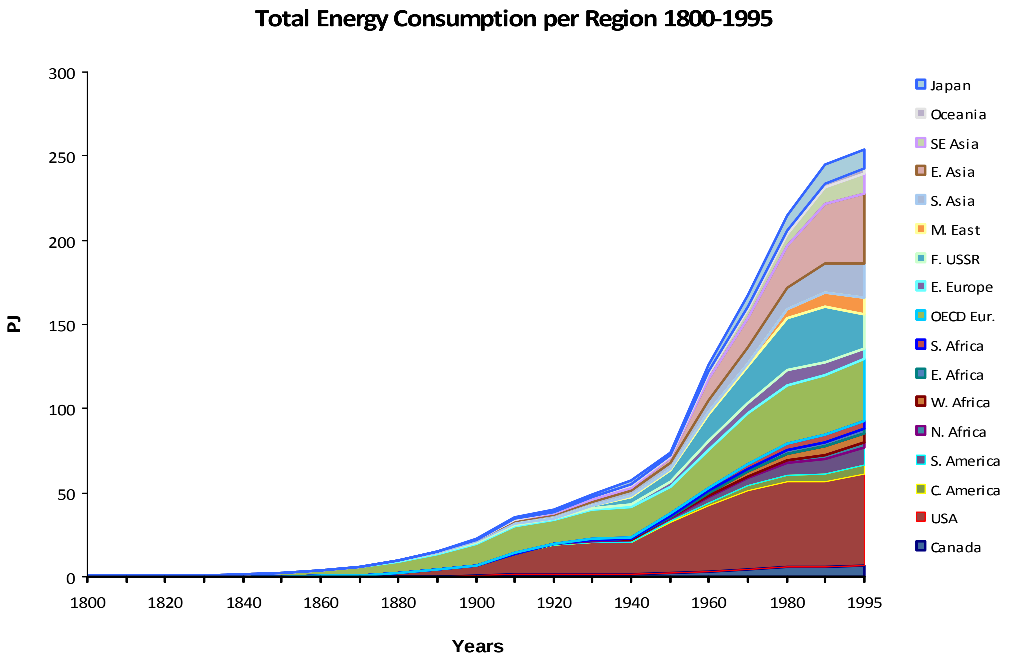
	Measuring unit	Hunters and gatherers	Agrarian regime	Industrial regime	Factor[5] industrial to agrarian
Energy use (DEC*) per capita	GJ/cap/yr	10-20	40-70	150-400	3-5
Material use (DMC±) per capita	t/cap/yr	0.5-1	3-6	15-25	3-5
Population density	cap/km^2	< 0,1	< 40	< 400	3-10
Energy use density (DEC per area)	GJ/ha/yr	<0.01	<30	<600	10-30
Material use density (DMC per area)	t/ha/yr	<0.001	< 2	< 50	10-30
Biomass share of DEC	%	> 99	> 95	10-30	0.1-0.3
Share of the non-energy use of materials	%	< 5	< 20	> 50	3-10

* DEC= Domestic Energy Consumption

± DMC = Domestic Material Consumption

Finally, Figure 6.3 depicts the world energy consumption per region, for 1800-1995, and the world fossil fuels production per region, for 1800-1990 (HYDE database):

[5] The column Factor approximates how many times the agrarian regime has multiplied during the industrial regime.



Source of Data: Etemad et al. (1991), EIA (1998). Derived from HYDE database, version 3.0

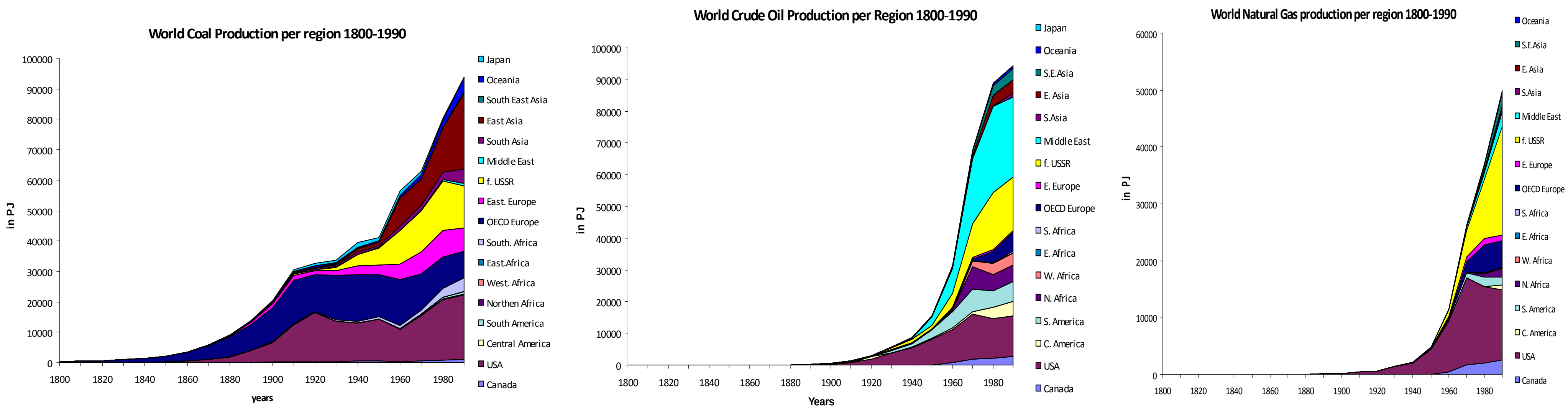


Figure 6.3 *a). World Energy Consumption per region, for 1800-1995; World Fossil fuels production per region for 1800-1990: b). World Coal production per region; c). World Crude Oil production per region; d). World Natural Gas Production per region. All energy measured in PJ (Data source: HYDE Database).*

6.3 Defining the Energy resources

Energy resources

Since energy resources is a subcategory of a broader category (natural resources), this section attempts a representation of energy resources as specific part of natural resources. A more detailed analysis can be found at the 4th chapter. Energy resources can be initially classified in two broad categories: first, according to their organic or non-organic origin can be classified in biotic and abiotic resources:

- **Biotic energy resources**. In the context of current category, fossil fuels, such as oil and coal[6], are classified as biotic natural resources due to the fact that they were derived from organic matter[7].
- **A-biotic energy resources**. The potential origin of a-biotic resources from biotic natural resources (i.e. the biotic origin of soil or the potential biotic origin of some ores and minerals in the extremely long-run period, etc.) remains out of the scopes of this introductory essay.

Secondly, energy resources can be distinguished according their rate of replenishment. In that sense, energy resources can be classified into renewable and non-renewable ones:

▪ **Renewable energy resources**. In the context of energy production, we define as renewable energy this amount of produced energy that derives from the utilization of renewable sources of energy, such as solar, geothermal, wind, tidal, water (gravital) energy, biofuels derived from biomass, and wood fuel. Figure 6.4 briefly depicts the world installed capacity of renewable energy sources for: a) geothermal energy; b) solar energy; and c) wind energy capacity.

[6] Coal and its other forms (charcoal, lignite, etc) are believed to have formed from prehistoric land plants and trees, while the most prevailing theory on petroleum's origin is that of the plankton. Source: Edx On-line course: Energy 101- Energy 101: Energy Technology and Policy. University of Austin, Texas, by Dr. Webber)

[7] Natural gas is not considered as biotic natural resources. Nevertheless there are forms of "biotic" gas, such as the bio-gas produced from organic matter (manure, biomass).

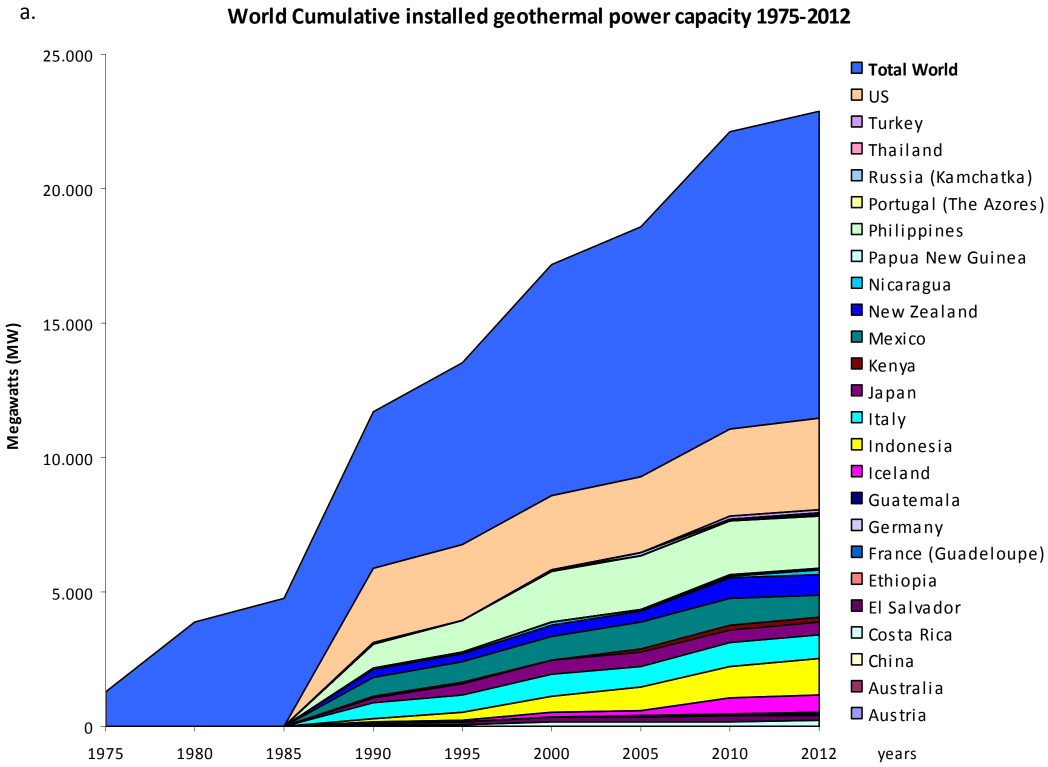
Renewable energy resources can be further sub-divided into two additional categories (*Bithas, 2012-p.231*):

- *Plentiful (non-exhaustible) renewable energy resources*. To mention some indicative examples, as non-exhaustible renewable energy resources are considered the sunlight (solar energy), the wind, geothermal, and tidal energy.

- *Limited (exhaustible) renewable energy resources*. This sub-category includes for example wood-fuel and other energy carrier types of biomass.

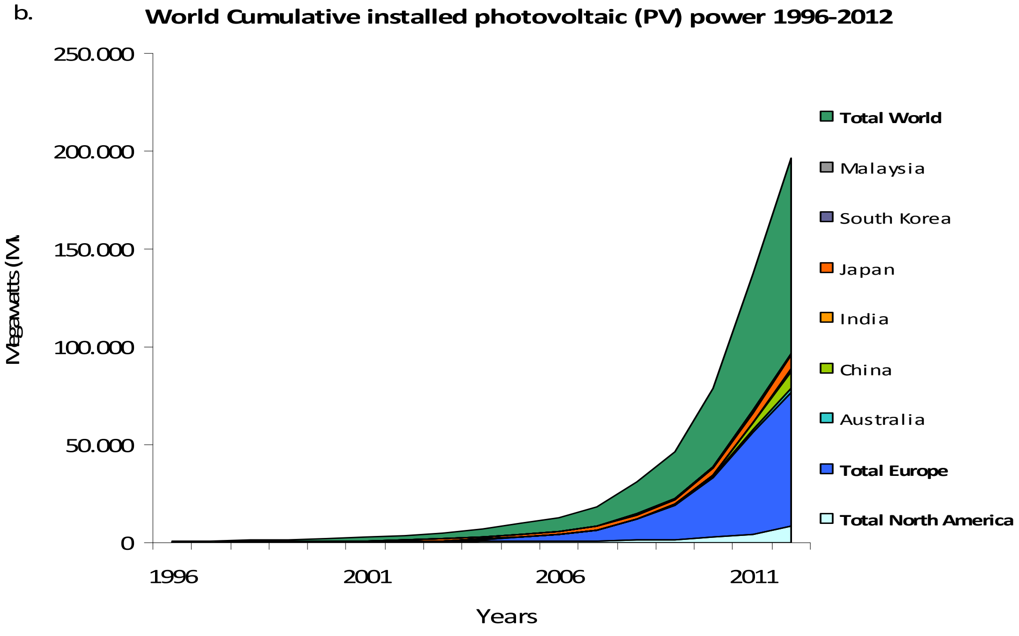
- **Non-renewable energy resources**. Fossils fuels are formed over very long geologic periods. Since their rate of formation is very slow[8], they cannot be replenished once they get depleted. Examples of non-renewable energy resources are crude oil, coal, and natural gas.

a.



[8] In an extremely long-run geological period, fossil fuels and minerals could be assumed to be renewable resources as well. However, this distinction into renewable and non-renewable resources remains essential, according to the average human life span as a reference point.

b.



c.

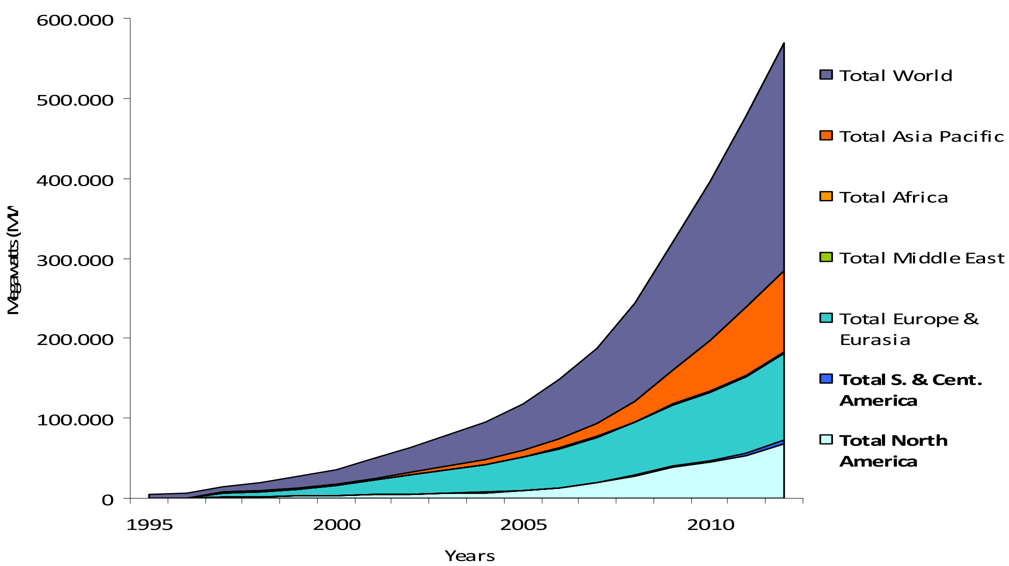


Figure 6.4 *a). World installed geothermal power capacity, for 1975-2012; b). World installed solar (pv) power capacity, for 1996-2012; c). World installed wind turbine capacity, for 1995-2012. (Data source: BP Statistical Review of World Energy, June 2013).*

6.3.1 What is Energy?

From a historical point of view, the word "*energy*" is derived from the Greek word "*energeia*", by combining two root forms meaning "*at*" and "*work*" (ενέργεια=εν+έργο), a metaphysical concept employed by Aristotle in the sense of "*action towards a goal*" (*Cleveland and Morris, 2009-p.166*).

Seeing from the viewpoint of physics, energy is a fundamental physical concept that can be described as the potential ability of a system to influence changes in other systems by (*Cleveland and Morris, 2009*):

- work (forced directional displacement)
- heat (chaotic displacement/motion of system microstructure)

In the context of derived work, before the Industrial Revolution there where mainly four sources of mechanical work, of any economic significance (*Ayres and Warr, 2009 –p.90*):

- Human labor (muscle work)
- Animal labor (muscle work)
- Water power (water mills)
- Wind power (wind mills)

Today, mechanical work is provided mainly by prime movers[9] which are mainly classified in two broad categories (*ibid*): hydraulic and steam turbines; and internal combustion engines (spark ignition gasoline engines; compression ignition diesel engines; and gas turbines)

This capacity to do work (either heat or mechanical work) is used to perform useful functions in modern human systems, such as heating and cooling, mechanical motion and transportation, machinery, lighting, food production, infrastructure building, and so on. The following section aspires to cast light into the different available forms of energy and to classify them in distinct categories

[9] An engine or a device by which a natural resource of energy (an energy vector) is converted into mechanical power (*Cleveland and Morris, 2009-p.403*).

6.3.2 Forms of energy

Energy exists in many different forms, which could be briefly represented by six broad categories, in the context of physical science and mechanical sense (*Cleveland and Morris, 2009)*:

- *Mechanical (Gravitational potential and Kinetic)*. In physics, mechanical energy is the sum of kinetic energy and potential energy of an object; hence, it can be broadly classified into potential energy and kinetic. As potential mechanical energy is consider the gravitational energy embedded in water falling from a higher to a lower point (e.g. hydroelectricity production from a dam), while there are other forms such as electrostatic and magnetic fields. Mechanical energy can be converted into kinetic (the work required to accelerate an object to a given speed), for example, through the internal combustion engine.

- ***Thermal (and Geothermal energy measured in Enthalpy)***. Thermal energy is the kinetic energy associated with the motion of atoms and molecules in a substance (heat). Besides the obvious space heating and cooking, thermal energy is broadly used for producing electricity.

- *Electrical (and electromagnetic).* Electricity is a fundamental form of energy in today's complex human systems. It is consisted of oppositely charged electrons and protons. Electrical energy produces many other energy forms, such as heat, light, kinetic, magnetic, as well as chemical changes.

- *Radiant.* Radiation is energy in the form of electromagnetic waves. Solar energy is a representative example of radiant energy form.

- *Chemical*. The energy produced or absorbed during the process of a chemical reaction. Some typical examples of chemical energy production is the food digestion by living organisms which provide them with the appropriate for their survival energy, the fire, the Batteries which is stored chemical energy that provides electricity, the fuel-cells, and so on.

- *Atomic (nuclear)* Energy released by radioactive decay, through a nuclear reaction or in the course of fission (splitting) or fusion (fusing) of atomic nuclei. Nuclear energy is used mainly for electricity production, while it can produce electromagnetic and kinetic energy, as well.

6.3.3 Primary and secondary energy forms

An important classification of energy is the distinction between primary and secondary energy forms. Specifically:

- *Primary Energy forms*

According A. Kydes of the U.S. Energy Information Administration (EIA) (*Cleveland and Morris, 2009-p.402*), primary energy is the energy embodied in natural resources prior to undergoing any human-made conversions or transformations. In other words, this category includes all these forms of energy found in nature that have not been the result of any previous conversion or transformation process. As it was previously presented, from a thermodynamic perspective, primary energy resources cannot be produced. In that context, fossil fuels (crude oil, coal, natural gas) are considered as primary energy sources. Further, solar and wind energy, natural uranium, gravitational energy of water, biomass and geothermal energy are considered as primary energy sources, too[10].

- *Secondary Energy forms*

With the notion "*secondary energy forms*" we define all the conversions and transformations of the primary energy sources into useful forms of energy that can be directly used in human societies. In that context, electrical energy is among the most crucial secondary forms of energy. Moreover, the fuel refining (e.g. gasoline from crude oil), or synthetic fuels (hydrogen fuel) and any transformation of fossil fuels in electricity, kinetic, or thermal energy, are explicitly considered as secondary energy conversion.

Table 6.2 presents the matrix of the potential conservations can be performed among different energy forms. The horizontal categories present the initial energy form, while the vertical columns present the potential conservations among the different energy forms (*Smil, 1994*).

[10] Source: http://en.wikipedia.org/wiki/Primary_energy and lecture notes from the on-line course: Edx Energy 101- Energy 101: Energy Technology and Policy. University of Austin, Texas, by Dr. Webber. Accessed June 2014.

From / To	*Electro-magnetic*	*Chemical*	*Nuclear*	*Thermal*	*Kinetic*	*Electrical*
Electro-magnetic	-	Chemilumines Cense	Nuclear bombs	Thermal Radiation	Accelerating charges	Electromagnetic Radiation
Chemical	Photosynthesis	Chemical Processing	-	Boiling	Dissociation by Radiolysis	Electrolysis
Nuclear	Gamma-Neutron reactions	-	-	-	-	-
Thermal	Solar absorption	Combustion	Fission/Fusion	Heat exchange	Friction	Resistence heating
Kinetic	Radiometers	Metabolism	Radioactivity/ nuclear bombs	Thermal Expantion/Internal Combustion	Gears	Electric motor
Electrical	Solar Cells	Fuel cells/ Batteries	Nuclear Batteries	Thermo-electricity	Electricity Generators	-

Table 6.2 *Matrix of energy conversions. Where two or more possibilities exist only one or two leading transformations are identified. (Source: Smil, 1994 – p. 3)*

6.3.4 Available and non- available Energy. An alternative approach

Besides the mainstream energy forms analyzed in previous sections, there is a third distinction of energy forms which essentially derived from a special branch of physics: thermodynamics. Thermodynamics actually own their introduction in physics on the seminal research of Sadi Carnot in 1824, on the efficiency of the steam engine. The elementary fact lies behind the creation of thermodynamics is that heat always moves from hotter to colder bodies. Since the laws of mechanics could not account for such a unidirectional movement, a non-mechanical explanation was essential in order to describe properly this natural phenomenon; the laws of thermodynamics were about to born. In 1865, R. Clausius briefly described the classical formulation of the first two laws of thermodynamics (*Georgescu-Roegen, 1971-p. 129*):

- *The energy of the Universe remains constant*

- *The entropy of the universe tends to a maximum*

The second law of Thermodynamics is alternatively called the "*entropy*[11] *law*". The complex concept of entropy can be briefly summarized as the movement from order (low entropy) to

[11] Derived from a Greek word that describes the evolution of a process

disorder (high entropy). In other words, high entropy notion describes a structure in which most or all energy is bound, and low entropy describes a structure which the opposite holds true (*Georgescu-Roegen, 1971-p.5*).

In a nutshell, in the context of classical thermodynamics, energy consists of two qualities (*Georgescu-Roegen, 1971-p.129; 1986-p.3)*: **free (or available)** and **bound (or unavailable)** energy[12]. Evidently, available (or free) energy, like heat, is always dissipated by itself into unavailable (or bound) energy forms. The universe, therefore, performs a continuous qualitative change of energy degradation, the final outcome of which is a state where all energy becomes unavailable, called the "*Heat Death*". The entropy law is briefly defined by the formula:

$$Entropy = (Unavailable\ Energy)/(Absolute\ Temperature) \qquad (1)$$

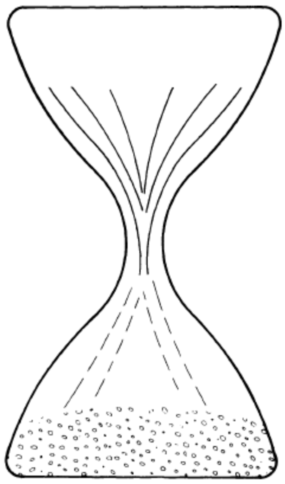


Figure 6.5 *The hourglass of the Universe (Source: Georgescu-Roegen, 1977-p.267)*

One simple example that better illustrates the entropy law and the notions of available and unavailable energy is the Figure 5.5. The hourglass (*Georgescu-Roegen, 1977*) of Fig 6.5 represents an isolated system (i.e. the whole universe), where the amount of energy remains constant at all times (first law of thermodynamics), while the hourglass of the

[12] G-R recognizes that this distinction of energy is certainly anthropomorphic, since energy is available or unavailable according to whether or not the humans can use it for their own purposes (Georgescu-Roegen, 1986)

universe, irrevocably, can never be turned upside down (second law of thermodynamics). The main assumption of this isolated system is that, irrevocably, the entropy always increases into a maximum (the bottom of the hourglass). This conclusion is of paramount importance concerning the energy analysis that follows and should always be accounted for, whenever energy and economy are interrelated, as it defines crucial limitations and obstacles that human technology ought to deal with, in the futile "*hunting*" towards more efficient energy utilization.

6.4 Energy measurement and aggregation

Aggregation of economic data has received substantial attention from economists for a number of reasons. Aggregating the vast number of inputs and outputs in an economy makes it easier for analysts to see patterns in the data and conceive valuable conclusions (*Cleveland et al., 2*000). An important issue, which rises from the need to "*homogenize*" the different and "*heterogeneous*" fuel types and energy categories, is the method of energy measurement. The appropriate selection of a measuring unit is of crucial importance for the conversion of different energy types into a comparable unit which could allow the aggregation of various energy resources. This section aspires to give a brief representation of the most common measuring units and methods utilized for energy aggregation by the vast majority of international official reports and research studies on energy use. In the present chapter, energy is mainly measured and aggregated in Exajoule (EJ) and Petajoule (PJ), or in million tons of oil equivalents (Mtoe). In addition, concerning electricity consumption, the measuring unit that has been used is Megawatts/hour (MWh).

Measuring thermal equivalents

The simplest form of energy aggregation and the most common among relevant studies is to add up the individual variables according to their thermal equivalents (*Cleveland et al., 2000*). We distinct the most commonly used methods of thermal equivalent energy aggregation:

British Thermal Unit (Btu)

British thermal unit is a widely used unit of measure generically defined as the average amount of energy required to produce a change in temperature of 1°F in one pound of pure liquid water, and is equivalent to about 1055 joules or 252 calories (*Cleveland and Morris, 2009 – p. 62-63*).

Tons of Oil equivalents (Toe)

Tons (or million tons in many cases) of oil equivalents is a measure of energy used to relate different fuels to the equivalent oil requirement, based on an energy value for oil of 42 Mega-Joule (MJ)/kg (*Cleveland and Morris, 2009 – p. 522*). It is actually the amount of energy released by burning one ton of crude oil, approximately[13] 42 Giga-Joule (GJ).

Joule (J)

Joule is the basic unit of energy in the meter-kilogram-second system and is translated as the amount of work done by a force of one Newton acting through a distance of one meter in the direction of the force (*Cleveland and Morris, 2009 – p. 279*). In current chapter, we use the measuring units of Peta-joule (PJ) and Exa-joule (EJ), where "*peta-*" has a prefix meaning for "*one quadrillion*" (10^{-15}), and "*exa-"* has a prefix meaning for "*one quintrillion*" (10^{18}), respectively.

Watt-hour

This is an exception to this category, since watt is not account for the thermal equivalents of an energy vector, but it is used occasionally as an energy aggregation unit. Watt per hour (Wh) is the unit of energy which is equal to the work done by one watt over a time of one hour. The energy unit used for everyday electricity, is the kilowatt per hour (kWh), and one kWh is equivalent to 3.6×106 J (3600 kJ or 3.6 MJ). Electricity usage is often given in units of kilowatt-hours per year (kWh/yr). This is actually a measurement of average power consumption, i.e., the average rate at which energy is transferred.

Alternative qualitative adjusted aggregations of energy vectors

According to Cleveland et al. (2004), despite its widespread use, aggregating different energy types by their heat units embodies a serious flaw: it ignores qualitative differences among energy vectors. In that sense, there is a different potential useful work per unit of heat content between different energy vectors. The seminal study of Schurr and Netschert (1960) delineates the importance that differences in energy quality between energy vectors have for the economic production. There are both economic and biophysical approaches to measuring energy quality (*Stern, 2010*). In that context, this section presents the most representative qualitative energy aggregating methods. The first paragraph reviews the

[13] As different crude oils have different calorific values, the exact value of the toe is defined by convention, and for most cases is an approximation.

most representative, among others, economic approach, while the second and the third paragraph review the biophysical approaches of energy quality measuring: the leading approach of *exergy* and the concept of *emergy*, respectively.

The pure price-based aggregation

According to the Dictionary of Energy (*Cleveland and Morris, 2009*): "*Divisia index is a method of aggregation that permits variable substitution among material types without imposing any prior restrictions on the degree of substitution*". A Divisia index is, thus, a theoretical construction of creating indexed number series for continuous-time data on prices and quantities (usually expressed in Btu). The resulting index number series is designed to incorporate quantity (in btu) and price changes over time from subcomponents which are measured in different units. There exist different methods and approaches of the Divisia index estimation such as: log mean Divisia index aggregation method; and discrete Divisia index aggregation method (*Cleveland et al., 2000*).

Nevertheless, aggregation of energy sources by using their relative prices has many shortcomings. To mention indicatively just the most important ones, the assumptions made about the equality of elasticity of substitution between energy resources, within Divisia index theoretical background, are pretty much unrealistic. A more detailed empirical contribution on that issue has been made in a recent study (*Stern, 2010*). Further, it is broadly accepted that energy prices do not accurately reflect the actual social and environmental cost lies beneath their market price (*Bithas, 2011*).

The concept of Exergy

Exergy is defined as the maximum amount of useful work (ordered motion, in terms of physics) that a system can perform as it approaches thermodynamic equilibrium with its surroundings by a sequence of a reversible process. It has been proposed by Zoran Rant in 1953 and is derived from the Greek words "εξ-" (external) and "έργο" (work) (*Cleveland and Morris, 2009 –p.181*). More detailed, exergy measures the useful work obtainable from an energy source or material, and is based on the chemical energy embodied in the material or energy, based on its physical organization relative to a reference state. Thus, exergy measures the degree to which a material is organized relative to a random assemblage of material found at an average concentration in the crust, ocean or atmosphere; the higher the degree of concentration the higher the exergy content. The physical units for exergy are the same as for energy or heat (*Cleveland et al., 2000*).

The concept of exergy, as a qualitative measurement of energy vectors, has been introduced in economic science by Robert Ayres and colleagues (*Ayres et al., 1996; Ayres et al., 2003; Ayres and Warr, 2009*). The real innovative conception of this seminal work lies on the notion of "*useful work*". Ayres assumes that since exergy is the maximum work that can be obtained by a given energy source, then the estimation of the actual derived work gives the amount of the efficient use of this given source of energy. In other words, the ratio of actual useful work (actual output) obtainable by an energy source, to the maximum work (exergy) input, results for any given process to the efficiency by which this energy source is utilized. In order to generalize his concept to the economy as a whole, Ayres identifies the different types of useful work performed in the economic system and allocates the exergy resources inputs to each type of work. Five forms of useful work are being considered:

- Electricity (can perform either mechanical or chemical work in high efficiency)
- Heat
- Light
- Mechanical driving
- Muscle work (Animal & Human)

As we can conclude from the Figure 6.6 below, the two steps from natural resources exergy to useful work supply involve transformation and conversion looses. Transformation looses depend on the efficiency of energy transformation sector (for example to transform crude oil in gasoline, useful for internal combustion engines). Conversion looses have to do with the efficiency of energy use equipment (internal combustion engine i.e.). Ayres' contribution to the efficiency (and loss) estimation between different types of useful work is presented in table 6.3. Evidently, with the exception of electricity which is considered as a pure form of useful work[14], most forms of useful work that humans utilize, are characterized by great losses. It goes without saying that the entropy law and thermodynamics play a decisive role

[14] Useful work can be divided into several categories: muscle work (human and animal); mechanical work (primary movers); and heat. Electricity can be regarded as a pure form of useful work, since it can be converted into heat, mechanical and chemical work, with little or no losses (*Ayres and Warr, 2009-p.92*)

in economic system's efficient function, despite the tremendous technological progress has been achieved so far.

Exergy Efficiency	
muscle Work	
Human muscle work	15% useful work
Animal work	4-5,4% useful work
mechanical work	
Trucks	~ 20%
Mid size american car	~ 8%
Mid size European-Japanize car	~ 10%
Urban driving	~ 12.6%
Highway driving	~ 20,2%
Steam electric plans (including loses in distribution	~ 33%
Hydraulic turbins	~ 80%
Electrical Power efficiency in mechanical work	≤90%
Fuel cells	~ 80%
Direct Heat	
Industry, space heating, cooking, commercial use	14-25max%
Electricity	
Eletricity can be regarded as a pure form of useful work, since it can be converted into mechanical, chemical work or heat with little or no loses at al.	

Table 6.3 *Estimations of exergy efficiency per useful work category (Source: Ayres and Warr, 2009)*

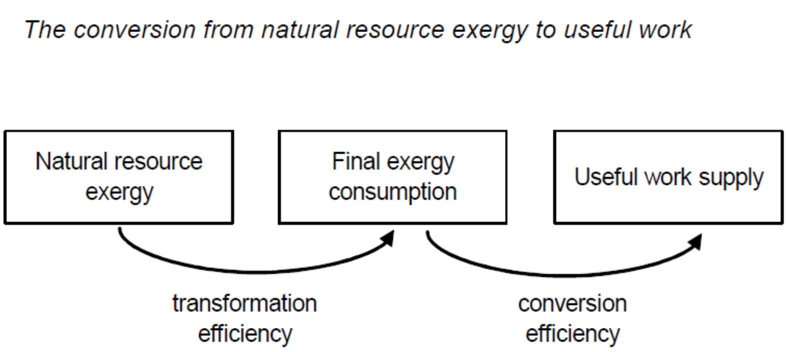


Figure 6.6 *The conversion from natural resource exergy to useful work*

The concept of Emergy

"…*Energy is measured by calories, btu's, kilowatt hours, and other intraconvertable units, but energy has a scale of quality which is not indicated by these measures. The ability to do work for man depends on the energy quality and quantity and this is measurable by the amount of energy of a lower quality grade required to develop the higher grade. The scale of energy goes from dilute sunlight up to plant matter, to coal, from coal to oil, to electricity and up to the high quality efforts of computer and human information processing*…" (*Odum, 1973*).

In early 1970's, Odum conceived an alternative and innovative method in order to measure and aggregate the energy quality being embodied in different energy resources. Emergy is actually a statement of all the energy and material resources used in the production process (that have produced a good or a service) calculated in units of one particular form of energy, often in solar energy units (*Cleveland and Morris, 2009-p. 163*). Specifically, emergy is measured in solar embodied joules, abbreviated as "*sej*" (*Hau and Bakshi, 2004*). Emergy analysis characterizes all derived products and services in equivalents of solar energy, namely, how much energy would be needed to do a particular task if solar radiation were the only input of energy in the economic system. To do that, Odum's theoretical concept addresses the Earth as a closed system with solar energy, deep Earth heat (geothermy) and tidal energy as major constant energy inputs. In that context, all living systems sustain one another by participating in a network of energy flow by converting lower quality energy into both higher quality energy and degraded heat energy. Since solar energy is the main energy input to the Earth, all other energies are scaled to solar equivalents to derive common units (*Hau and Bakshi, 2004*).

While emergy concept, together with the exergy concept, are considered as highly sophisticated and interdisciplinary energy aggregation methods, have received though extensive criticism. Similarly with enthalpy and exergy, emergy is still one-dimensional due to the fact that energy sources are evaluated on the basis of the quantity of embodied solar energy and crustal heat (*Cleveland et al., 2000*).

6.5 The Decoupling effect and the Energy Intensity of the economy

6.5.1 A Literature review of the Energy Intensity evaluation

As one of the most widely cited macroeconomic indicators for measuring sustainability through estimates of decoupling effect, the Energy/GDP ratio has been the focus of a significant number of published studies. The majority of these studies examine the decoupling effect at the level of a single country (*Ostblom, 1982; Bossanyi, 1979; Garbaccio and Jorgenson, 1999*); and of a group of countries (*Reister, 1987; Howarth et al., 1993; Mulder and de Groot, 2004; Warr et al., 2010*), while a few have recently attempted a global decoupling estimate (*Krausmann et al., 2009; UNEP, 2011*). Concerning studies which estimate decoupling for a single country, there are several among them which empirically support that energy consumption grew at a much slower pace despite the significant increase in GDP (*Ostblom 1982; Garbaccio and Jorgenson, 1999; Stern, 2011*). Similarly, empirical studies using groups of developed countries show a clear decline in the Energy/GDP ratio throughout most of the last half of the 20th century (*Nilsson, 1993; Dincer, 1997*). In this context, according to *MacKillop (1990)*, post-war energy intensity (at least for OECD countries) can be separated into two different time periods: before 1973 when energy and economic growth were coupled; and after 1973 when they were clearly decoupled. Since the early 1970's, various reports have identified a permanent decoupling between energy and economic growth (*IEA, 1982; World Bank, 1992*). Last, recent empirical studies estimating decoupling at the global level further support the fact that there has been a delinking of the GDP from the use of energy: a trend that until today seems immutable (*Krausmann et al., 2009; UNEP, 2011a*).

Taking a different direction, certain studies (*de Bruyn and Opschoor, 1997*) claim that this "*delinking*" trend does not prove persistent, while others nourish scepticism (*Auty, 1985; Cleveland and Ruth, 1999*) on whether this shift to a service economy will eventually bring dematerialization and thus delink energy use from economic growth (*Herring, 2006; Kander, 2005*). In this context, an early study on decoupling (*Bullard and Foster, 1976*) argues that substantial technological and lifestyle changes may be required if energy and economic growth are to be decoupled, while emphasizing the importance of population and GDP per Capita growth rates in the decoupling debate.

According to the methodological framework three are the general types of studies that can be identified (*Madlener, 2011*):

• Studies employing sophisticated econometric techniques

• Studies employing elasticities for computing the responsiveness of energy consumption relative to GDP.

• Studies estimating Energy/GDP ratios (The so-called Energy Intensity)

Among the most representative dialogues dealing with the first category are Environmental Kuznets Curves (EKCs) and the E-GDP Causality debate. The literature concerning Environmental Kuznets Curves suggests that the relationship between per Capita income (GDP per Capita) and environmental pressure (measured in aggregated pollution or natural resource consumption levels) may take an inverted U shape, thus indicating a disconnection of environmental pressure from economic growth and subsequently supporting in an indirect manner the decoupling effect between energy consumption and GDP growth (*Grossman and Krueger, 1993; Panayotou, 1997; Stern, 2004; Luzzati and Orsini, 2009; Halkos and Tzeremes, 2009*).

In addition, the literature concerning the causal relationship between energy consumption and economic growth (*Fallahi, 2011; Warr and Ayres, 2010*) has utilized estimates that are based on the GDP per Capita ratio in order to investigate the direction of causality (*Soytas and Sari, 2003; Lee, 2006; Soytas and Sari, 2006; Huang, 2008*). ***The causality dialogue will be discussed and reviewed in detail in the 7th Chapter.***

The second category concerns the estimation of elasticity decoupling factors and indexes, mainly proposed by OECD (2002) and UNEP (2011). The third category includes all these studies which estimate the energy input required for the production of one unit of GDP, the well known energy intensity E/GDP ratios.

Nevertheless, as far as the second and the third category of studies is concerned, no direct use of GDP per Capita indicator can be identified in the relevant literature salient to the decoupling effect. This observation will play a decisive role throughout the empirical estimates of the present chapter.

6.5.2 Implications from the physical properties of production

Is current growth undertaking a transition towards less energy and material intensity (*Cornillie and Fankhauser, 2004; Schäfer, 2005*)? Are our economies becoming less dependent on natural resources (*Weizsäcker et al., 1997; Herring, 2006*)? Has the long-standing dialogue on the constraints of economic growth imposed by natural resources scarcity been resolved in favour of the "optimistic school" (*Bithas and Nijkamp, 2006; Bithas, 2008*)? Will the transition to a modern service economy bring dematerialization of production and consequently environmental improvement (*Powell and Snellman, 2004; Kander, 2005; Wölfl, 2005; Spohrer and Maglio, 2008*)? To use an updated terminology: is the proposal of van den Bergh (2011) for a-growth feasible, or should the sustainable path be sought in the proposal of Kallis (2011) for degrowth?

Material Type	**MJ/kg**	**Remarks**
Aluminum	227-342	*Metal from bauxite*
Bricks	2 - 5	*Baked from clay*
Cement	5 - 9	*Raw materials*
Copper	60-125	*Metal from ore*
Glass	18-35	*Sand and other materials*
Gravel	0,08-0,1	*From quarries, rivers*
Iron	20-25	*From iron ore*
Paper	25-50	*From standing timber*
Plastics	60-120	*From crude oil*
Steel	20-50	*Finished from ore*
Water	0,001-0,01	*From streams, reservoirs*
Wood	3 - 7	*From standing timber*

Table 6.4 *Energy intensity of common materials' production (MJ consumed per one kg of produced output (Source: Smil, 1994- p.13).*

There exist many ways to examine the above questions. One possibility is to use real data in order to estimate contemporary trends in the relationship between production and natural resources inputs. This can be performed in two ways: first, by estimating the natural resources inputs[15] required per unit of production output, measured in quantities (kg). Table 6.4 presents estimates of the energy intensity of various selected common materials' production (MJ/kg); and, second, by estimating the natural resources inputs required per unit of economic output (GDP in monetary values). In essence, the latter concerns the empirical estimation of the so-called decoupling effect. In that sense, the predominant way in order to estimate the decoupling effect is through indicators of the prototype: natural resources inputs (quantities)/ economic production output (GDP, in aggregate monetary values).

The Energy Intensity EI is broadly defined as the ratio of energy use to GDP, namely the amount of energy that is required to produce a unit of GDP. There exist many alternative applications of the E_t/GDP_t prototype that could be briefly summarized in four categories:

- Total Energy Consumption $(TEC)_t/GDP_t$ (*Cleveland et al., 1984; Kauffman, 1992, 2004*)

- Total Primary Energy Supply $(TPES)_t/GDP_t$ (*Krausmann et al., 2009*)

- Domestic Energy Consumption $(DEC)_t/GDP_t$ (*Haberl et al., 2006*)

- Useful $Work_t/GDP_t$ (*Ayres and Warr, 2009; Serrenho et al., 2014*)

Contemporary analysis is mainly directed towards criticizing the methods and the techniques concerning the appropriate energy measurement (*Ayres et al., 2003; Ayres and Warr, 2009; Warr and Ayres, 2010; Serrenho et al., 2014*). Towards this direction, many deal with the proper energy aggregation (*Cleveland et al., 2000; Stern, 2011*), while others analyse the substitution trends between qualitative differences among energy resources (*Kaufmann, 1992; 2004*). Eventually, all these efforts are mainly dealing with the appropriateness (or not) of the nominator of the E_t/GDP_t prototype, while the relevant literature completely ignores the important implications and constraints raised by the use of GDP, as the

[15] Natural resources inputs usually measured in two distinct ways: concerning material flows (material intensity), the measurement is performed in kg or in tons, metric tons, etc. (weight units); while, concerning the energy flows (energy intensity), the measurement is performed in energy aggregation measuring units, such as Exajoule, Btu, useful work, tons of oil equivalent, etc. (*for more details, see the 3rd Chapter*)

dominant denominator, in the vast majority of the published studies. GDP index has been severely and extensively criticized by many distinguished scholars, concerning its inability to reflect the actual welfare that the economic system creates (*Ayres, 1996; van den Bergh, 2010; Daly, 2013; Constanza et al., 2014*).

A significant number of publications from 1970 to the present have identified at least a relative decoupling of GDP from natural resource inputs over the last 50 years (*Bullard and Foster, 1976; Ostblom, 1993; Park et al., 1993; Bleischwitz et al., 2007; Steger and Bleischwitz, 2009; Krausmann et al., 2009*). As a consequence, it seems that modern economic growth has entered a period of transition towards less dependence on natural resources (*Ross et al., 1987; Ziolkowska and Ziolkowski, 2011*).

Essentially, the estimation of decoupling of economic growth from energy inputs refers to the estimation of the decoupling of the production process from energy requirements. Production is a material-physical process which transforms inputs (energy, material) into outputs (goods and "*waste*"). In this context, an attempt to investigate the decoupling of outputs from inputs should be based on the close consideration of the physiology of the process and the physical properties of inputs and outputs.

Essentially, Chapter 6 attempts an estimation of the decoupling of economic growth from energy use at the global level. The innovative element is the use of Energy/[GDP $_{\text{per Capita}}$] ratio instead of the Energy/GDP ratio that currently dominates in the relevant studies. The Energy/[GDP $_{\text{per Capita}}$] ratio can better account for the real world properties of economic production and, hence, economic goods (*See Chapter 4*). The GDP per Capita indicator approximates, to some extent, the physical dimensionality of the economic production. Energy requirements are closely related to the physical dimensions of goods. GDP per Capita implicitly takes into account the very fact that goods are used by human beings. Therefore goods should have certain physical dimensions and, consequently, "*embody*" certain amounts of energy. In that context, the estimation of decoupling of energy-economic growth on the basis of Energy/[GDP $_{\text{per Capita}}$] ratio emerges as an improvement that better approaches the physiology of the economic process, whose specific properties vanish through the use of pure monetary units, such as GDP. Presumably, this proposed approximation of the dimensionality of the production process through the Energy/[GDP $_{\text{per Capita}}$] ratio offers opportunities for an essential interdisciplinary estimation of decoupling by taking into account the natural traits of real world goods, as well as the relevant impacts of demographic trends.

The broadly used Energy/GDP ratio takes into account the physical properties of energy inputs. On the other hand, it does fail to consider the physical properties of goods being the "*useful*" part of production process output. Economic goods serve human needs and preferences. To do so, economic goods should have certain physical dimensions whose shaping requires a certain amount of energy. As a result, empirical estimations and projections of decoupling should have been rigorous if they had been assessed on the basis of an indicator able to account for the dimensionality of real world goods. The present study proposes the Energy/[GDP $_{\text{per Capita}}$] ratio as an indicator which offers an indirect approximation of the dimensionality of real world goods. It also takes into account the energy "embodied" in the production of the real world's goods something which is of particular importance when attempting projections concerning the future potentials decoupling economic growth from energy inputs entails. Limits on the potentials for reducing energy inputs may be revealed once the dimensionality of goods is estimated even indirectly. On the contrary, the energy inputs required for the production of one unit of GDP, as reflected in the Energy/GDP ratio, may be projected as low as one wishes. GDP is an abstraction that reflects in monetary units the aggregate production of an economy. Based on this, the majority of empirical decoupling estimates indicate a decline in the energy inputs necessary for producing a unit of GDP. The projection of those estimates raises optimism that there may be substantial potential for further decoupling. Indeed, a dimensionless and homogenous monetary unit could require only an infinitesimal energy input. However, such an estimate ignores that monetary units reflect the monetary values of real goods. And real goods are "*shaped*" along certain physical dimensions which can be processed by using substantial energy inputs. In this context, we propose the use of Energy/[GDP $_{\text{per Capita}}$] ratio as an approximation that can take into account the physical dimensionality of production which should be systematically considered whenever the relationship between the economic process and natural resources is being investigated. Furthermore, the Energy/[GDP $_{\text{per Capita}}$] ratio takes into account the demographic trends that strongly influence the evolution of decoupling. Population growth and relative trends determine the composition and structure of the GDP and, therefore, should be taken into account whenever attempting to estimate decoupling and decoupling potentials.

In a nutshell, we assert that essential estimation of the decoupling of economic growth from energy use requires an interdisciplinary approach that systematically considers the real world properties of the production process. We assert that the Energy/[GDP $_{\text{per Capita}}$] ratio incorporates economic, energy, physical, and demographic aspects and may thus bring out some new elements in the analysis of decoupling.

6.5.3 Data overview

We carry out our calculations of global E/GDP and E/[GDP per Capita] ratios based on annual data for the period 1900-2009. Energy supply data were taken from Krausmann et al. (2009), one of the most significant recent studies on global decoupling estimation.

Regarding the USA case, domestic energy consumption (in PJ) was taken from Gierlinger and Krausmann (*2011; Data available at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm*), for the period 1870-2005.

In Japan's case study, data on DEC (in PJ) were drawn from Krausmann et al. (*2011; Data available at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm*).

Concerning the case of India, data on DEC (in PJ) were derived from Singh et al. (*2011; Data available at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm*).

In order to maintain a sense of consistency, we draw data for the GDP and the population from relevant databases utilized by the aforementioned studies, providing a straight comparability of our empirical results with them. As a result, data on the GDP and population are drawn from Maddison (*Maddison, 2003; 2008*).

The GDP is measured in million 1990 International Geary-Khamis dollars. The Geary-Khamis dollar is a hypothetical unit of currency that has the same purchasing power parity (PPP) that the United States dollar had in the USA in 1990. It was proposed by Roy C. Geary in 1958 and was further developed by Salem H. Khamis (*Geary, 1958; Khamis, 1972*). Population is expressed in million persons. Energy supply is expressed in Exajoule (EJ). One EJ is 1018 joules, equivalent to 1015 British Thermal units (Btu) (*Cleveland and Morris, 2009*), while data on GDP and population were drawn from Maddison (2008).

6.5.4 Empirical analysis and results for the global level

The global aggregate energy case: comparing E/GDP with E/[GDP per Capita]

E/GDP ratio annual estimates are presented in Figure 6.7, where E is the aggregation of all major energy sources expressed in EJ (*Krausmann et al., 2009*): oil; coal; natural gas; bio-fuels; hydroelectric, nuclear, and geothermal electricity. GDP is the global aggregate GDP expressed in 1990 Geary-Khamis International $.

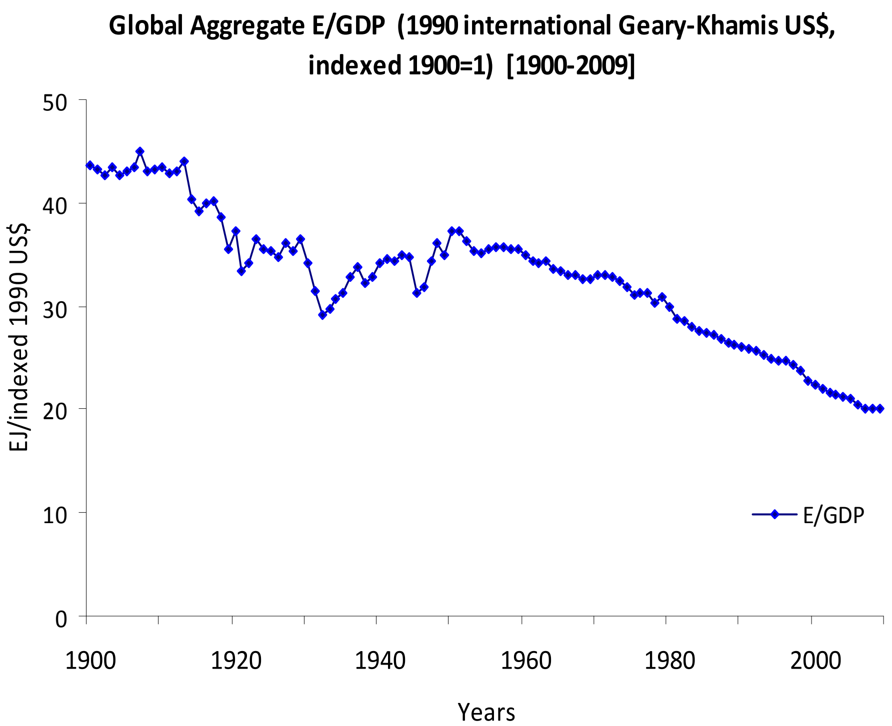


Figure 6.7 *The global aggregated Energy/GDP ratio for 1900-2009, where global aggregated Energy is: oil; coal; natural gas; hydroelectric, nuclear, and geothermal electricity; bio-fuels. GDP is indexed as 1900=1.*

According to Figure 6.7, the period 1900-1913 saw stability in energy intensity without marked variations. 1913 marks the beginning of a general decline in energy intensity which continues steadily during World War I (1914-1918), reaching in 1921 its lowest energy intensity value since 1900. The period 1923-1929 is characterized by relative stability with a pattern similar to that of 1900-1913. The Great Depression of 1929 caused a notable energy intensity decline, which reached its lowest point in 1933. From that point on, energy intensity rose gradually until the end of World War II. The year 1951 marks a historical turning point: the E/GDP ratio peaked for the last time at about the same energy intensity level as 1918. Thereafter, a steady decline in energy intensity occurred with only a few brief interruptions (oil crises of 1973 and 1979). This unprecedented decline of energy intensity culminated in 2008 at the lowest point of the entire series which had started in 1900. As a result, at least the evidence for relative decoupling is very strong for the period 1951-2009.

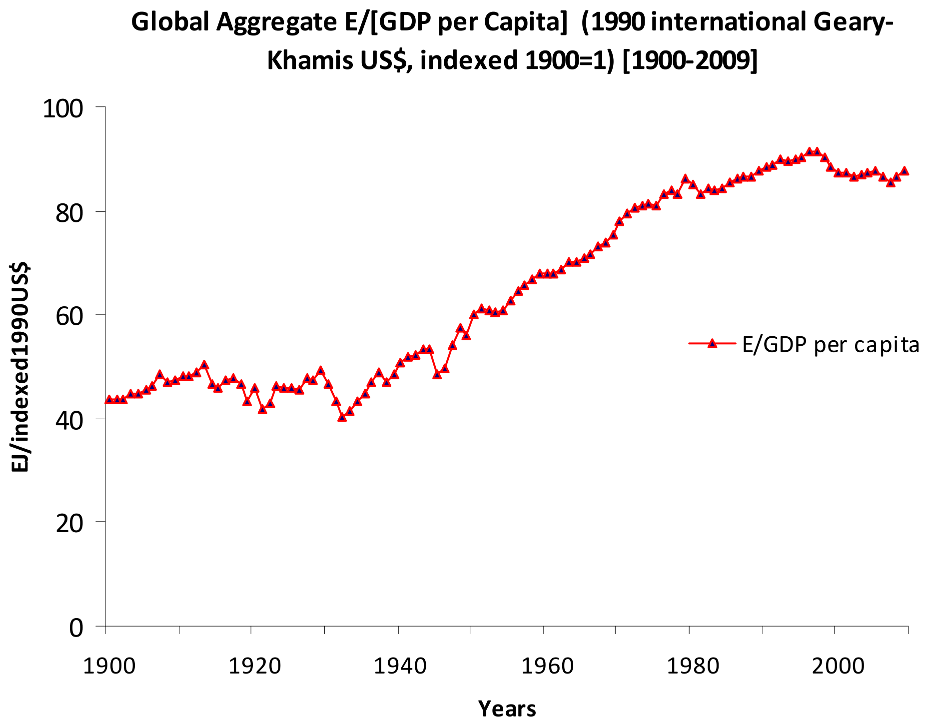


Figure 6.8 *The global aggregated Energy/[GDP $_{per\ Capita}$] ratio for 1900-2009, where global aggregated Energy is: oil; coal; natural gas; hydroelectric, nuclear, and geothermal electricity; bio-fuels.*

In Figure 6.8, we estimate the E/[GDP $_{per\ Capita}$] ratio, reflecting the energy used for the production of one unit of per Capita GDP. The results for this ratio depict a different pattern concerning the decoupling of economic growth from energy resources. A gradual increase in energy intensity starting with the early 20th century is interrupted during WWI. Afterwards, energy intensity continues to increase until the onset of the Great Depression. The last relative minimum of the ratio is observed in 1945 (end of WWII). Thereafter, the upward trend continues with only a few interruptions. In 1996, the E/[GDP per Capita] reaches its highest peak so far. Evidence of a small decline in energy intensity appears as of 1997 which seems to stabilize from 2002 to 2009. In sum, according to the empirical estimates of the E/[GDP $_{per\ Capita}$] ratio that we propose, no substantial evidence of even relative decoupling of energy required for the production of a per Capita unit of GDP can be traced.

The global aggregate fossil fuels energy case: comparing fossil fuels E/GDP with fossil fuels E/[GDP per Capita]

In this section we estimate the relationship between fossil fuels energy carriers and economic growth. Fossil fuels are exclusively examined here as being the "*backbone*" among available energy sources with more than 80% of the global energy supply since 1960s (*Krausmann et al., 2009*). We estimate both the E/GDP and E/[GDP per Capita] ratios, where E is the aggregate energy supply derived solely from fossil fuels (aggregate oil, coal, and natural gas). Results are presented in Figures 6.9 and 6.10 for both ratios, respectively.

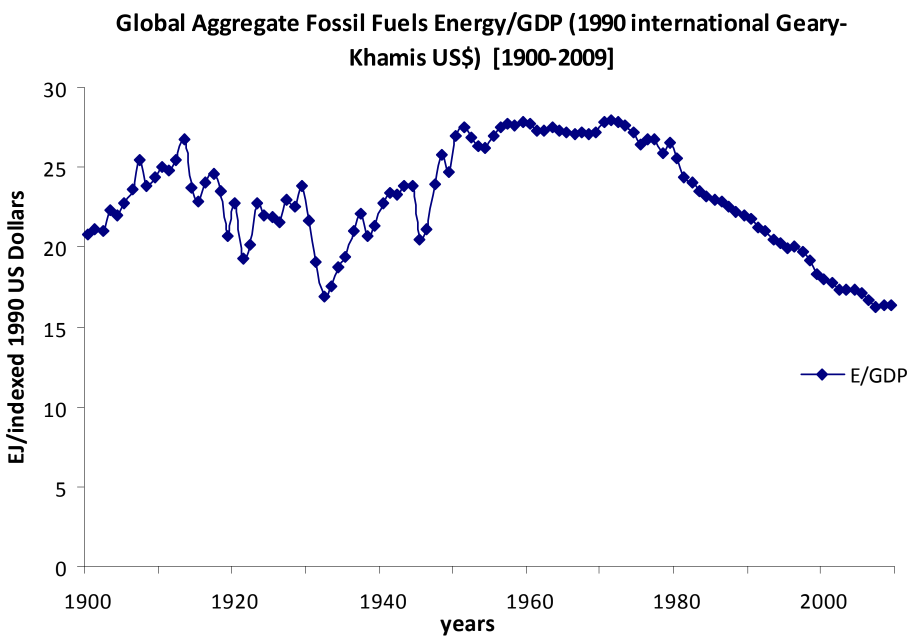


Figure 6.9 *The global aggregated fossil fuels Energy/GDP ratio for 1900-2009, where global aggregate fossil fuels are: oil; coal; natural gas.*

Figure 6.9 presents similarities to Figure 6.7 with regard to the way both ratios evolved. We observe similar decoupling periods during WWI, the Great Depression, and WWII. From 1955 to 1971, the fossil fuels decoupling enters a period of relatively small fluctuations. The very same period highlights the dominant role of fossil fuels among energy sources whose share in global energy supply alters from 76% in 1955 to 84.6% in 1971. It is obvious that, starting with 1971, energy use increased at a much slower pace than the monetary size of the global economy. Nevertheless, fossil fuels remained the most significant energy source with a share varying between 80-84% of the global energy supply during 1963-2009 (*Krausmann et* *al., 2009*). Evidence of relative decoupling of fossil fuels in Figure 6.9 is quite strong during 1971-2009.

The pattern of fossil fuels decoupling changes dramatically when using the E/[GDP per Capita] ratio (Fig 6.10). Relative decoupling observed in Figure 6.10 is rather imperceptible compared to that identified in Figure 6.9, concerning the periods of WWI, the Great Depression, and WWII. Afterwards and starting with 1951-52, the E/[GDP per Capita] ratio increases continuously only to be interrupted briefly in 1979. Since then, smooth fluctuations indicate a relative stabilization especially in the fossil fuels intensity.

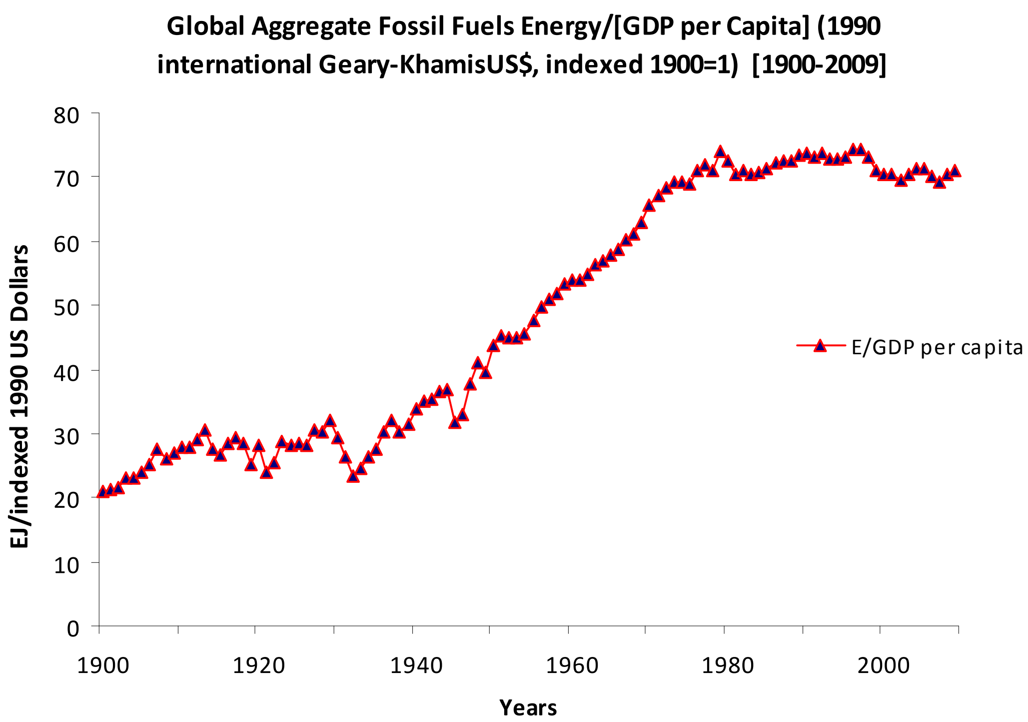


Figure 6.10 *The Global aggregated fossil fuels Energy/GDP per Capita ratio for 1900-2009, where global aggregate fossil fuels are: oil; coal; natural gas.*

As a result, no substantial evidence of relative decoupling appears with regard to estimates of the E/[GDP per Capita] ratio in Figure 6.10. In contrast, with E/GDP pattern evolution, E/[GDP per Capita] ratio presents evidence of coupling between fossil fuels use and economic growth at least for the period from 1945 to the early 1980's.

Figure 6.11 depicts more clearly the contrast in the way the two indicators evolved during 1900-2009. Fossil fuels E/GDP & E/[GDP per Capita] ratios have been rescaled to the value of one for the base year 1900. The pattern of each ratio follows a drastically different evolution than the other: After 1971, the E/GDP ratio shows transparent decoupling of fossil fuels use, while the E/[GDP per Capita] ratio evolves in such a way as to indicate coupling.

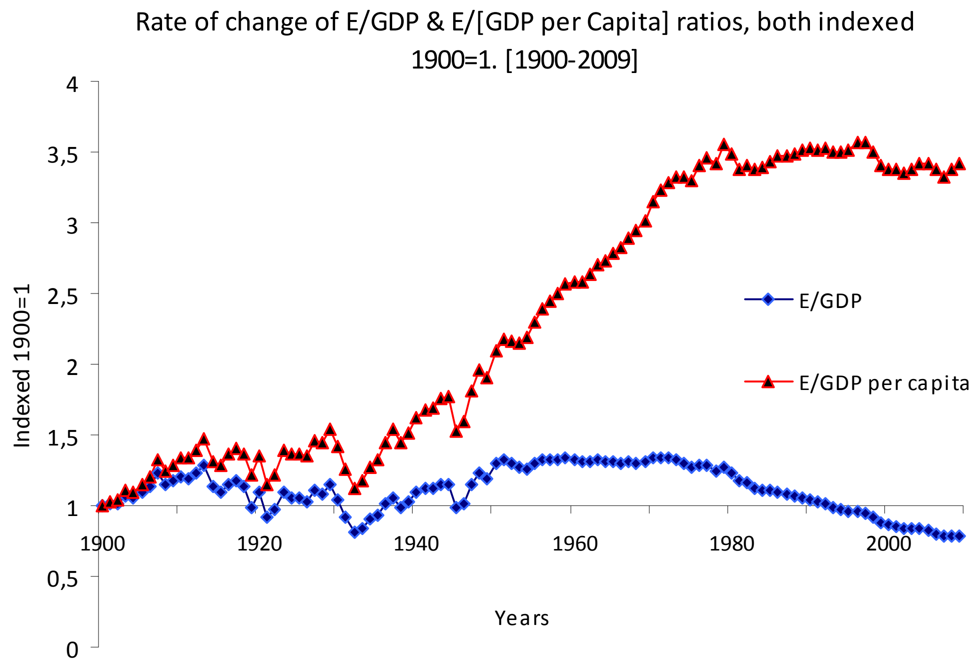


Figure 6.11 *Rate of change for fossil fuels E/GDP & E/GDP per Capita ratios in the 1900-2009 period. (Rate of change indexed by 1900=1).*

Disaggregating fossil fuels energy carriers: re-estimating decoupling among the components of aggregate fossil fuels

In this section we disaggregate fossil fuels into three distinct energy sources (oil, coal, and natural gas). These estimations aim at revealing the patterns of decoupling for the energy carriers that are most important taking into account their mutual substitution over time.

In 1900, the total global energy supply was about 44EJ (*Krausmann et al., 2009*) out of which 48% was the share of fossil fuels. 95% of fossil fuels were dominated by coal. By the end of WWI, fossil fuels accounted for 61% of the global energy supply (Table 6.5). Thus: 90% coal;

8% oil; and 2% natural gas. However, it was after WWII that oil began to take gradually the lion's share in fossil fuels composition; fossil fuels accounted for 65.5% of the global energy supply. Thus: 61.5% coal; 29% oil; and 9.5% natural gas. In 1951 (a milestone for decoupling indicated by the Total Energy supply/GDP ratio), fossil fuels accounted for 74% of the total global energy use.

Table 6.5 *The percentage contribution of each energy type in world energy consumption for selected years during 1900-2009 (Data Source: Krausmann et al., 2009)*

years	Coal%	Oil%	Natural Gas%	Hydro-, nuclear, geotherm. electr.	Biofuels %	Fossil fuels as % of total energy consumption
1900	94.72%	4.11%	1.17%	0.00%	52.21%	47.79%
1914*	91.28%	6.82%	1.90%	0.05%	41.35%	58.60%
1918	89.97%	7.89%	2.15%	0.09%	39.06%	60.85%
1929†	76.70%	18.67%	4.63%	0.26%	34.45%	65.30%
1933	72.13%	22.73%	5.14%	0.49%	40.44%	59.07%
1940±	70.57%	23.40%	6.03%	0.54%	32.81%	66.65%
1945	61.59%	28.95%	9.46%	0.82%	33.58%	65.60%
1951	53.05%	31.86%	15.10%	0.83%	25.36%	73.81%
1972	27.88%	51.14%	20.98%	1.53%	13.61%	84.86%
1973¥	26.53%	52.66%	20.81%	1.58%	13.07%	85.35%
1979ŧ	27.41%	50.60%	21.99%	2.12%	11.98%	85.89%
1990	31.00%	42.76%	26.23%	5.28%	11.54%	83.19%
2000	27.86%	46.20%	25.94%	8.57%	10.95%	80.48%
2005	31.61%	42.97%	25.42%	8.33%	10.34%	81.33%
2009	35.03%	39.35%	25.62%	8.35%	10.69%	80.96%

* WWI

† The Great Depression

± WWII

¥ The first oil shock

ŧ The second oil shock

Coal was still the dominant component among fossil fuels (53%), but it was already on the way of being substituted by oil (32%) and natural gas (15%). Before the outbreak of the first oil crisis in 1973, fossil fuels were by far the dominant energy source, accounting for 85% of the total global energy supply while oil (52.5%) had a clear advance on coal (26.5%) and on natural gas (21%). In fact, oil became the dominant fossil fuels component after 1962. During the second oil crisis in 1979, fossil fuels covered 86% of the global energy supply (Thus: 27.5% coal; 50.5% oil; and 22% natural gas). Last, in the period 2000-2009, fossil fuels contribution was reduced to 81% of the global energy supply. In that period, an increase of the coal share from 28% (2000) to 35% (2009), substituted oil (from 46% in 2000, to 39.5% in 2009), while natural gas contribution remained stable at about 25.5%.

On the left-hand side of Figure 6.12, we estimate Oil Supply/GDP (a); Coal Supply/GDP (b); and Natural Gas Supply/GDP (c) ratios. The right-hand side of Figure 6.12 presents estimates of Oil Supply/GDP per Capita; Coal Supply/GDP per Capita; and Natural Gas Supply/GDP per Capita in Figures d, e, and f, respectively.

The Oil Supply/GDP ratio (a) peaked at the beginning of the first oil crisis in 1973 and since then decreased continuously until 2009. After peaking in 1979, the Oil Supply/GDP per Capita ratio (d) followed a milder decline until 2009, only to be briefly interrupted during 1995-1998.

Estimations for coal are presented in Figures *b* and *e* where, compared to each other, the two ratios evolve quite differently. The most remarkable differences were observed in 2000-2009 with the most notable one being that the Coal Supply/GDP per Capita ratio presented strong coupling while the Coal/GDP remained rather stable.

In Figure c, the Natural Gas Supply/GDP ratio shows signs of decoupling after 1980. On the other hand, the Natural Gas Supply/GDP per Capita ratio (f) declines after 1995, again presenting a relatively stable trend during 1998-2009. It is worth noting that it was after the early 1980’s that natural gas emerged as a significant energy carrier source.

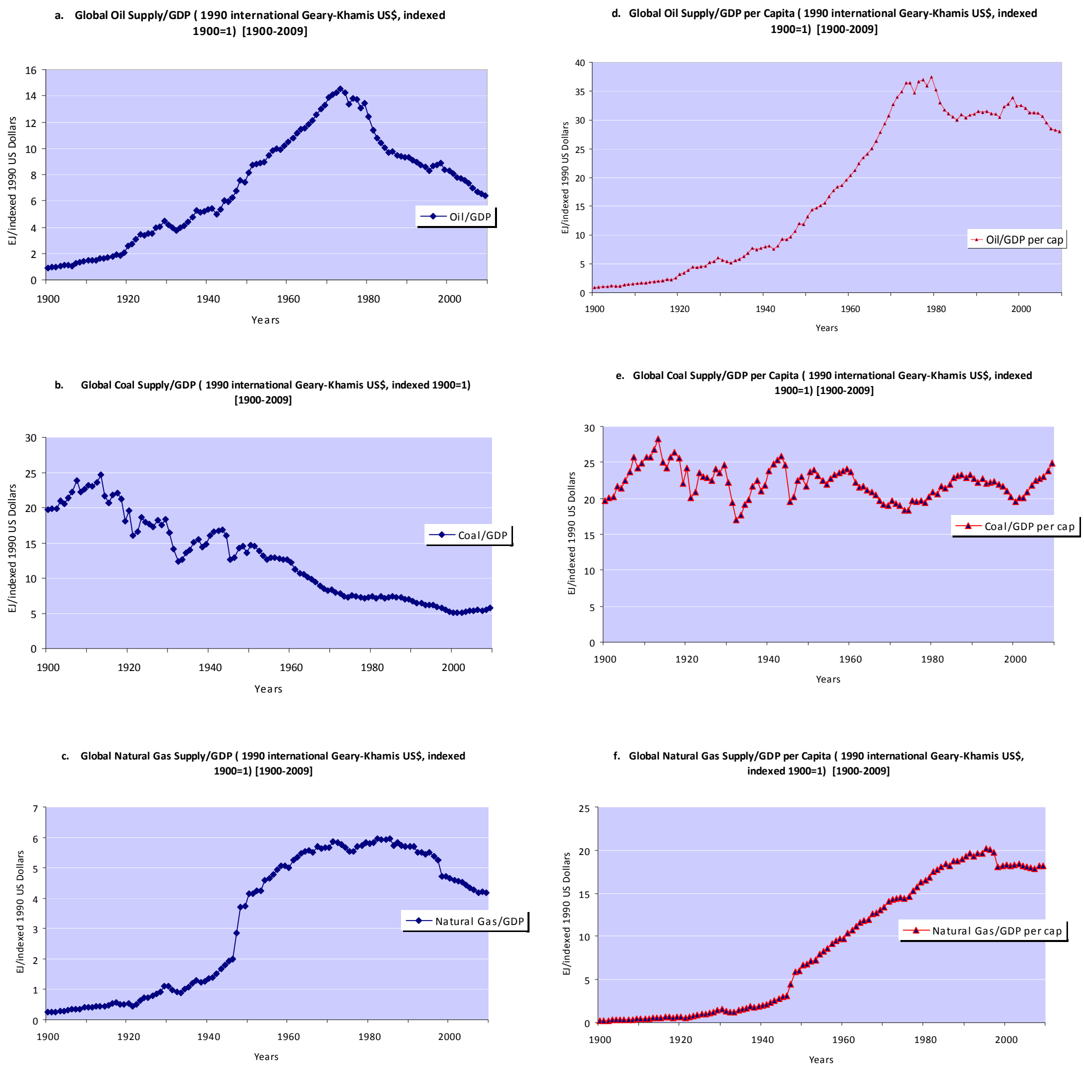


Figure 6.12. *Disaggregate fossil fuels. (a). Global Oil Supply/GDP ratio; (b). Global Coal Supply/GDP ratio; (c). Global Natural Gas Supply/GDP ratio; (d). Global Oil Supply/GDP per Capita ratio; (e). Global Coal Supply/GDP per Capita ratio, (f). Global Natural Gas Supply/GDP per Capita ratio, estimated for 1900-2009.*

Estimating the Global Decoupling Index (DI) for fossil fuels E/GDP and E/[GDP per Capita] ratios

In this section, the Decoupling Index (DI) proposed by Fischer-Kowalski and colleagues in the United Nations Environment Report for Decoupling (UNEP, 2011) is estimated. The Decoupling Index refers to the ratio of the change in the rate of consumption of a given resource, to the change in the rate of economic growth (in terms of GDP), within a certain time period (typically one year). We attempt to modify the DI in two ways:

- By using the change in the rate of energy supply instead of the rate of energy consumption. At a global aggregate level, the distinction between energy consumption and energy supply is meaningless.

- In order to smooth out short-term fluctuations of the economic cycles, by using moving averages, we estimate a time period of one (1) decade instead of the proposed one-year period.

First, we estimate the DI for the E/GDP ratio:

$$\frac{(E_t - E_{t-1})/E_{t-1}}{(GDP_t - GDP_{t-1})/GDP_{t-1}} = \frac{\Delta E}{\Delta GDP} \qquad (2)$$

where t is an averaged time period of one (1) decade. Hence, represents the change from the average of one decade to the next. Secondly, we estimate the DI for E/[GDP per Capita], using the same formula but with GDP being replaced by the GDP per Capita throughout.

Kowalski et al. (*UNEP, 2011*) propose the following interpretation for DI:

- When DI>1, no decoupling is taking place.
- When DI=1, the turning point between absolute coupling and relative decoupling is represented.
- When 0<DI<1, relative decoupling is taking place.
- When DI=0, it is implied that the economy is growing while resource consumption remains constant. This is the turning point between relative and absolute decoupling.
- When DI<0, the relationship can be described as absolute decoupling.

Figure 6.13 shows estimates of the DI for both the E/GDP and E/[GDP per Capita] ratios.

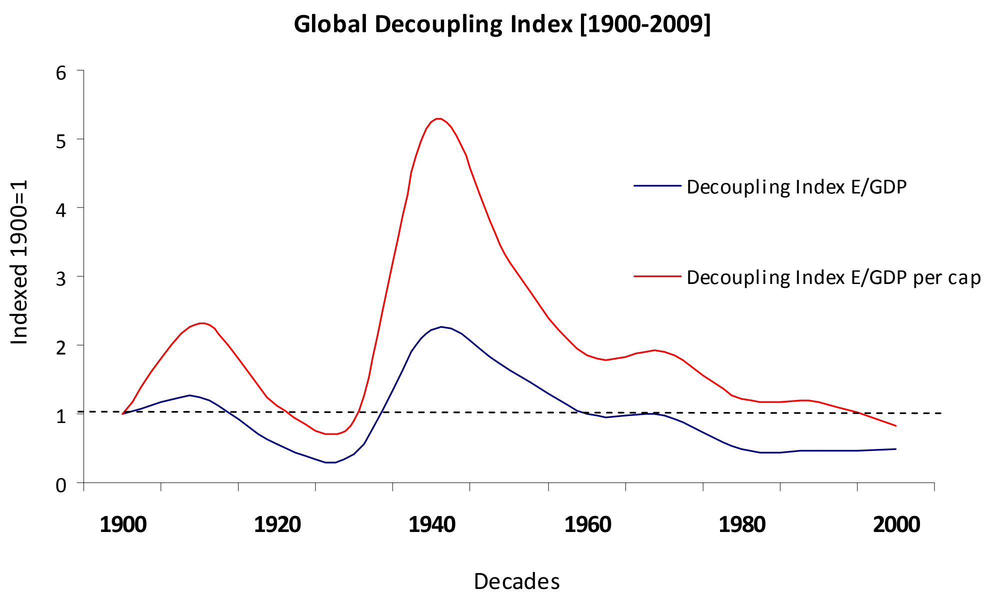


Figure 6.13 *Global Decoupling Index (1900-2009) for aggregate fossil fuels. Estimates the ratio of the rate of change of fossil fules supply to the rate of change of economic growth for E/GDP and E/GDP per Capita ratios.*

For the years 1920 and 1939, the DI estimated from the E/GDP ratio shows signs of relative decoupling in its values. The lowest DI value (0.41) is observed during the period 1930-1939. For the next three decades, DI takes values ≥1 but drops again below 1 after 1970. As a result, in the period 1970-2009, global economic growth appears to have been in a state of relative decoupling from energy supply. On the contrary, results from estimating the DI using E/[GDP per Capita] are quite different. There is no clear sign of any significant relative decoupling at any time within the entire century (1900-2000). An indication of relative decoupling appears only in the period 1930-1939, when the DI value was 0.9. However, this is sufficiently close to value 1, which marks the “borderline” between coupling and relative decoupling, so as not to represent strong evidence for relative decoupling. It should be noted that the lowest DI value (0.82) occurred in the 2000-2009 period, which possibly indicates the start of a relative decoupling period.

Evidently, there is a clear difference between the empirical results of Δ (E)/Δ (GDP) ratio and the Δ (E)/Δ (GDP per Capita) ratio. Nevertheless, no signs of absolute decoupling can be traced for either one of these two Decoupling Indexes.

6.5.5 Energy Intensity of the USA for 1870-2005

This section aspires to cast light into the energy consumption trends of the US economy, among the most representative highly developed post-industrial economies. By the end of the examined period, the USA is simultaneously the largest energy consumer[16] and the biggest economy of the world. The following analysis reveals the decisive role that energy inputs have played in the unprecedented growth of the US economy, throughout the examined period (1870-2005).

USA Domestic energy consumption for 1870-2005

Figure 6.14 depicts the energy consumption trends of each energy type consumed in the USA, for the period 1870-2005, measured in Peta-Joule (PJ). Evidently, the agricultural biomass and timber is the most important energy resource during 1870-1906. After 1906, the coal consumption increases more rapidly in comparison to the biomass consumption.

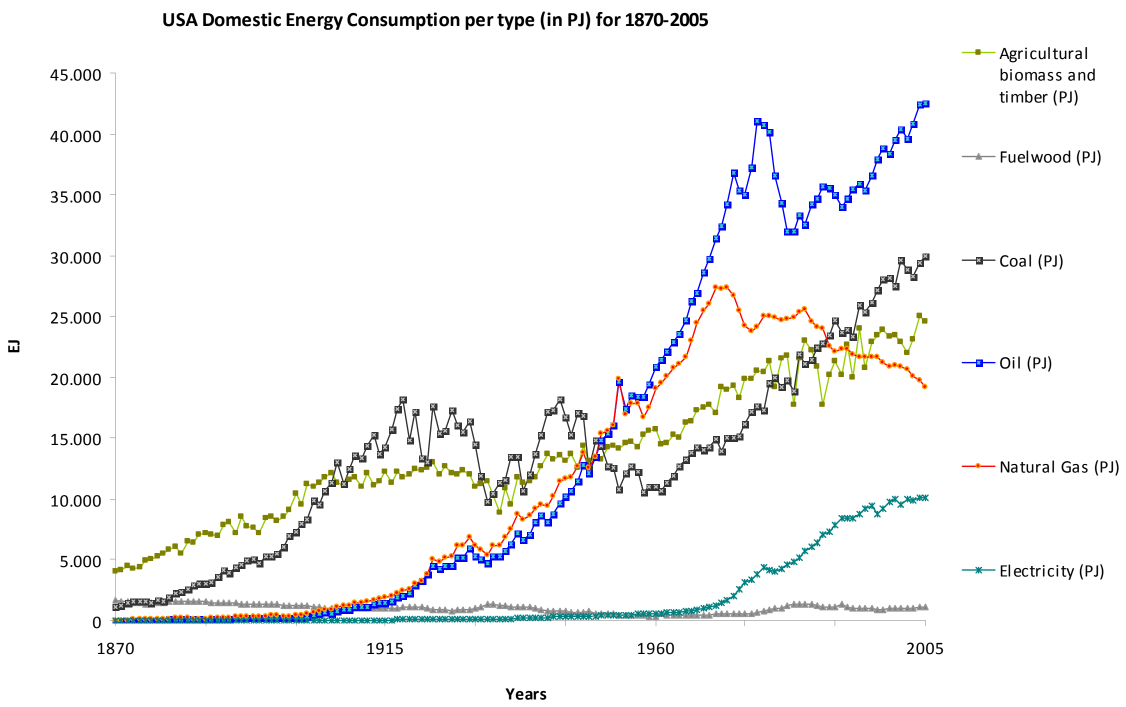


Figure 6.14 *USA Domestic energy consumption in PJ, per energy type, for 1870-2005*

[16] At least for the period examined in this section (until 2005). However, after 2009, China takes the lion's share in total Primary energy Consumption, yet US economy remain the largest economy of the world according 2012 GDP estimations of the World Bank.

The oil and natural gas consumption remain relatively lower through the aforementioned period. The period of the so-called "*Great Depression*[17]" (1929-1932) is characterized by sheer decreasing trends of all the utilized energy resources. The year 1950, however, signals a strong increment in energy consumption trends. The oil and the natural gas become the predominant energy sources, while coal and biomass consumption increase as well, after 1958. Evidently, after WWII the US economy is characterized by a massive industrialization, infrastructure building and, hence, excessive energy consumption. The oil shocks of 1973 and 1979 are clearly depicted in oil consumption trends; evidently, a soft disturbance in oil consumption is observed in 1973, followed by a prolonged oil consumption decline, after the severe disturbances caused by the second oil crisis, to the oil market. The aftermaths of the second oil shock lasted until 1983, where a constant increase in oil consumption is observed, until the end of the examined period (2005). On the other hand, natural gas consumption follows a declining trend after 1972, shortly interrupted only during 1976-1985. Coal consumption increases constantly since 1958, while agricultural biomass and timber consumption depicts a general increasing trend. Electricity consumption increases progressively from 1960. Finally, fuel-wood consumption remains in relatively low levels, compared to the other energy inputs.

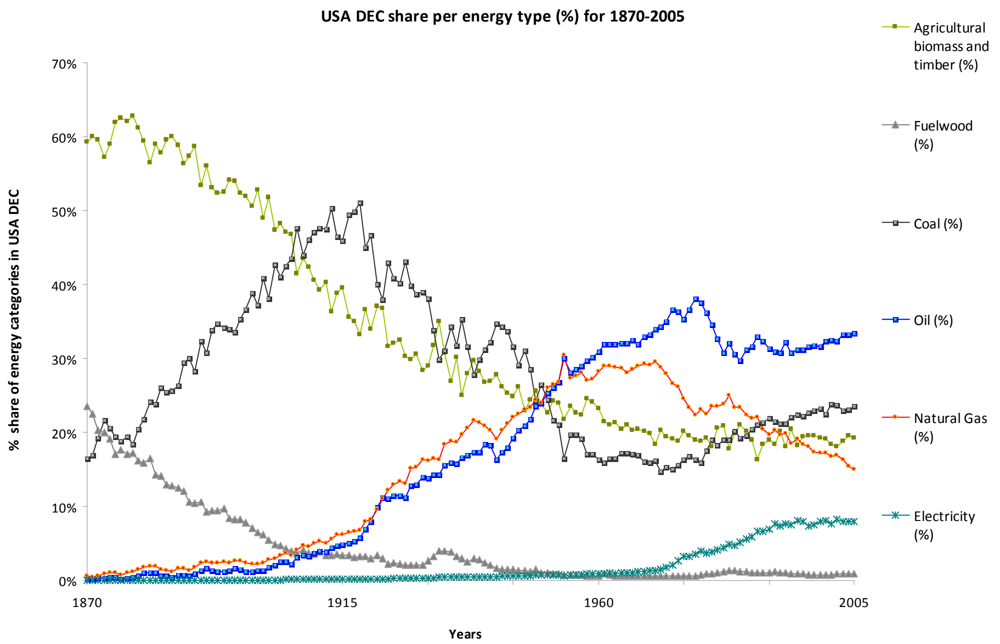


Figure 6.15 *USA share (%) of each energy type in total US Domestic energy consumption, for 1870-2005*

[17] The economic crisis followed the collapse of the Wall Street's stock market, in 1929, is broadly known since then as the Great Depression.

Figure 6.15 presents the percentage (%) contribution of each energy type to the total US domestic energy consumption (DMC). These trends will be discussed in detail in the section which disaggregates the energy intensity of each energy resource type.

USA Energy intensity and per capita DEC consumption, for 1870-2005

This section estimates the decoupling of the US domestic energy consumption from the US economic growth (in terms of GDP and GDP per capita), for 1870-2005 period. Figure 6.16 presents the estimations of the standard Energy Intensity (EI) DEC/GDP indicator and the proposed DEC/[GDP $_{\text{per Capita}}$] indicator, respectively. Additionally, it estimates and compares the DMC$_{\text{per capita}}$ ratio with the two EI indicators. In order to eliminate the different scale that all examined indicators form, and allow comparisons among them, all ratios are indexed into a base year (1870=100). Indexing process performed as i.e.:

$$\text{Indexed value of 1871} = 100 + \frac{(\$value\_1871 - \$value\_1870)}{\$value\_1870} \qquad (3)$$

, where \$value 1870 remains constant for all time series, as being the base year.

The standard EI DEC/GDP indicator (marked with the blue line) presents a relative stability in 1880-1920. The WWII period is characterized by a strong EI decline, lasting until the end of WWII in 1945. The short period of EI increment, during 1946-1948, is followed by a constant a continuous decreasing of EI, until 2005. On the other hand, the proposed DEC/[GDP $_{\text{per Capita}}$] indicator presents a dissimilar evolutionary path. Specifically, the proposed indicator (marked with the red line) results in a massive EI increase, during 1870-1923. The period 1933-1944 (Great Depression and WWII) results in a strong EI reduction. Nevertheless, the period 1945-1948 depicts again a strong EI increase, followed by a relative stability in 1949-1977. After 1977, and until the end of the examined period in 2005, the DEC/[GDP $_{\text{per Capita}}$] ratio presents a constant EI reduction. A close look into the DMC $_{\text{per capita}}$ (the grey line in Fig 6.16) reveals that both DEC/[GDP $_{\text{per Capita}}$] and DMC $_{\text{per capita}}$ ratios follow a similar pattern for the period 1870-1929, while evolve in stark contrast during the Great Depression and WWII periods. Further, it should be also denoted that while DEC/[GDP $_{\text{per Capita}}$] ratio results in a relatively stable trend, during 1959-1979, the DEC $_{\text{per Capita}}$ ratio, on the contrary, depicts a strong increase of the per capita DEC for the same period. Similarly, while the DEC/[GDP $_{\text{per}}$

Capita] ratio constantly decreases in 1985-2005 period, the DEC per Capita ratio shows a relative stability.

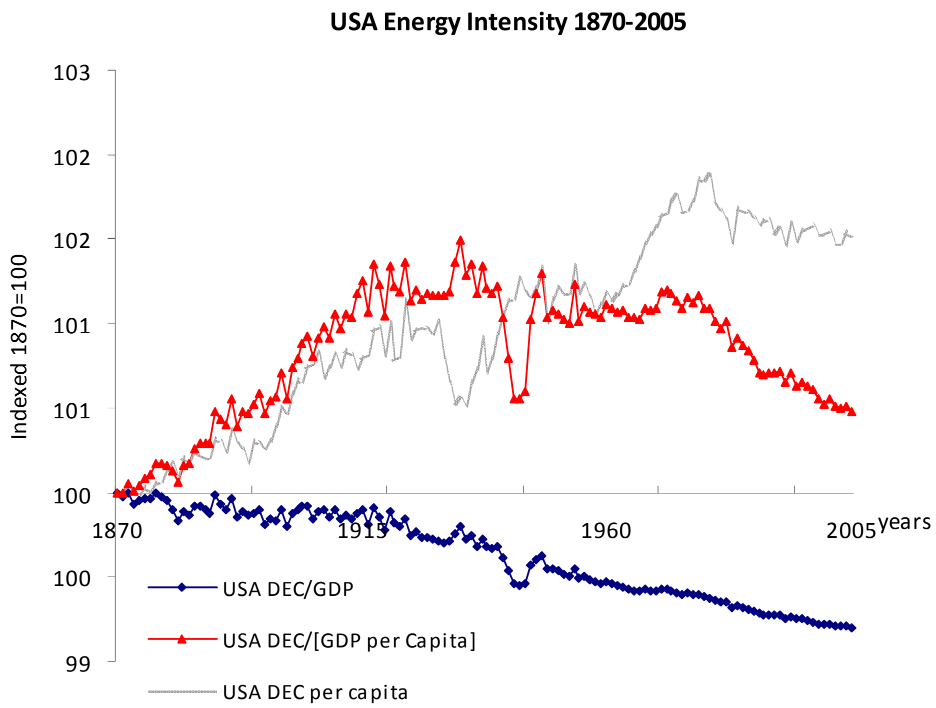


Figure 6.16 *The per capita DEC consumption and energy intensity of the US economy estimated by the standard DEC/GDP and the proposed DEC/ [GDP per Capita] indicators (all indexed 1870=100), for 1870-2005.*

Estimating the divergence between the standard DEC/GDP and the proposed DEC/[GDP per Capita].

A crucial step beyond the initial indexing to a base year would be the essential estimation of the different evolutionary path in which both EI indicators are evolved. Towards this objective, an alternative analysis will be applied in order to reveal the difference between the two indicators. In Fig 6.17 we estimate the divergence and the percentage changes of the standard DEC/GDP and the proposed DEC/[GDP per Capita]. Divergence[18] is defined as:

Divergence = (% change of DMC/[GDPpc]) – (% change of DMC/GDP) (*4*)

[18] The difference between the divergence estimates in the 5th Chapter is that here we take the difference of the percentage changes of the two variables from the base year, instead of their difference from 100, as the value of base year. Actually, the result remains indifferent of whether the method will be applied as it was presented in Chapters 4-5 or as it is applied in Chapter 6.

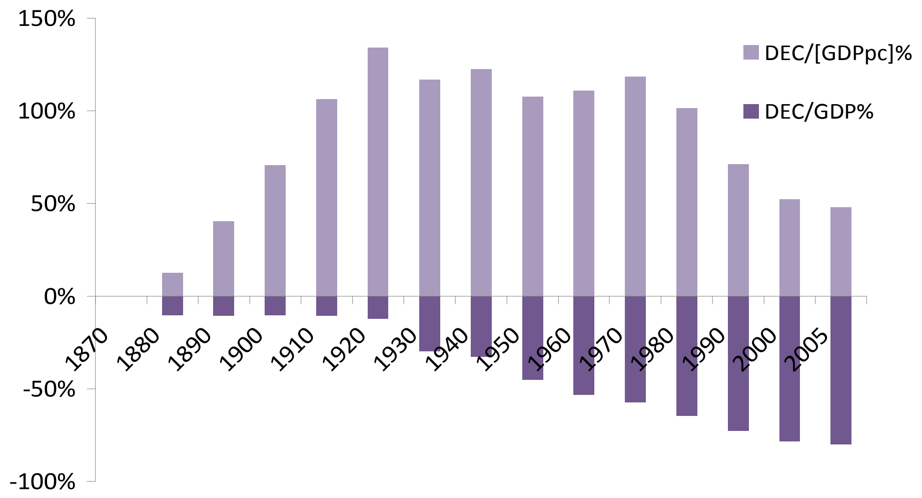


Figure 6.17 *The divergence between indexed DEC/GDP and DEC/[GDP $_{per\ Capita}$] ratios, and the percentage (%) change of each indicator from 1870 as a base year, for 1870-2005.*

Figure 6.17 shows the estimated divergence between the two indicators Evidently, for the greatest part of 1870-1939, most of the divergence's proportion is the result of DEC/[GDP $_{per\ Capita}$] evolution. The WWII period results in a period with 50% contribution of both indicators to divergence. The 1947-1987 period marks the continuous declining contribution of DEC/[GDP $_{per\ Capita}$] to divergence, with the simultaneous increased contribution of DEC/GDP. The year 1987 sets a turning point in the contribution of divergence, since the DEC/GDP increases its contribution to divergence, while DEC/[GDP $_{per\ Capita}$] constantly decreases.

The US Decoupling ratio and the Decoupling factor (proposed by OECD), for 1870-2005.

The previous sections displayed the decoupling effect by plotting the two indexed indicators on the same graph. A second level of analysis has been applied in order to evaluate the divergence between the different patterns the two indicators result in. However, it goes without saying that it is still not clear whether the occurred decoupling is a relative or an absolute one. For that purpose, this section estimates the proposed by OECD (2002) Decoupling ratio and the, derived from the former ratio, Decoupling factor. The Decoupling ratio is the ratio of the value of the decoupling indicator at the end and the start of a given time period and defined as follows (*OECD, 2002-p.19*):

$$Decoupling\_Ratio = \frac{(EP / DF)_{end-of-period}}{(EP / DF)_{start-of-period}} \quad (5)$$

Where EP=Environmental Pressure = DEC, in current example; and DF= Driving Force = GDP and GDP per capita, in current example.

The Decoupling Ratio is estimated in fig 6.18.a. If the ratio is less than 1, decoupling has occurred during the examined period. Since Decoupling ratio does not indicate whether decoupling was absolute or relative, OECD (2002) proposes a next level of analysis, the Decoupling Factor which is defined as (*OECD, 2002-p.20*):

$$\text{Decoupling Factor} = 1 - \text{Decoupling Ratio} \quad (6)$$

The Decoupling Factor, estimated in fig. 6.18.b, is zero or negative in the absence of decoupling and has a maximum value of 1, when environmental pressure (DEC in current case study) reaches zero

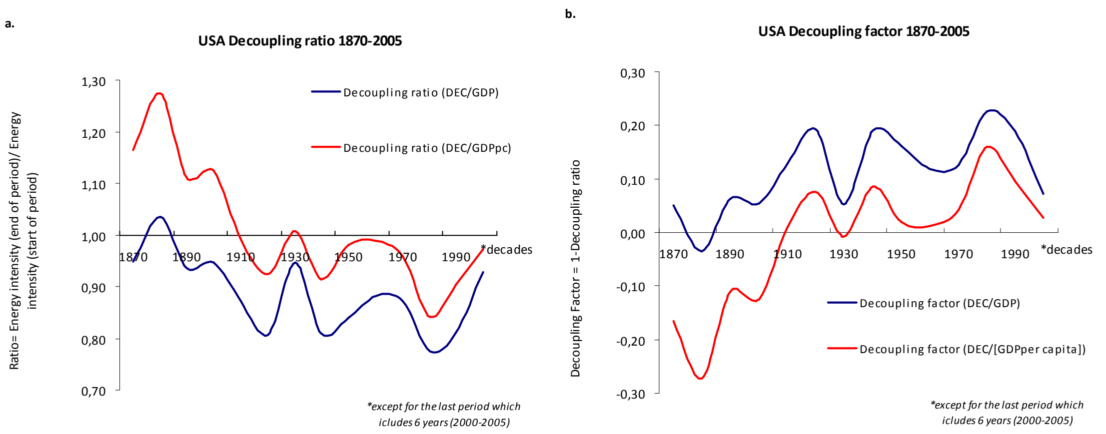


Figure 6.18 *a) The estimation of Decoupling ratio, and b). The estimation of Decoupling Factor, of DEC of USA during 1870-2005.*

The US Decoupling Index, for 1870-2005.

In this section, the Decoupling Index (DI) proposed by UNEP (2011) is estimated[19] for USA. Specifically, fig 6.19 depicts the DI for both the standard DEC/GDP and the proposed DEC/[GDP $_{\text{per Capita}}$] indicators, respectively. Evidently, the DI $_{\text{DEC/GDP}}$ (the blue line in fig. 6.19) results in relative decoupling (values below 1) for the most of 1870-2005. Further, an extreme value of absolute decoupling (DI=-1.45) can be traced for 1930-1940 decades. In conclusion, only a short non-decoupling period can be traced for DI $_{\text{DEC/GDP,}}$ during 1900-1910.

On the contrary, the DI $_{\text{DEC/[GDPpc]}}$ presents mainly two coupling periods (1870-1930 and 1950-1980), while a short relative decoupling period can be traced during 1930-1940. However, special focus should be given in the period 1980-2005, where both DI $_{\text{DEC/GDP}}$ and DI $_{\text{DEC/[GDPpc]}}$ follow similar relative decoupling pattern.

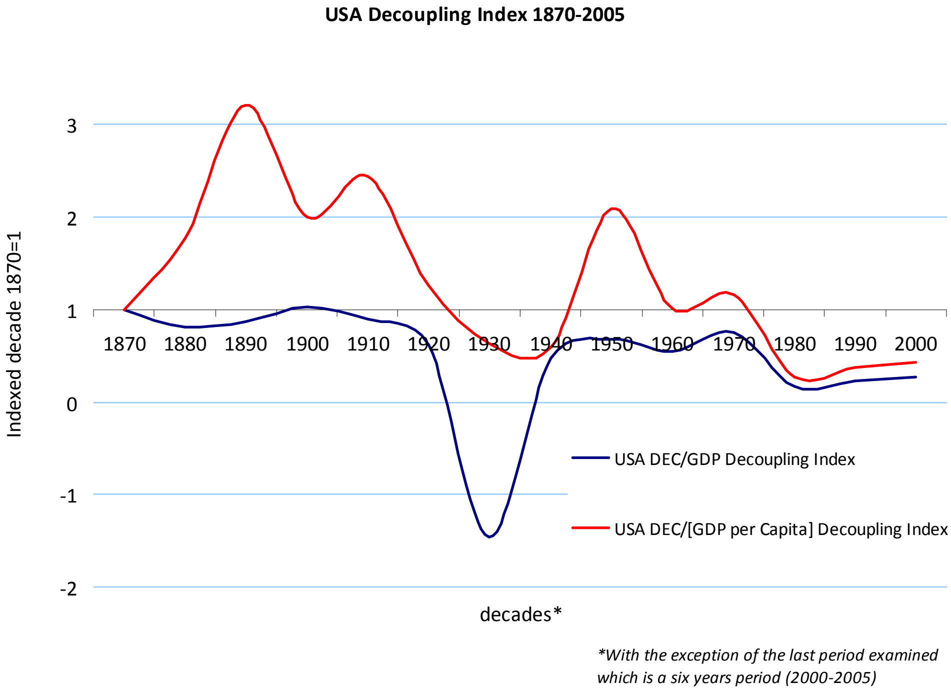


Figure 6.19 *The estimation of USA Decoupling Index, 1870-2005.*

19 For the methodological context of Decoupling Index estimation, see Chapter 3.

USA disaggregated energy intensity and per capita consumption for each energy type, for 1870-2005

This section estimates the disaggregated EI for each individual energy sources. In brief, the left hand sited diagrams present the total and the per capita consumption of the specific energy type, both indexed into a base year (1870=100). Similarly, the right hand sited diagrams present the estimations of both the standard and the proposed EI indicators for the specific energy type, indexed (1870=100). Evidently, with the exception of natural gas consumption, the US domestic consumption of all energy types increases through recent economic history. If we accept the verity that the per capita consumption of energy resources approximately reflects the biophysical attributes of actual economic process, then an intrinsic merit is revealed for the proposed indicator; it is a better approximation of the energy intensity that actual production has. This is reflected into the similar evolutionary pattern, the per capita consumption and the proposed EI indicator result in, for most of the examined cases.

Furthermore, a comparison between fig. 6.16, which depicts the percentage share of each energy type into the total US DEC, and the disaggregated EI figures of this section, reveals an important trend; when the share of an energy type declines, there is a simultaneous decoupling trend depicted in the EI indicators and vice-versa. This observation can be summarized as: decoupling occurred when the share of the specific energy source consumption declines too, while coupling seems to be occurred when the share of the specific energy source consumption increases as well.

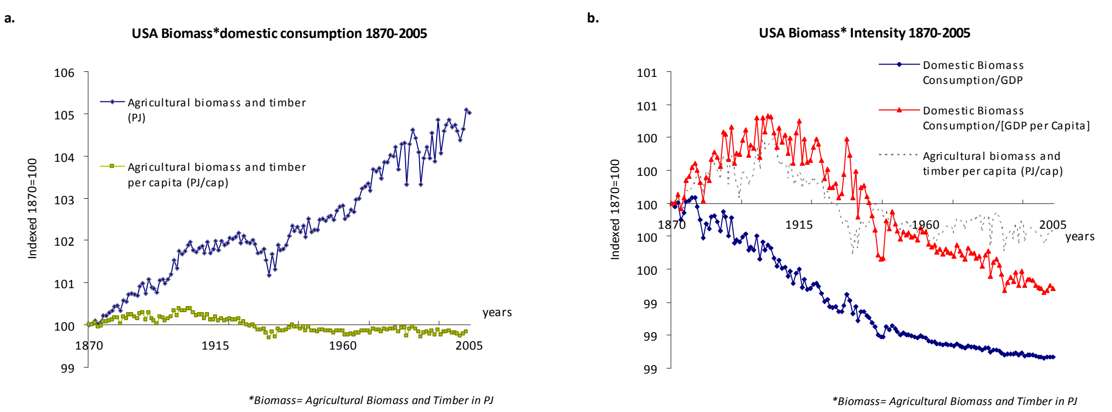


Figure 6.20 *a) Biomass total and per capita consumption; and b) biomass intensity, in USA for 1870-2005 (Indexed 1870=100).*

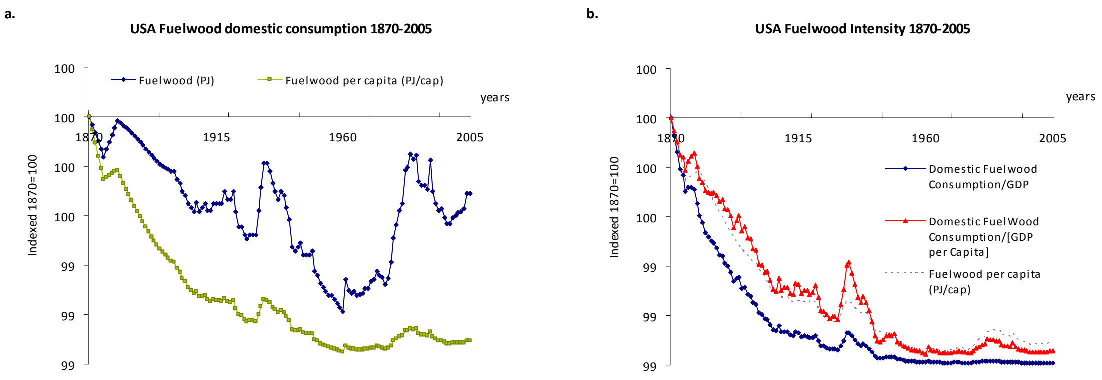


Figure 6.21 *a) Fuel-wood total and per capita consumption; and b) fuel-wood intensity, in USA for 1870-2005 (Indexed 1870=100).*

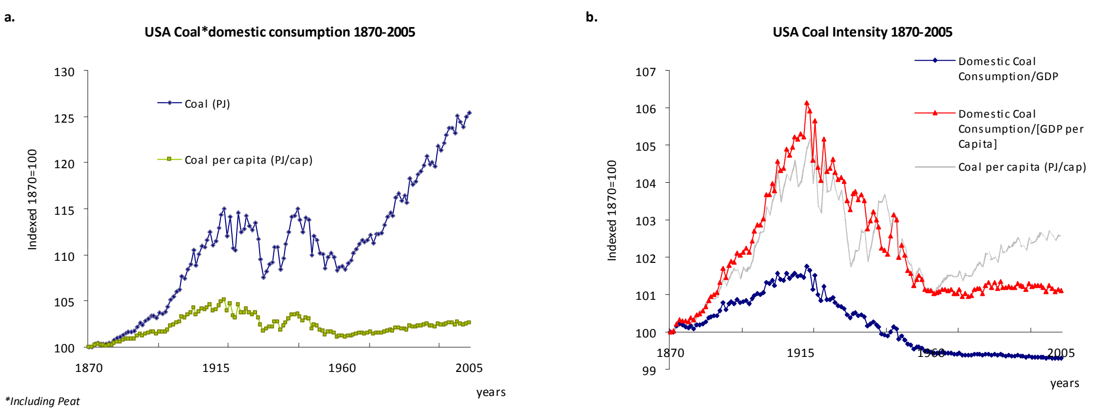


Figure 6.22 *a) Coal total and per capita consumption; and b) coal intensity, in USA for 1870-2005 (Indexed 1870=100)*

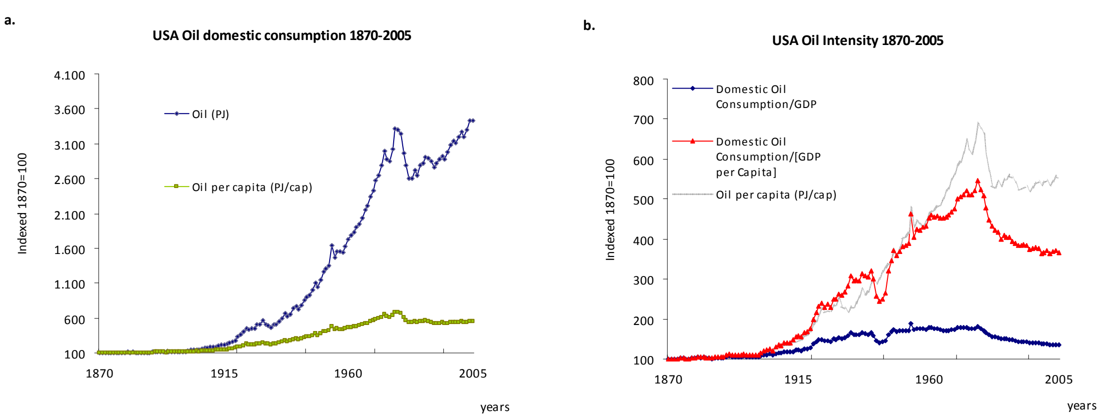


Figure 6.23 *a) Oil total and per capita consumption; and b) oil intensity, in USA for 1870-2005 (Indexed 1870=100)*

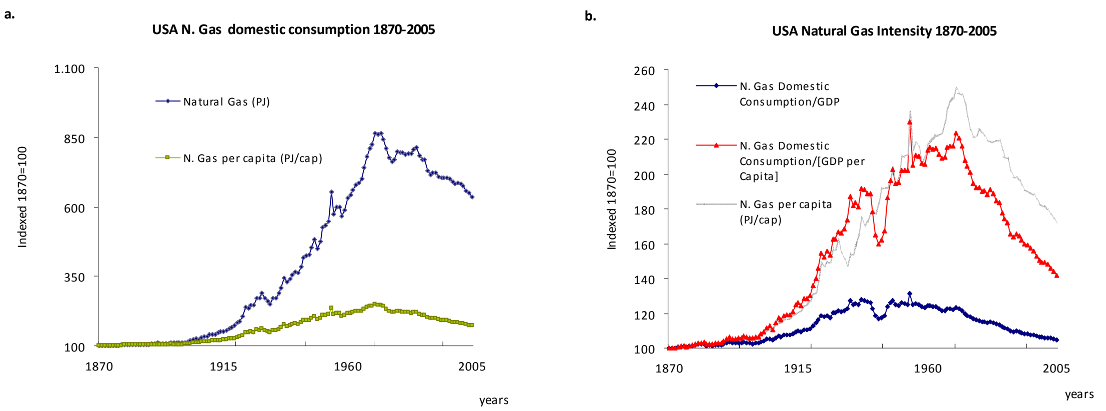


Figure 6.24 *a) N. gas total and per capita consumption; and b) n. gas intensity, in USA for 1870-2005 (Indexed 1870=100)*

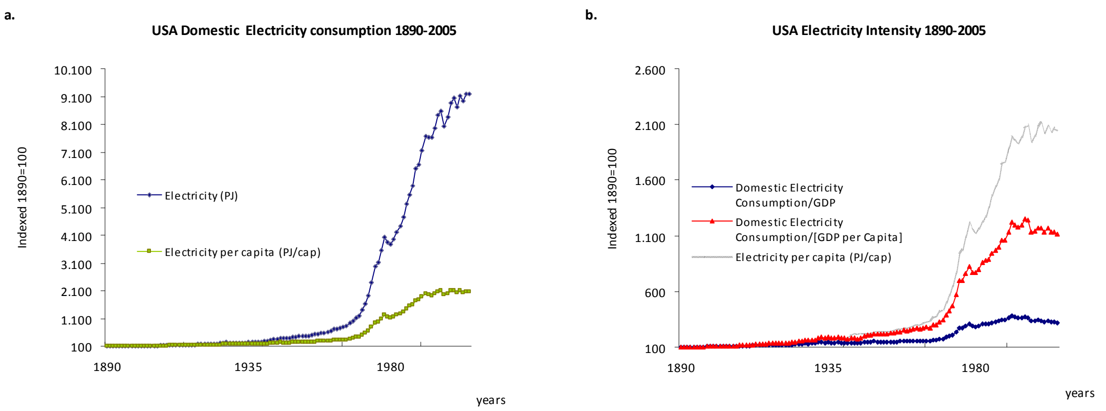
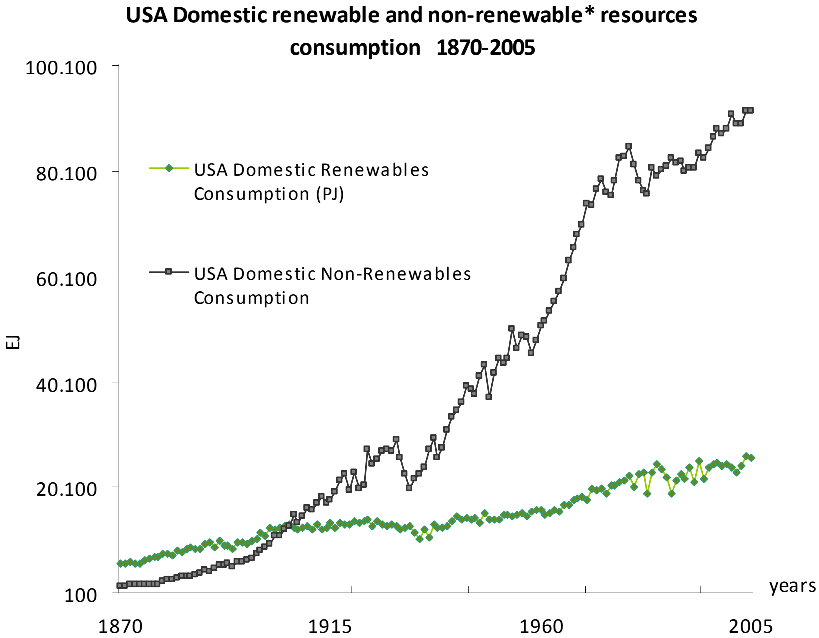


Figure 6.25 *a) Electricity total and per capita consumption; and b) electricity intensity, in USA for 1890-2005 (Indexed 1870=100)*

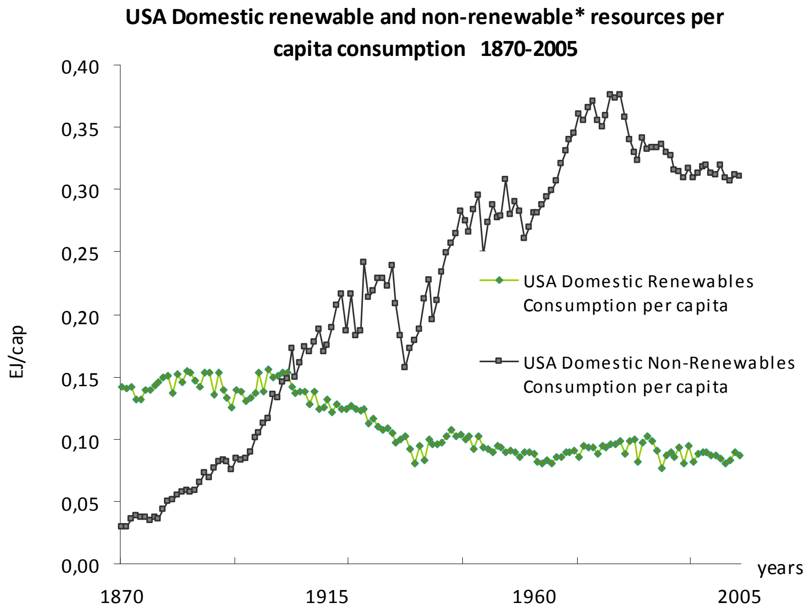
USA renewable and non-renewable energy consumption for 1870-2005

The transition of the US economy, from the agrarian stage of development to the highly industrialized developed nation of today, is clearly depicted in fig. 6.26. The year 1906 is a milestone that signals the transition from the renewable energy resources consumption, to the non-renewable era of fossil fuels consumption. As far as the per capita consumption concerned, the fig. 6.27 shows a decline in the per capita consumption of the non-renewable resources, during 1979-2005, while the per capita consumption of the renewable resources present a relative stability during 1962-2005. Nevertheless, despite the fact that the per capita level of non- renewable resources consumption declines, the total non-renewable resources consumption continues to increase drastically.



** Electricity consumption is not included in either of both natural resources categories due to lach of data concerning the proportion of electricity produced from renewable and non-renewable resources, respectively.*

Figure 6.26 *Domestic consumption of renewable and non-renewable energy resources, in USA for 1870-2005.*



** Electricity consumption is not included in either of both natural resources categories due to lach of data concerning the proportion of electricity produced from renewable and non-renewable resources, respectively.*

Figure 6.27 *Domestic per capita consumption of renewable and non-renewable energy resources, in USA for 1870-2005.*

6.5.6 Energy Intensity of Japan for 1878-2005

Japan is examined and evaluated as a second representative case study of a highly developed post-industrial economy. What is more, Japan is considered to be an exceptional example of absolute dematerialization over a prolonged period, as it is asserted by recent studies (*Krausmann et al., 2011; UNEP, 2013*). This section estimates the energy intensity of the Japanese economy and the observed divergence between the standard and the proposed EI indicator, explores its energy consumption trends per energy type, investigates the different consumption patterns of the renewable-nonrenewable energy resources, and evaluates the potential decoupling trends through the estimation of the decoupling factor and the decoupling index.

Japan's Domestic energy consumption for 1878-2005

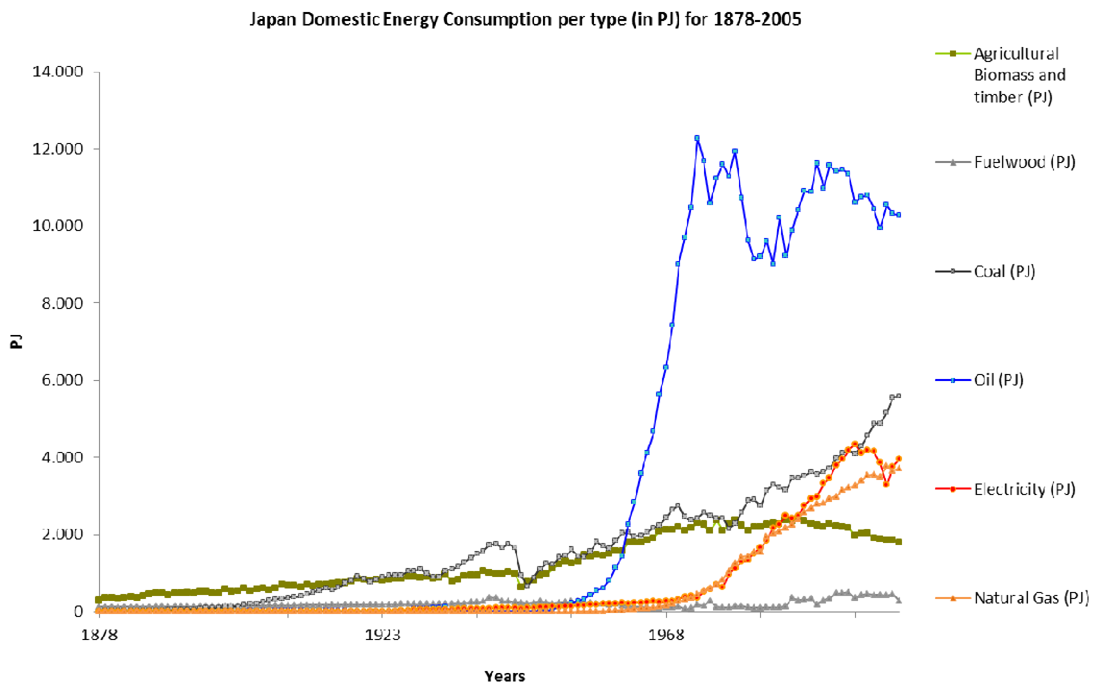


Figure 6.28 *Japan's Domestic Energy Consumption per energy type, in EJ, for 1878-2005.*

Figure 6.28 presents the domestic energy consumption per energy type of Japan, during 1878-2005. Oil's domestic consumption increases dramatically during 1950-1973, marking the massive industrialization followed the postwar period. Nevertheless, the consequences of two oil shocks (1973; 1979) are depicted in the reductions observed in oil consumption during 1973-1985. A short period of increment (1986-1992) is followed by a constant decline of oil consumption during 1993-2005. On the other hand, natural gas and coal consumption present a constant increasing trend from 1970s until the end of the examined period (2005). Finally, biomass consumption is decreasing smoothly from the mid-1980s on, while wood-fuel use smoothly increases after 1988, and the increment of electricity consumption is briefly interrupted during 2000-2003 to start increasing again.

Figure 6.29 presents the contribution of each energy type to the aggregate Japanese DMC. These trends will be discussed later on, in the section of disaggregated EI per energy resource type.

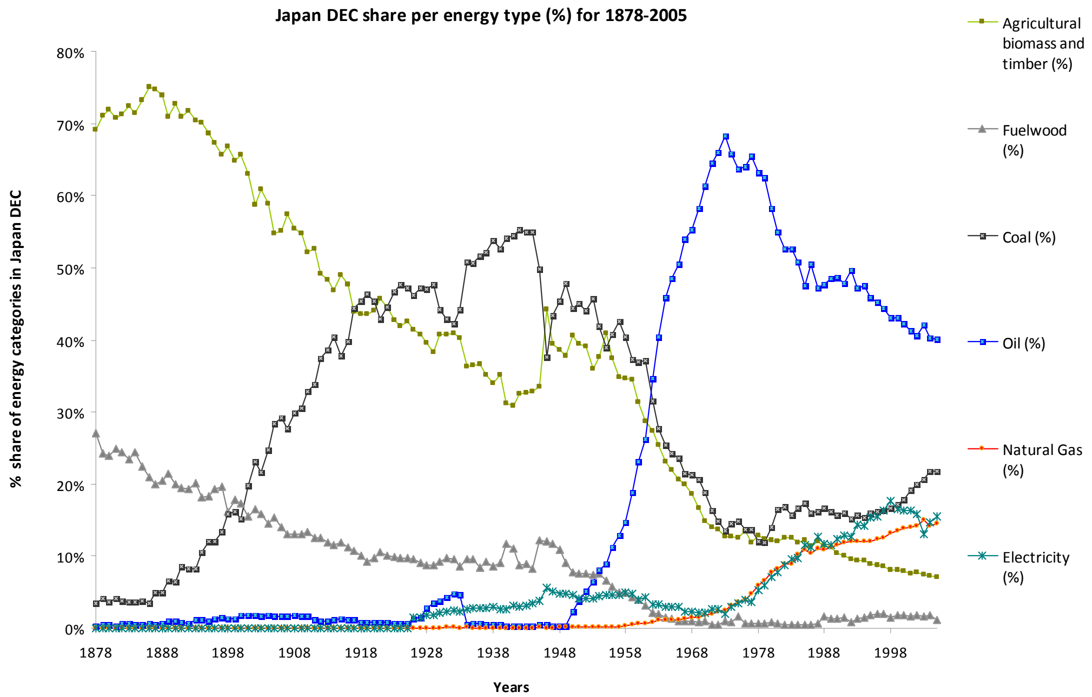


Figure 6.29 *Percentage (%) share of each energy type to the total Japanese DEC , for 1878-2005.*

Japan's Energy intensity and per capita DEC consumption, for 1878-2005

Figure 6.30 estimates the EI of the Japanese economy with the standard DEC/GDP and the proposed DEC/[GDP $_{per\ Capita}$], both indexed into a base year (1878=100). Evidently, a significant difference in the way both indicators evolve is depicted in fig. 6.30. The standard EI DEC/GDP indicator, with the exception of an increasing EI period during 1878-1914, generally results in a fluctuated decreasing EI trend. Finally, during 1985-2005 presents a relative stability. On the contrary, the proposed DEC/[GDP $_{per\ Capita}$] indicator mainly results in an increasing EI throughout 1878-1973, only briefly interrupted by a period of relative stability (1930-1943) and a declining period (1950-1958). The period 1974-1982 signals a strong decoupling trend, followed by a relatively stable period until 2005.

Figure 6.31 presents the Japanese DEC $_{per\ capita}$. The per capita DEC of Japan shows a dramatic decrease during 1941-1945 (WWII), reflecting the devastating consequences of the WWII on the Japanese economy. The postwar period is characterized by an increasing DEC $_{per\ capita}$, interrupted during 1973-1981 (the two Oil crises period), to increase again until 1996. Since 1997 and until 2005, DEC $_{per\ capita}$ presents a fluctuated stability.

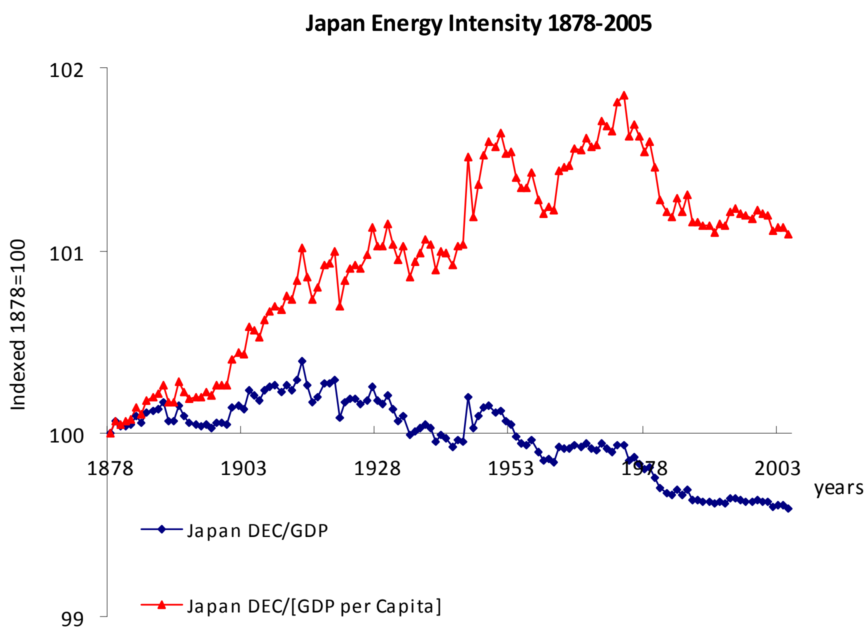


Figure 6.30 *The Energy Intensity of Japan, estimated with DEC/GDP and DEC/[GDP $_{per\ Capita}$] indexed (1878=100) , for 1878-2005.*

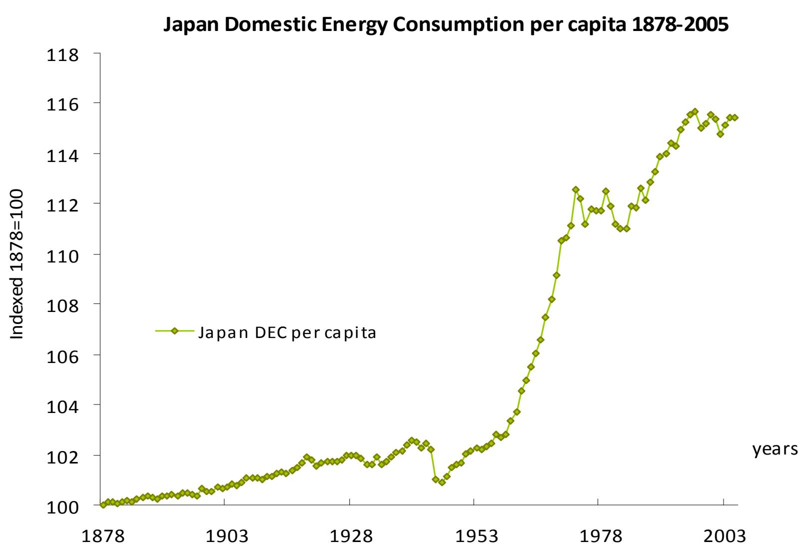


Figure 6.31 *The Japanese DEC $_{per\ Capita,}$ indexed (1878=100) , for 1878-2005.*

Estimating the divergence, and the percentage change of the standard DEC/GDP and the proposed DEC/[GDP $_{per\ Capita}$].

This section estimates the divergence between the percentage change of the standard DEC/GDP and the proposed DEC/[GDP $_{per\ Capita}$] from 1880 as base year, for Japan (fig. 6.32).

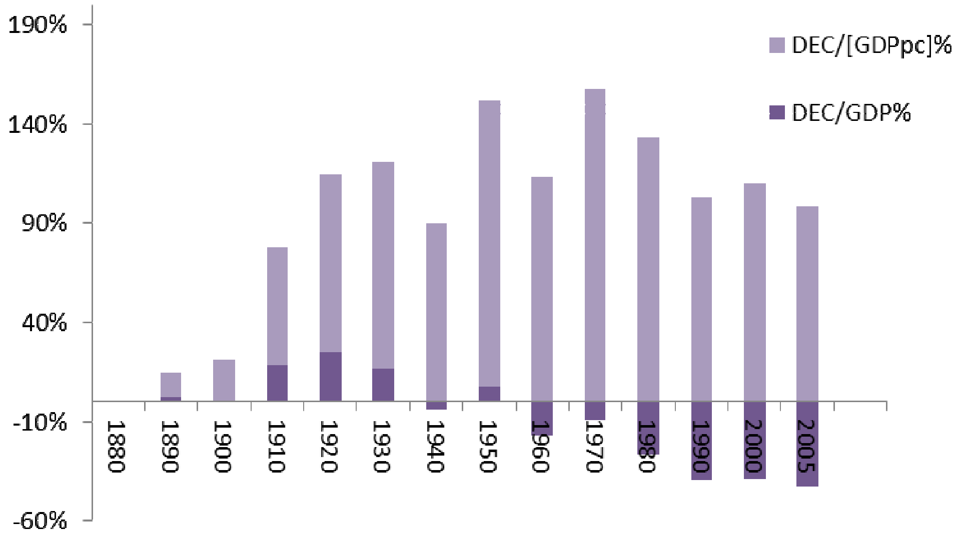


Figure 6.32 *The divergence of the percentage change of DEC/GDP and DEC/[GDP $_{per\ Capita}$] ratios from 1880=base year, for 1880-2005.*

Japan's disaggregated energy intensity and per capita consumption for each energy type, for 1878-2005

We further disaggregate the Japanese DEC to its energy components. Figures 6.33-6.38 present the total and the per capita consumption of the relevant energy source (the a. part of each diagram), while the b. part of each diagram presents the energy intensity estimation of the indicative energy source, performed by both the standard as well as the proposed EI framework. Total Biomass consumption has peaked in 1988 and decreases constantly since 2005, while per capita biomass consumption peaked in 1973. Both the standard and the proposed EI indicators depict a declining biomass intensity trend, after 1973. On the other hand, the Japanese total, and the per capita, wood fuel consumption peaked quite recently (1997), something that is depicted by both EI indicators; the result in a stable and a smoothly increasing wood fuel intensity trend for 1971-2005. As far as the fossil fuels concerned, coal and natural gas total (and per capita) consumption, continuously increases after WWII and specifically throughout the 1950-2005. While coal intensity, estimated by the proposed EI indicator, presents decreasing trend for the period 1950-1980, however, after 1990 depicts an increment in coal intensity. On the other hand, the natural gas intensity constantly increases, as depicted by both EI indicators. Finally, the total and per capita oil consumption results in fluctuations after 1973, probably due to the two oil shocks occurred in 1973 and 1979, respectively. These declining trends of oil consumption (and intensity) explained partially by the increasing coal and natural gas consumption trends, which gradually substitute oil use. Yet, it should be underlined that Japan is considered to be a pioneer in energy efficiency policies and institutions, which could explain some of the observed EI declining trends. Nevertheless, concerning Japan's energy flows and EI trends, no substantial evidence for absolute energy decoupling trends can be traced.

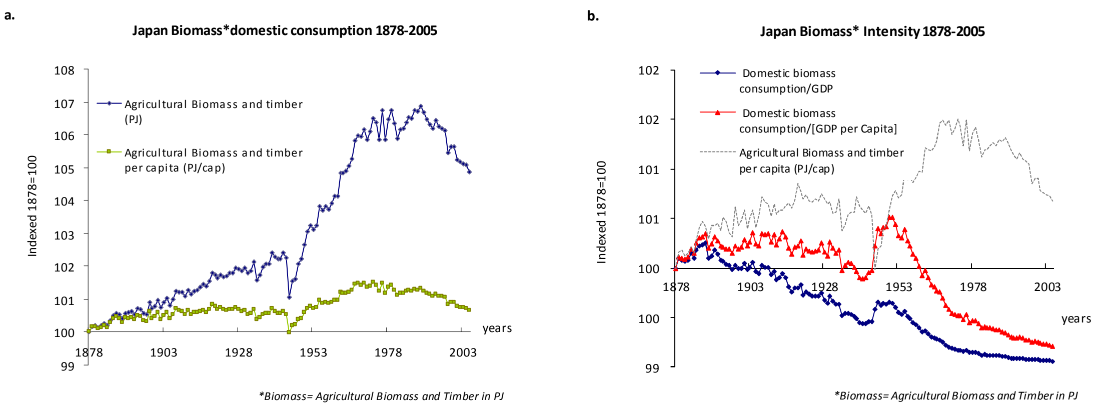


Figure 6.33 *a) Biomass total and per capita consumption; and b) biomass intensity, in Japan for 1878-2005 (Indexed 1878=100).*

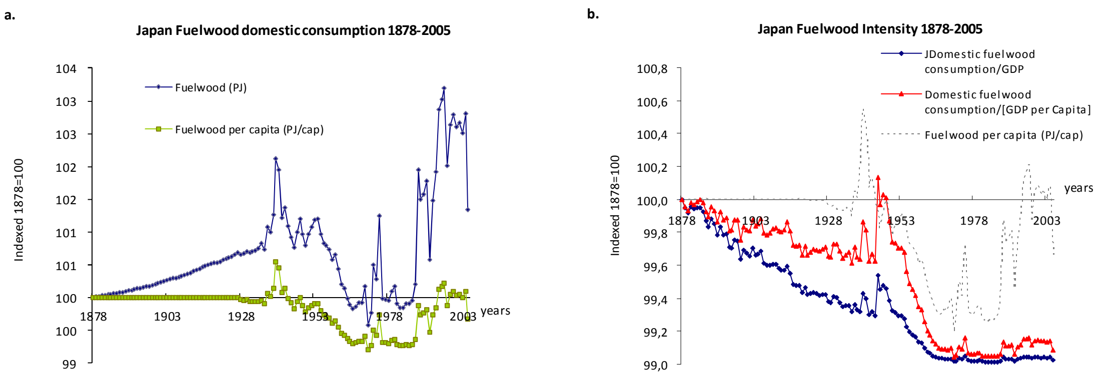


Figure 6.34 *a) Fuel-wood total and per capita consumption; and b) fuel-wood intensity, in Japan for 1878-2005 (Indexed 1878=100).*

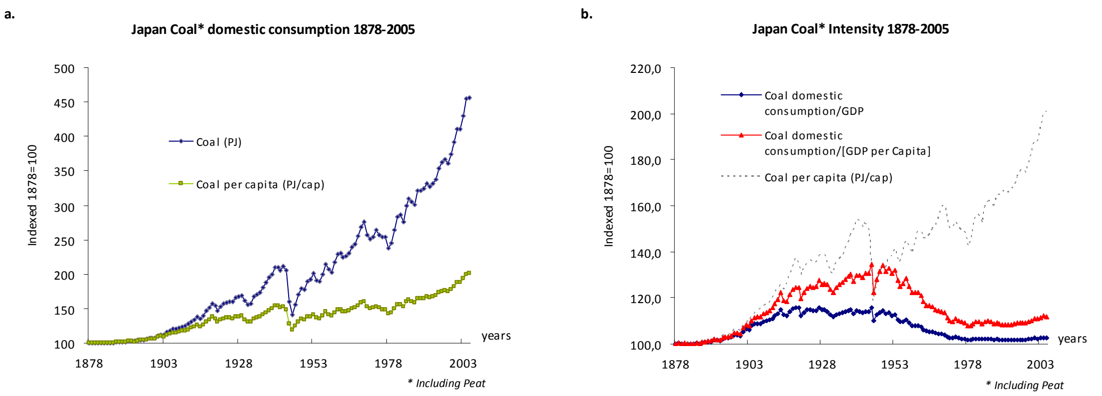


Figure 6.35 *a) Coal total and per capita consumption; and b) coal intensity, in Japan for 1878-2005 (Indexed 1878=100).*

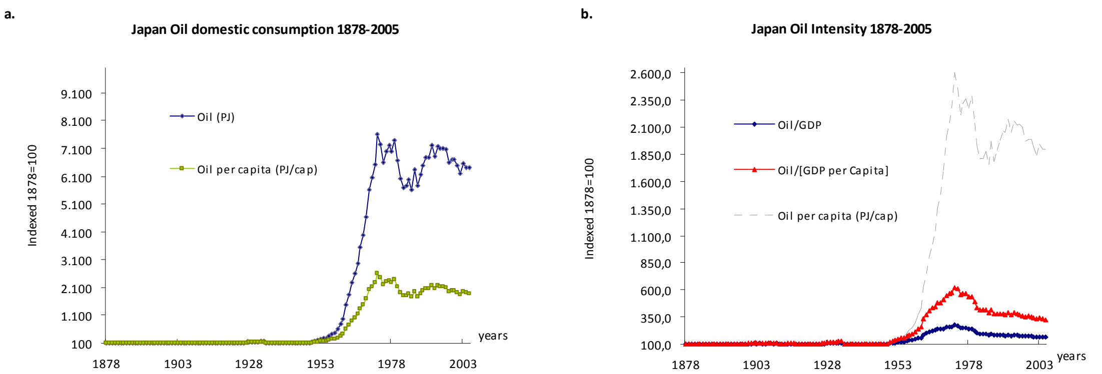


Figure 6.36 *a) Oil total and per capita consumption; and b) oil intensity, in Japan, for 1878-2005 (Indexed 1878=100).*

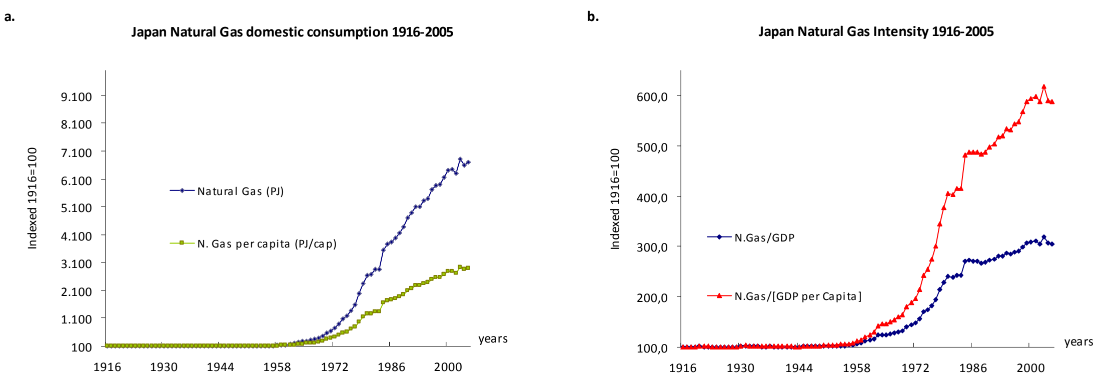


Figure 6.37 *a) N. gas total and per capita consumption; and b) n. gas intensity, in Japan, for 1878-2005 (Indexed 1878=100).*

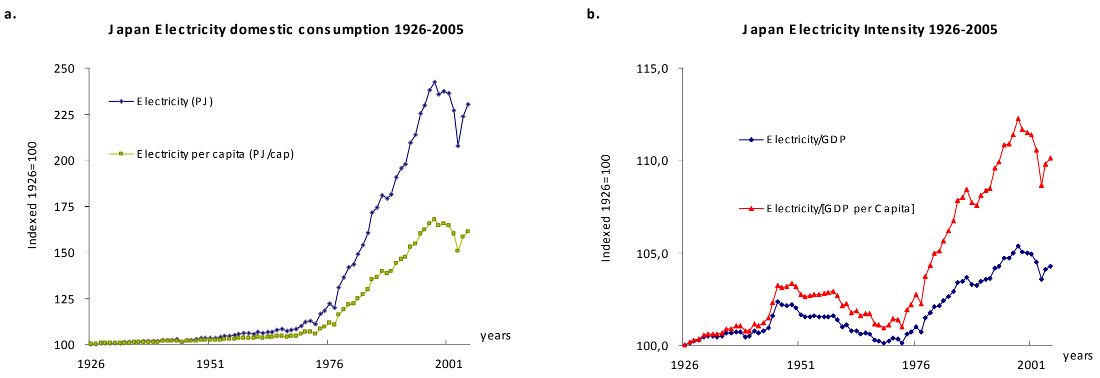
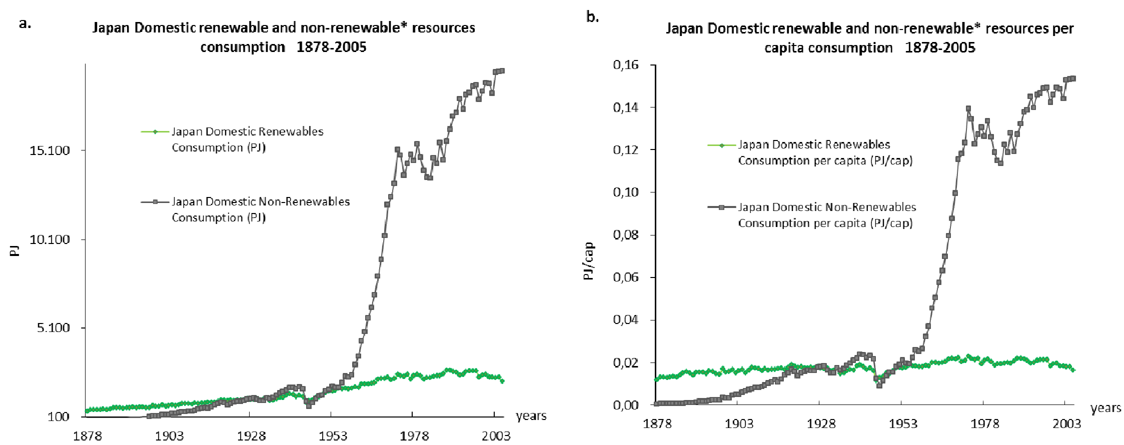


Figure 6.38 *a) Electricity total and per capita consumption; and b) electricity intensity, in Japan for 1926-2005 (Indexed 1926=100).*

Japan's renewable and non-renewable energy consumption (total and per capita), for 1878-2005

As a highly advanced post-industrial economy, Japan has accomplished the transition from the agrarian economy to the industrial one, many decades ago. Evidently, the consumption of non-renewable resources takes progressively the lion's share after 1925, to result in a dramatic take off, after 1950. The total renewable consumption increases constantly throughout the period examined, displaying a smooth reduction only during the last examined decade (1995-2005) (Fig 6.39a). On the other hand, the per capita renewable resources consumption remains stable throughout the examined period, depicting a smooth decline during 1995-2005 (Fig. 6.39b).



** Electricity consumption is not included in either of both natural resources categories due to lach of data concerning the proportion of electricity produced from renewable and non-renewable resources, respectively.*

** Electricity consumption is not included in either of both natural resources categories due to lach of data concerning the proportion of electricity produced from renewable and non-renewable resources, respectively.*

Figure 6.39 *a) Japan's domestic renewable and nonrenewable resources consumption (in PJ); b) Japan's per capita domestic renewable and nonrenewable resources consumption (PJ/cap), for 1878-2005*

The Japanese Decoupling ratio and the Decoupling factor (proposed by OECD), for 1880-2005

This section estimates the proposed by OECD (2002) Decoupling ratio and the Decoupling factor. The Decoupling Ratio (DR) is estimated in fig 6.40.a. For DR values less than 1, decoupling has occurred during the examined period. At this first stage we can see clearly the periods that decoupling occurred for both the standard and the proposed EI indicator. Evidently, figure 6.40a. depicts several periodically repeated periods of both decoupling and not decoupling, for both EI indicators, respectively.

The Decoupling Factor (DF) is estimated in fig. 6.40.b. The DF value is zero or negative in the absence of decoupling and has a maximum value of 1, when environmental pressure (DEC in current case study) reaches zero. Figure 6.40b depicts several fluctuated periods of both decoupling and not decoupling, for both EI indicators, a periodical trend that seems to move smoothly onwards, thus to the defined area (0<decoupling<1) of decoupling.

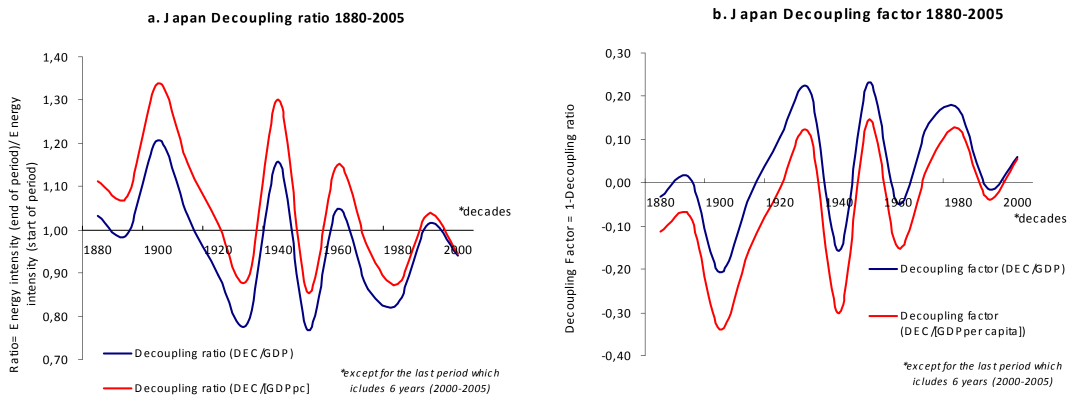


Figure 6.40 *a) The estimation of Decoupling ratio, and b). The estimation of Decoupling Factor, for Japan, during 1880-2005.*

The Japanese Decoupling index (proposed by UNEP), for 1870-2005.

Figure 6.41 estimates the Decoupling Index (DI), proposed by UNEP (2011), for both the standard (DEC/GDP) and the proposed (DEC/[GDP $_{per\ Capita}$]) EI indicators. The standard EI indicator results in one coupling period (1890-1920). However after 1920, the DI (DEC/GDP) evolves in the “relative decoupling” area (1>DI>0) throughout the rest of the examined period (1930-2000). Nevertheless, an exception could be traced during 1960-1970 decades, where DI values are extremely close to 1, which is defined as the “boarder line” between relative decoupling and coupling. On the contrary, the DI estimated for the proposed EI indicator (DEC/[GDP $_{per\ Capita}$]), results in a dissimilar evolutionary path. Evidently, DI (DEC/[GDP $_{per\ Capita}$]) results in a continuous coupling relationship during 1880-1970. However, during 1980’s and until 2000’s, both the standard and the proposed EI indicators show similar trajectories and result in relative decoupling, respectively. Remarkably though, DI does not revealed any “absolute decoupling” period either for the standard of for the proposed indicator, contrary to the contemporary literature asserting that Japan is probably a typical example of a country that performs an absolute decoupling (*Krausmann et al., 2011; UNEP, 2011*).

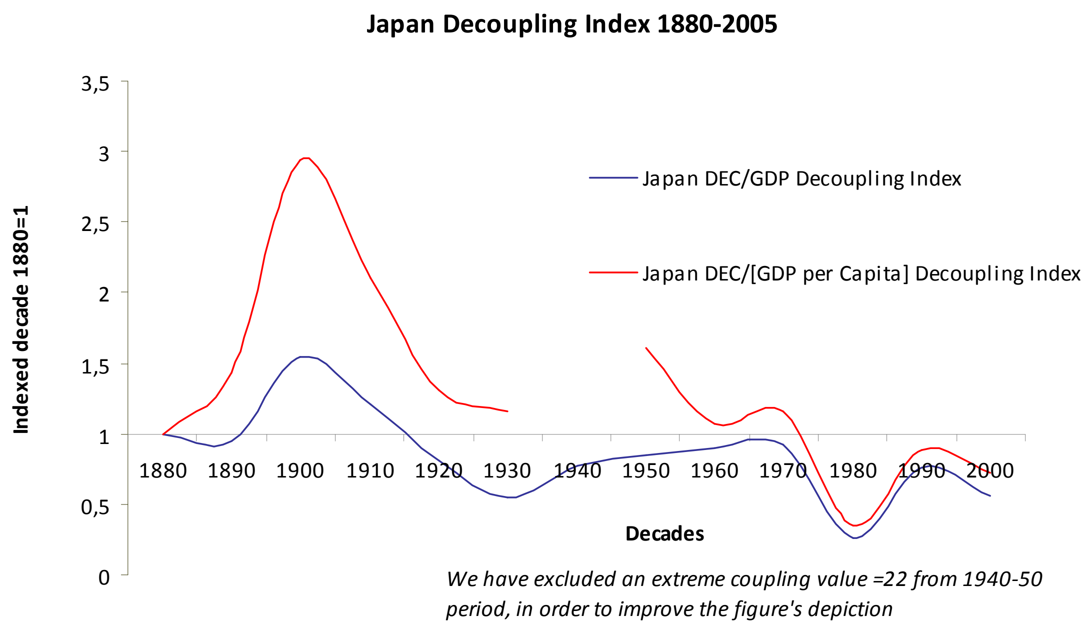


Figure 6.41 *The estimation of Japan’s Decoupling Index, for 1880-2005.*

6.5.7 Energy Intensity of India for 1961-2008

Together China and India consist of the two giant developing economies of Asia. These two overpopulated countries represent the one third[20] of global population (2013), and move rapidly towards a transition from the agrarian stage of growth to the massive industrialization. This section scrutinizes India, as a representative example of a rapidly developing country.

India's Domestic energy consumption for 1961-2008

Figure 6.42 presents India's energy mix. Evidently, agricultural biomass and timber remain by far the most essential energy inputs of the Indian economy, marking the slow transition to a post agrarian stage of the country, which has not yet been achieved. Concerning fossil fuels, Coal (including peat) and Oil are constantly increasing their use, while natural gas depicts increasing, yet lower than coal and oil, trends as well. Fuel wood seems to be stabilized after mid-1990s, while electricity consumption remains extremely low, remarking once again that India has not accomplished yet the transition to the stage of being an industrial economy.

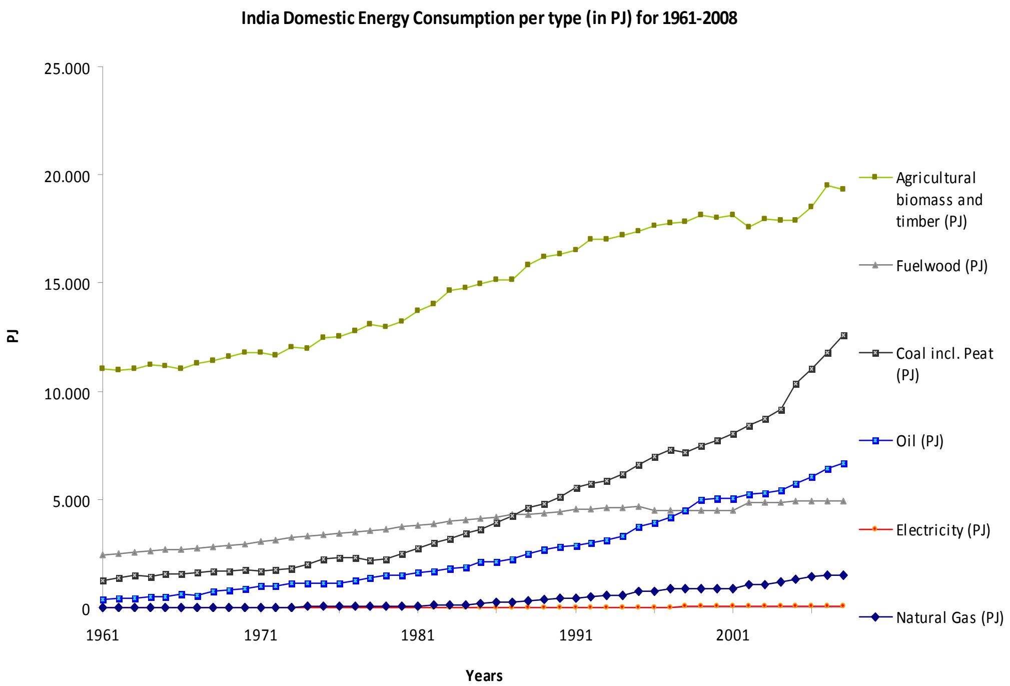


Figure 6.42 *India's Domestic Energy Consumption per energy type, in PJ, for 1961-2008.*

[20] 2.586.250 thousand persons in 2013, according to the Total Economy Database (updated until January 2014)

Figure 6.43 presents the percentage share (%) of each energy type to the total domestic energy consumption of India. From this point of view, agricultural biomass and timber depict a constant decreasing share in DEC, throughout the examined period. On the other hand, the fossil fuels (oil, coal, natural gas) increase their share. However, the share of electricity consumption remains relatively very low, something which may reflect the fact that, despite the remarkable growth that the Indian economy has performed, more than 400 million of India's people still live in poverty, while an estimated 300 million people are not connected to the national electrical grid[21].

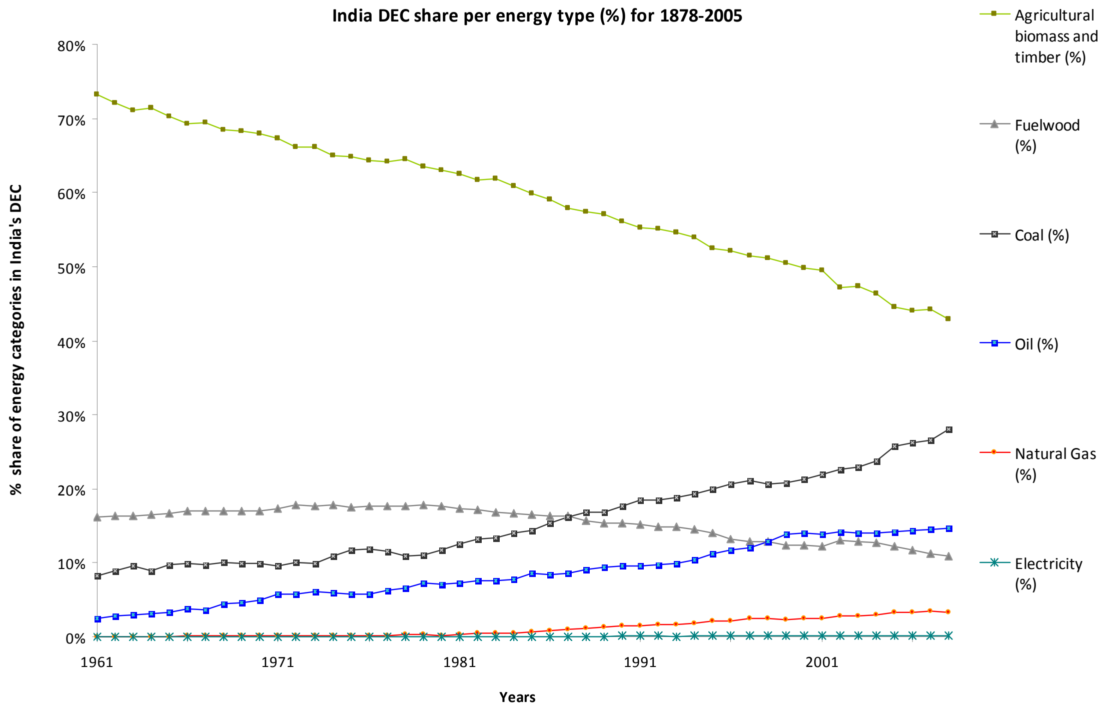


Figure 6.43 *Percentage (%) share of each energy type to the total Indian DEC, for 1961-2008.*

India's Energy intensity and per capita DEC consumption, for 1961-2008

According the World Bank, massive investments will be needed to create the housing and to build the proper infrastructure that the country necessitates. One in three rural people lack access to an all-weather road, and only one in five national highways is four-lane. Ports and airports have inadequate capacity, and the old railway network needs massive investments for rebuilt[22]. Evidently, the future of India's transition towards development calls for more

[21] Source: http://www.worldbank.org/en/country/india/overview Accessed July 2014.

[22] *Ibid*

energy and material inputs. However, Figure 6.44 narrates a different story: India's standard DEC/GDP ratio results in an almost constant decreasing trend during 1961-2008. This evidence contradicts the DEC per capita ratio (Fig. 6.44 and 6.45) which increases during 1979-1997, remains constant during 1998-2003, and increases rapidly again during 2003-2008. Further, total Indian DEC (Fig. 6.45) increases throughout the examined period.

On the other hand, the proposed EI indicator (DEC/[GDP $_{\text{per Capita}}$] increases almost constantly until 1992. However, after 1992, the proposed EI indicator constantly decreases during 1993-2008. It goes without saying that India's future demand for infrastructure building will irrevocably increase energy consumption trends. In that sense, it remains essential the fact that the declining EI trends performed by the standard indicator remain unrealistic, while the declining trends of the proposed EI indicator, after 1992, may be the result of unequal income distribution and high poverty rates. In any case, the latter assumption needs further rigorous investigation.

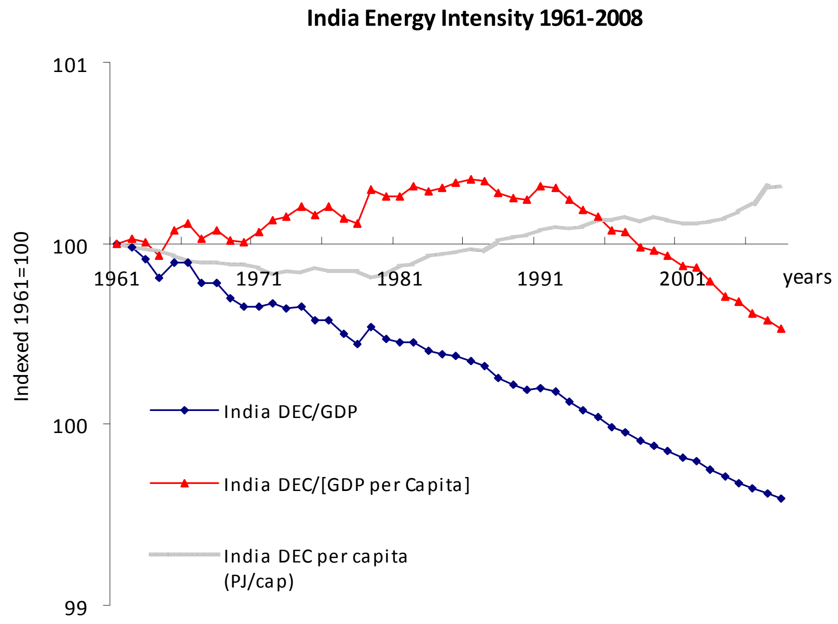


Figure 6.44 *The per capita DEC consumption and energy intensity of the Indian economy estimated by the standard DEC/GDP and the proposed DEC/ [GDP $_{\text{per Capita}}$] indicators (all indexed 1961=100), for 1961-2008.*

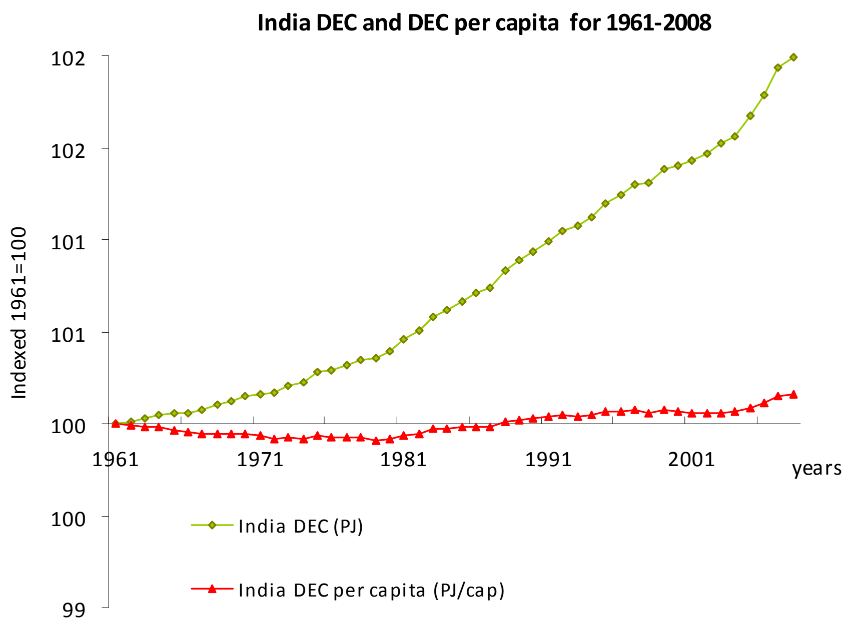


Figure 6.45 *The DEC and the per capita DEC consumption of the Indian economy (all indexed 1961=100), for 1961-2008.*

Estimating the divergence of the percentage change of the standard DEC/GDP and the proposed DEC/[GDP $_{per\ Capita}$] from 1961 as base year

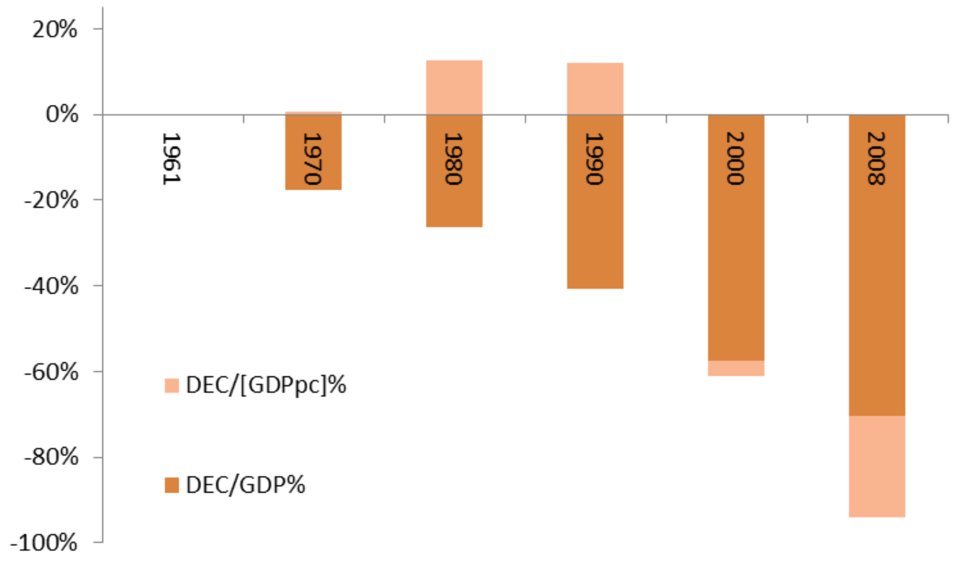


Figure 6.46 *The divergence of the percentage change of DEC/GDP and DEC/[GDP $_{per\ Capita}$] from 1961 as base year , for 1961-2008.*

Figure 6.46 estimates the divergence of the percentage change of DEC/GDP and the DEC/[GDP $_{per\ Capita}$] indicators from 1961, as a base year. Evidently, the divergence between the two EI indicators peaks in early 1990s and gradually declines until the end of the examined period (2008). According Figure 6.46, the greatest part of divergence, namely the percentage (%) change of each EI indicator to divergence, is contributed by the declining trend of the standard EI indicator. Nevertheless, after 2000s, the percentage changes of both standard and the proposed EI indicators decline simultaneously, with the standard DEC/GDP being declining more intensively.

India's disaggregated energy intensity and per capita consumption for each energy type, for 1961-2008

A more detailed analysis of India's EI trends calls for a further disaggregation of domestic energy consumption, by energy type. Figures 6.47-6.52 present: at the left hand-sided a) the total and the per capita specific energy type consumption; and at the right hand-sided b) the per capita consumption compared with both the standard and the proposed specific energy type intensity, all indexed into a base year.

India is heading towards a transition from the agrarian to the industrialization stage. Evidently, per capita biomass and fuel-wood consumption (renewable resources) are decreasing, while EI estimated by the standard and the proposed framework is constantly decreasing[23] (Fig 6.47; 6.48).

On the other hand, the fossil fuels domestic consumption is constantly increasing in both total and per capita terms. Moreover, EI estimated by the proposed framework is increasing for coal and natural gas, while declines for oil after 2000 (Fig 6.49-6.51). Further, domestic electricity consumption (both total and per capita) is increasing, due to the massive electrification of the country (Fig 6.52).

Conclusively, India, being a highly developing country, is a very energy-intensive economy and in sheer transition towards a more industrialized economic basis, heavily dependent on non-renewable fossil fuels energy inputs.

[23] Concerning the proposed indicator though, the decline in EI trends starts in the mid-1980s, contrary to the standard indicator who is constantly decreasing throughout 1961-2008.

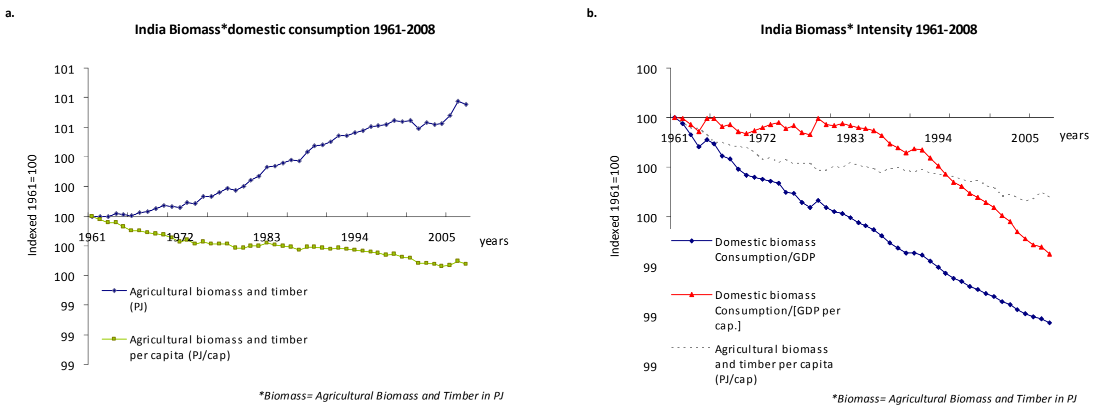


Figure 6.47 *a) Biomass total and per capita consumption; and b) biomass intensity, in India for 1961-2008 (Indexed 1961=100).*

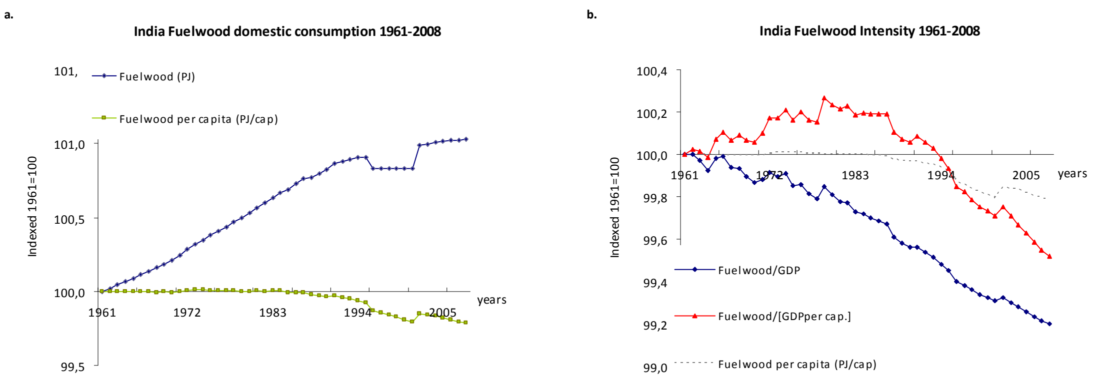


Figure 6.48 *a) Fuel-wood total and per capita consumption; and b) fuel-wood intensity, in India for 1961-2008 (Indexed 1961=100).*

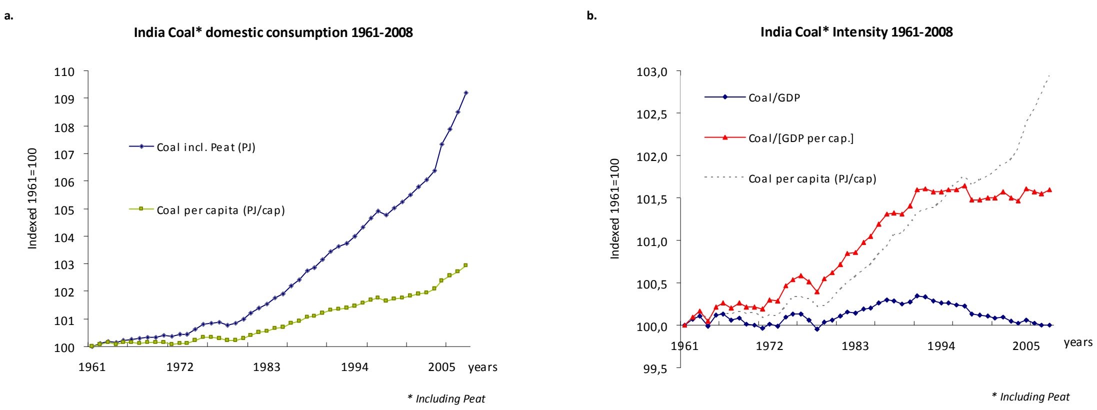


Figure 6.49 *a) Coal total and per capita consumption; and b) coal intensity, in India for 1961-2008 (Indexed 1961=100).*

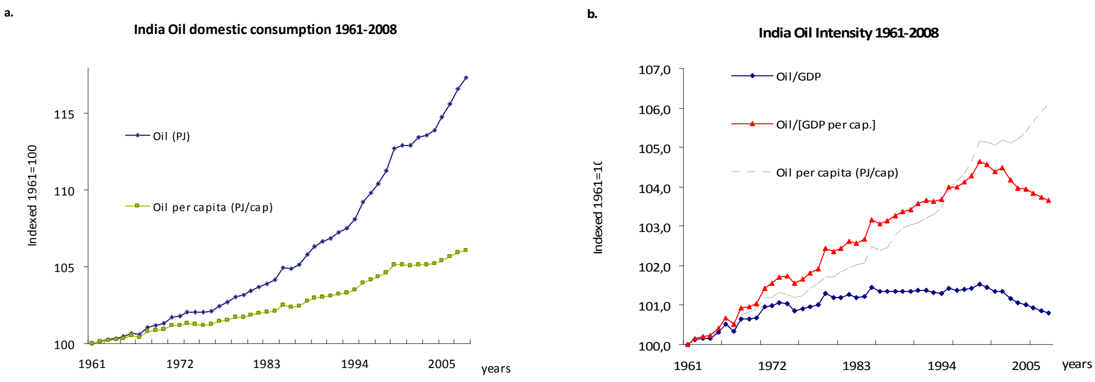


Figure 6.50 *a) Oil total and per capita consumption; and b) oil intensity, in India, for 1961-2008 (Indexed 1961=100).*

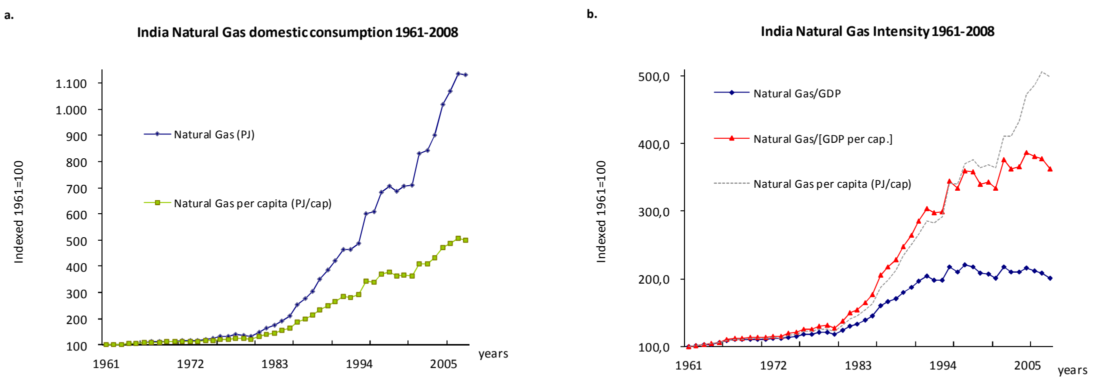


Figure 6.51 *a) N. gas total and per capita consumption; and b) n. gas intensity, in India, for 1961-2008 (Indexed 1961=100).*

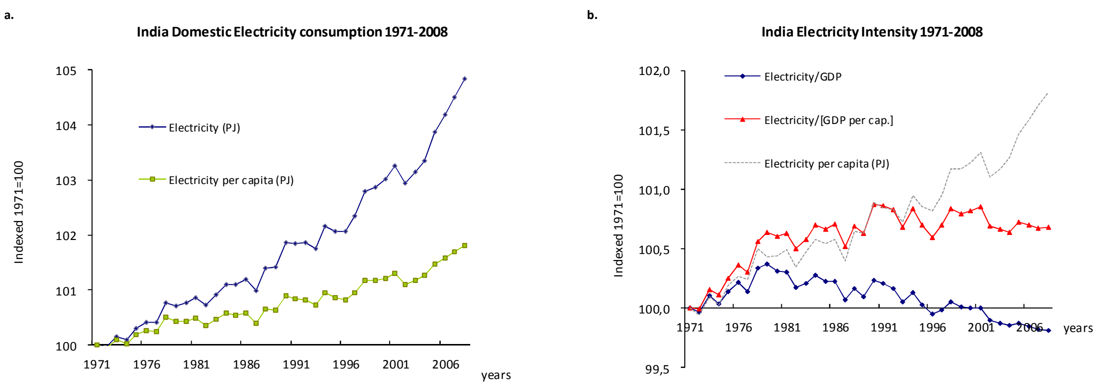


Figure 6.52 *a) Electricity total and per capita consumption; and b) electricity intensity, in India for 1971-2008 (Indexed 1971=100).*

India's renewable and non-renewable energy consumption (total and per capita), for 1965-2008

The figure 6.53 depicts in more detail the transition of the agrarian Indian economy, towards the industrialization stage. Apparently, India is still heavily depended on renewable biomass consumption, yet the consumption of non-renewable resources is increasing dramatically, as well (Fig 6.53a). What is more, the per capita renewable consumption is decreasing diachronically through the examined period, contrary to the increasing per capita consumption of non-renewable resources (Fig 6.53b).

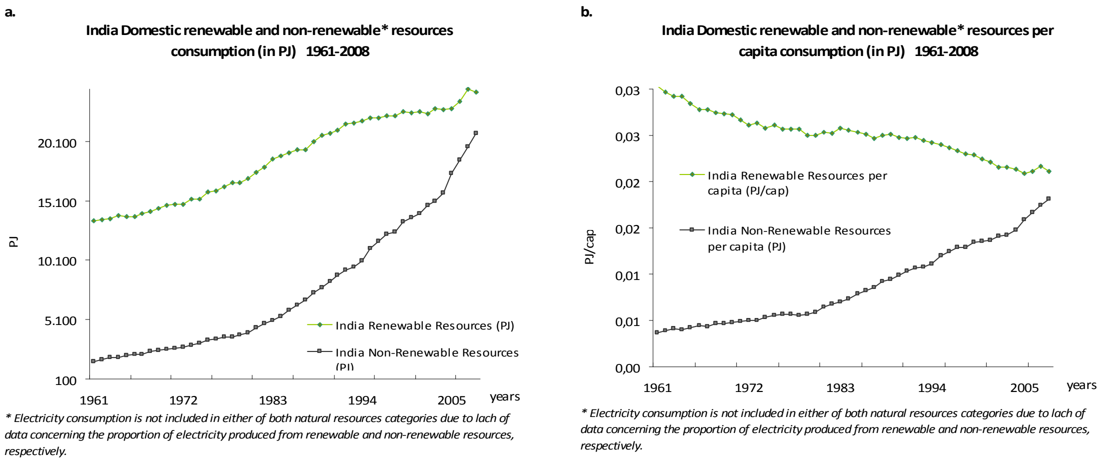


Figure 6.53 *a) India's domestic renewable and nonrenewable resources consumption (in PJ); b) India's per capita domestic renewable and nonrenewable resources consumption (PJ/cap), for 1961-2008.*

Notwithstanding, oppositely to the – renewable versus non-renewable – consumption trends we have estimated for USA and Japan, where the transition to industrialization was clearly depicted in the relevant diagrams, concerning India, this transition is not yet completed, though it seems to be a matter of time, before the non-renewable resources use surpass the use of the, still dominant, renewable resources consumption.

The Indian Decoupling ratio and the Decoupling factor (proposed by OECD), for 1965-2008

Figure 6.54 estimates the proposed by OECD (2002) Decoupling ratio (DR) and the Decoupling factor (DF), respectively. For DR values less than 1, decoupling has occurred during the examined period. Figure 6.54a depicts sheer decoupling for the standard EI framework throughout the period examined. On the other hand, the proposed EI evaluation framework reveals two different stages of intensity; coupling for 1960-1980 and decoupling for 1980-2008. The Decoupling Factor (DF) is estimated in Figure 6.54b. The DF value is zero or negative in the absence of decoupling and has a maximum value of 1, when environmental pressure (DEC in the current case study) reaches zero. Figure 6.54b results with DR, namely constant decoupling for the standard EI indicator and mixed results for the proposed EI indicator. In conclusion, the proposed framework reveals an early period of coupling between primary energy consumption and income (GDP per capita) that lasts until 1980s.

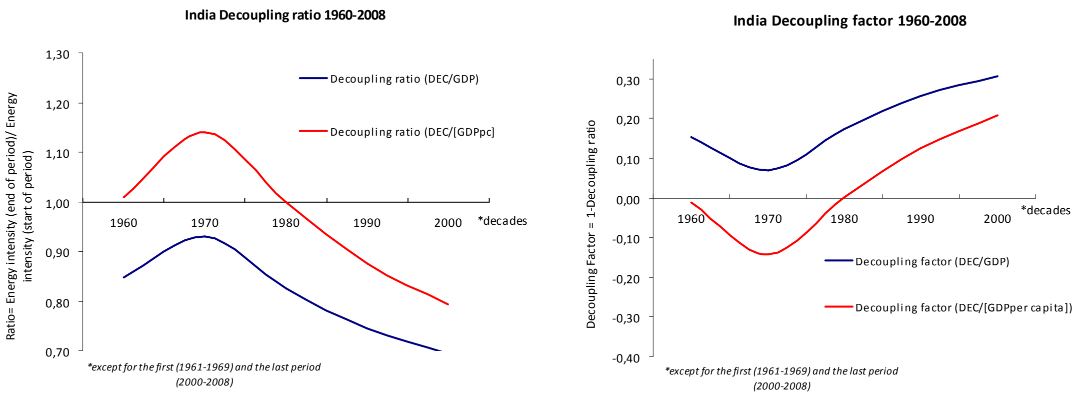


Figure 6.54 *a) The estimation of Decoupling ratio, and b). The estimation of Decoupling Factor, for India, during 1965-2008.*

The Indian Decoupling index (proposed by UNEP), for 1965-2008

Figure 6.55 estimates the Decoupling Index (DI), proposed by UNEP (2011). The standard EI indicator results in a constant relative decoupling evolutionary path for the period examined (1960-2000). On the other hand, the proposed EI indicator exposes a coupling relationship until early 1990s, to enter in the area of relative decoupling, during the last two decades of the examined period. Furthermore, neither of the two EI frameworks results in an absolute decoupling trend, according Figure 6.55.

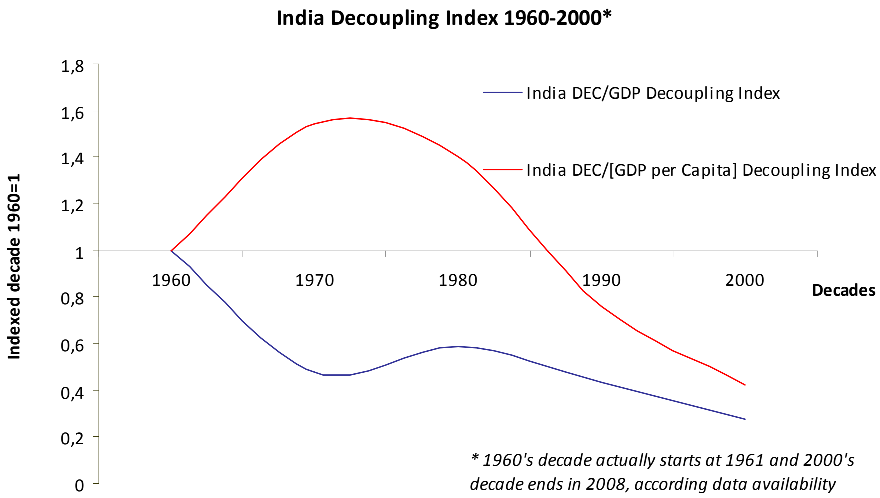


Figure 6.55 *The estimation of India's Decoupling Index, for 1960-2000.*

6.6 Energy consumption and energy intensity trends of various developed and developing countries, for 1965-2012

This final section aspires to provide a brief insight of the primary energy consumption trends and the energy intensity of various developed and developing countries. Towards this scope, an updated energy database has been utilized (BP, 2013). However, it should be mentioned, that this section bases its estimations on primary energy consumption. What is more, while in the context of MFA, we had estimated "*DEC=domestic extraction/production – exports + imports*", BP accounts domestic "*consumption*" in a different way, namely, "*Inland demand plus international aviation and marine bunkers and refinery fuel and losses*". By all odds, it is assumed that there are not substantial differences between the two methods. In any case, the investigation of difference is beyond the scopes of the present chapter.

Data sources

Data on primary energy consumption (*in Mtoe*) for all the examined cases of this section have been derived from the most recently updated version (2013) of **BP's "Statistical Review of World Energy 2013"** (available at: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy-2013/review-by-energy-type.html), while data on GDP and population are drawn from the most recently updated version (January 2014) of the conference board **"The Total Economy Database"** (available at: https://www.conference-board.org/data/economydatabase/). GDP is expressed, for both case studies, in million 1990 International Geary-Khamis dollars per year (million 1990 GK$/y), while population is expressed in million persons per year.

6.6.1 China

This section investigates China's Energy Intensity (EI), as the most representative highly-developing country of the world. Figure 6.56a presents the total primary energy consumption and the per capita primary energy consumption, for China, both indexed (1965=100) for 1965-2012. The year 2002 is a milestone that signals a dramatic increase in both ratios, lasting until 2012. Evidently, the Chinese economy consumes massive amounts of energy during the last decade (2002-2012)[24], according fig 6.56a.

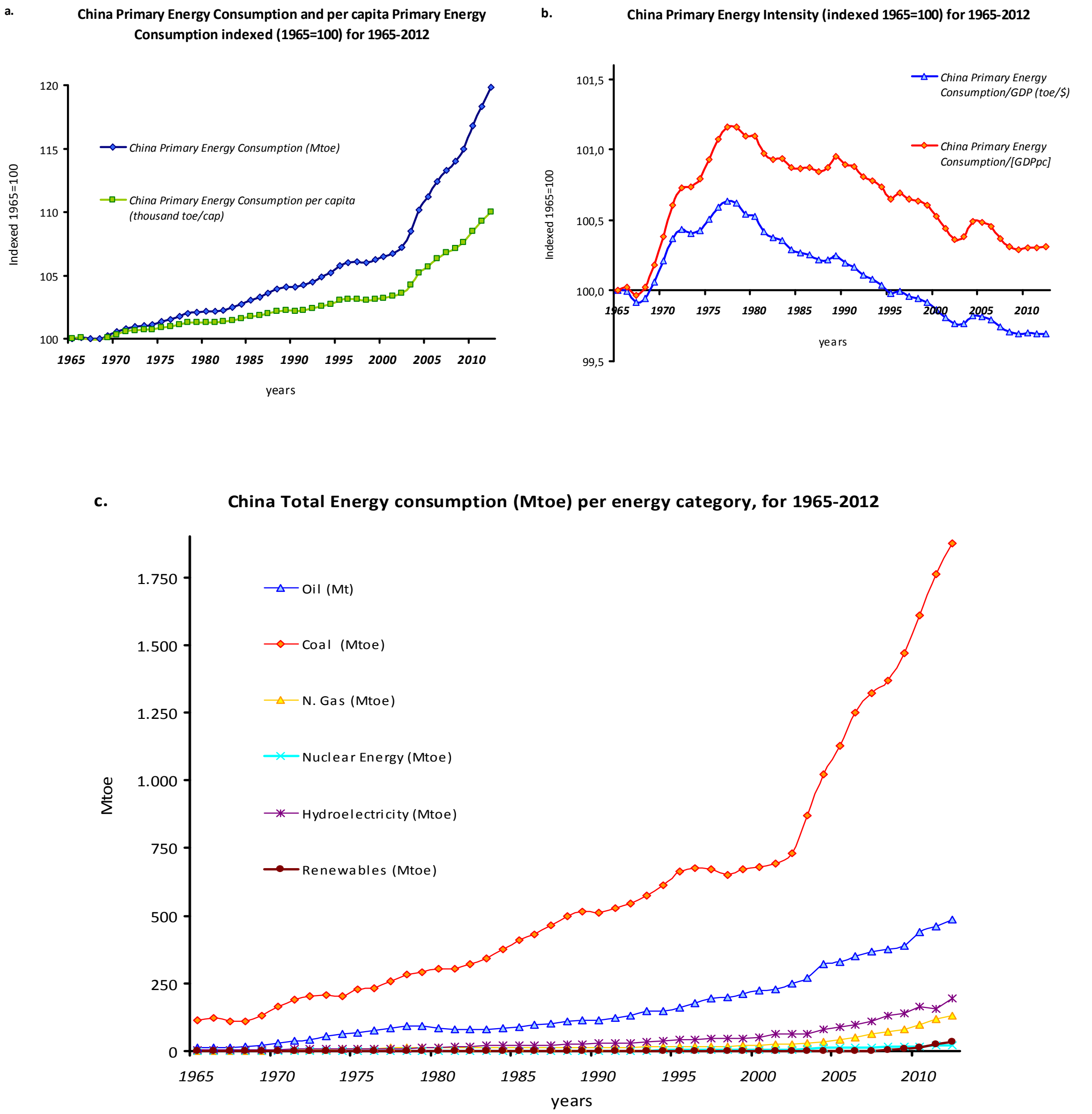


Figure 6.56 *a). China primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). China's primary energy intensity (indexed 1965=100); c). China's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

On the other hand, fig. 6.56b presents the estimates for both the standard and the proposed EI indicators (indexed 1965=100). Both indicators reveal a sheer coupling trend until 1978.

[24] After 2009, China takes from USA the lion's share in total Primary energy Consumption becoming the world's bigger energy consumer, according to the BP's database.

However, during 1979-2002, a fluctuated reduction in EI is depicted by both indicators. Lastly, 2002 shows stabilization in the EI trends, lasting until 2012 and depicted by both indicators. During 2002-2012, the period of extreme increase in primary energy consumption (fig. 6.56a), the EI seems to be stabilized for both indicators, with the proposed EI indicator giving a hint for a smooth EI increase, during 2009-2012.

Finally, the figure 6.56c reveals the main energy input that feeds the Chinese economic growth engine; the coal consumption. Evidently, China is the world's leader in coal imports, especially after 2002, where a dramatic increase in coal's consumption is depicted in fig. 6.56c.

6.6.2 Brazil

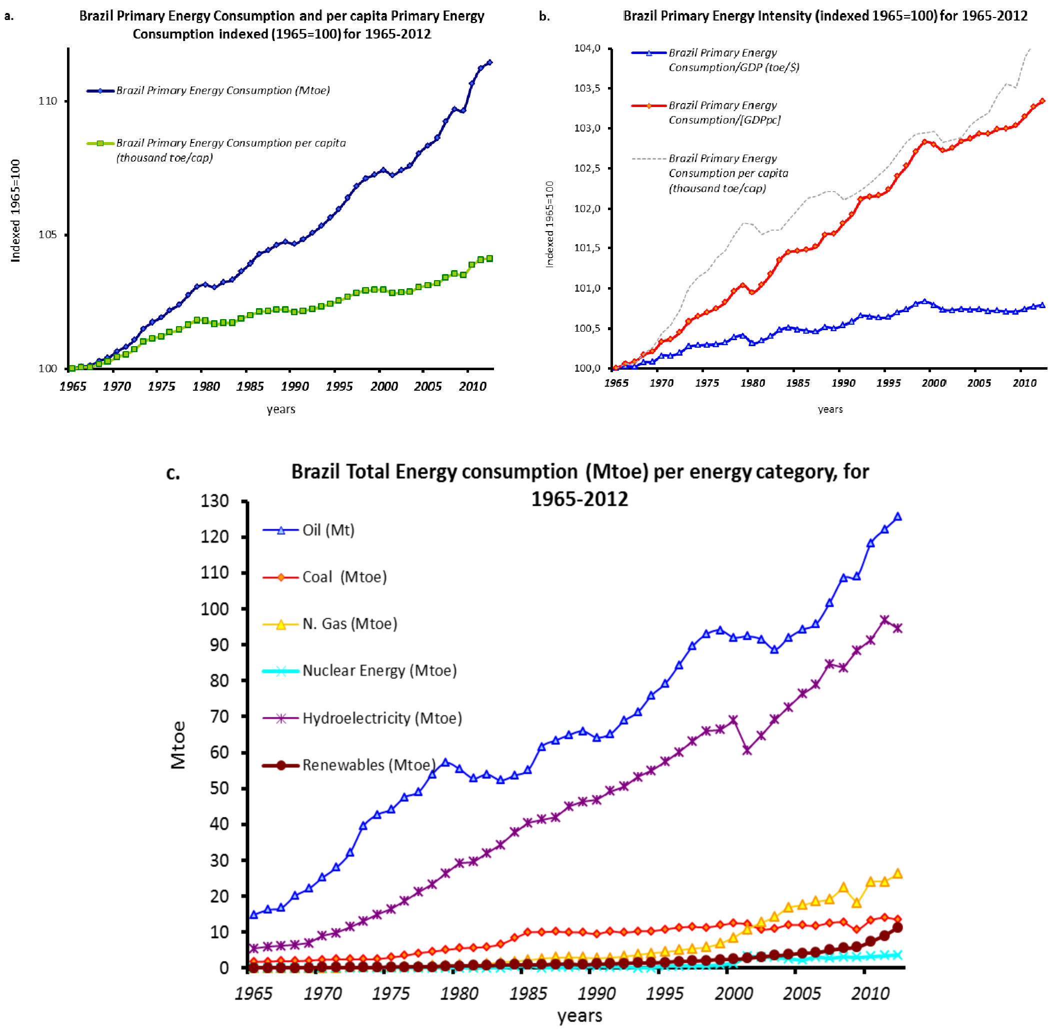


Figure 6.57 *a). Brazil primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Brazil's primary energy intensity (indexed 1965=100); c). Brazil's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

Brazil is the world's seventh wealthiest economy[25] and the largest country (in terms of area and population) in Latin America. Figure 6.57.a presents the total primary energy consumption and the per capita primary consumption in Brazil, both indexed (1965=100). Figure 6.57.b shows the primary energy intensity trends for the standard and the proposed indicators plus the per capita energy consumption, all indexed (1965=100). Evidently, both indicators result in an increasing trend in energy intensity; however the proposed indicator depicts a stronger energy intensity increase, especially during 2000-2012, a period where the standard energy intensity indicator shows relative stability.

Further, the primary energy consumption per capita increasing (the industrial metabolism of Brazil) presents a similar evolutionary pattern with the proposed energy intensity indicator. Finally, figure 6.57.c presents the Brazilian primary energy consumption (in mtoe) per energy type. Oil consumption and hydroelectricity are by far the most predominant energy inputs feeding the economic growth engine of Brazil. This is an expected result since Brazil is an oil producer country[26] and a very rich country concerning water resources. The production of oil has been growing in Brazil since 2000's while massive off-shore oil reserves were discovered in the Tupi area in 2007 (*OECD Observer, 2011*), further enhancing the primary energy production of the country and signaling potentials for more increased Energy Intensity during the following years.

6.6.3 Mexico

Mexico is the largest economy in Latin America and among the most important emerging economies[27]. According EIA, Mexico is one of the ten largest oil producers in the world, the third-largest in the Western Hemisphere[28]. Consequently oil plays a decisive role in Mexico's economic growth, something that is clearly depicted in the primary energy mix (fig 6.58c), where oil consumption is by far the most important energy input. However, oil's contribution is constantly decreasing in the total energy mix of the country, being gradually

[25] According to World Bank's GDP data for 2012

[26] According to the US Energy Information Administration (EIA), Brazil is the 8th largest total energy consumer and 10th largest producer in the world, while Brazil was the largest producer of liquid fuels in South America for 2012. (Source: http://www.eia.gov/countries/country-data.cfm?fips=br) Accessed September 2014.

[27] Source: http://www.worldbank.org/en/country/mexico Accessed September 2014.

[28] Source: http://www.eia.gov/countries/cab.cfm?fips=MX Accessed September 2014.

replaced by natural gas. However, Mexico is a net importer of natural gas, so higher levels of natural gas consumption will likely depend upon more imports from other countries (Source: EIA, footnote 20).

Figure 6.58a presents the primary energy consumption and the per capita energy consumption in Mexico, for 1965-2012 (indexed 1965=100). Evidently, both ratios increase constantly throughout the examined period. Figure 6.58b estimates the EI by using both the standard and the proposed framework. Essential differences are depicted in the evolutionary path that the two indicators follow; remarkably, while the standard EI indicator shows a relative stability after early 1990's, the proposed E Indicator depicts a constant EI increase for all the examined period.

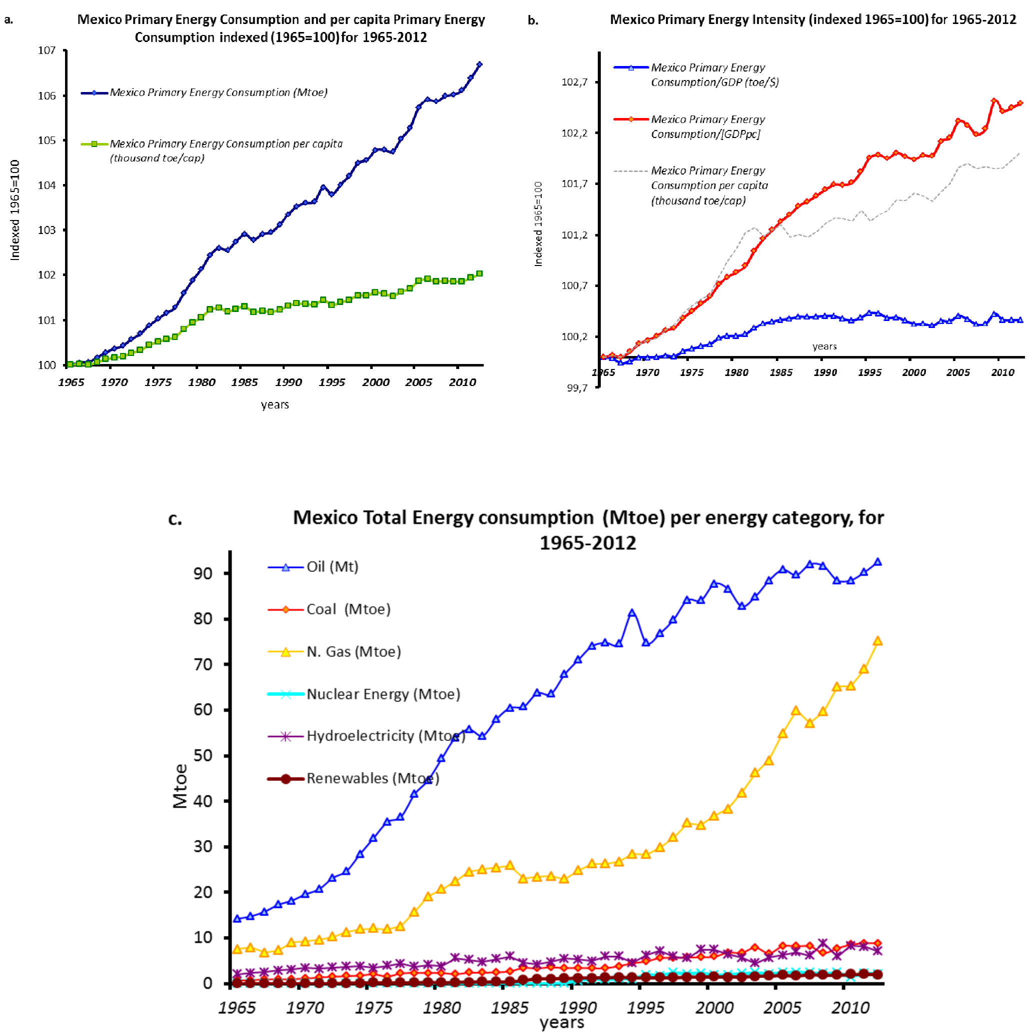


Figure 6.58 *a). Mexico's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Mexico's primary energy intensity (indexed 1965=100); c). Mexico's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

6.6.4 Argentina

Argentina is the largest natural gas producer of South America and a significant oil producer. Evidently Figure 6.59c. depicts the domination of natural gas (after 1995) as the main energy input, followed by oil consumption. Total and per capita primary energy consumption is constantly increasing throughout the examined period (fig 6.59a.), while the energy intensity trends estimated by the proposed EI indicator display continuous energy intensity increase, only briefly interrupted in mid-2000s, to start increasing again after 2009.

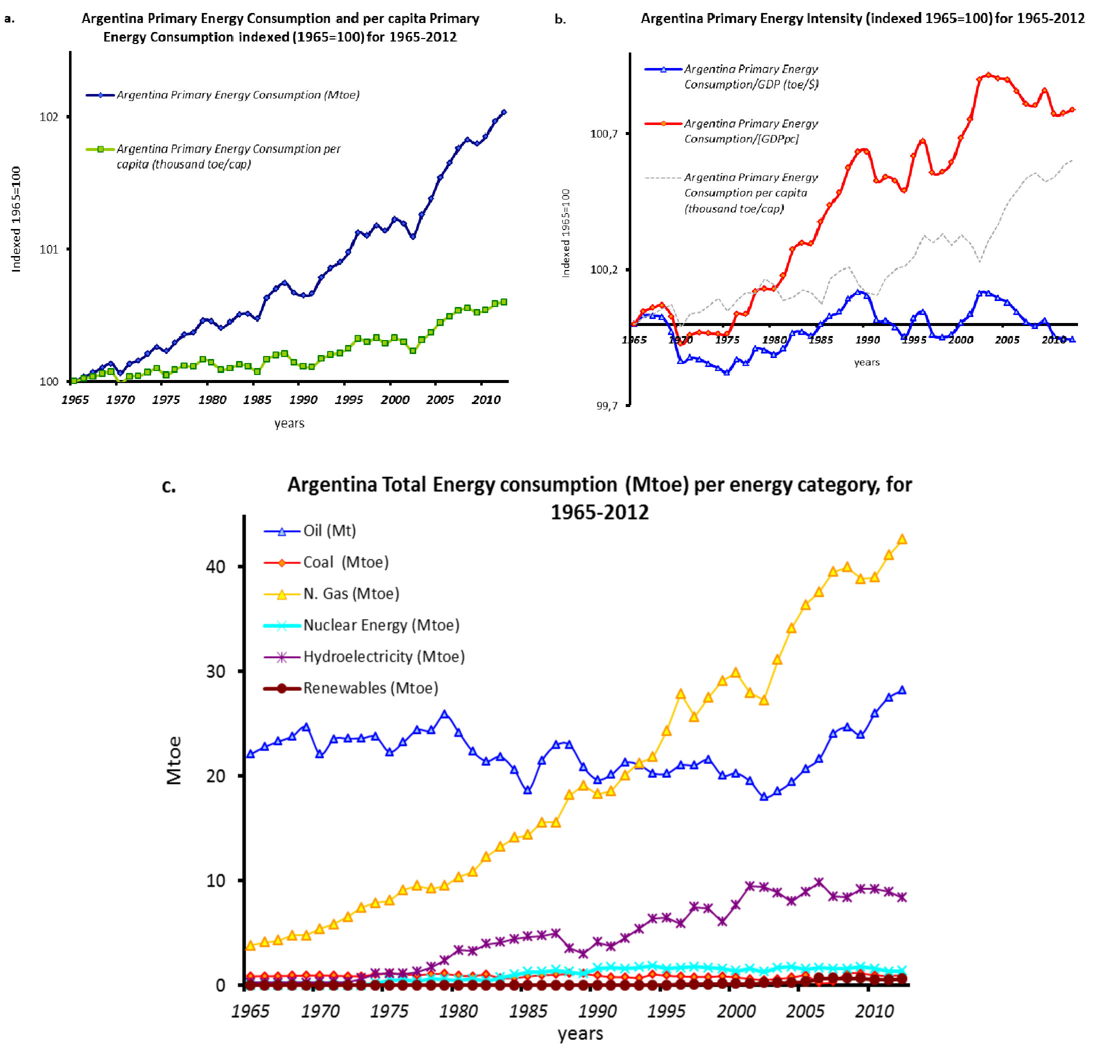


Figure 6.59 *a). Argentina's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Argentina's primary energy intensity (indexed 1965=100); c). Argentina's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

In conclusion, the Argentinian economy, after having revived from the economic recession of early 2000s and returned into increasing economic growth trends[29], is strongly energy intensive country.

6.6.5 Saudi Arabia

Saudi Arabia has almost one-fifth of the world's proven oil reserves, is the largest producer and exporter of total petroleum liquids in the world, and maintains the world's largest oil production[30].

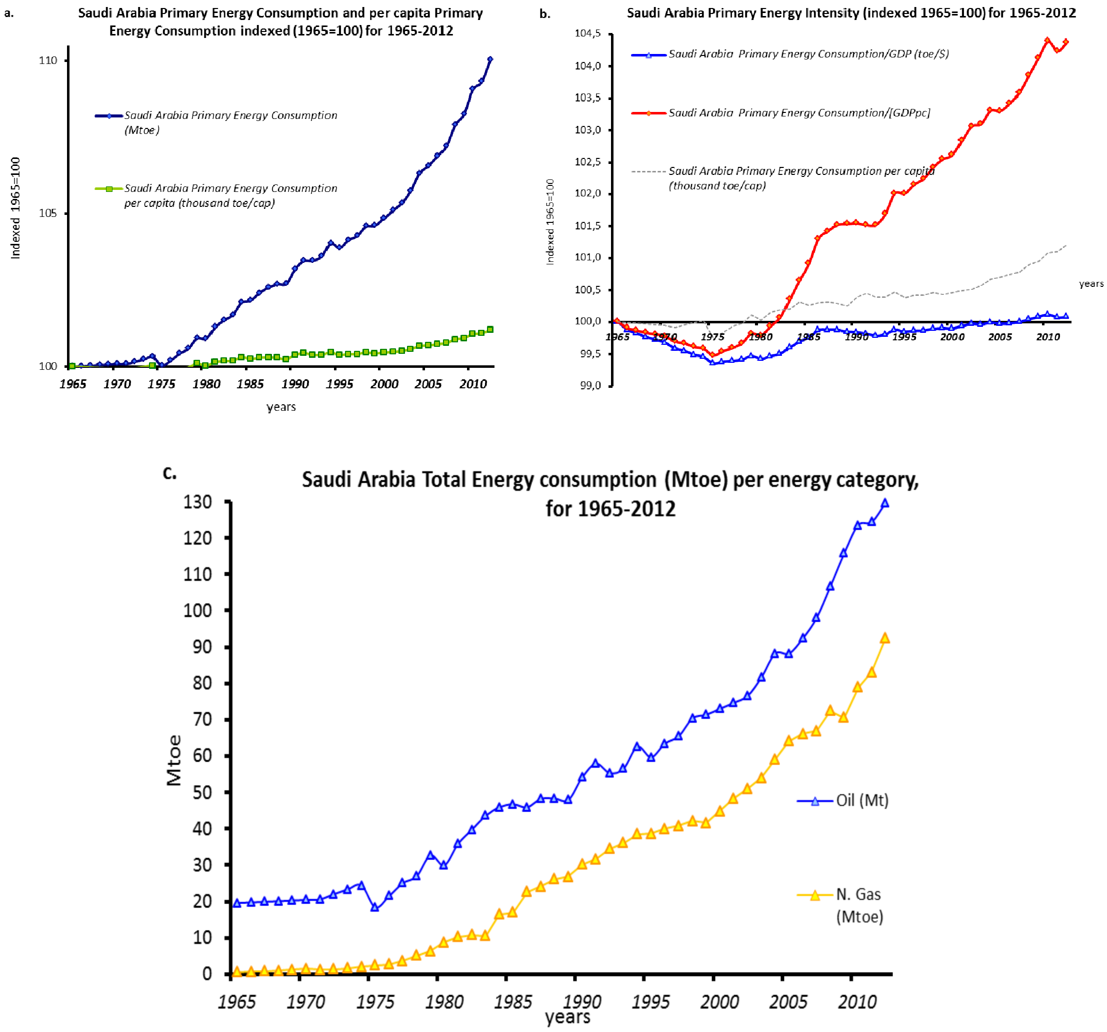


Figure 6.60 *a). Saudi Arabia's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Saudi Arabia's primary energy intensity (indexed 1965=100); c). Saudi Arabia's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

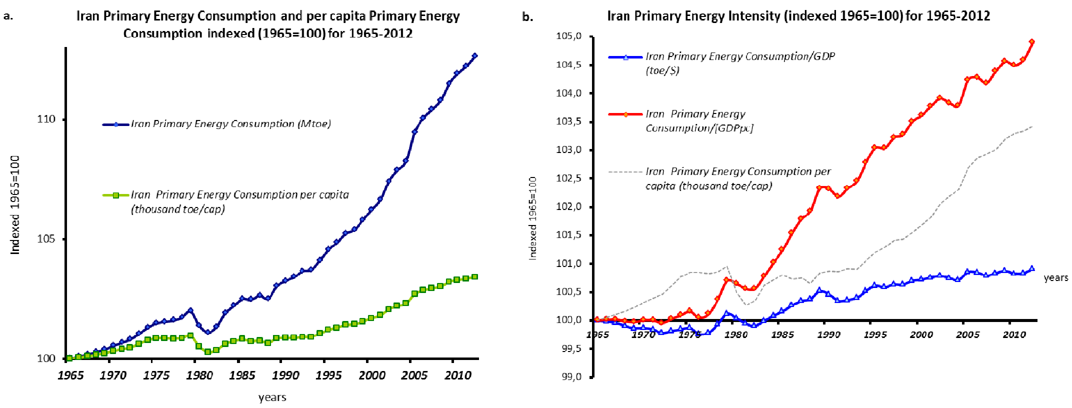
[29] Source: The World Bank (2012) http://www.worldbank.org/en/country/argentina/overview Accessed September 2014.

[30] Source: http://www.eia.gov/countries/cab.cfm?fips=SA Accessed September 2014.

Evidently, oil consumption is the most prevailing energy source input of country's energy profile. Further, Saudi Arabia have the fifth largest (proven) natural gas reserves in the world behind Russia, Iran, Qatar, and the United States, according to EIA estimates (*ibid footnote 21*). Total and per capita primary energy consumption (actually oil and natural gas consumption) of Saudi Arabia (fig. 6.60a) shows a strongly increasing trend (with the exception of a brief decline occurred in late 1970s). Similarly, the proposed EI indicator performs, after 1970, a dramatic increase in TPES intensity, more substantial that the smooth EI increase the standard EI indicator displays after 1985 (fig. 6.60b). It goes without saying that the Saudi Arabian economy, a very energy intensive economy, is strongly linked to the oil and natural gas consumption.

6.6.6 Iran

Iran is a very interesting case study since it holds the world's fourth-largest proven oil reserves and the world's second-largest natural gas reserves[31]. This energy profile is clearly depicted in Figure 6.61c, where natural gas and oil consumption are the predominant energy inputs of the Iranian economy. After 1980, both primary energy and per capita primary energy consumption increase dramatically (Fig 6.61a). The EI of the Iranian economy increases for both the standard and the proposed indicator, with the latter resulting in a more intensive increment which better approaches the increasing trend of the Iranian DEC per capita (Fig. 6.61b). Evidently, the Iranian economy is strongly linked to the oil and natural gas consumption.



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31 Source: http://www.eia.gov/countries/cab.cfm?fips=ir Accessed September 2014.

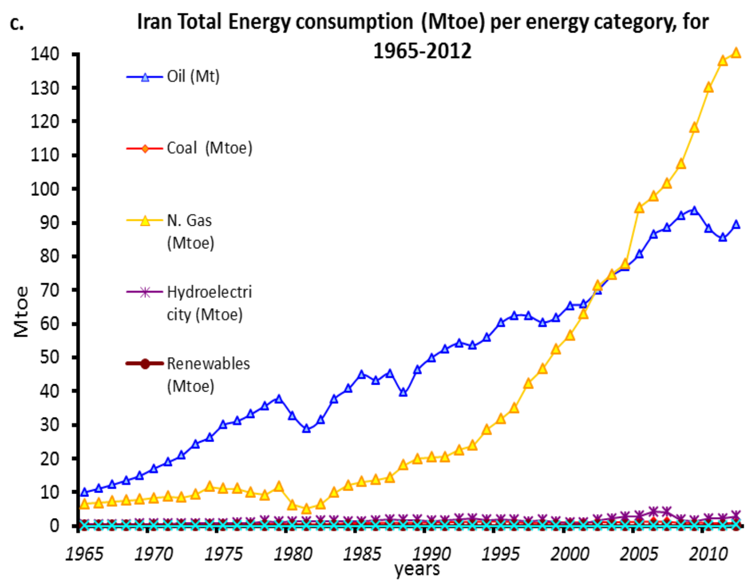

Figure 6.61 *a).Iran's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Iran's primary energy intensity (indexed 1965=100); c). Iran's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

6.6.7 Turkey

Turkey is the 18th largest economy in the world, according the World Bank. In less than a decade, per capita income in the country has nearly tripled and in 2013 has exceeded $10,000[32]. Moreover, Turkey plays an important role in the world energy markets as a regional energy transit hub and simultaneously as a growing energy consumer. Evidently, Turkey's energy demand has increased rapidly over the past few years and likely will continue to grow in the future[33]. According to the International Energy Agency (IEA), energy use will continue to grow at an annual growth rate of around 4.5% from 2015 to 2030, approximately doubling over the next decade[34]. Turkey's total and per capita primary energy consumption show a continuous increment during 1965-2012 (Fig. 6.62a). Furthermore, Figure 6.62c reveals that the fossil fuels dominate the Turkish energy mix, followed by Hydroelectricity production and a smooth recent increase of the renewable energy production. Finally, as far as the EI trends of the Turkish economy concerned, the standard EI indicator shows a relative stability during 1990-2012. On the other hand, the proposed EI indicator results in a constant EI increment trend (Fig 6.62b) which approximates the per

[32] Source: http://www.worldbank.org/en/country/turkey/overview Accessed September 2014.

[33] Source: http://www.eia.gov/countries/cab.cfm?fips=TU Accessed September 2014.

[34] Ibid

capita primary energy consumption evolutionary path. Apparently, Turkish economy remains extremely energy intensive, a trend that seems to be prevailing in future projections.

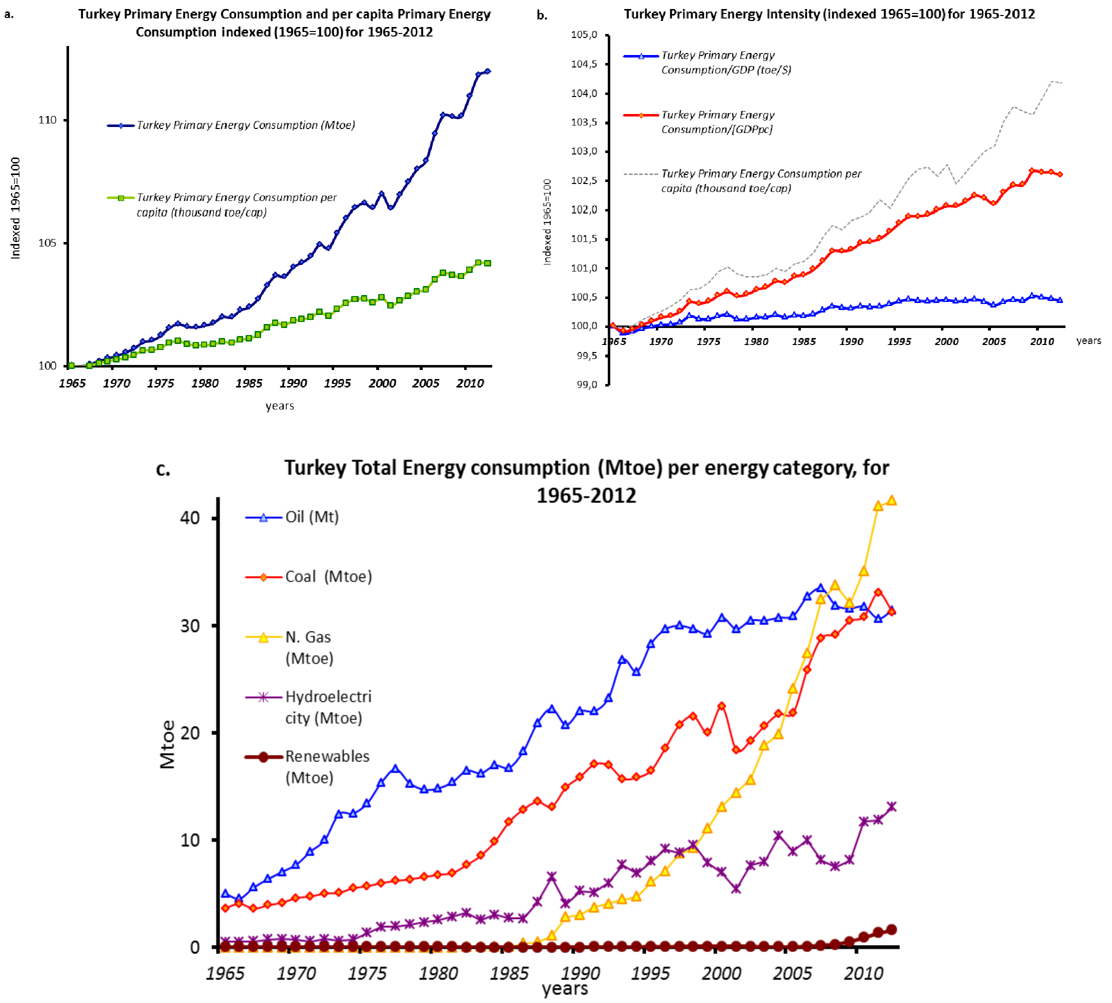

Figure 6.62 *a).Turkey's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Turkey's primary energy intensity (indexed 1965=100); c). Turkey's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

6.6.8 Canada

Canada is considered to be among the most prosperous, wealth and stable developed economies of the world. Moreover, Canada is one of the world's five largest energy producers (Canada controls the third-largest amount of proven oil reserves in the world, after Saudi Arabia and Venezuela and is the world's third-largest producer of dry natural gas) while remains the principal source of U.S. electricity, oil and natural gas imports[35]. Canada's

[35] Source: http://www.eia.gov/countries/cab.cfm?fips=CA Accessed September 2014.

domestic primary energy consumption is dominated by oil and natural gas consumption, followed closely by hydroelectricity production[36].

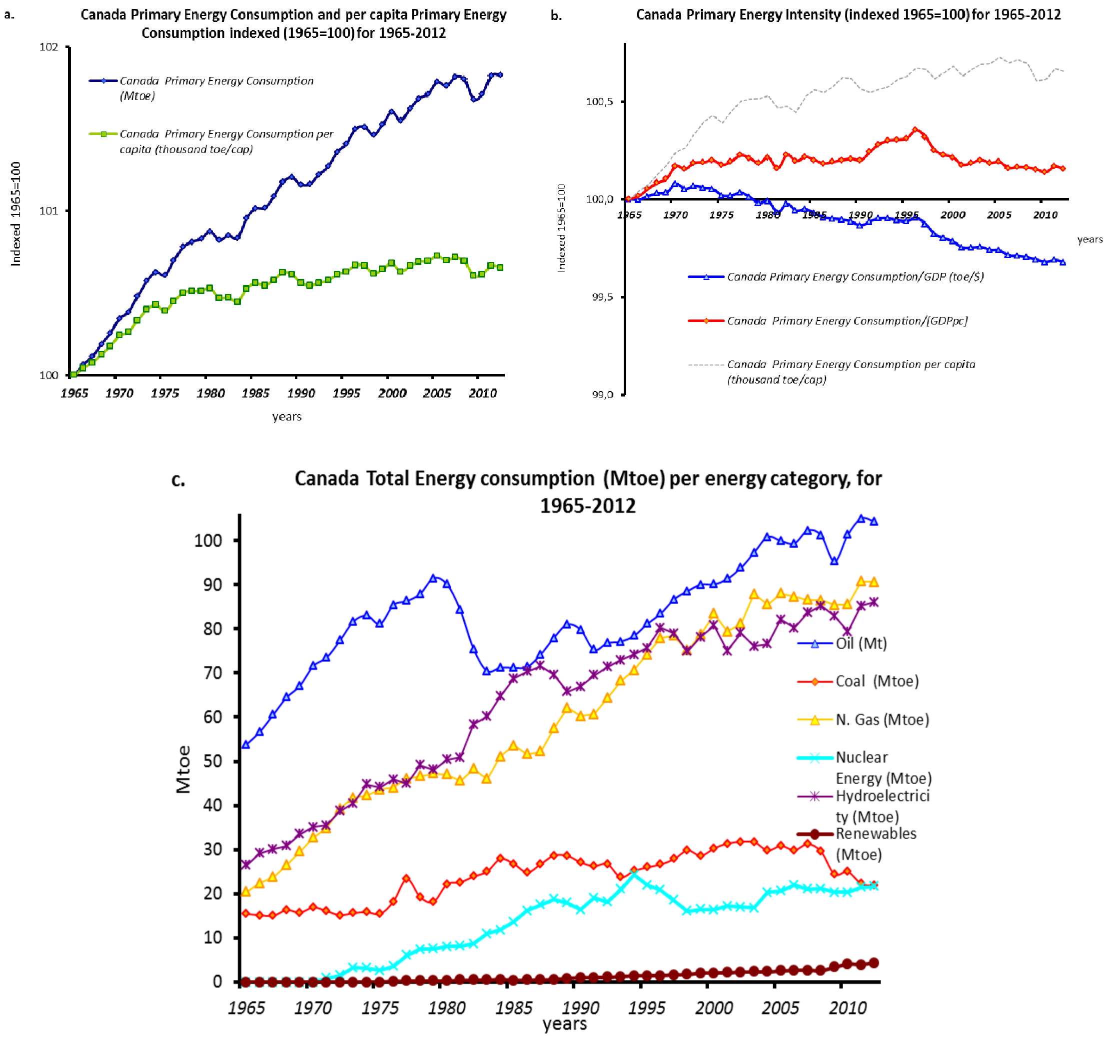

Figure 6.63 *a).Canada's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Canada's primary energy intensity (indexed 1965=100); c). Canada's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

Coal consumption shows a reduction after 2007, while nuclear and renewable electricity production smoothly increases their use (Fig. 6.63c). Evidently, total primary energy consumption in Canada increases almost constantly, while the per capita primary energy consumption presents a smooth stabilization after mid-1990s. Finally, Figure 6.63b exhibits the different way that the standard (general decline) and the proposed (stability) EI

[36] Only China and Brazil produce more hydroelectricity than Canada (Source, ibid)

indicators evolve. In conclusion, it seems that Canada is recently (after 2000) stabilizing its per capita energy consumption trends and its energy intensity, yet it remains an economy which still uses huge amounts of non-renewable resources (oil and natural gas), besides the renewable ones (hydroelectricity), according Figure 6.63c.

6.6.9 Australia

Australia was the world's second largest coal exporter (in 2011) and the third largest exporter of liquefied natural gas (LNG) in 2012[37]. Evidently, Australia is heavily dependent on fossil fuels for its primary energy consumption, with coal having the lion's share in Australia's energy consumption since 1985, followed by oil[38] which seems to substitute coal use after 2006, and natural gas (Fig. 6.64c). Hydroelectricity and renewables consumption, while increasing after 2006, still remain in relatively low level. Remarkably though, despite the fact that Australia holds the world's largest recoverable reserves of uranium (about 31 %) and is the third largest producer and exporter of uranium for nuclear-powered electricity[39], the country does not have any nuclear power-plants.

Australia's total and per capita primary energy consumption seems to stabilizing (2005-2012), after a long period of extensive augmentation (Fig. 6.64a). Finally, Figure 6.64b reveals substantial differences between the standard and the proposed EI indicator. While the EI decreases constantly, after 1977, according the standard framework, the proposed indicator exposes a macro-coupling period, lasting until late 1990s, and followed by a relative stability in EI. What is more, the trajectory of the per capita primary energy consumption of Australia depicts substantial similarities with the proposed EI indicator. Conclusively, Australia presents a strong linkage between primary energy consumption and economic growth throughout the period examined (1965-2012).

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[37] According EIA, Australia is among the most significant net hydrocarbon export countries of OECD, exporting over 70 percent of its total energy production.
(Source: http://www.eia.gov/countries/cab.cfm?fips=AS) Accessed September 2014.

[38] Australia is a net importer of crude oil. Accessed September 2014

[39] According to the World Nuclear Association.

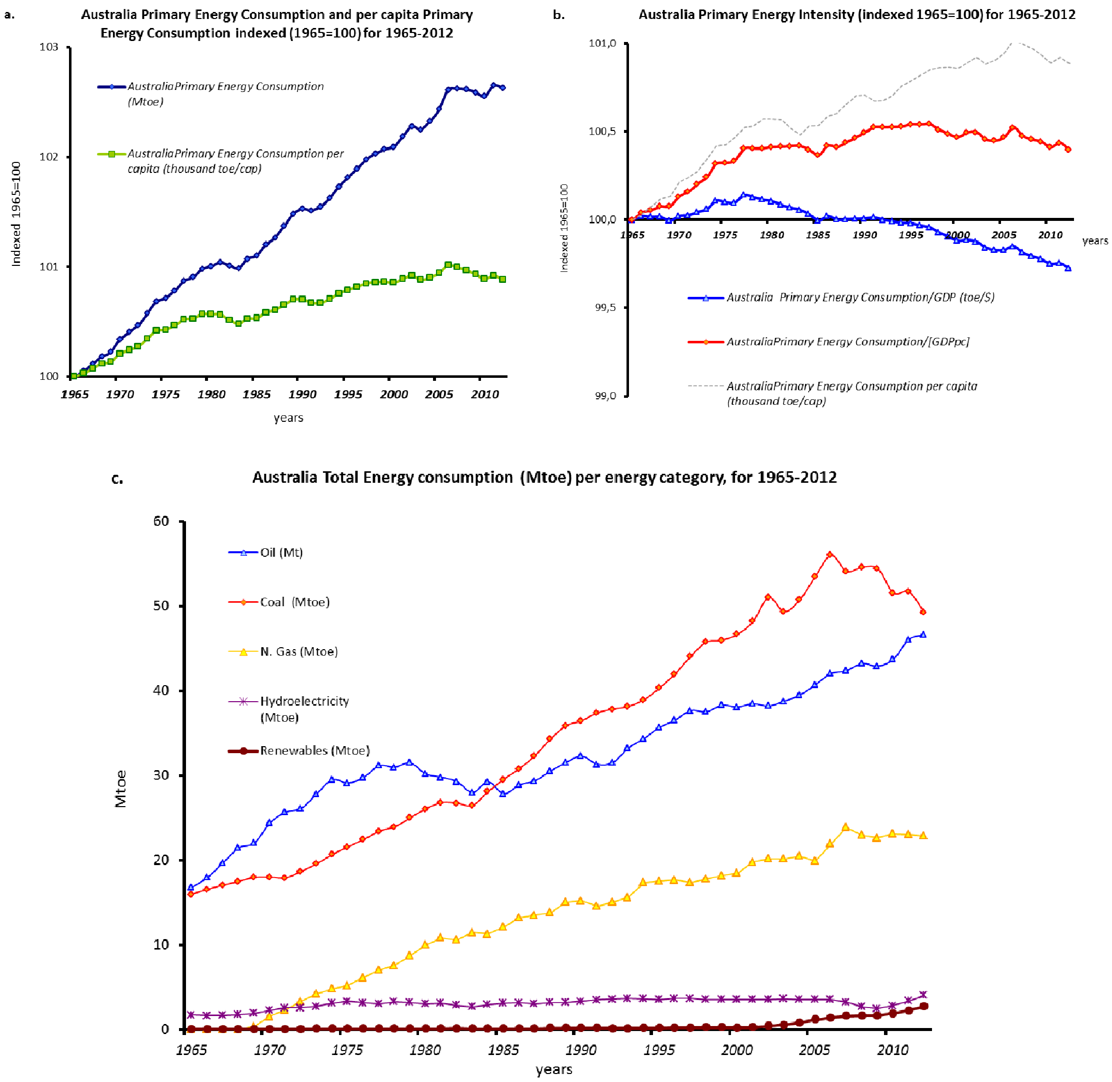

Figure 6.64 *a).Australia's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Australia's primary energy intensity (indexed 1965=100); c). Australia's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

6.6.10 South Africa

According U.S. Energy Information Administration, South Africa has a large energy-intensive coal mining industry[40]; hence its economy is based mainly on coal consumption, which is particularly used for electricity production[41] (Fig 6.65c). South Africa has limited reserves of

[40] Source: EIA (http://www.eia.gov/countries/country-data.cfm?fips=sf) Accessed September 2014

[41] Coal consumption in South Africa is expected to continue to increase as new coal-fired power stations are scheduled in the next few years due to the country's rising demand for electricity. (Source: http://www.eia.gov/countries/cab.cfm?fips=SF) Accessed September 2014

oil and natural gas. The increasing oil consumption trend that is depicted in Fig. 6.65c is imported. Natural gas, hydroelectricity and renewable consumption remain very low throughout 1965-2012. South Africa's total and per capita primary energy consumption is steadily increasing throughout 1965-2012, with only two brief interruptions taking place in mid-1990s and mid-2000s, respectively (Fig. 6.65a).

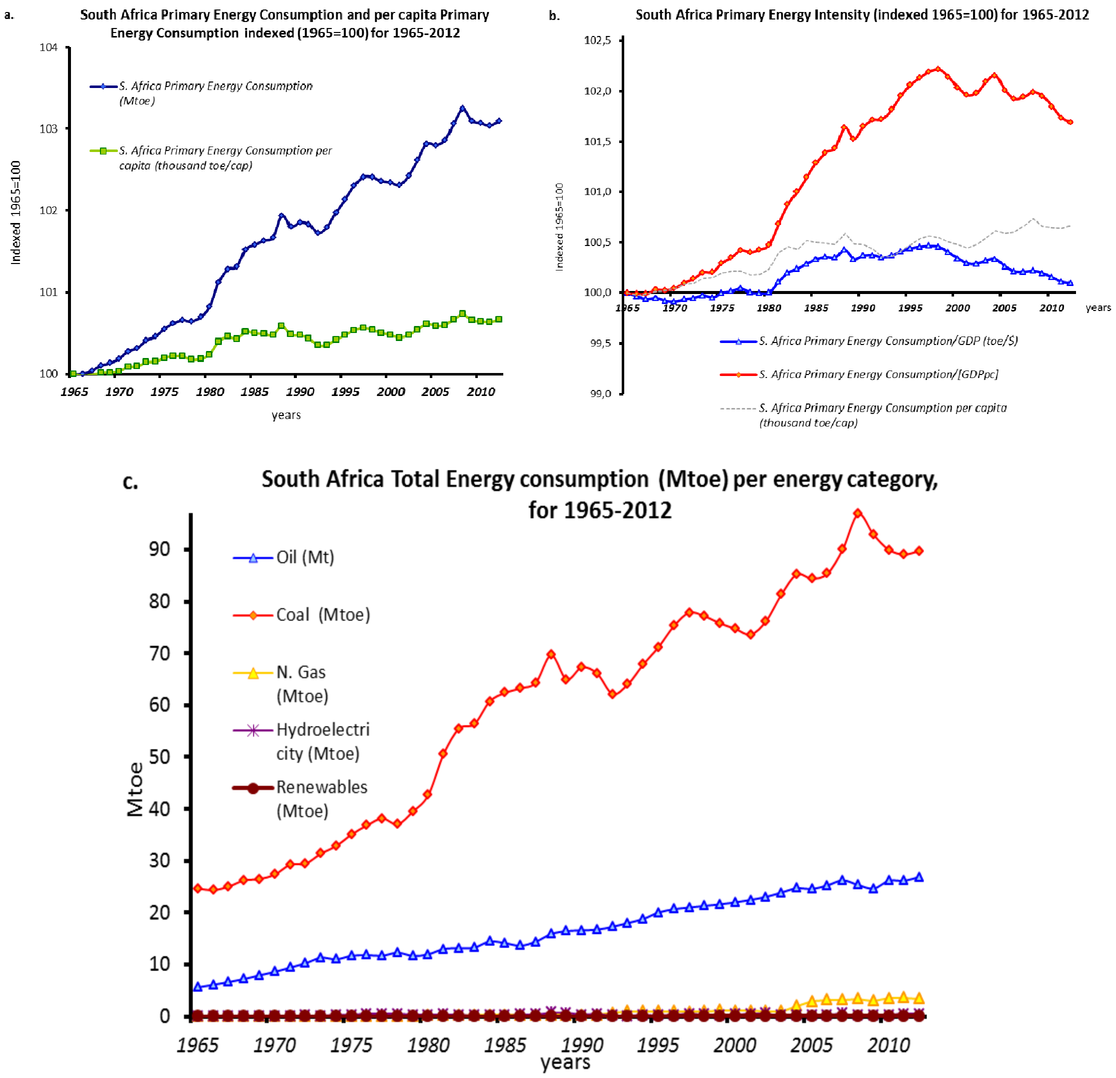

Figure 6.65 *a). South Africa's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). South Africa's primary energy intensity (indexed 1965=100); c). South Africa's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

South Africa is a very energy-intensive economy, with the proposed EI indicator depicting an extremely intensive linkage between primary energy consumption and income (Fig. 6.65b). From 1998 on, both EI indicators depict fluctuated energy intensity trends, while the per capita primary energy consumption increases constantly. Finally, it worth mentioning that, despite the remarkable growth rates, South Africa has one of the highest inequality and exclusion rates in the world[42].

6.6.11 Taiwan

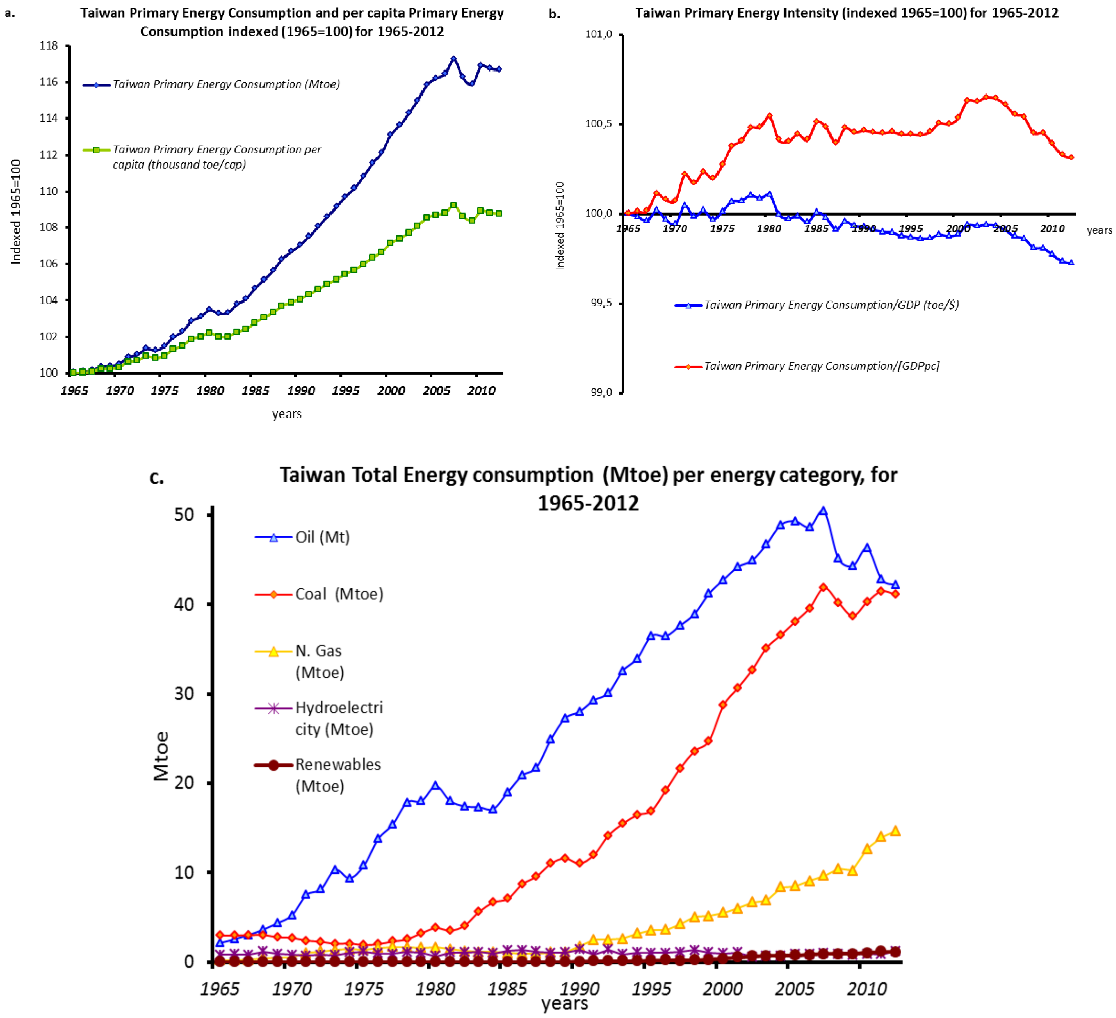

Figure 6.66 *a).Taiwan's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Taiwan's primary energy intensity (indexed 1965=100); c). Taiwan's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

Taiwan's economic growth is primarily dependent on oil and coal consumption, while natural gas consumption steadily increases after 1990 (Fig. 6.66c). Since Taiwan has limited domestic energy resources, rely most of its energy inputs on imports. Taiwan's total and per capita primary energy consumption is constantly increasing since 1965; however, a stabilization of these trends seems to be occurring after 2007 (Fig. 6.66a). According Figure

[42] Source: The World Bank (http://www.worldbank.org/en/country/southafrica/overview) Accessed September 2014

6.66b, Taiwan is an energy-intensive economy, with the proposed EI indicator resulting in a strong linkage between primary energy consumption and income. Nevertheless, both EI indicators depict an EI reduction after 2005, probably due to the fact that both total and per capita primary energy consumption is stabilizing after 2007 (Fig. 6.66a). These recent decreasing trends in Taiwan's EI may be the result of recent global financial crisis, since the domestic economy started reviving again after 2010.

6.6.12 South Korea

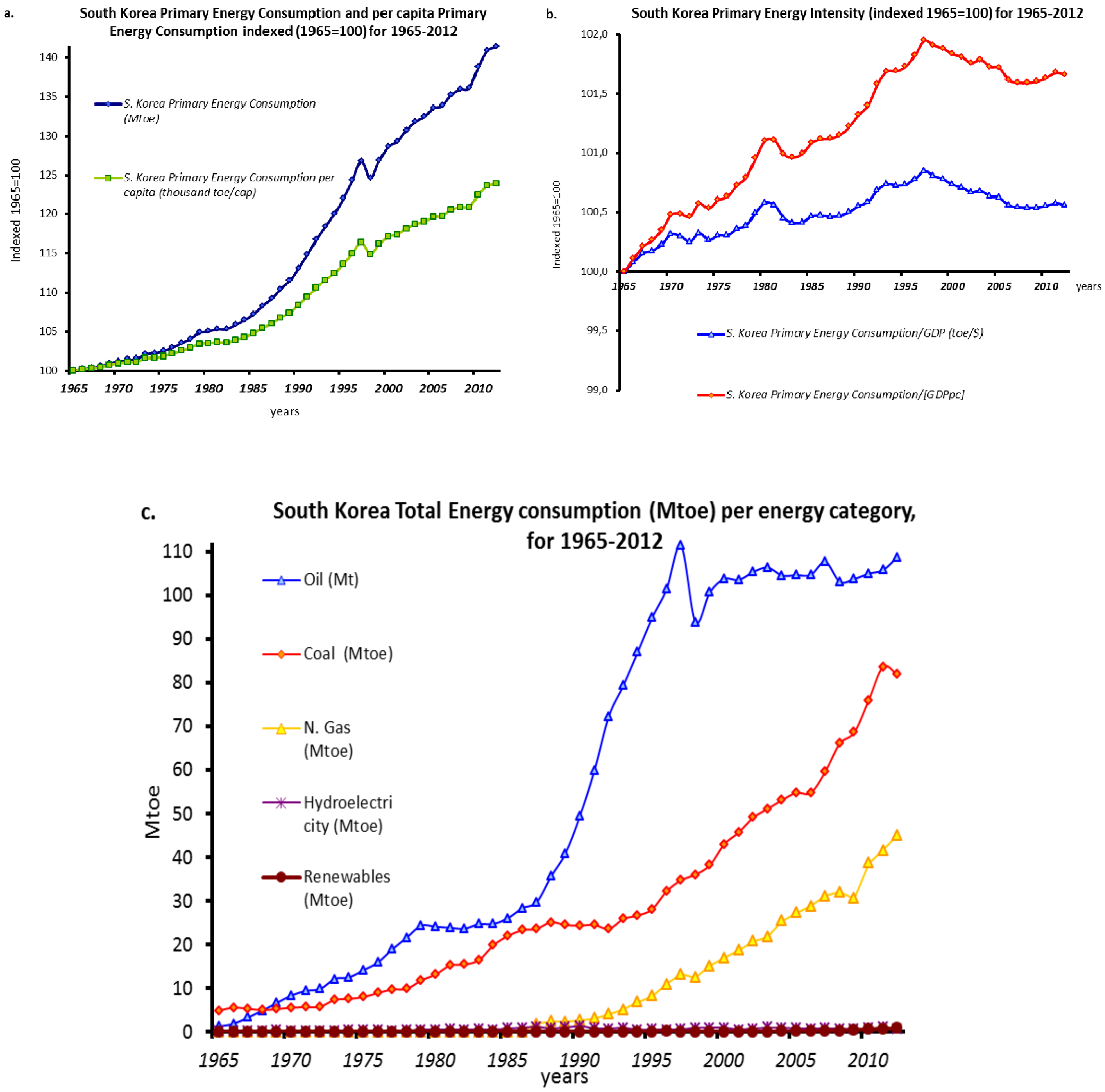

Figure 6.67 *a). South Korea's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). South Korea's primary energy intensity (indexed 1965=100); c). South Korea's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

With energy imports covering the 97% of the country's energy demand, South Korea is consider as one of the world's leading energy importers[43]. A snapshot of South Korea's energy consumption profile (Fig. 6.67c) reveals the great dependency that the domestic economy has on the non-renewable fossil fuels. Further, the total and the per capita primary energy consumption increase constantly during 1965-2012, with only one brief interruption occurring 1997-1998. South Korea is an energy-intensive economy (Fig. 6.67b), with both EI indicators depicting increasing EI trends; only a period of short EI reduction is depicted during 1997-2006, to continue its upward trends again, during 2007-2012.

6.6.13 Italy

The Italian economy is heavily dependent on oil and natural gas imports to meet its energy needs[44]. Furthermore, only recently the Italian economy managed to stabilize the consequences of the extensive recession period that deeply affected the euro-zone; yet the economic growth remains weak[45]. In that context, there is a great probability that the declining total and per capita primary energy consumption trends, after 2008, may reflect the deep impact that financial crisis have in energy consumption (Fig. 6.68a).

Moreover, oil consumption seems to be substitute with natural gas after 2000, while coal consumption and hydroelectricity remain relatively stable. Nevertheless, both oil and natural gas consumption is clearly declining after 2009. On the other hand, an increasing trend is observed, after 2000, concerning the renewable resources which seem to increase sharply after 2009 (Fig. 6.68c). The energy intensity of the Italian economy, after a peak in mid-1970s, reduces until mid-1980s, to remain relatively stable for the rest of the examined period (1985-2012). The most remarkable result, though, is that both the standard and the proposed EI indicators following extremely similar evolutionary paths throughout the whole examined period.

[43] Source EIA: http://www.eia.gov/countries/cab.cfm?fips=KS Accessed September 2014

[44] Source EIA: http://www.eia.gov/countries/country-data.cfm?fips=it Accessed September 2014

[45] Source IMF : http://www.imf.org/external/pubs/ft/survey/so/2013/car092613a.htm Accessed September 2014

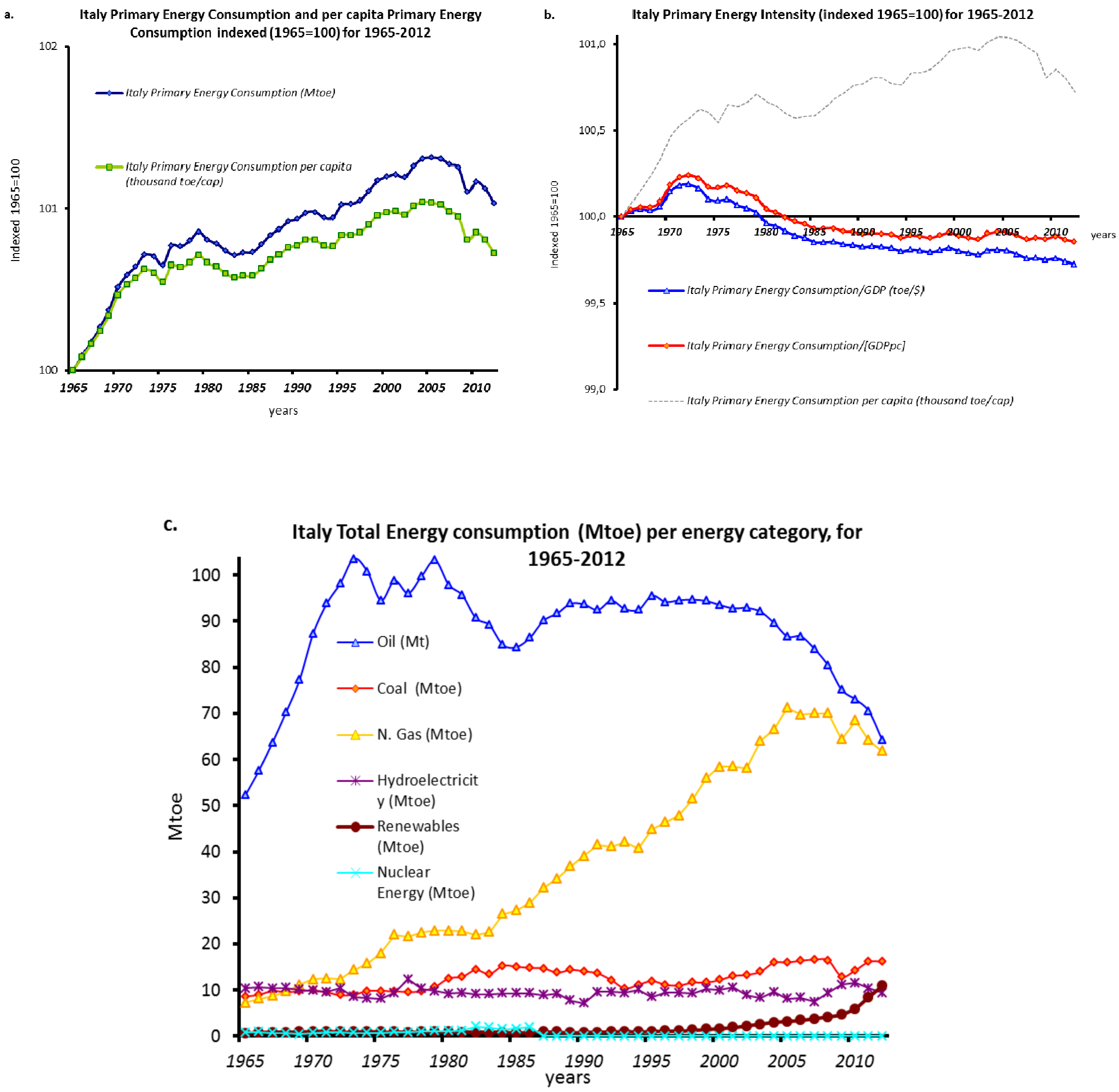

Figure 6.68 *a).Italy's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Italy's primary energy intensity (indexed 1965=100); c). Italy's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

6.6.14 Germany

Germany is the fourth-largest economy in the world after the United States, China, and Japan (according 2012 data) and the largest national economy in Europe, while remains the 3rd largest exporter in the world[46].

[46] Source Wikipedia : http://en.wikipedia.org/wiki/Economy_of_Germany Accessed September 2014

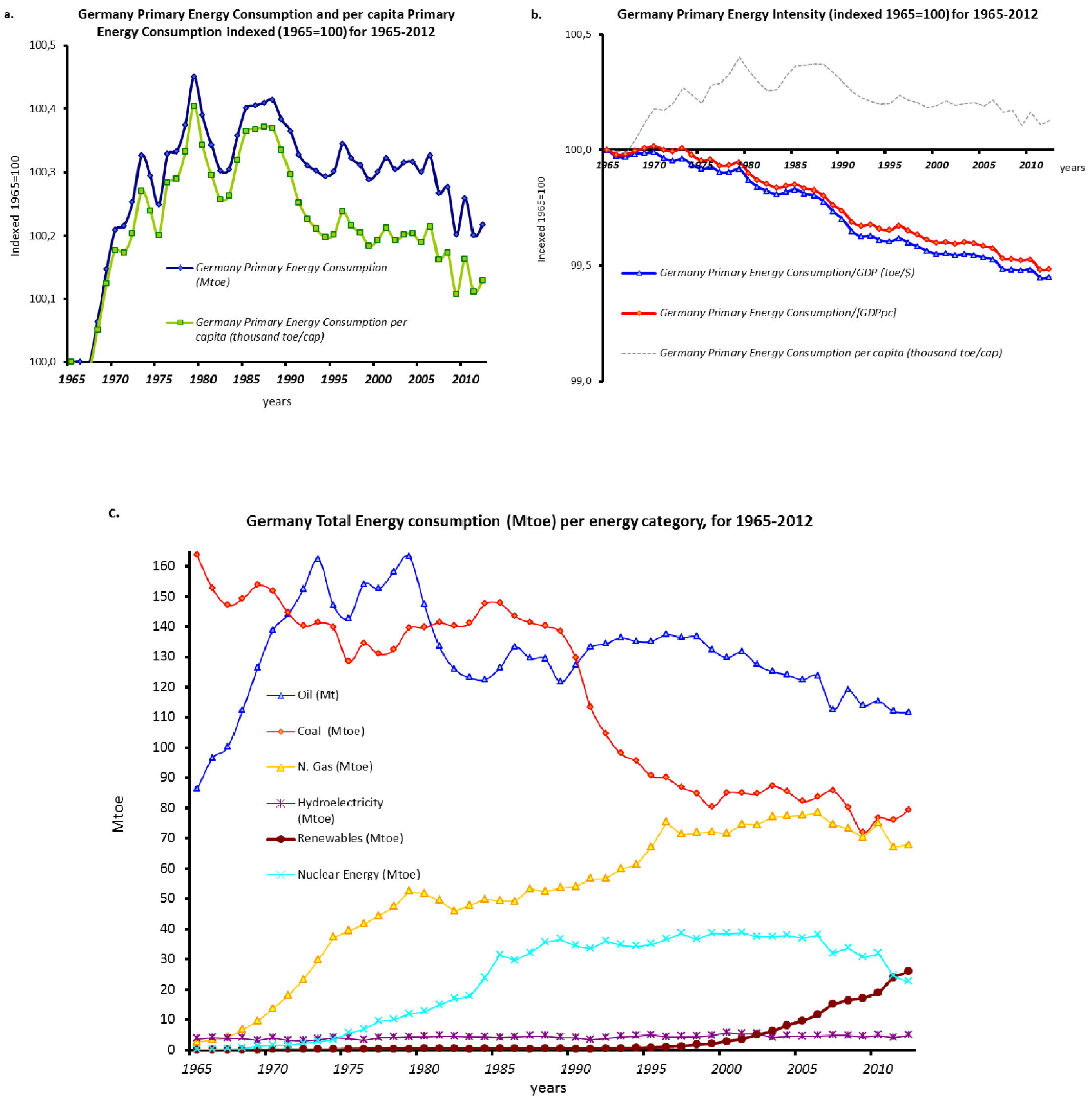

Figure 6.69 *a). Germany's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Germany's primary energy intensity (indexed 1965=100); c). Germany's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

Furthermore, Germany is the largest energy consumer in Europe and the eighth-largest energy consumer in the world (according 2012 data)[47]. The German economy has presented a remarkable improvement in energy efficiency as a result of combined technological advance and the implementation of energy efficiency policy regulations[48].

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[47] Source EIA: http://www.eia.gov/countries/country-data.cfm?fips=GM Accessed September 2014

[48] Energy Efficiency Policies and Measures in Germany, ODYSSEE-MURE report, 2012. (Avaialble at: http://www.isi.fraunhofer.de/isi-media/docs/x/de/publikationen/National-Report_Germany_November-2012.pdf) Accessed September 2014

The results of these policies can be traced on the declining trends of the total and per capita primary energy consumption trends, after 1990 (Fig. 6.69a) something that is further supported by the continuously declining EI trends, after 1980, as depicted by the estimates of both the standard and the proposed EI indicators (Fig. 6.69b). Additionally, both the standard and the proposed EI indicators follow exactly the same evolutionary pattern throughout the whole examined period, as in the case of Italy.

Finally, Germany seems to stabilize its oil and natural gas consumption trends, while a short coal consumption increase after 2010 was the result of the nuclear power decline[49]. Renewable energy consumption is massively increasing after 2000, as a result of Germany's energy agenda direction towards energy efficiency, renewable resources and commitment for nuclear power reduction (Fig. 6.69c).

6.6.15 France

France has the second-largest economy in Europe (in terms of GDP), after Germany, and the fifth largest in the world (According data for 2012). With low domestic energy production[50], the country relies on energy imports to meet most of its oil and natural gas consumption. France was the world's 12th largest oil consumer in 2012[51]. Oil consumption seems to be stabilized after 1985, showing a declining trend after 2008, while nuclear energy consumption is becoming after 2000 the predominant energy type. Furthermore, natural gas consumption is increasing, while coal and electricity consumption seem stabilized, following similar consumption patterns after 1993. Finally, renewable energy consumption gains ground after 2005 (Fig. 6.70c).

Total and per capita primary energy consumption is almost constantly increasing until 2008, where a declining pattern prevails for both indicators, probably due to the financial crisis of the Eurozone that have started earlier on during the same year (Fig. 6.70a). Finally, as far as

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[49] Coal consumption increased after Japan's Fukushima reactor accident occurred in March 2011, and Germany used coal as a substitute for nuclear power in electricity generation. Germany was the world's eighth-largest producer of coal in 2012. Nearly all coal production serves the power and industrial sectors. (Source EIA: http://www.eia.gov/countries/country-data.cfm?fips=GM) Accessed September 2014

[50] With the exception of nuclear energy production. The country's main source of electricity generation is nuclear power, and France is second to the United States in terms of operable nuclear capacity, according EIA.

[51]Source EIA: http://www.eia.gov/countries/country-data.cfm?fips=fr Accessed September 2014

the EI estimates concerned, both the standard and the proposed indicator present a period of relative stability, between 1980 and 1995, with both indicators depict a smooth decreasing trajectory after 2000 (Fig. 6.70b). In any case, the EI decrement is generally very soft and may be explained to some extend by the per capita consumption declining trends, during the same period (Fig 6.70b). Compared to the leading European German economy, the French economy, as the second largest economy of E.U., seems to have much less potentials for performing a strong decoupling of primary energy consumption from economic activity.

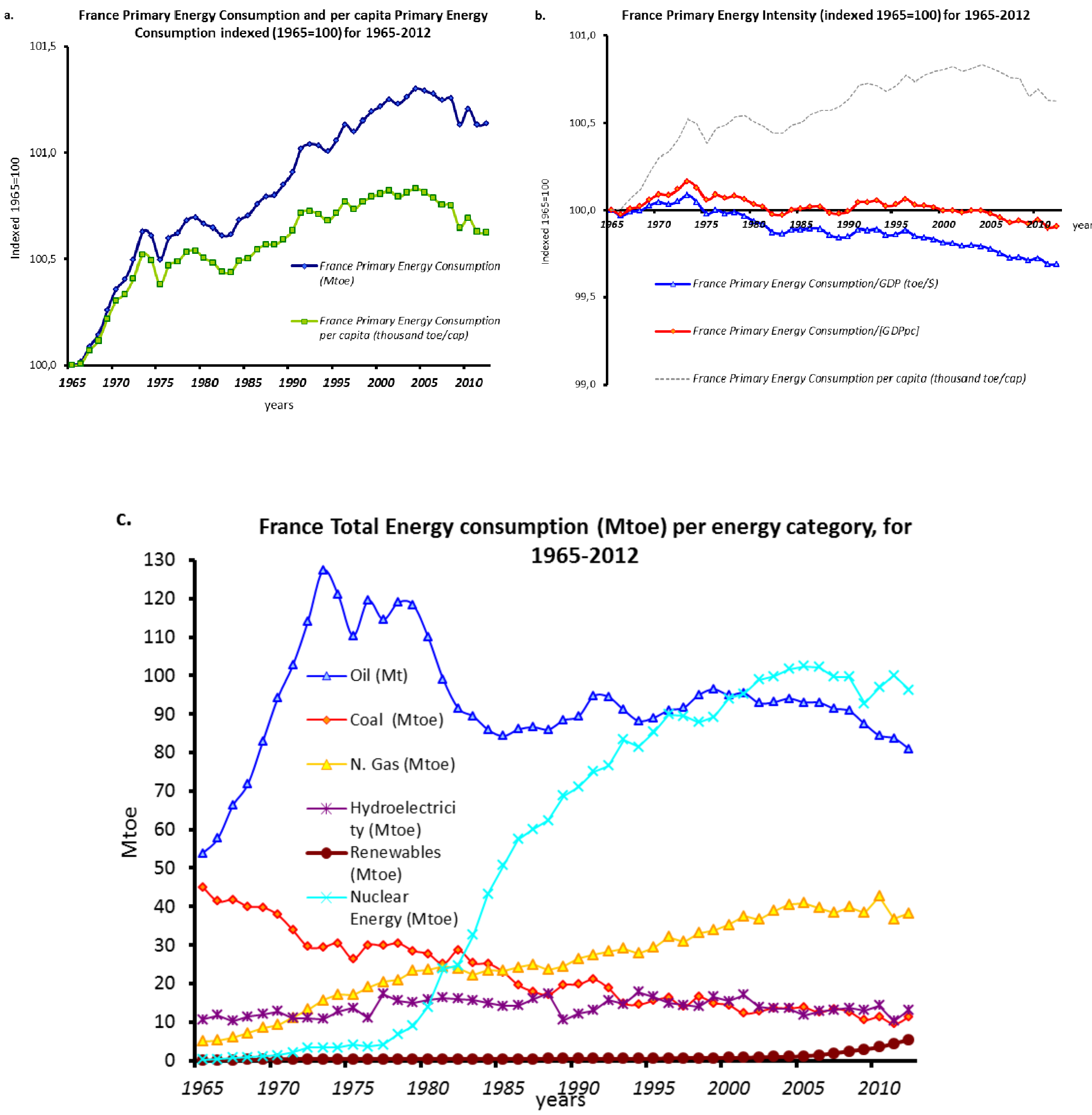

Figure 6.70 a). *France's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). France's primary energy intensity (indexed 1965=100); c). France's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

6.6.16 United Kingdom

The United Kingdom (UK) is the largest oil producer and the second largest natural gas producer in the European Union. Nevertheless, after many years of being an oil and natural gas exporter, UK became, after 2004, a net-importer for both fuels due to the peak of domestic oil and natural gas production occurred in late 1990's[52].

UK's total and per capita primary energy consumption present several fluctuations during the examined period; nevertheless, a constant increase in both indicators' trends is depicted during 1980-2005, to end up with a remarkable decline during 2006-2012 (Fig. 6.71a). Furthermore, UK's EI, as estimated by both the standard and the proposed framework, result in a remarkably similar evolutionary pattern for both EI indicators which simultaneously depict a constant decline in EI, with only two brief periods of relative stagnation (Fig. 6.71b: 1989-1996; 2007-2012).

Nevertheless, the focus of the analysis should be in the fact that a few years after domestic fuels' peak occurred (hence, an access to cheaper energy exploitation had reached to an end) there is observed, after 2006, stabilization in the (persisting until then) EI declining trends. Evidently, the UK government has developed some key energy concepts in order to address the declining domestic energy production, such as: promoting energy efficiency, decreasing fossil fuels[53] use (see Fig. 6.71c), heavily investing in renewable energy (it is worth mentioning that nuclear electricity production plays an important role in UK's electricity consumption, with clear intentions to increase in the future, simultaneously with renewable increase), and promoting energy trade cooperation with neighbors like Norway[54]. In any case, there is a long way (and a rigorous investment in renewable infrastructures) until these policies result again in declining EI trends.

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[52] Source: EIA (http://www.eia.gov/countries/country-data.cfm?fips=uk) Accessed September 2014

[53] Nevertheless, the coal consumption has increased rapidly during 2009-2012 in order to substitute the declining imported oil and natural gas consumption (Fig 6.71).

[54] *Source: Ibid*

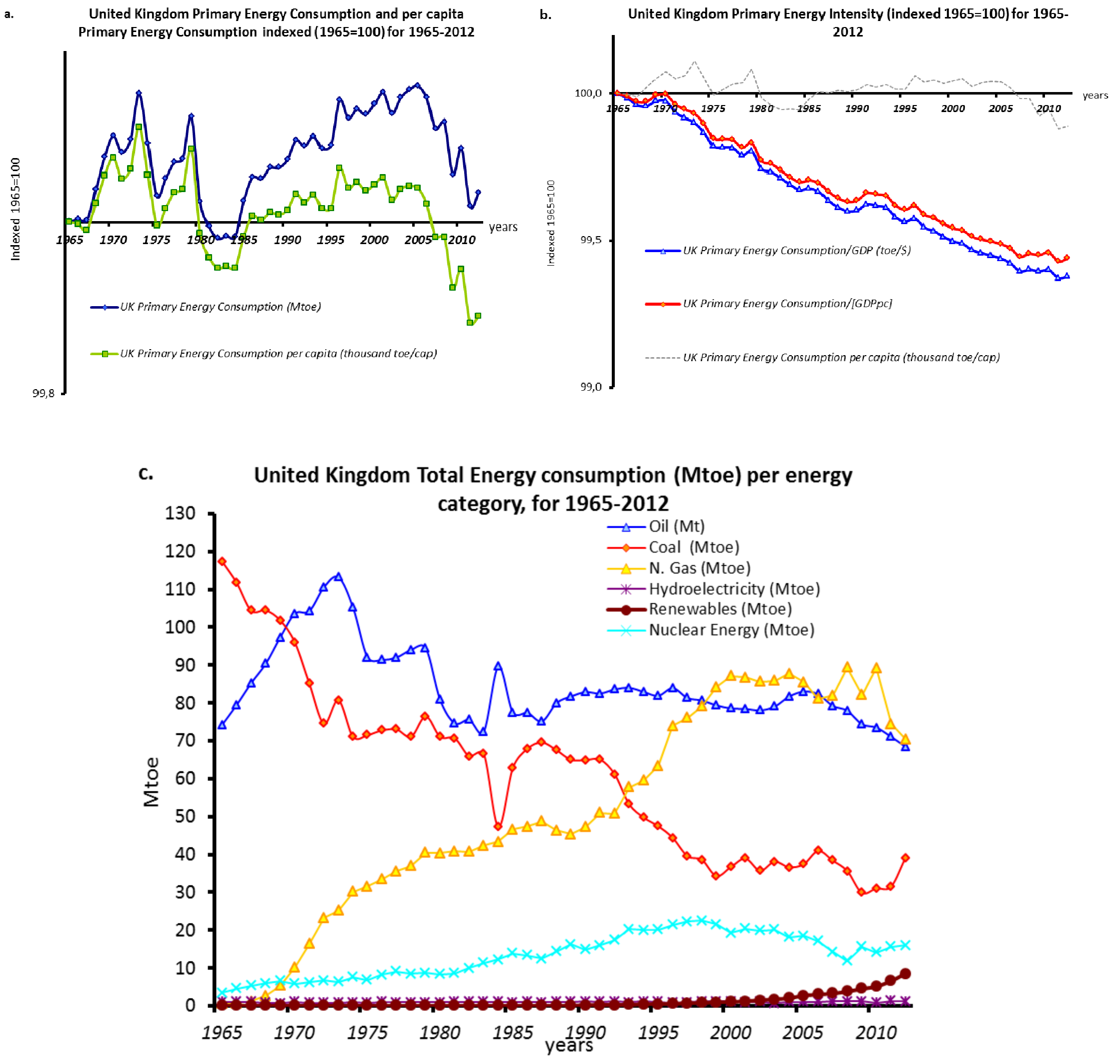

Figure 6.71 *a). UK's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). UK's primary energy intensity (indexed 1965=100); c). UK's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

6.6.17 Russia

Russia is the second-largest producer of natural gas (Russia holds the largest natural gas reserves in the world) and third-largest (after USA and Saudi Arabia) liquid fuels producer in the world[55]. Russian economy is highly dependant on natural gas consumption, followed by oil consumption. Further, Russia has significant reserves of coal (Russia has the second largest recoverable coal reserves, after USA); however coal consumption is relatively constant during 1995-2012. Finally, nuclear and hydroelectricity consumption further

[55] *Source EIA: http://www.eia.gov/countries/cab.cfm?fips=rs* Accessed September 2014

conclude the Russian energy profile, while renewable energy consumption remains in very low levels (Fig. 6.72c).

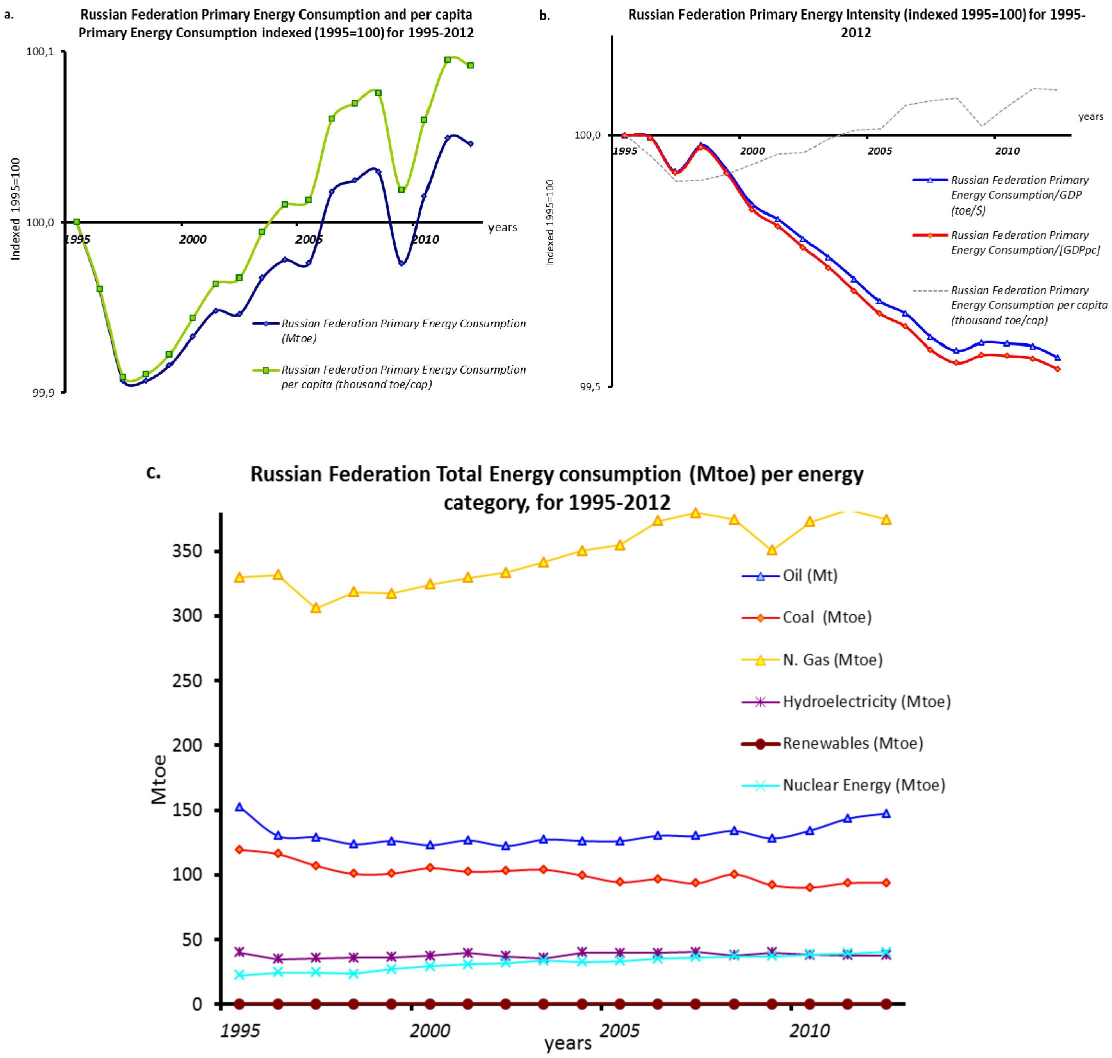

Figure 6.72 *a). Russia's primary energy consumption and per capita primary energy consumption (indexed 1965=100); b). Russia's primary energy intensity (indexed 1965=100); c). Russia's total primary energy consumption per energy category (in mtoe), for 1965-2012.*

The total and per capita primary energy consumption follow a similar increasing trend after 1997, overcoming the dramatic economic situation (and the declining energy consumption trends) followed the dissolution of the Soviet Union (on 26 December 1991). A strong decrement in both trends is only briefly occurred in 2008-2009, during the global financial crisis, followed again by a rigorous increase in energy consumption (Fig. 6.72a).

Remarkably though, EI of the Russian economy follows a constant declining trend, as depicted by both the standard and the proposed EI framework. Evidently, both the standard and the proposed indicators follow the same evolutionary pattern. Nevertheless, the last period 2008-2012 shows a slowdown of energy intensity, probably due to the global financial crisis of 2008.

6.7 Discussion

To some extent, the difference between the two energy intensity ratios was to be expected, on the basis of their algebraic structure. However, the real focus of the analysis should be on the comparison of the indexed evolutionary path that each ratio presents, and this difference is substantial and important. We identify two causes for the different historical evolutions of DEC/GDP and DEC/[GDP $_{\text{per Capita}}$], as well as of the relevant ratios of section 6.6 utilizing PEC, instead of DEC: the **physical properties** of the real world production combined with the **demographic trends** of an increasing population, reflected on the DEC/[GDP $_{\text{per Capita}}$], result in different estimates than those based on the DEC/GDP ratio.

Specifically, the world DEC/GDP ratio shows a substantial decline especially in the post-WWII period. This result holds true for aggregate energy and for its coal component. Fossil fuels were the major energy resource throughout the post-war period. During that same period, coal was a significant energy resource albeit with a declining consumption trend (coal was dominant among fossil fuels from 1900 to 1961, continued to decline up to 1979 and, since then, its supply has been fluctuating between 30-35% of total fossil fuels). Simultaneously, the relationship between oil inputs and growth shows substantial decoupling after 1970. In 1973, the oil supply accounted for 52.5% of the total fossil fuels inputs, subsequently remaining the dominant energy source in the period 1970-2009. Natural gas had a marginal contribution to total energy use before 1950. After the 1950's and up to 2009, natural gas increased its contribution reaching its maximum in the 1980's (26% of the fossil fuels total). Natural gas presents a period of decoupling after 1980, exactly within the period where it contributes substantially to the energy use. Consequently, world DEC/GDP ratio follows a historical path indicating a severe decoupling of GDP from energy use. This holds true for aggregate energy as well as for the dominant energy resources in the respective periods of their essential contribution. The main explanations lie with technological advances, shifts towards higher quality energy sources, and changes in the composition of the GDP with higher production rates for "soft products" (*Kaufmann, 1992; Grubler, 1998; Ekins, 2000; Ockwell, 2008*) (*See also Chapter 3*).

The countries that examined by the present chapter, sum up to the 75.58% of the global economy (in 2013, according to the Total Economy Database). In a nutshell, the US DEC/GDP presents an almost constant EI decline until 2005, with only some short interruptions briefly occurred in several periods. Similarly, the Japan's DEC/GDP shows an almost constant EI decline after 1914, with two brief interruptions during WWII and 1961-1974 periods, while the India's DEC/GDP depicts an almost permanent declining trend throughout 1961-2008. These declining trends seem to be predominant, concerning the standard EI estimation, for the rest of the countries examined in section 6.6; yet there are some exceptions of the prevailing "*EI decrement*". In fact, several examined developed countries show a diachronic increment in EI trends: South Korea; South Africa; Turkey; Iran; Saudi Arabia; Argentina; Mexico; Brazil.

On the other hand, the world DEC/[$GDP_{per\ Capita}$] ratio follows a substantially different evolutionary pattern. The aggregate energy use for the production of one unit of GDP per Capita kept increasing until the 1980's. From that point on, there have been only marginal fluctuations. The Oil/[$GDP_{per\ Capita}$] ratio increased until the 1980's which marked the start of a period of smooth decline, broken by intervals of stability. From the 1960's on, the Coal/ [$GDP_{per\ Capita}$] ratio declined and increased substantially after 2000. The Natural Gas/[$GDP_{per\ Capita}$] ratio increased until the 1990's at which point, after a sharp decline, it remained almost stable. Furthermore, the US DEC/[$GDP_{per\ Capita}$] indicator results in a general EI increase, during 1870-1977 (with the exception of the WWI, the Great Depression, and WWII periods). After 1977, and until the end of the examined period in 2005, the US DEC/[$GDP_{per\ Capita}$] ratio presents a constant EI reduction. Concerning the Japanese DEC/[$GDP_{per\ Capita}$] ratio, a constant, briefly interrupted, increment in EI is observed, which lasts until 1974. A short EI decreasing period is observed during 1975-1983, followed by a period of relative stabilization. On the other hand, the Indian DEC/[$GDP_{per\ Capita}$] depicts an increment during 1961-1992, to start an extensive EI decline after 1993. The significance of the different way in which both the standard and the proposed framework are evolved, could be traced in the further country analysis of section 6.6; remarkably, increasing or long-run stagnant EI trends can be identified for all the developing countries that examined, while various developed countries present similar results, namely: Canada; Australia; Taiwan; Italy; France.

Beyond the country level analysis, we assert that current growth patterns, once envisaged at the aggregate global level, are heavily dependent on energy inputs. Energy supply is still a crucial parameter which triggers and feeds economic growth. The tremendous technological advances, concerning both the effectiveness of the production process and energy sources exploitation, have been offset by other factors. Among these factors we recognize the physical properties of real world goods and the increasing population (demographic trends). The need for "*basic goods*" (which have relatively substantial physical "*dimensions*" and require higher energy inputs during the production) serving the needs of an increasing population, may restrict the potentials of further decoupling growth from energy flows.

6.8 Conclusions

Decoupling of economic growth from energy resources

Estimates of the decoupling of economic growth from energy use are based on the empirical assessment of the DEC/GDP ratio. Historically, this ratio has followed a decreasing path for global as well as most of the developed economies. Projections from this trend raise optimism for a transition into an era of relative independence from natural resources and hence an era of a-growth. However, the DEC/GDP ratio fails to take into account some fundamental characteristics of the economic production. We propose the DEC/[GDP $_{\text{per Capita}}$] ratio as a better approximation, in comparison to the DEC/GDP ratio, of the energy requirements of the real world production process. The evolutionary pattern of DEC/[GDP $_{\text{per Capita}}$] ratio incorporates two fundamental evolutions that DEC/GDP ratio fails to account for: the physical properties of production (HSP) and the demographic evolution (BHS). Economic goods changed drastically throughout the time periods studied by the present study and by the relevant studies found in recent literature. Technological advance makes possible the satisfaction of certain human needs by producing goods that require less energy inputs while, at the same time, the structure of production is shifting towards "*soft*" goods (services). Evidently, these trends are sufficiently reflected on DEC/GDP ratio. On the other hand, the DEC/[GDP $_{\text{per Capita}}$] ratio accounts for the physical properties of production process, thus the physical dimensionality that economic goods incorporate. Simultaneously, DEC/[GDP $_{\text{per Capita}}$] reflects the population impacts (BHS) on the energy requirements of production. An increasing population requires more "*basic goods*" for the satisfaction of "*basic needs*". "*Basic goods*" (such as dwelling, transport, food, etc.) have substantial physical dimensions and consequently require certain energy inputs. As a result, the relevant decoupling estimates are rather moderate. Empirical estimation of DEC/[GDP $_{\text{per Capita}}$] for global growth indicates increasing energy intensity until the 1980's when relative stability commenced. Similar results are identified for several national economies, such as USA, Canada, Australia, Mexico, Brazil, India and France, just to name indicatively a few of them. Differences between the evolutionary patterns of DEC/GDP and DEC/[GDP $_{\text{per Capita}}$] ratios result in different expectations of the potential for decoupling in the future.

If production is perceived as a dimensionless abstraction measured in monetary units (thus, GDP), then, there are high expectations of reducing the energy requirements for its creation. On the other hand, if economic production is envisaged as a mixture of goods and services facilitating human needs (BHS), then, although there might be some potential for decoupling, there also exist constraints because of the physical properties of the real world goods. This puts the scientific dialogue among growth optimists, a-growth, and de-growth within a more realistic framework.

In order to feed this dialogue with substantial empirical evidence there is a need for further empirical studies on disaggregated energy carriers and at disaggregate spatial level. Furthermore, the dimensionality of GDP may require the development of more rigid indicators, beyond the use of GDP per capita. In any case, Chapter 6 aspires to trace for the first time, even indirectly, the physical dimensionality of the production process (HSP).

The "Beyond Fossil fuels" era

Since the mastery of fire and the Agricultural Revolution, the journey of mankind towards eternity has been essentially characterized by its ability to harness energy. Stages of abundance and increased consumption are sooner or later replaced by periods of scarcity, uncertainty and massive technological progress, and vice versa, through a perpetual balance between shortage and cornucopia. Among the innumerable technologies that humans have developed through centuries, Nicholas Georgescu-Roegen (*1972; 1975; 1979; 1982; 1983; 1986*) distinguishes two milestone inventions that essentially increased human power, named them as "*Promethean technologies*" by the name of the Titan "*Prometheus*" who, according ancient Greek mythology, stole the knowledge of fire from gods and bring it to man: the **first Promethean gift (Prometheus I)** was the mastery of fire. The use fire enabled the qualitative (chemical to thermal) conversion of energy (*Cleveland, 2003*). In G-R's own words: "*The mastery of fire enabled man not only to keep warm and cook the food, but,* *above all to smelt and forge metals, and to bake bricks, ceramics, and lime. No wonder that the ancient Greeks attributed to Prometheus (a demigod, not a mortal) the bringing of fire to us*" (*Georgescu-Roegen, 1982 -p. 30*). This first period of Prometheus I technology could be referred as the Wood Age, where wood was serving as the only source of caloric power (*Georgescu-Roegen, 1983*). The **second Promethean gift (Prometheus II)** was the heat engine. The heat engine achieved the qualitative conversion of heat energy to mechanical and kinetic work – the conversion of caloric power into motor power –. The gift of Prometheus II enable humans to derive mechanical and kinetic power from a new and more intensive source, the fire fed by fossil fuels (*Georgescu-Roegen, 1983-p.30*). We actually still live, and mainly base our production process (social/ industrial metabolism), at the Prometheus II technological level, despite the tremendous technological progress occurring in numerous other energy production technologies (i.e. nuclear electricity, renewable resources, etc)[56].

According to Heinberg (2011), we are living the fifth great turning point in Mankind's history. The first was the discovery of fire, 2 million years ago (The first Promethean gift, as Georgescu-Roegen described it). The second great invention was the development of the language. The third turning point was the agricultural revolution, 10.000 years ago. The 4th turning point was the industrial revolution occurred about 2 hundred years ago, engaging the remarkable contribution of fossil fuels usage in economic production and growth (the internal combustion engine was the so-called 2nd Promethean gift according to Georgescu-Roegen).

At present time we are facing the transition to the 5th turning point from a fossil fuel based economy into something else which, still, it is not clearly defined (The 3rd Promethean gift, according G-R). Among the most realistic and well-established approaches for the future is the concept proposed by Jeremy Rifkin (*Rifkin, 2011*) which assumes that internet technology and renewable energy are merging to the "*Third Industrial Revolution*". However, since the replacement of fossil fuels is still based on economic assumptions, theoretical solutions and expectations for further technological breakthroughs, caused by the inevitable

[56] Yet, as G-R clears it out (*Georgescu-Roegen, 1986-p.17*), solar energy is still a "parasite" of the other primary energy resources, while brave feeding tariff financial advantages are still required in order to be economically viable as technology and compete the still cheaper fossil fuels. Further, G-R points out that the ordinary nuclear reactor is not a new promethean recipe; rather it only replaces fossil fuels as a resource of heat.

increment of the fossil fuels price, it is not quite clear what the day beyond fossil fuels would look like. The question remains: Does mankind approach an era of "*peak everything*" without owning a clear-cut plan of how to deal with this emerging scarcity?

In his own words, that still sound so up to date, G-R concludes that (*Georgescu-Roegen, 1983-p.30*): "*…The problem now is whether a new Prometheus will solve the present (energy) crisis, as Prometheus II solved that of the Wood Age (the shortage of wood resources). But it is not pessimism to point out that no one can be sure one way or the other about the future Promethean gift…*"

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7TH CHAPTER

A meta-analysis investigation of the direction of the Energy–GDP causal relationship

Implications for the growth-degrowth dialogue and the natural resources scarcity issue

"Research papers using the same methods with the same variables, just by changing the time period examined, have no further potential to make a contribution to the existing energy–growth literature"

F. Karanfil, 2009-p. 1193.

7.1 Introduction

In his own words, Serge Latouche, the founder of the term "*Décroissance*"[1] declares that "*degrowth*" is not just a concept; more than that, it is a political slogan with theoretical implications, while it has not a symmetrical meaning to "*growth*" (*Latouche, 2010*). Actually, Latouche invented the term "*degrowth*" in his effort to entitle a collection of essays, written by Nicholas Georgescu-Roegen, on entropy law and the economic process, by smoothing out the negative implications of the word "*declining*" – used by Georgescu-Roegen – with the use of the more elegant term "*degrowth*" (*ibid*). Contemporary literature on degrowth has various definitions about what this term means. Kallis (2011) defines sustainable degrowth as a, socially and economically, sustainable and equitable reduction – and eventually stabilization – of society's throughput (energy and matter flows).

More specifically, the Research and Degrowth Declaration defines degrowth as: "*a voluntary transition towards a participatory and ecologically sustainable society […] the objectives of degrowth are to meet basic human needs and ensure a high quality of life, while reduce the ecological impact of the global economy to a sustainable level, equitably distributed between nations"* (*Research and Degrowth, 2010-p.524*). In that context, degrowth is actually envisioned as the crucial stage before the transition to the Daly's Steady State Economy (*O' Neil, 2012*). According to Figure 7.1, the growth era of wealthy nations should follow an essential degrowth path in order to reach a Steady State Economy (SSE), whilst the developing economies should follow a path of decelerating growth.

However, it should be denoted that an economy with constant throughput which, nevertheless, exceeds the negative capacities of the containing ecosystem, is not an actual SSE. Apparently, it is essential for energy and matter flows not to exceed the ecological limits, in order to establish a SSE. Consequently, degrowth is perceived as the crucial "*volunteer mechanism*" that is required before a SSE could be established (*O'Neil, 2012*). In other words, degrowth is a process whose end goal is a SSE (*Kerschener, 2010*). What is more, Kerschener (2010) concludes that the concepts of degrowth and SSE are complementary.

[1] Degrowth is the English translation of the French term "Décroissance", proposed by Serge Latouche.

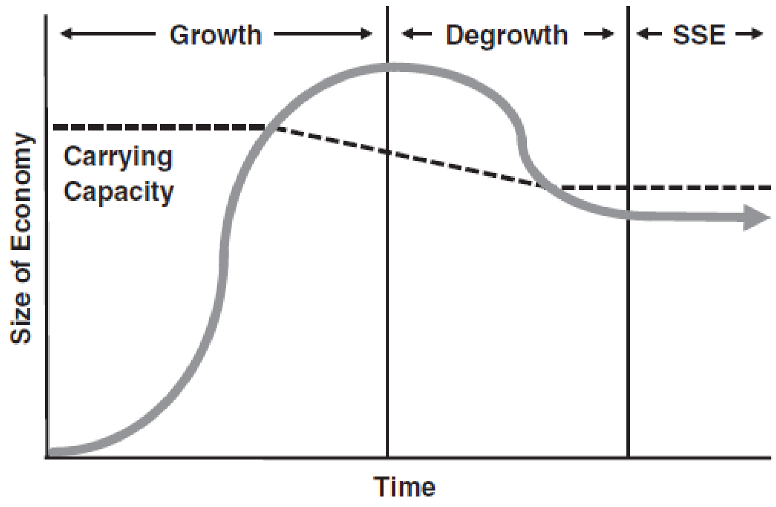

Figure 7.1 *The degrowth transition to a Steady State (Source: O'Neil, 2012-p.222)*

Whilst the theoretical background of degrowth definition has approached a mature and concrete level of consistence, the empirical interpretation of what really degrowth could be - or could be measured as degrowth -, still remains obscured. Van den Bergh (2011-p.881), in his critisicm on degrowth, illustrates its five main practical interpretations:

1. GDP degrowth
2. Consumption degrowth
3. Worktime degrowth
4. Radical degrowth
5. Physical degrowth

Instead of degrowth, Van den Bergh proposes the term "*a-growth*" since we should be neutral or indifferent about GDP growth, due to the fact that GDP calculation misleads the actual social welfare. Since GDP is an impropriate approximation of Social Welfare, we should no longer take it seriously; hence ignore it as a social goal. In that sense, a-growth is an appropriate and less ambitious term, compared to degrowth (*Van den Bergh, 2011*).

Seen from a different angle, the contemporary debate on growth, a-growth and degrowth (*van Griethuysen, 2010; van den Bergh, 2011; Kallis, 2011; Kallis et al., 2012; Victor, 2012*) represents, in fact, an update of the long-standing dialogue over the scarcity of natural resources at the aggregate level, and constraints on economic process and growth (*D'Alessandro et al., 2010; Kaivo-oja et al, 2014*). The inevitable limits on growth imposed by the scarcity of natural resources - as delineated in the early works of Georgescu-Roegen (1971, 1977) and Meadows et al. (1972) - are reiterated in modern degrowth approaches (*Borowy, 2013; Infante Amate and de Molina, 2013; Lietaert, 2010; Research & Degrowth, 2010*). The steady state economy (*Daly, 1974, 1996*), as a "*remedy*" for scarcity and environmental degradation, inspired a-growth (*van den Bergh, 2011*) and degrowth approaches (*Kerschner, 2010; O'Neill, 2012; Schneider et al., 2010*). On the other hand, optimistic approaches which are based on the expectation of continual technological advance and the possibility of substitution of natural inputs with man-made capital (*Solow, 1956, 1957*) support the continuation of current growth trends (*Baumol, 1986; Solow, 1974, 1978, 1993, 1997*).

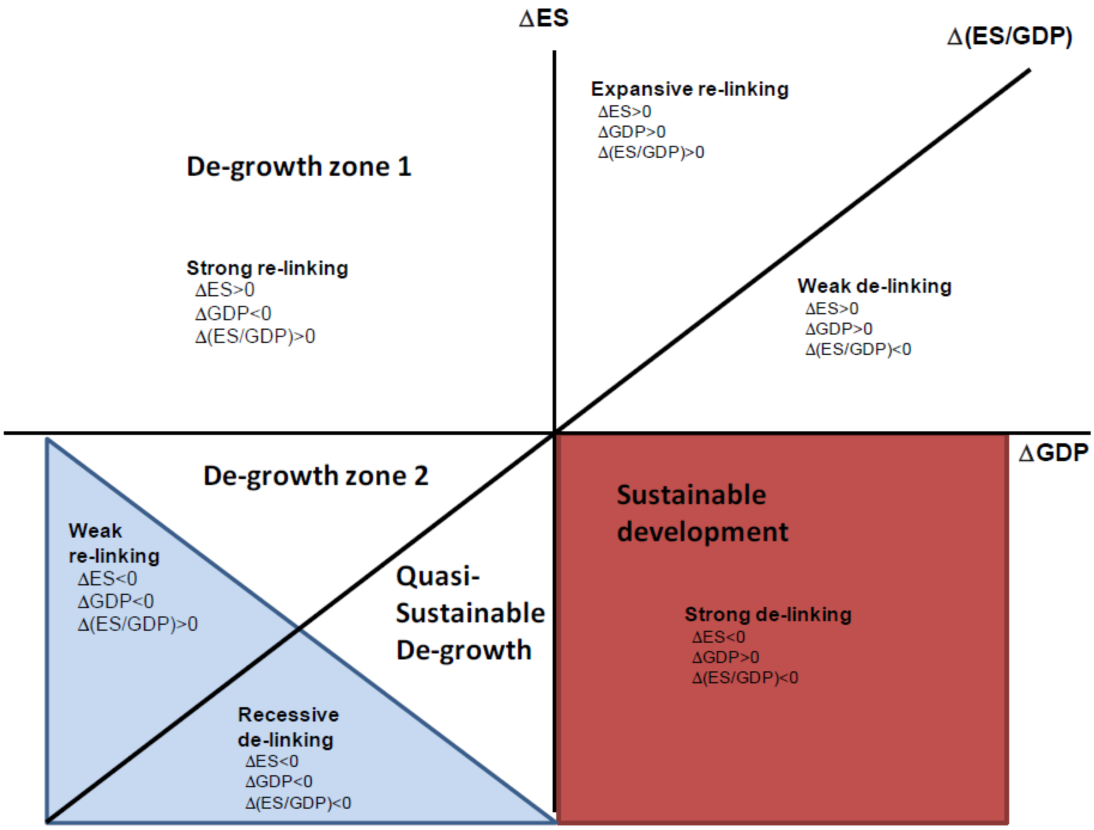

Figure 7.2 *Degrowth and Decoupling (Source: Kaivo-oja et al., 2014-p. 1479)*

Results from this debate may have direct implications for sustainability science, as the availability of natural resources is regarded as one of the conditions for sustainable development (*Bithas, 2008; Bithas and Nijkamp, 2008; Howarth, 2007; Hueting, 2010; Spangenberg, 2010*). Nowadays, it should be possible for the various theoretical approaches to be placed on a sounder basis as empirical evidence becomes available. The key question of the ongoing debate on degrowth is whether the past correlation of energy and matter flows with GDP growth, and the failure of absolute decoupling (*Jackson, 2009; Bithas and Kalimeris, 2013*), call for more structural investigation of the relationship between natural resources and GDP growth (*Kallis, 2011*). Towards this suggestion for fertile empirical analysis, present research aspires to cast light into the empirical establishment (or not) of the, still theoretical, degrowth dialogue. Two aspects of contemporary empirical analysis stand out as crucial for the empirical investigation of the growth-degrowth dialogue: decoupling natural resources use from GDP growth (*Bithas and Kalimeris, 2013; Cleveland et al., 1984; Krausmann et al. 2009; Fiorito, 201*3) and the direction of the causal relationship between energy use and economic growth (*Kraft and Kraft, 1978*). Concerning the first aspect of Decoupling, Figure 7.2 depicts an overall view of the linking process between the economy and the environment. The horizontal axis represents changes in GDP (ΔGDP); the vertical axis represents changes in environmental impacts (ΔES); while the environmental intensity of GDP is represented by the diagonal axis (Δ[ES/GDP]) (*Kaivo-oja et al., 2014*). In line with Figure 7.1, Figure 7.2 gives a brief representation of the interrelation between the decoupling effect and the degrowth debate. Evidently, many degrowth researchers indeed envisioned a downscaling of production and consumption that will lead in the sustainable development stage. In this context, according Fig 7.2, the degrowth process will gradually follow a path, from a strong re-link (coupling) of the economy, to the weak re-link (smooth coupling) and then to a recessive de-link (decoupling) that will finally end up with a strong de-link (strong decoupling), in the Sustainable Development stage (Fig. 7.1). The chapters 5 and 6 investigated thoroughly the decoupling between energy and material (non-fuel) resources and GDP growth, reaching in results that further support the argument of Jackson (2009), about what he calls as "*the myth of decoupling*".

The present chapter attempts to trace the existence of a "*macro*"[2] direction in the findings on energy-GDP causality and attempts to identify the factors that determine this "macro" direction. In addition, the implications of a macro direction of the E-GDP causality nexus on the energy scarcity and growth-degrowth debate will be investigated. The present research carries out meta-analyses for the first time in the history of the causality dialogue, employing two different methodologies: Rough Set Data Analysis (RSDA) and multinomial

[2] As "*macro*" direction, on the Energy-GDP causality nexus, we define the existence of a prevailing direction that holds in the vast majority of cases and is not influenced by the case-specific characteristics of each case study.

logistic regression. The conclusions of this chapter have been recently published at the Journal of Cleaner Production (*Kalimeris et al. 2014*).

Clearly, energy (exergy), as the only source of "*useful work*", is indispensable for the economic process (*Warr et al., 2010*). Natural resource economists and practitioners place the energy issue at the core of contemporary economic analysis and policy (*Bentley, 2002; D'Alessandro et al., 2010*). The literature on causality results in four different estimates of the direction of causality: from energy (E) to GDP, from GDP to E, bi-directional causality, and no causality in either direction (*Ozturk, 2010; Payne, 2010*). If the causality tends to run from GDP to E, or if there is no causal relation between the two, then there might be substantial potential for further growth. In this context, energy scarcity does not impose a severe constraint on prospects for economic growth (*Ang, 2007; Ghosh, 2002; Soytas et al., 2007*). The energy use which is induced by growth can be adjusted within the limits of energy availability. The aggregate output of the economic process could be oriented towards less energy-intensive goods and technological advance could decouple economic process from energy constraints. Causality running from GDP to E implies further potential for the effective use of energy and restructuring of the economy towards less energy-intensive sectors. On the contrary, if the direction of causality from E to GDP prevails, then limited energy resources will impose serious constraints on growth potentials (*Magazzino, 2011; Wolde-Rufael, 2010a*). Involuntary degrowth will be the inevitable result of the exploitation of current energy resources unless new "*promethean*" technologies emerge and new energy resources become available in an economically viable way (*Georgescu-Roegen, 1976, 1984*). A well designed voluntary degrowth process is envisioned as a "*line of defence*" against this forthcoming scenario of natural resources scarcity.

The present chapter is organized as follows: Section 7.2 reviews the relevant literature on the energy-GDP growth causal relationship, extending previous surveys of the literature to cover the period from 1978 to 2011; Section 7.3 presents the methodological framework; Section 7.4 presents the results of meta-analysis by rough set analysis; Section 7.5 presents the results of meta-analysis by multinomial logistic regression analysis of the same data set; finally, Sections 7.6 and 7.7 consist of further discussion of the results and the overall concluding remarks, respectively.

7.2 The causality debate between energy consumption and economic growth

There has been a growing literature over the last three decades concerning the issue of the causal relationship between energy consumption and economic growth measured in terms of GDP. This ongoing debate has produced at least 172 research papers so far. These encompass a wide variety of approaches. They focus on different countries, groups of countries or even parts of a country, and employ various econometric methodologies, time periods and proxy variables. In more detail, the four possible findings regarding the direction of the causal relationship between energy consumption and economic growth, already introduced above, are as follows (*Ozturk, 2010; Payne, 2010*):

- **Neutrality hypothesis or no causality (E≠GDP):** no causal relation exists between GDP growth and energy consumption. This implies that energy consumption is not correlated with GDP growth and it follows that energy scarcity and conservative policies in relation to energy use do not affect economic growth (*Ozturk, 2010*). The "*neutrality hypothesis"* has been documented by *Akarca and Long (1980), Yu and Hwang (1984), Yu and Choi (1985), Erol and Yu (1987), Yu and Jin (1992), Cheng (1996), Glasure and Lee (1997), Fatai et al. (2002), Soytas and Sari (2003), Altinay and Karagol (2004), Soytas and Sari (2006a), Jobert and Karanfil (2007), Lee (2006), Soytas et al. (2007), Halicioglu (2009), Payne (2009), Soytas and Sari (2009), Acaravci and Ozturk (2010), Payne and Taylor (2010) and Payne (2011a.).*

- **Conservation hypothesis (GDP→E):** unidirectional causality running from GDP growth to energy consumption. This hypothesis implies that GDP growth causes energy consumption. It suggests that an economy that functions in such a causal relationship is less energy dependent; consequently, any conservation policies concerning energy consumption will have little or no adverse effect on economic growth (*Ozturk, 2010*). The "*conservation hypothesis"* has empirical support in findings of *Kraft and Kraft (1978), Abosedra and Baghestani (1989), Cheng and Lai (1997), Cheng (1998, 1999), Soytas et al. (2001), Aqeel and Butt (2001), Soytas and Sari (2003), Narayan and Smyth (2005), Al-Iriani (2006), Lee (2006), Yoo and Kim (2006), Zachariadis (2007), Mozumder and Marathe (2007), Zamani (2007), Mehrara (2007), Lise and Van Montfort (2007), Lee and Chang (2007b), Ang (2008), Karanfil (2008), Hu and Lin (2008), Zhang and Cheng (2009), Ghosh (2009), Narayan and*

Smyth (2009), Chang (2010), Ozturk et al. (2010), Lean and Smyth (2010) and Kumar (2011).

- **Growth hypothesis (E→GDP)**: unidirectional causality running from energy consumption to GDP. It implies that energy consumption causes GDP growth. The "*growth hypothesis*" suggests that the availability of abundant cheap energy sources promotes economic growth. In that sense, while increases in energy consumption may contribute to further economic growth, reductions in energy consumption may have negative effects on growth (*Ozturk, 2010*). The "*growth hypothesis*" is supported by empirical findings of *Ramcharran (1990), Stern (1993), Masih and Masih (1996, 1998), Glasure and Lee (1997), Stern (2000), Asafu-Adjaye (2000), Soytas and Sari (2003), Morimoto and Hope (2004), Wolde-Rufael (2004), Thoma (2004), Lee (2005), Lee and Chang (2005), Soytas and Sari (2006b), Lee (2006), Ang (2007), Lee and Chang (2007a), Narayan and Singh (2007), Soytas and Sari (2007), Yuan et al. (2007), Lee and Chang, 2008; Narayan and Smyth (2008), Abosedra et al. (2009), Akinlo (2009), Apergis and Payne (2009a, 2009b), Odhiambo (2009b), Chang (2010), Tsani (2010), Warr and Ayres (2010), Wolde-Rufael (2010a), Magazzino (2011), Payne (2011b), Asghar and Rahat (2011), Fotros and Maabudi (2011), Heo et al. (2011), Alam et al. (2011), Tiwari (2011), Yin and Wang (2011) and Arifin and Syahruddin (2011).*

- **Feedback hypothesis (E↔GDP) or bi-directional causality**: a bi-directional causality flows between GDP and energy consumption. Both energy consumption and GDP growth trigger each other. The "*feedback hypothesis"* is documented by *Hwang and Gum (1991), Ebohon (1996), Masih and Masih (1996, 1997), Asafu-Adjaye (2000), Yang (2000), Hondroyiannis et al. (2002), Glasure (2002), Soytas and Sari (2003), Paul and Bhattacharya (2004), Oh and Lee (2004), Ghali and El-Sakka (2004), Han et al. (2004), Lee (2006), Soytas and Sari (2006b), Yoo (2006a, 2006b, 2006c), Zou and Chau (2006), Climent and Pardo (2007), Francis et al. (2007), Ho and Siu (2007), Mahadevan and Asafu-Adjaye (2007), Zachariadis and Pashourtidou (2007), Lee et al. (2008), Yuan et al. (2008), Erdal et al. (2008), Tang (2008), Odhiambo (2009a), Belloumi (2009), Mishra et al. (2009b), Apergis and Payne (2010a, 2010b), Belke et al. (2011), Shuyun and Donghu (2011), Kouakou (2011) and Kahsai et al. (2012).*

The empirical findings on the energy consumption-economic growth nexus consist of a variety of often conflicting results; nothing approaching a consensus has emerged in the literature. This raises important questions concerning the appropriateness of the chosen methodology and the selected variables (*Beaudreau, 2010*). The main purpose of the present paper is to cast light on the importance of the questions and criticism raised by Beaudreau (2010) as well as other researchers (*Karanfil, 2009; Mehrara, 2007*), by carrying out a systematic review of the empirical literature. We extend previous surveys of the literature on the energy-GDP growth causal relationship to cover the period 1978-2011. Our review is based on two previous literature surveys of the energy-GDP causality debate (*Ozturk, 2010; Payne, 2010*) as well as on additional effort by the authors to bring the survey up to 2011. The literature survey revealed 172 studies. We augment the narrative review by means of a meta-analysis in which the causality direction found by each case study is related to the study's micro characteristics. In fact, two meta-analyses, employing different methodologies, are carried out: one is Rough Set Data Analysis and the other is multinomial logistic regression. According to Glass (1976), the meta-analysis method can be described as the statistical analysis of the results of a large collection of analyses for the purpose of integrating their findings (analysis of analyses). To put it differently, the basic purpose of meta-analysis is to provide the same methodological rigour to a literature review that is required of experimental research. A meta-analysis establishes the presence of an effect and can be a valuable tool for resolving differences in a debate or determining important moderators of an effect (*DeCoster, 2004*).

From the above, it appears that the findings in the literature on the relationship between energy consumption and economic growth could hardly be further from providing a consensus, as they support the four possible conclusions regarding the causality direction with almost equal frequencies. Meta-analysis aims at bringing some order to this chaos, by ascertaining whether the four findings are related in any degree to the characteristics of the studies. For example, does a particular econometric method tend to lead with relatively high probability to one particular conclusion about causality?

The attributes of studies that were selected for the meta-analysis as ones that potentially might influence conclusions, and also could generally be extracted from the published papers, were the following:

- *The time period examined*. Whereas some studies investigate a very short period of time, up to 10 years (*Abosedra et al., 2009; Sari et al., 2008*), others examine a period between 10 and 40 years (*Chang et al., 2001; Chontanawat et al., 2006, 2008; Erol and Yu, 1987; Kraft and Kraft, 1978*), and several studies are based on a period of 40 years or more (*Aqeel and Butt, 2001; Cheng, 1999; Soytas and Sari, 2003; Stern, 1993; Yin and Wang, 2011*). There is also a study that investigates different time regimes within a country (*Fallahi, 2011*). Zachariadis (2007) criticizes the use of small samples as it may be associated with the well-known loss of power of econometric tests. In this sense, we assume that the length of the time period might have an important influence on the final results.

- *The classification of countries studied*. Countries may be classified according to their economic development status (*Acaravci and Ozturk, 2010; Apergis and Payne, 2010a; Belke et al., 2011; Chiou-Wei et al., 2008; Costantini and Martini, 2010; Huang et al., 2008; Jinke et al., 2008; Lee and Chang, 2007a; Ozturk et al. 2010; Soytas and Sari, 2006b; Zachariadis, 2007; Huang et al., 2008*), geographical criteria (*Chang et al., 2011; Esso, 2010; Francis et al., 2007; Kahsai et al., 2012; Kumar, 2011; Lee and Chang, 2008; Lee et al., 2008; Mishra et al., 2009a, 2009b; Narayan and Smyth, 2009; Wolde-Rufael, 2006; Wolde-Rufael, 2009; Yoo and Kwak, 2010*), their energy imports and exports profile (*Eggoh et al., 2011; Mahadevan and Asafu-Adjaye, 2007; Squalli, 2007*) or other country classifications and trade agreements among countries (*Al-Iriani, 2006; Apergis and Payne, 2009c, 2010c*). There are also studies referring to a former (USSR) union of countries (*Reynolds and Kolodziej, 2008*), while a few others scrutinize separate parts (cities) or economic sectors (e.g. industry) of a country (*Halicioglu, 2007; Ho and Siu, 2007; Soytas and Sari, 2007; Thoma, 2004; Wolde-Rufael, 2004; Yanqin, 2011; Zhixin and Xin, 2011*).

- *Methodology.* A broad variety of methodological approaches has been implemented in order to reveal the causality between energy consumption and economic growth, and in which direction it operates. These approaches can be classified into three broad classes (*Beaudreau, 2010*): early tests, cointegration tests and post-cointegration tests. Since the very beginning of the causality debate until the late 1990s, most studies (*Abosedra and Baghestani, 1989; Cheng, 1997; Erol and Yu, 1987; Kraft and Kraft, 1978; Nachane et al., 1988; Stern, 1993; Yu and Hwang, 1984*) utilized a methodology based on both

Granger (*Granger, 1969*) and Sims (*Sims, 1972*) causality econometric tests, including the modified Engle-Granger causality test (*Engle and Granger, 1987*) and Hsiao's Granger causality test (*Hsiao, 1981*). From the mid-1990s, the causality debate was enhanced by new methodological approaches (*Johansen and Juselius, 1990*) based on the cointegration method (*Cheng, 1999; Masih and Masih, 1996; Stern, 2000; Yoo, 2005; Yuan et al., 2007*) and other alternatives such as Toda-Yamamoto (1995) causality tests (*Fatai et al., 2002; Wolde-Rufael, 2005), Pedroni (1999) panel cointegration (Costantini and Martini, 2010; Lee, 2005; Mahadevan and Asafu-Adjaye, 2007*), ARDL (*Pesaran et al., 2001; Sari et al., 2008; Shin and Smith, 2001*) bounds test (*Akinlo, 2008; Ghosh, 2009; Fatai et al., 2004; Ozturk and Acaravci, 2010, 2011; Zachariadis, 2007*) and at least 12 other methods (*Asghar and Rahat, 2011; Belke et al., 2011; Chiou-Wei et al, 2008; Fallahi, 2011; Hu and Lin, 2008; Narayan and Prasad, 2008; Thoma, 2004*).

- *The energy source*. Various energy inputs have been examined in the energy-GDP causality debate. We can divide the literature into groups of studies estimating energy input contributions from fossil fuels at an aggregate and disaggregate level (*Bowden and Payne, 2009; Narayan and Wong, 2009; Reynolds and Kolodziej, 2008; Yoo, 2006a; Wolde-Rufael, 2010b; Zou and Chau, 2006*), electricity consumption or production (*Akinlo, 2009; Altinay and Karagol, 2005; Chen et al., 2007; Ghosh, 2002; Jinke et al., 2008; Jumbe, 2004; Murray and Nan, 1996; Ramcharran, 1990; Shiu and Lam, 2004; Thoma, 2004; Yoo and Kim, 2006; Zachariadis and Pashourtidou, 2007*), nuclear energy consumption or production (*Heo et al., 2011; Payne and Taylor, 2010; Wolde-Rufael, 2010a; Yoo and Jung, 2005*), and renewable energy consumption or production (*Apergis and Payne, 2011; 2012, 2012; Bithas and Banti, 2002; Payne, 2011b; Tiwari, 2011*), as well as an exergy approach (*Warr and Ayres, 2010*) and the use of the divisia index of quality weighted energy consumption (*Stern, 1993, 2000; Zarnikau, 1997*).

7.3 The methodological framework

The model used in the present study can be briefly described in three general stages:

1. **Data preparation** (Data Coding)

2. **Rough Set Data Analysis** (Data Reduction, Rules Generation) and validation of the results (Choise of Decision rules that better explain the dataset)

3. **Multinomial logistic regression** that was applied in order to further investigate the strength of each attribute's contribution to the causality results.

7.3.1 The database construction

According to Hawcroft and Milfont (2010), the procedure of meta-analysis can be described in brief as: (1) a search for studies; (2) selection of studies that meet the criteria for inclusion in the meta-analysis; and (3) coding the attributes of eligible studies. These steps result in the construction of the database for the meta-analysis.

Firstly, the literature review process followed the procedure described thoroughly by Seuring and Müller (2008). Secondly, we excluded some studies from the initial sample of 172 studies. Among those excluded were literature reviews (*Ozturk, 2010; Payne, 2010*), special points of view (*Beaudreau, 2010; Karanfil, 2009*) and a few studies that failed to provide essential input for the requisite categories (*Adams and Shachmurove, 2008; Carrion-i-Silvestre et al., 2005; De Janosi and Grayson, 1992; Duro et al., 2010; Ferguson et al., 2000; Holtedahl and Joutz, 2004; Huang, 1993; Mishra et al., 2009a; Narayan et al. 2010; Sari and Soytas, 2007; Wolde-Rufael, 2010b; Yoo and Lee, 2010; Yu et al., 1988*), or lacked accessibility to further details beyond the study's abstract. We excluded studies that examined other key variables such as causality between employment and GDP, employment and energy consumption, energy intensity and so on. However, studies at least partially examining the energy-GDP nexus, or focussing on an industry sector and relevant industrial production as a part of the specified country's economy instead of GDP (*Feng et al., 2009; Fotros and Maabudi, 2011; Halicioglu, 2007; Hondroyiannis et al., 2002; Narayan et al., 2007; Sari et al., 2008; Thoma, 2004; Ziramba, 2009*), were included in our meta-analysis.

A small number of earlier studies employ GNP instead of GDP. We included these studies without distinction from the large majority that examine GDP. Nevertheless, it should be mentioned that the use of GDP as an aggregate indicator of economic process has been severely criticized for obscuring crucial attributes of real-world economic production (*Daly, 2013; van den Bergh, 2010*); hence, the exclusive use of this indicator by the vast majority of the studies within the causality debate may have further implications affecting the result of directionality.

Studies that estimate causality for a group of countries are separated into their component countries whenever possible. This procedure of separating countries led to 686 cases with complete data, representing the 158 published studies. The great majority of these studies (135, 85.4 %) were published from 2000 onwards (derived cases: 606, 88.3%). Sixteen studies (10.1 %) were published in the 1990s (derived cases: 50, 7.3%) and six studies (3.8%) in the 1980s (derived cases: 29, 4.2%), with just one from the 1970s (0.6 %). Ranking studies according the journal in which they were published reveals that almost 57% of the 158 studies appeared in *Energy Economics* (52 studies, 32.9 %) and *Energy Policy* (38 studies, 24.1%). A further 17.7% was published in various other high impact-factor[3] journals such as *Applied Energy* (8, 5.1 %), *Journal of Policy Modeling* (8, 5.1 %), *Energy* (5, 3.2 %), *Ecological Economics* (4, 2.5 %) and *Applied Economics* (3, 1.9 %). The remaining 21% of the studies included in the meta-analysis were published in 17 other journals, while a small number of published working papers (3, 1.9%) and papers published in peer-reviewed conference proceedings (4, 2.5%) complete the dataset.

Some studies included both short-run and long-run causal relationship implications (*Alam et al., 2011; Apergis and Payne, 2009c; Apergis and Payne, 2010c; Belloumi, 2009; Ciarreta and Zarraga, 2009; Magazzino, 2011; Narayan et al., 2010; Ozturk and Acaravci, 2011; Zhixin and Xin, 2011*) and in these cases we used only the short-run results as we did not aim to distinguish between short-run and long-run causality results in the meta-analysis. The growth hypothesis (E→GDP) was supported by 193 cases (28.1%), the conservation hypothesis (GDP→E) by 163 (23.8%), the feedback hypothesis (E↔GDP) by 175 (25.5%) and the neutrality hypothesis or no causality (E≠GDP) by 155 (22.6%).

7. 3.2 Coding of study attributes

-*The year of publication* attribute was coded according to the date of publication, as: 1970s; 1980s; 1990s; and 2000-2011.

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[3] For the "impact factor (IF)", we explicitly use the latest 5-year Impact Factor (2012), according to Journal Citation Reports, published by Thomson Reuters. Because of changes in a journal's IF, examination of any relationship between the results of studies and the journal's IF remains rather a hard task.

-*The length of the study period* was grouped into ten-year periods: less than 10 years; 10-19 years; 20-29 years; 30-39 years; 40 years or more.

-*The level of economic development* of the country under study was coded as: G7 member; OECD member (excluding G7); high developing non-OECD members; and other non-OECD countries. A separate category was used for studies that examined only part of a country (city or region) or an economic sector of a country.

-The categorization of *econometric methodology* follows the general lines of Payne (2010). Six categories were distinguished, which can be labelled briefly as: Sims and Engle-Granger causality; Johansen-Juselius; Toda-Yamamoto causality; Pedroni panel cointegration; ARDL bounds test; and other methods.

-*The energy types* examined in the causality debate are recorded in nine categories: total fossil fuels consumption (coal, oil, and natural gas); electricity consumption (or production); energy consumption per capita (primary or electricity, etc.); total energy consumption (primary fuels plus electricity); oil or petroleum consumption (or production); coal consumption (or production); natural gas consumption (or production); nuclear energy consumption (or production); and renewable energy consumption.

-*The energy measurement unit* is a crucial issue in the relationship between energy consumption and economic growth (*Cleveland at al., 1984; Kaufmann, 1992; Warr et al., 2010; Stern, 2011*). However, a substantial number of studies avoid giving a clear definition of the energy measurement unit (*Cheng and Lai, 1997; Masih and Masih, 1996; Wolde-Rufael, 2004*). Our classification of the energy measurement methods used in the causality debate is into nine distinct types: Btu's; oil equivalent; electricity (watts); coal equivalent; exergy; crude quantity; Devisia Index; Joules; and not defined, for those studies that do not specify the unit of energy measurement.

-An attribute "*One or more countries*" was included to cater for those studies of more than one country that could not be broken down into results for the individual component countries. It thus includes two categories: single country, if the estimated causality direction referred to a single country; and group of countries, if the estimated causality direction referred to an overall group of countries that could not be separated.

-Finally, the dependent variable *"Causality direction"* was coded into four distinct categories: the *growth hypothesis* E→GDP; the *conservation hypothesis* E←GDP; the *bi-directional hypothesis* E↔GDP; and the *neutrality hypothesis* E≠GDP.

Table 7.1 *Frequencies of attributes recorded for the meta-analysis of 686 cases from 158 studies of the relationship between energy consumption and economic growth*

		n	%
	Total number of cases	686	100
Length of study period (years)[1]	<10	5	0.7
	10-19	8	1.2
	20-29	191	27.8
	30-39	353	51.5
	40+	127	18.5
Economic development of study country	G7	121	17.6
	Other OECD	163	23.8
	Non-OECD high development	148	21.6
	Other non-OECD	245	35.7
	Region of country	9	1.3
One or more countries	Single country	637	92.9
	Group of countries	49	7.1
Econometric methodology	Sims & Engle-Granger	207	30.2
	Johansen-Juselius	189	27.6
	Toda-Yamamoto	116	16.9
	Pedroni	52	7.6
	ARDL bounds test	52	7.6
	Other	70	10.2
Energy input source	Energy per capita	272	39.7
	Total energy	214	31.2
	Electricity	139	20.3
	Coal	22	3.2
	Oil	14	2.0
	Gas	13	1.9
	Other[2]	12	1.7
Energy measurement method	Oil equivalent	357	52.0
	Electricity	168	24.5
	Btu	49	7.1
	Coal equivalent	25	3.6
	Crude quantity	12	1.7
	Other[3]	8	1.2
	Undefined	67	9.8

[1]Not defined in 2 cases
[2] Nuclear 5, renewables 4, total fossil fuels 3
[3]Devisia index 5, Joule 2, exergy 1

Table 7.2 *Causality result of analysis in relation to length of study period, characteristics of study country, and econometric methodology employed. Percentages sum to 100 within each row.*

		Causality result							
		E→GDP		GDP→E		E↔GDP		E≠GDP	
		n	%	n	%	n	%	n	%
Length of study period (years)	<20	4	30.8	4	30.8	4	30.8	1	7.7
	20-29	60	31.4	50	26.2	37	19.4	44	23.0
	30-39	93	26.3	89	25.2	103	29.2	68	19.3
	40+	35	27.6	20	15.7	30	23.6	42	33.1
Economic development of study country	G7	25	20.7	25	20.7	33	27.3	38	31.4
	OECD	43	26.4	35	21.5	41	25.2	44	27.0
	High development	49	33.1	34	23.0	45	30.4	20	13.5
	Non-OECD	72	29.4	67	27.3	56	22.9	50	20.4
	Region	4	44.4	2	22.2	0	.0	3	33.3
One or more countries	Single country	177	27.8	148	23.2	162	25.4	150	23.5
	Group of countries	16	32.7	15	30.6	13	26.5	5	10.2
Econometric methodology	Sims & Engle-Granger	46	22.2	43	20.8	60	29.0	58	28.0
	Johansen-Juselius	59	31.2	36	19.0	70	37.0	24	12.7
	Toda-Yamamoto	31	26.7	38	32.8	8	6.9	39	33.6
	Pedroni	26	50.0	10	19.2	15	28.8	1	1.9
	ARDL bounds test	11	21.2	19	36.5	13	25.0	9	17.3
	Other	20	28.6	17	24.3	9	12.9	24	34.3

Table 7.3 *Causality results in relation to energy source and energy measurement employed in study. Percentages sum to 100 within each row.*

		Causality result							
		E→GDP		GDP→E		E↔GDP		E≠GDP	
		n	%	n	%	n	%	n	%
Energy input source	Electricity	39	28.1	37	26.6	23	16.5	40	28.8
	Energy per capita	68	25.0	61	22.4	95	34.9	48	17.6
	Total energy	71	33.2	50	23.4	46	21.5	47	22.0
	Oil	4	28.6	3	21.4	4	28.6	3	21.4
	Coal	3	13.6	6	27.3	4	18.2	9	40.9
	Gas	2	15.4	4	30.8	1	7.7	6	46.2
	Other	6	50.0	2	16.7	2	16.7	2	16.7
Energy measurement	Btu	6	12.2	19	38.8	5	10.2	19	38.8
	Oil equivalent	105	29.4	78	21.8	110	30.8	64	17.9
	Electricity	51	30.4	45	26.8	28	16.7	44	26.2
	Coal equivalent	4	16.0	5	20.0	7	28.0	9	36.0
	Crude quantity	2	16.7	5	41.7	3	25.0	2	16.7
	Other	4	50.0	1	12.5	3	37.5	0	.0
	Undefined	21	31.3	10	14.9	19	28.4	17	25.4

The 686x7 data matrix consisting of the six numerically coded attributes and the outcome of each study is available on-line as supplementary material. Table 7.1 shows the frequencies of the categories of each attribute in the total sample of 686 studies.

The associations between each attribute and the outcome variable, that is, the causality findings, are shown in Tables 7.2 and 7.3. Chi-squared tests show that every attribute is statistically significantly associated with the outcome, with the exception of the attribute "single country versus group of countries" (P=0.17; P is at most 0.023 for the other attributes). Examples of the many features that can be seen in these tables include: an increased proportion of neutral results (E≠GDP) in longer-term studies (duration 40 years or more) but fewer in studies of high-developing non-OECD countries and in studies of groups of countries; relatively more E→GDP results using the Pedroni panel cointegration methodology; and relatively fewer GDP→E findings when the study measured energy in oil equivalent. However, these findings are not independent of each other, because there are also strong associations between the attributes. For one example, studies in G7 countries tend to be longer term than in others: 49% cover at least 40 years, compared to 12% of studies in other countries. For another example, the Sims or Engle-Granger methodologies have been employed in 48% of studies that measured energy as energy per capita, compared to 19% of studies using other measurement methods. Because of these associations, it is desirable to carry out multivariate analyses that consider all attributes simultaneously.

7.4 Rough Set Data Analysis (RSDA)

7.4.1 The method

Rough Set Data Analysis (RSDA) is an operational research method applied to conceive and evaluate quantitative data and qualitative characteristics. It can identify causal relationships and express them through decision rules. The attributes and characteristics of different objects (cases) are analyzed and classified. The attributes are related to the decision variable (dependent variable) through decision rules reflecting rigorous causal relationships. The mathematical background of RSDA is presented in full in the relevant literature *(Duntsch and Gunther, 1998; Pawlak, 1982, 1991; Slowinski, 1993*). RSDA theory takes for granted the existence of a finite set of objects for which some information is known in terms of factual (qualitative or numerical) knowledge of a class of attributes (features, characteristics) (*Bithas and Nijkamp, 1997a, 1997b*). The rough set model is intended to be a structural, non-numerical method of information analysis, thus its quantitative aspects are of secondary interest (*Duntsch and Gunther, 1998*). As a result, RSDA can classify the attributes of objects-cases and determine the most important ones. We selected RSDA mainly because it is a simplified method used to discover information overlooked by other methods, to preprocess the data for further analysis and to strengthen results found previously by other methods (Rupp, 2005). RSDA has been developed as an alternative data analysis tool by Pawlak (1982, 1991) and further developed by Slowinski (1993). We carried out our analyses using the Rosetta Rough Set Toolkit (*Øhrn and Komorowski, 1997; Komorowski et al, 2002*) which offers a wide range of ready-to-apply statistical tools and filters.

7.4.2 RSDA results

RSDA application obtains preliminary information from the decision table (that is, the data matrix described above) by generating decision rules. Decision rules are expressed as conditional statements ('if then'), in which the 'if' conditions specify the initial conditions, while the 'then' inference statements indicate the logically valid conclusions. In this way, RSDA can be used as a tool for conditional transferability of the results from case studies to a new situation. A decision rule is thus an implication relationship between the description of the attributes and the decision attribute (causality direction). A rule is exact if the combination of the values of the attributes in that rule implies only one single combination of the values of the decision attributes, whereas an approximate rule only states that more than one combination of values of the decision attributes correspond to the same values of the attributes (*Bithas and Nijkamp, 1997a, 1997b*). A complete description of the rule generation procedure can be found in the relevant literature (*Kusiak, 2001; Øhrn and Komorowski, 1997; Rupp, 2005; Pawlak, 1991*).

After the decision table has been defined and coded, any objects with incomplete values must be removed. As we have no such objects, we proceed to the next step. The decision table is unnecessarily large in part because it is redundant. The same or indistinguishable objects may be represented several times. This requires the reduction of repeated attributes. The rejected attributes are redundant since their removal cannot worsen the decision attribute values (classification). Computing reducts is rather a complex procedure. However, there exist good heuristics based on genetic algorithms (*Komorowski et al., 2002*) that compute sufficiently many reducts by using the Rosetta Toolkit. The discernibility procedure of a genetic algorithm produces a set of minimum attribute subsets that define functional dependencies. An example of the discernibility function is given below:

f(6) =

*(A3 Country + D Causality results) **

*(A2 time period + A3 Country) **

*(A2 time period + A5 Energy Category + A6 Energy Measurement) **

*(A1 Year of publication + A5 Energy Category + A6 Energy Measurement) **

*(A1 Year of publication + A6 Energy Measurement + D Causality results) **

*(A1 Year of publication + A3 Country + A6 Energy Measurement) **

*(A1 Year of publication + A4 Methodology + A6 Energy Measurement) **

*(A1 Year of publication + A4 Methodology + A5 Energy Category + A7 Single or group of countries + D Causality results) **

(A1 Year of publication + A2 time period + A4 Methodology + D Causality results)

end

A part of the reducts generated from the data analysis is shown in Figure 7.3 below:

	Reduct
1	{A1 Year of publication}
2	{A1 Year of publication, A2 time period, A3 Country}
3	{A1 Year of publication, A2 time period, A5 Energy Category}
4	{A2 time period, A3 Country, A6 Energy Measurement}
5	{A1 Year of publication, A2 time period, A6 Energy Measurement}
6	{A2 time period, A4 Methodology, A6 Energy Measurement}
7	{A2 time period, A3 Country, A4 Methodology, A5 Energy Category}
8	{A3 Country, A4 Methodology, A6 Energy Measurement}
9	{A1 Year of publication, A3 Country, A5 Energy Category}
10	{A1 Year of publication, A3 Country, A6 Energy Measurement}
11	{A2 time period, A3 Country, A5 Energy Category, A6 Energy Measurement}
12	{A2 time period, A3 Country, A6 Energy Measurement, A7 Single or group of countries}
13	{A3 Country, A5 Energy Category, A6 Energy Measurement}
14	{A1 Year of publication, A3 Country}
15	{A2 time period, A3 Country, A4 Methodology}
16	{A3 Country, A4 Methodology, A5 Energy Category}
17	{A2 time period, A3 Country, A4 Methodology, A6 Energy Measurement}
18	{A2 time period, A6 Energy Measurement}
19	{A1 Year of publication, A2 time period}
20	{A2 time period, A4 Methodology}
21	{A1 Year of publication, A2 time period, A3 Country, A6 Energy Measurement}
22	{A1 Year of publication, A2 time period, A3 Country, A5 Energy Category}
23	{A1 Year of publication, A2 time period, A3 Country, A4 Methodology}
24	{A1 Year of publication, A3 Country, A4 Methodology}
25	{A2 time period, A3 Country, A4 Methodology, A5 Energy Category, A6 Energy Measurement}
26	{A3 Country, A4 Methodology, A5 Energy Category, A6 Energy Measurement}
27	{A1 Year of publication, A3 Country, A4 Methodology, A6 Energy Measurement}
28	{A1 Year of publication, A6 Energy Measurement}

Figure 7.3 *Example of reducts generated by the Rosetta toolkit*

Once the reducts have been computed, the rules are easily constructed by overlaying the reducts over the originating decision table and reading the values by using the Rosetta Toolkit. An example of the rules generated is given in Figure 7.4.

	Rule
128	A1(3) AND A3 (3) AND A6 (3) => D (1) OR D (4) OR D (2) OR D (3)
129	A1(3) AND A3 (2) AND A6 (3) => D (4) OR D (2) OR D (3) OR D (1)
130	A1(4) AND A3 (1) AND A6 (7) => D (1)
131	A1(4) AND A3 (2) AND A6 (9) => D (4)
132	A1(4) AND A3 (4) AND A6 (1) => D (3)
133	A2 (3) AND A3 (4) AND A5(4) AND A6 (1) => D (1)
134	A2 (4) AND A3 (2) AND A5(4) AND A6 (9) => D (4)
135	A2 (4) AND A3 (2) AND A5(4) AND A6 (1) => D (2)
136	A2 (3) AND A3 (4) AND A5(4) AND A6 (2) => D (1)
137	A2 (3) AND A3 (4) AND A5(3) AND A6 (3) => D (2)
138	A2 (3) AND A3 (3) AND A5(3) AND A6 (3) => D (1)
139	A2 (3) AND A3 (4) AND A6 (1) AND A7 (1) => D (1)
140	A2 (4) AND A3 (2) AND A6 (2) AND A7 (2) => D (3)
141	A2 (3) AND A3 (3) AND A6 (2) AND A7 (2) => D (2)
142	A2 (4) AND A3 (2) AND A6 (3) AND A7 (2) => D (2)

Figure 7.4 *Example of original rules generated by the Rosetta toolkit*

In the present study, 235 rules were generated from the decision table. Very few of these rules were exact.

An example of a rule is:

If A2 (5) AND A4 (3) AND A5(4) AND A6 (9) then decision for causality: => D (1)

Support=3

Coverage= 0.004373

Accuracy= 100%

The interpretation of this rule is: if attribute A2 "*Length of study period*" takes the value (5) "*More than 40 years*", and attribute A4 "*Econometric methodology*" takes the value (3) "*Toda-Yamamoto*", and attribute A5 "*Energy input source*" takes the value (4) "*Total energy consumption*", and attribute A6 "*Energy measurement*" takes the value (9) "*Not defined*", then the causality direction is D(1), thus "*E→GDP*". For this rule, the conditional attributes have a support of 3 objects from the total of 686 objects (support=3), which accounts for 0.43% of the total objects in the decision table (coverage=0.004373) and 100% of these 3 objects (Accuracy=100%) have a decision value =D(1). In general, only rules with relatively high support (hence, higher coverage) and high accuracy should be considered (Kusiak, 2001). To continue with the previous example, despite the fact that this rule presents the highest possible level of accuracy (100%), it fails as far as both support and coverage levels are concerned. To put it differently, it applies to too few cases to be able to offer a useful description relative to the dataset as a whole.

Once preliminary results have been obtained, validation techniques ensure that the knowledge obtained by rules is interpretable in functional relationships. A further filtering procedure is performed in order to find the rules that are accurate representations of the dataset. The filtering procedure is a practical sorting of rules according to their quantitative aspects (accuracy, coverage, etc) in order to reveal the most significant ones. Filtering the set of 235 rules, originally generated, produced a subset of 173 decision rules. An indicative part of the derived results is presented below:

QualityRuleFilterLoop
{FILTERING=Torgo; REMOVE.UNDEFINED=T; INVERT=F; RESOLUTION=Dynamic; RESOLUTION.THRESHOLD=100; RESOLUTION.FRACTION=0.01; FILENAME=Undefined; DECISIONTABLE=causality$, CLASSIFIER=StandardVoter; RULES=No name; FRACTION=0.0; IDG=F; SPECIFIC=F; VOTING=Support; NORMALIZATION=Firing; ROC.CLASS=1; FALLBACK.CERTAINTY=0.5}

Threshold	Rules	AUC	SE
0.764249	1.0	0.510358	0.026466
0.757669	2.0	0.515066	0.026504
0.755181	3.0	0.518832	0.026532
0.754839	4.0	0.528145	0.026592
0.754601	5.0	0.530915	0.026608
0.753886	6.0	0.533686	0.026623
0.753226	9.0	0.552093	0.026694
0.753067	12.0	0.557414	0.026706
0.752857	20.0	0.571606	0.026719
0.752591	26.0	0.582249	0.02671
0.751613	50.0	0.65092	0.026262

0.751534	94.0	0.683531	0.025797
etc			

Quality	Rule index
0.764249	90
0.757669	106
0.755181	89
0.754839	1
0.754601	202
0.753886	88
0.753226	60
0.753226	64
0.753226	174
etc	

The great majority of the rules (173) obtained in this way failed to fulfil the prerequisites of high support and high accuracy, for every alternative combination of statistical methods and filtering techniques that was applied. The procedure always resulted in large numbers of approximate rules with high accuracy but low support (few objects), and with low accuracy in combinations with higher support. Under these circumstances, it is impossible to choose accurately and consistently between generated rules. In conclusion, RSDA failed to provide concrete and effective results concerning the direction of causality.

7.5 Multinomial Logistic Regression Analysis and Results

Logistic regression analysis has become the standard statistical model for examining the influence of various factors on a dichotomous outcome in a regression framework. It estimates the probability of the occurrence of the outcome category of interest by modeling the relationship between one or more independent (explanatory) variables and the log odds (logit) of the dichotomous outcome. In the present study, the dependent variable is the causality direction result, which is not dichotomous but consists of four categories. We therefore apply the multinomial logistic regression model (*Agresti, 1996*). This analysis fits simultaneously three models, holding one outcome category as reference category and comparing each of the other three categories to it. Hence, choosing E≠GDP as reference category, the three regression models that are fitted are:

1. *E→GDP compared to E≠GDP*
2. *GDP→E compared to E≠GDP*
3. *E↔GDP compared to E≠GDP*

If π_j is the probability that the causality result is the category $j = 1, 2, 3, 4$, then these regression models are of the logit form:

$$\log \frac{\pi_j}{\pi_4} = \alpha_j + \beta_{1j} x_1 + \beta_{2j} x_2 + \ldots . + \beta_{pj} x_p$$

for *j=1,2,3*, where the constants α_j and regression parameters β_{ij} are to be estimated from the data by the method of maximum likelihood. Because all our explanatory variables are categorical, every independent variable x_i will be replaced by a set of dummy variables. For each of the attributes we must also set a reference category. For example, for the attribute "*Econometric methodology*" we chose the subcategory "*others*". The choice of reference category does not affect the overall statistical significance of an attribute, nor the estimates of the probabilities π_j derived from the fitted model.

Likelihood ratio tests in the analysis that regressed causality results against sets of dummy variables representing all six attributes identified two attributes as statistically significant: "*Econometric methodology*" (P<0.001) and "*Energy measurement*" (P=0.016). Each of the other attributes had P>0.1. The analysis was repeated using only these two attributes as explanatory variables in order to obtain the final results for presentation. Estimates are shown in Table 7.4. Results are expressed in terms of the rate ratio $\exp(b_{ij})$, where b_{ij} is the estimate of a regression coefficient β_{ij}. This gives the multiplicative effect of the corresponding dummy variable on the probability ratio π_j / π_4. A rate ratio (RR) greater than unity indicates that membership of the attribute category indexed by this dummy variable increases the probability of outcome *j* compared to the reference category E≠GDP. RR<1 indicates a reduced probability of outcome *j* compared to the reference category and RR=1 indicates that there is no differentiation in outcomes between membership of this attribute category and the reference category.

Table 7.4 *Multinomial logistic regression results: rate ratios with their 95% confidence intervals.*

		Rate ratio and 95% CI versus E≠GDP		
Attribute	Categories	E→GDP	GDP→E	E↔GDP
Econometric methodology	Sims & E-G	1.14 (0.53-2.43)	1.12 (0.51-2.44)	2.46 (1.01-5.98)
	Johansen-Juselius	4.34 (1.90-9.94)	2.39 (1.00-5.72)	8.80 (3.40-22.8)
	Toda-Yamamoto	0.99 (0.44-2.22)	1.55 (0.70-3.43)	0.53 (0.17-1.60)
	Pedroni	35.5 (4.29-293)	14.0 (1.60-123)	33.0 (3.69-295)
	ARDL	1.95 (0.66-5.78)	3.14 (1.13-8.75)	4.70 (1.46-15.1)
	Other*	1	1	1
Energy measurement	Btu	0.18 (0.06-0.58)	1.28 (0.45-3.61)	0.13 (0.04-0.47)
	Oil equivalent	0.96 (0.45-2.05)	1.74 (0.73-4.16)	1.00 (0.46-2.21)
	Electricity	0.87 (0.38-2.00)	1.60 (0.63-4.03)	0.52 (0.21-1.27)
	Other†	0.39 (0.12-1.27)	1.16 (0.34-4.01)	0.47 (0.15-1.49)
	Undefined*	1	1	1

* Reference category †Including coal equivalent

In interpreting the results of Table 7.4, we concentrate on those rate ratios for which the confidence interval does not include the value unity (so that RR≠1 is supported). In the case of *energy measurement*, the differentiation appears to be between measurement in Btu's and the other categories. Studies in which energy was measured in Btu's have a reduced probability of demonstrating E→GDP or E↔GDP, but an increased probability of finding GDP→E, compared to the neutrality hypothesis (see also Table 7.3). From cross-tabulations between the attributes (data not shown), these studies are commonly of 30-39 years duration (65.3%), conducted among G7 countries (38.8%) or other OECD members (46.9%), and often analyze total energy (57.1%). For the *econometric methodology* attribute, three methodologies – Johansen-Juselius, Pedroni and ARDL – all have increased probabilities of demonstrating any other causality result than the neutrality hypothesis, compared to the Sims and Engle-Granger, Toda-Yamamoto and other methodologies (see also Table 7.3). Some of these effects seem to be very strong, although the extremely wide confidence intervals make it difficult to make precise statements. This lack of precision is due to low numbers of cases in certain combinations of data: for example, only one of the 52 studies using the Pedroni methodology concluded in favor of the neutrality hypothesis (Table 7.3).

Table 7.5 *Combinations of attribute categories with the highest fitted probabilities of one outcome from the multinomial logistic regression analysis.*

	Categories of:			Number of cases	
Favoured result	Methodology	Energy measurement	Fitted probability	n	% of total
E→GDP	Toda-Yamamoto	Btu	0.416	10	1.5
	Pedroni	Btu	0.463	2	0.3
	ARDL	Btu	0.517	8	1.2
GDP→E	Johansen-Juselius	Oil equivalent	0.423	99	14.4
	Johansen-Juselius	Undefined	0.453	13	1.9
E↔GDP	Sims	Btu	0.502	16	2.3
	Johansen-Juselius	Btu	0.483	10	1.5
	Toda- Yamamoto	Other	0.418	3	0.4
	Other	Other	0.452	1	0.1
E≠GDP	Pedroni	Oil equivalent	0.501	44	6.4
	Pedroni	Electricity	0.580	4	0.6
	Pedroni	Other	0.428	1	0.1
	Pedroni	Undefined	0.559	1	0.1

The results of the analysis may also be demonstrated by calculating the estimated probabilities of each causality result based on the estimated regression coefficients for energy measurement and econometric methodology. Figure 7.5(a-e) present these probabilities diagrammatically and Table 7.5 gives the combinations that are the most strongly associated with one particular outcome, in that it occurs with a relatively high fitted probability (>0.4). These combinations account for 212 of the cases (30.9%) but several occur rarely, some in as few as one case. The commonest of these combinations are of oil-equivalent energy measurement with either the Johansen-Juselius methodology (support=99 cases, 14.4% of the total, with fitted probability 0.423 of the outcome GDP→E) and the Pedroni methodology (support=44 cases, 6.4% of the total, with fitted probability 0.501 of the outcome E≠GDP). These are the strongest results of the analysis. The most frequent combination of all is of the Sims or Engle-Granger methodology with oil-equivalent energy measurement (122 cases, 17.8%), for which the fitted probabilities of the four outcomes are not very different from each other (E→GDP 0.205, GDP→E 0.327, E↔GDP 0.241, E≠GDP 0.227).

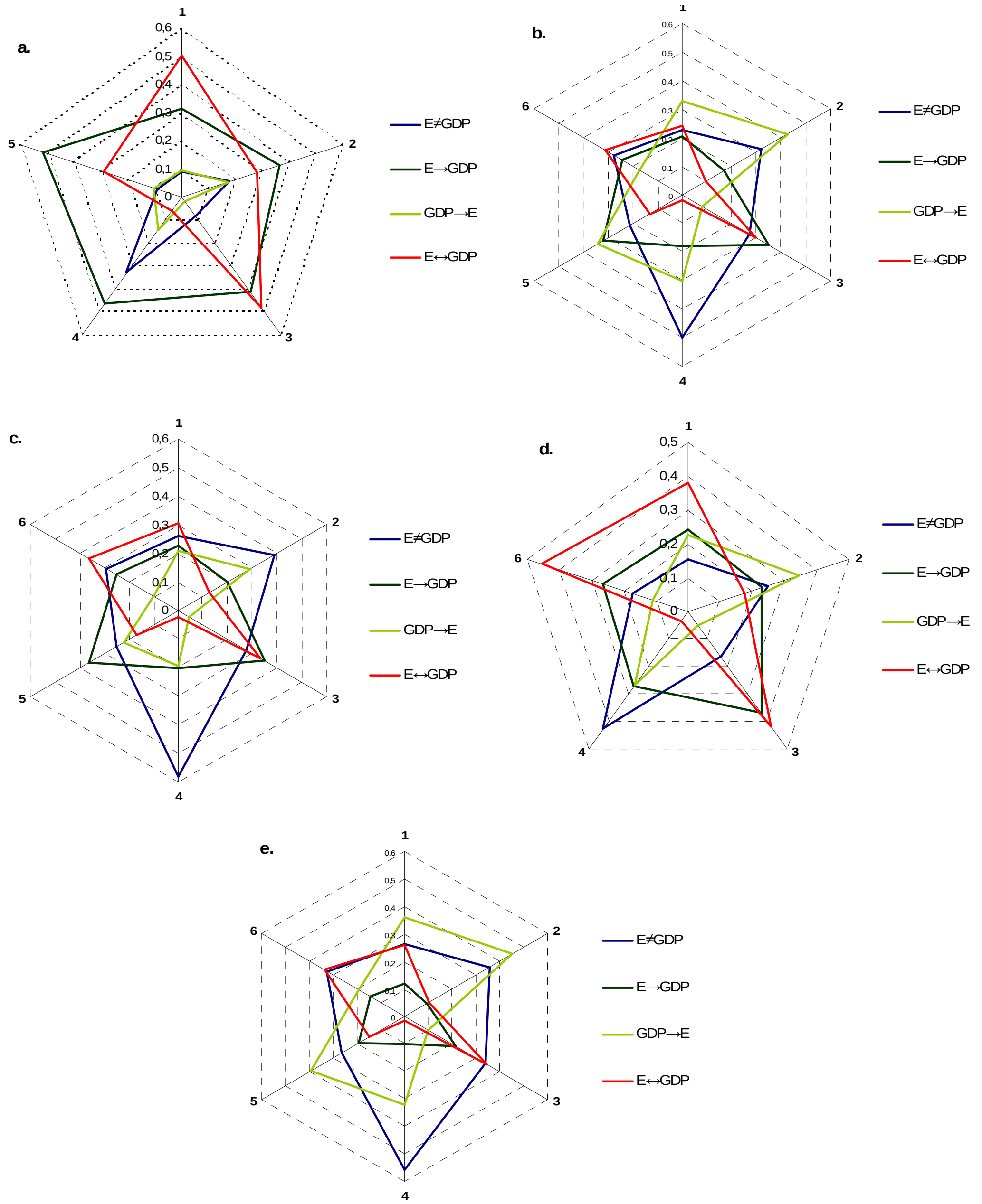

Figure 7.5: *Representation of Tables 4 and 5. Each radar-type diagram shows the fitted probabilities of each of the four outcomes for each of the six categories of Methodology: (a) for Energy Measurement in Btu's; (b) for Energy Measurement in oil equivalent; (c) for Energy Measurement in Electricity; (d) for Energy Measurement in coal equivalent; (e) for Energy Measurement "not defined". Methodology categories are: (1) Sims & Engle-Granger Causality; (2) Johansen- Juselius for Cointegration; (3) Toda Yamamoto Causality; (4) Pedroni Panel Cointegration; (5) ARDL Bounds test; (6) Others.*

7.6 Discussion

The present chapter focuses on the identification of general trends in the direction of the energy-growth causal relationship. The analysis tested the existence (or otherwise) of causal relationships among the selected attributes of the energy-growth nexus which explain the direction of causality. The investigation was based on both statistical methods and on methods of operational research. To this end, we performed a Rough Set Data Analysis (RSDA) and a multinomial logistic regression on a database consisting of 686 cases-sets of results derived from 158 published studies.

The RSDA indicated that there are no accurate rules – causal relationships among the attributes of the economies studied – that determine the causality direction. No solid causal relationships that define the direction of causality could be established. As a result, the direction (or the absence of any direction) of causality cannot be described by a theoretically testable argument. This conclusion is further supported by the findings of multinomial logistic regression; these also failed to define a robust causal relationship between the attributes of case studies and the direction of causality. A weak "*rule*" – causal relationship – such as the indication that the combination of the "Johansen-Juselius" methodology with "*oil-equivalent*" energy measurement usually leads to support for the conservation hypothesis (GDP→E), is of marginal importance as it does not lead to a fundamental rational explanation concerning the causality direction. Taking into account the findings of both RSDA and multinomial logistic regression, we are forced to argue that the direction of causality cannot obey a general "macro" rule among the attributes of the energy-economy nexus. In that context, it seems that the way causality runs depends on the specific conditions of each case study and is probably sensitive to the methodology adopted. The meta-analysis results support the argument of Mehrara (2007) who comments on the energy-GDP growth causality debate: "*when it comes to whether energy use is a result of, or a prerequisite for economic growth, there are no clear trends in the literature. Depending on the methodology used, and country and time period studied, the direction of causality between energy consumption and economic variables has remained empirically elusive and controversial*".

Nevertheless, empirical analysis in recent years identifies the existence of a fundamental relationship between energy use and economic growth (*Bithas and Kalimeris 2013; Cleveland et al., 1984; Warr et al., 2010*). Regardless of the directionality, the most crucial conclusion of the causality debate so far is, for most authors, that energy is an important determinant of economic growth. The uninterrupted function of the economic process requires substantial energy inputs (*Altinay and Karagol, 2005; Ghali and El-Sakka, 2004; Hondroyiannis et al., 2002; Lee, 2006; Soytas et al., 2001; Yuan et al., 2008*).

7.7 Conclusions

Given the demand for designing effective energy policies, the causality debate should offer a coherent understanding of the energy-growth nexus. The direction of causality between energy use and economic growth could be a decisive component of this nexus. Over the last three decades, the ongoing debate on the direction of causality between energy consumption and economic growth – closely following advances in econometric theory, energy economics and environmental economics – has produced a significant amount of scientific literature. However, despite all this research, the state of knowledge still remains quite indeterminate and controversial. The attempt in the present study to examine the concreteness and consistency of the debate's results by means of meta-analysis failed to define a robust macro causality direction and, moreover, failed to identify general factors and causal relationships determining the directionality. Under constraints imposed by the inability to identify a macro direction of causality, the numerous individual case studies may be perceived as influenced by conditions specific to each case and time. On the other hand, the failure of meta-analysis to reveal valid causal relationships defining the directionality at the aggregate level ultimately reflects the contradictory results that the debate itself presents. These contradictions and conflicts within the empirical results have been highlighted by many researchers (*Beaudreau, 2010; Mehrara, 2007; Ozturk, 2010*). Although progress in econometric methods provides several powerful tools for the analysis and understanding of the energy-economic growth relationship, applied studies using these tools are open to the criticism that many of these studies yield conflicting and even contradictory findings which makes it difficult to draw macro policy implications. As Karanfil (2009) and Ozturk (2010) comment: "*research papers using the same methods with the same variables, just by changing the time period examined, have no further potential to make a contribution to the existing energy–growth literature*". In that context, we may conclude that the directionality is the result of very specific conditions pertaining to each case study and may be influenced strongly by the analytical methods and econometric techniques applied. In the light of this conclusion, policy implications based on the direction of causality should be carefully worded as they are not based on solid theoretically and empirically testable arguments and hence could be sensitive to various factors.

Nevertheless, we argue that the impossibility of determining a general rule governing the directionality between energy and growth cannot question the very fact that growth requires energy and that the efficiency gains induced by technological advances have not alleviated this strong link. In that context, future research on E-GDP causal relationship could benefit by focusing on and investigating the following aspects:

- An effort to bridge three different fields of empirical analysis: the energy-GDP nexus; the decoupling effect; and the Environmental Kuznets Curves (EKC). A historical analysis of a country or a group of countries, in the light of the simultaneous empirical evidence of causal relationship between energy use and GDP growth (the causality investigation) in tandem with energy use intensity per unit of GDP (decoupling effect) and the EKC, could contribute to a fruitful comparison among methodologies and results and lay the foundation for a more integrated and substantial approach to the complex relationship between the use of natural resources and economic growth.

- A step beyond energy measurement in thermal equivalents to a more accurate energy efficiency measurement, such as the "*exergy*" and "*useful work*" approach (*Warr and Ayres, 2010; Warr et al., 2010*), and the Divisia index adjustment (*Stern, 1993, 2000; Zarnikau, 1997*) may reveal new empirical evidence, since only 5 out of 158 studies (0.33%) attempted an alternative measurement of energy use in terms of qualitative adjustments.

- In accordance with the previous point, an effort to evaluate and incorporate energy price fluctuations and price elasticities, instead of energy quantities, is absent from the vast majority of studies published within the causality dialogue. In this context, econometric studies examining the relationship between energy prices and the economic process (*Hamilton, 1996, 2008*) could offer a sound basis for progress in this direction

- As already mentioned in a previous section, the GDP has been the subject of extensive and severe criticism for many years as being an aggregate indicator which masks certain crucial aspects entailed by the economic process (*Bithas and Kalimeris, 2013; Daly, 2013; van den Bergh, 2010*). In the context of the causality debate, an effort to overcome the shortcomings arising from the use of GDP could be traced in the very few studies (just 7, 4.4%) that examined alternative variables such as percentage value added of an economic sector (*Costantini and Martini, 2010; Feng et al., 2009; Sari et al., 2008*), or business cycles (*Thoma, 2004*) instead of GDP. Towards this direction, a more disaggregated analysis may offer more substantial conclusions.

- Finally, as Payne (2010) proposes, a more robust classification of countries into groups with similar energy consumption patterns together with similar levels of development status could contribute to more coherent empirical estimates.

Beyond its prima facie interest, the analysis and evaluation of those aspects in future research may eventually provide the empirical basis for the - still theoretical - degrowth and a-growth dialogues. The present chapter could be perceived as a small contribution towards this direction.

Appendices

Appendix A. The Dataset

The Decision table (Coded Dataset) of 686 case studies is available online at: www.eesd.gr (Databases section).

Alternatively at Elsevier: http://dx.doi.org/10.1016/j.jclepro.2013.12.040

Appendix B. Attributes Coding

For the 158 studies comprising our database, the following 8 categories (attributes) are recorded:

- The year of publication
- The time series period that is being examined
- The econometric method utilized to answer the question of causality
- A single country or a group of countries is being examined
- The wealth categorization of the country or group of countries
- The type of energy input
- The energy measuring method
- The causality direction of the result (the decision attribute)

The following tables present the coding process that has been used for the construction of the dataset (Appendix A):

Table B1. Attribute "year of publication"

Decade of Publication	year	Studies	Decade Total (n)
70s	1978	1	1
	1979	0	
80s	1980	1	5
	1981	0	
	1982	0	
	1983	0	
	1984	1	
	1985	1	
	1986	0	
	1987	1	
	1988	1	
	1989	0	
90s	1990	1	16
	1991	2	
	1992	1	
	1993	1	
	1994	0	
	1995	1	
	1996	2	
	1997	5	
	1998	2	
	1999	1	
2000-2011	2000	4	136
	2001	3	
	2002	4	
	2003	1	
	2004	14	
	2005	8	
	2006	8	
	2007	23	
	2008	17	
	2009	20	
	2010	14	
	2011	20	
Total			**158**

Table B2. Attribute "examined time period" Coding

Coding	Time period	n
1	*less than 10*	5
2	*between 10-20 years*	8
3	*Between 20-30 years*	191
4	*Between 30-40 years*	353
5	*more than 40 years*	127
6	*no period defined*	2
	Total	686

Table B3. Attribute "Country categorization" Coding

Coding	**Country Classification**	**Country**	**n**
1.	G7	France Germany Italy Japan UK USA Canada	121
2.	OECD countries (-G7) According to www.oecd.org 2012	Australia Austria Belgium Chile Czech Republic Denmark Estonia Finland Greece Hungary Iceland Ireland Israel S. Korea Mexico Luxeburg Netherlands New Zealand	163

		Norway	
		Poland	
		Portugal	
		Slovak Republic	
		Slovenia	
		Spain	
		Sweden	
		Switzerland	
		Turkey	
3.	High Developing Countries (non-OECD members)	Russia China India Brazil Indonesia Taiwan Singapore Hong Kong Malaysia Gulf Cooperation Countries South Africa	148
4.	Non-OECD	Remaining countries not included in previous grouping	245
5.	City or part or sector of a country		9
	Total		686

Table B4. Attribute "Methodology" Coding

Coding	Methodology	Methodology categories	n
1	Sims & Engle-Granger Causality	Sims Causality	207
		Granger Causality	
		Hsiao's Granger causality	
		Engle-Granger Causality	
2	Johansen- Juselius for Cointegration	with VDC	189
		with VECM	
		with Pair-wise	
		with IRF	
3	Toda Yamamoto Causality		116
4	Pedroni Panel Cointegration	(all combination forms used)	52
5	ARDL Bounds test		52
6	Others	VAR	70
		Dolado Lutkepohl causality	
		Beak & Broch non-linear	
		Dynamic Panel estimation causality	
		Hodrick-Prescott filter	
		Carrion-i-Silvestre	
		Hansen and Seo threshold co-integration test	
		Westerlund(2006) panel cointegrationtest	
		Gregory and Hansen	
		Graph Theoretic Approach	
		Markov-switching vector autoregressive (MS-VAR)	
		Erik-Gunnar (E-G) two steps method	
		GLS	
		Bootstrapped Granger causality	
TOTAL			686

Table B5. Attribute "Energy Type" Coding

	Energy Type	n
1	Total Fossil fuels Consumption (Coal, Oil, Gas)	3
2	Electricity Consumption (or production)	139
3	Energy Consumption per capita (primary or electricity etc)	272
4	Total (Primary fuels+electricity) Energy Consumption	214
5	Oil &/or petroleum Consumption (or production)	14
6	Coal Consumption (or production)	22
7	Gas Consumption (or production)	13
8	Nuclear Energy Consumption (or production)	5
9	Renewables energy consumption	4
	Total	686

Table B6. Attribute "Energy measurement method" Coding

Energy Measurement method		n
1	Btu's	49
2	Oil equivalent	357
3	Electricity (watt)	168
4	Coal equivalent	25
5	EXERGY	1
6	Crude quantity	12
7	Devisia Index	5
8	Joule	2
9	Not defined	67
	Total	686

Table B7. Attribute "Single country or group of countries" Coding

	Group of countries or single country	n
1	Single Country examined	637
2	Group of countries examined	49
	total	686

Table B8. Decision variable (causality result) Coding

	Causality results	
1	E→GDP	193
2	E←GDP	163
3	E↔GDP	175
4	E≠GDP	155
	Total	686

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Epilogue

Conclusions

"For the end of economy is not the physical augmentation of goods but always the fullest possible satisfaction of human needs."

(Carl Menger, Principles of Economics, 1871: p.190)

"…*Once upon a time, throughout the heyday for classical economics, demography belonged to political economy. The supply of labour was one of the most important endogenous variables in the systems of Smith, Malthus, Mill and Marx. One feature of neoclassical economics that distinguishes it from the classical version is the removal of population as a variable subject to economists' analysis...*"

Paul Samuelson, (1985-p. 166).

From the early foundation of the economic theory of growth right up until the most recent modern econometric analyses, economic growth and the understanding of its driving forces play a decisive role in the economic sciences and trigger monumental debates (*Chapters 1-2*). It goes without saying that the unparalleled economic growth of the last century led to an excessive consumption of non-renewable natural resources (*Chapters 5-6*). Especially after World War II, the developed countries gradually accomplished their construction of infrastructure and industrialized their production processes. This transition from the agrarian stage of development - dominated by renewable biomass consumption - to the industrial era of the excessive utilization of non-renewable natural resources, led to the remarkable augmentation of the social/industrial metabolism of the most developed countries (*Chapters 5-6*). During the last two decades, more and more developing countries have been gradually heading towards an industrialization regime, following the same industrialization path as the developed countries. Giant developing economies such as China and India in Asia, and Brazil and Mexico in Latin America, follow a strong growth path which is accompanied, irrevocably, by excessive consumption of non-renewable natural resources (*Chapters 5-6*).

Seen under the spectrum of different development stages and patterns of consumption of natural resources among countries, the externalities of the economic process, such as human-induced climate change and the irrevocable degradation of the ecosystem services, reveal the salient and multifaceted impacts of these increasing growth trends upon the anthroposphere. It is now firmly believed that human activities are functioning as a geological agent competitive to the natural ones, an observation that has led geologists to label this new geological era with the term "*the anthropocene*" (*Chapter 5*).

On the other hand, the vast majority of the developed countries seem to be decreasing their material and energy intensity trends. Evidently, in almost all cases of developed countries, decoupling trends are predominant (*Chapters 5-6*). One conventional explanation would be based on the historical neoclassical argument: the observed decoupling trends are the result of improvements in efficiency; hence the technological advance of the developed countries. Indeed, we can distinguish two fundamental reasons, among others, that lie behind these trends: unprecedented technological progress and the historical substitutions of lower quality energy resources (wood and other biomass) for higher quality energy carriers (fossil fuels).

However, contrary to the latent optimism concerning decoupling potentials, there remains an inconvenient unexplained contradiction that seriously questions these decoupling trends: the per capita consumption trends, hence, the social/industrial metabolism of most of the developed countries (with just a few exceptions, such as the United Kingdom, Germany, and Japan) and the vast majority of developing countries, is constantly increasing over time. Furthermore, as Chapters 5-6 demonstrated, this increment is progressively based more and more on nonrenewable resources. In that context, although the efficiency improvement (thus, technological change) argument is indeed fundamental, it fails to explain the dramatically increasing per capita consumption trends. This still unexplained contradiction causes mixed reactions which are, somehow, reflected in the decoupling debate. Evidently, in most recent studies that investigate the decoupling effect, the awkwardness of this peculiar contradiction is latent in most authors' conclusions (*See Chapters 3-4*). Contemporary research on decoupling has recently been characterized by a progressive effort to explain the decoupling trends, with the most prevailing explanations being: efficiency improvements; substitutions between different energy and material types; the outsourcing of the developed countries' heavy industries to the developing ones; the reconstruction of developed economies towards the so-called "service-sector" economy; and international trade (*Chapters 3-4*).

On the other hand, the empirical results of the proposed methodological framework accentuate some neglected aspects of the link between natural resources and the economic process. By evaluating the Natural Resources-Economy link to the more traceable monetary level of the per capita GDP, the present dissertation attempts to downscale the aggregate economic output to a more tangible monetary level. As the GDP index consists of an aggregate amalgam of abstract monetary units, it fails to incorporate certain aspects of the actual output of the economic process. Since the economic system ought to serve human needs, then the homogenous monetary units of the produced goods, which the aggregate GDP bears, fail to reflect the actual context of these needs. What is more, the economic system produces welfare-utility for human beings, not abstract monetary units. Hence, the actual output of the economic process is economic welfare-utility. By downscaling the aggregate GDP to the monetary level of GDP per capita, the welfare-utility that the economic system produces can be approximated more accurately. Apart from being a better measure of the economic welfare-utility, than the aggregate GDP, the GDP per capita incorporates the crucial demographic dynamics which define the properties that the economic output ought to entail. In that broad context of argumentation, the utilization of the indexed GDP per capita, as a measurement of the economic welfare-utility, evaluates the link between natural resources and the welfare-utility creation (*Chapter 4*).

At the global level, the proposed framework reveals a strong coupling relationship between mass and energy consumption and welfare-utility over the last 109 years (*Bithas and Kalimeris, 2013*). Moreover, the proposed energy and mass intensity framework follows very similar trends to the social/industrial metabolism, concerning the global economy. This result is further confirmed for most of the examined national levels, although with some exceptions such as Japan, the United Kingdom, Germany, Russia Federation, France, Italy, and so on. The main conclusion of the empirical decoupling estimates could be summarized in a few lines (*Chapters 5-6*): "***there is a general coupling relationship between natural resources consumption and welfare-utility creation. Indeed, at the global aggregate level and for most of the examined cases, the amount of natural resources required to produce one unit of welfare-utility is increasing through time.***"

The effort to cast light on the E-GDP causality nexus by means of Meta-Analysis, revealed the general inability of this dialogue to produce a coherent and accurate macro trend concerning the directionality between energy consumption and economic growth (*Chapter 7*). Furthermore, the endeavor to interrelate the theoretical degrowth and a-growth debates with the empirical implications of the E-GDP causal relationship, failed to give a fruitful integration between these two contemporary scientific dialogues (*Kalimeris et al., 2014*). In any case, the ethical commitment of the developed countries to stabilizing and gradually reducing their consumption trends, while simultaneously allowing the developing countries to build their infrastructure and to increase the welfare of their citizens as well (their social/industrial metabolism) to a certain prearranged level, will be the key question of the future. This is where the actual core of the Degrowth debate is located; *the voluntary gradual degrowth of the western societies should be accompanied by a certain period of growth for the developing countries, before they too will be able to stabilize their* *social/industrial metabolism trends* (*Chapter 7*). However, it should be noted that the proposed energy and material intensity framework (*Chapter 4*) may prove very critical and restrictive for the theory of degrowth, since it reveals the strong relationship between natural resources and economic welfare-utility (*Chapters 5-6*). *In this sense, a potential movement of developed countries towards substantial degrowth might turn out to bear more unfavorable implications for their welfare, according to the proposed decoupling framework.* The pressing question for the degrowth stage and the forthcoming Sustainable Development stage is: how much of this expansion of the developing countries can be added by development (thus, from qualitative changes, namely institutional and technological changes, innovation, etc), and how much must come from growth (thus, from quantitative changes in the output and the resources inputs of the economic process) (*Costanza, et al., 1997*)? An additional and complementary question, based on the proposed decoupling framework, should be: which restrictions and limitations set the demographic dynamics on a potential degrowth process, in relation to the aggregate scarcity of natural resources? Further research is required in this direction.

It goes without saying that the theoretical concept of Biophysical Human Scale (BHS), presented in Chapter 4, calls for a more in depth analysis. Indeed, the proposed framework of decoupling evaluation captures only partially and indirectly the dynamics and the range of the BHS concept. Apparently, the very same holds true for the Human Scale of Production (HSP) concept, as the logical outcome of the theoretical BHS establishment. In any case, the empirical estimates of the present dissertation remain essential as far as the decoupling potentials concerned. In a nutshell, the empirical section has demonstrated the increasing per capita energy-mass consumption, for the vast majority of the economic levels examined. These trends are reflecting the indirect impact of BHS on resources consumption (indirect because human beings do not consume resources per se, but only through the exosomatic metabolism of the economic system). On the other hand, the resources required per unit of GDP are decreasing for the vast majority of the examined economies. Evidently, the empirical estimates reveal an increasing divergence between the increasing per capita energy-mass consumption and the decreasing energy-mass intensity of the economic process. The endeavor to cast light upon this peculiar divergence highlights the core question of the present dissertation: *Is the observed decoupling an actual fact?* Following this line of questioning, the next level of empirical analysis compared and evaluated the alternative framework for decoupling evaluation. The proposed framework revealed that the resources required per unit of economic welfare-utility are increasing at the global level, in most of the examined cases. In line with CHANS approach (*Liu et al., 2007*), human systems (economy) are coupled with natural systems (natural resources use), once the economic output is accounted in terms of economic welfare-utility. Undoubtedly, the proposed framework is an indirect approximation of the actual BHS. Evidently, a more sophisticated analysis is required in order to trace the actual biophysical dimensionality that the human beings entail for the production process. In the absence of such evidence, the empirical estimates of the present thesis should be seen as a first step towards the better understanding of the multifaceted resources-economy link.

The complex relationship between the use of natural resources and human prosperity remains a hot issue within economic science. The man-made socioeconomic system, being a subsystem of the biosphere's system, functions competitively with all the other natural subsystems. These socio-economic megatrends, acting as a geological agent, still require enormous megatrends of natural resources flows, despite the tremendous benefits of the technological megatrends (Fig. 7.1). The contemporary scientific analysis on the negative implications of human-induced climate change[1] [2], waste production, biodiversity loss and the subsequent degradation of the ecosystems' services[3] are some definite signs of the dramatic externalities that the socio-economic subsystem causes (*Steffen et al., 2015; McGlade and Ekins, 2015; NOAA, 2015*) to the natural systems. The peak in global oil production may only be delayed by market speculations and the global economic crisis (*Heinberg, 2011*). Be that as it may, the gradual substitution of oil for natural gas, the exploitation of shale oil and deep sea deposits, still expensive at current prices, are some potential answers to the energy puzzle of the future. However, many distinguished scholars firmly believe that, due to climate change, we should intentionally leave fossil fuels buried[4], while others claim that the energy problem may inevitably require a future massive turn towards nuclear technology (*Lovelock, 2006*). Contrary to the nuclear solution of the energy

[1] http://www.ncdc.noaa.gov/sotc/summary-info/global/2014/12 Accessed January 2015

[2] http://www.theguardian.com/environment/2015/jan/15/sea-levels-rising-faster-than-previously-thought-says-new-study Accessed January 2015

[3] http://www.sciencemag.org/content/early/2015/01/14/science.1259855.abstract Accessed January 2015

[4] http://www.theguardian.com/environment/2015/jan/07/much-worlds-fossil-fuel-reserve-must-stay-buried-prevent-climate-change-study-says Accessed January 2015

puzzle, others lay their hopes on Hydrogen (*Rifkin, 2002*) as a future potential fuel, as the result of the forthcoming third industrial revolution that will be based on renewable resources, internet-like power grid technology, fuel cell vehicles, and so on (*Rifkin, 2011*).

Dealing with the economic future calls for a rigorous and multifaceted theoretical context that integrates the reality of physical laws within the intricate relationship of coupled human-natural systems (*Liu et al., 2007*). In that sense, a misinterpretation today of a phenomenon such as the decoupling effect, might give the wrong signals to policy makers and practitioners, causing irreparable damage to the prosperity of future generations. Undoubtedly, the golden section among the serious environmental externalities, the quest for the next promethean gift that will solve the energy (and mass) scarcity, and the galloping demographic and household dynamics in most developing countries, would be a laborious task. In any case, the present dissertation should be viewed as a very small contribution towards this direction.

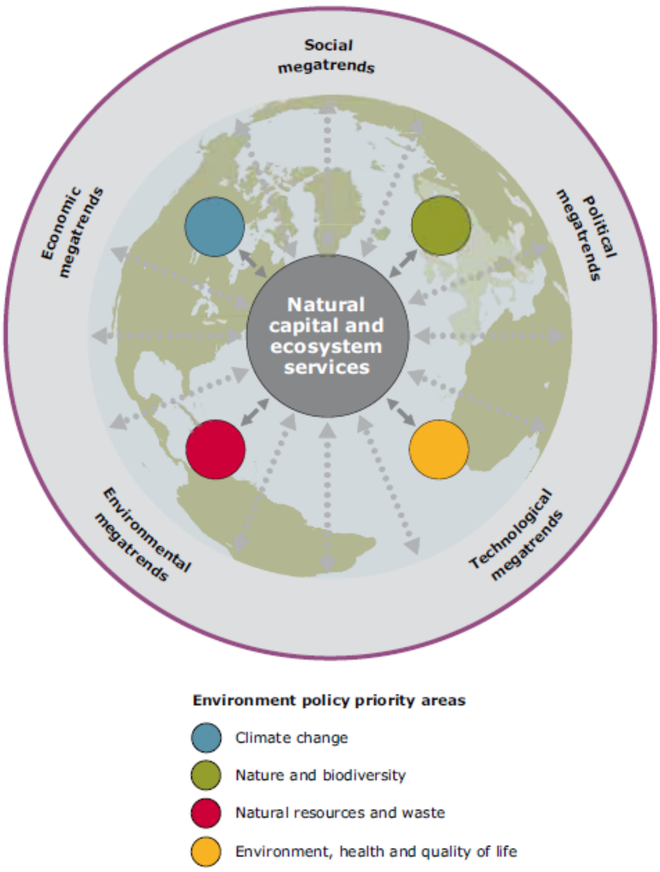

Figure 7.1 *Environmental policy priority areas (Source: EEA, 2010)*

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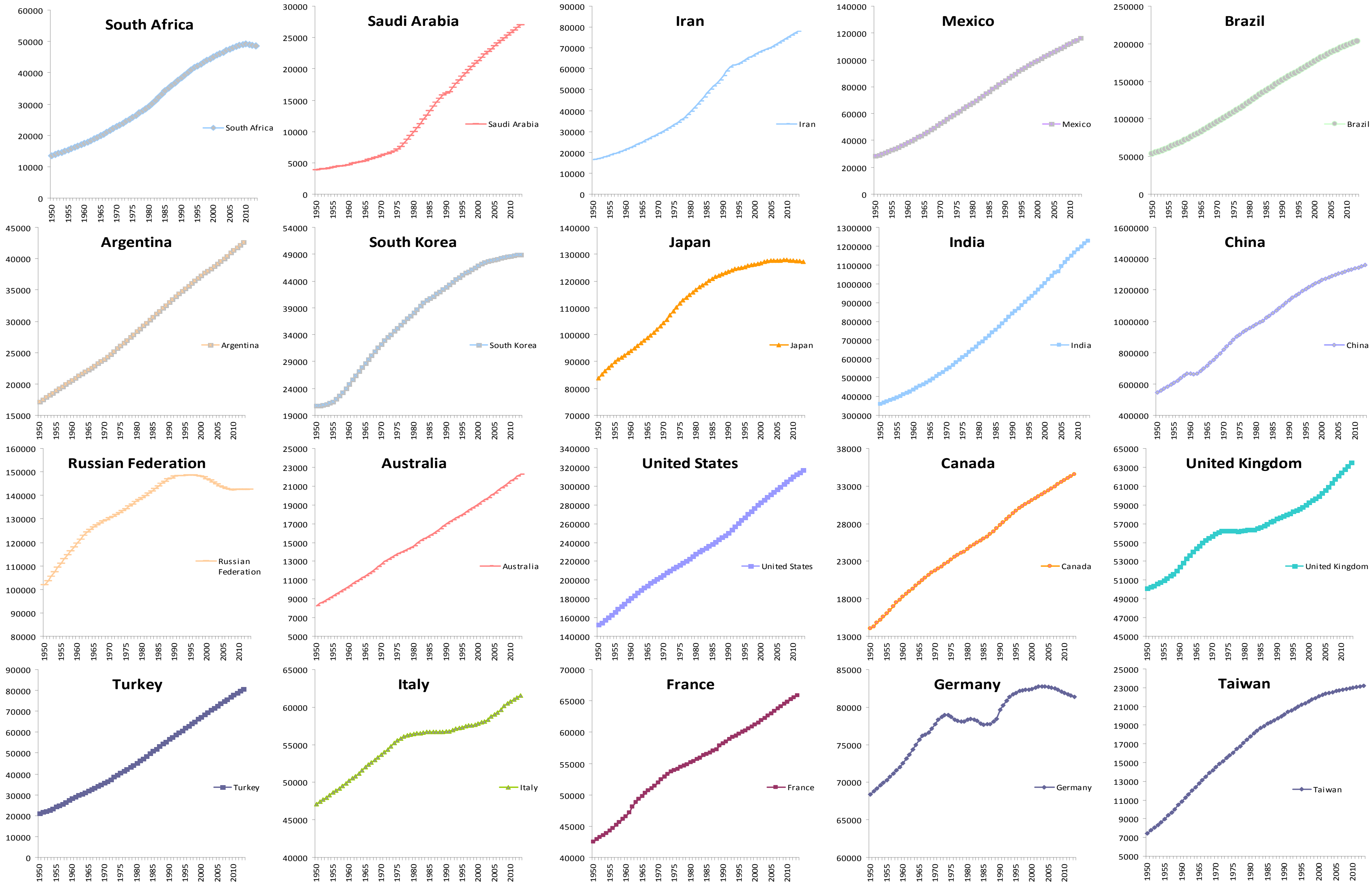
Annex I

Population growth[1]

1950-2013

[1] All data (1000 pers/yr.) of this section are drawn from The Total Economy Database (Retrieved January 2014)


South Africa
Saudi Arabia
Iran
Mexico
Brazil
Argentina
South Korea
Japan
India
China
Russian Federation
Australia
United States
Canada
United Kingdom
Turkey
Italy
France
Germany
Taiwan

Annex II

GDP and GDP per capita[2]

1950-2013

[2] All data (All cases are Indexed 1950=1, except of the Russian Federation which is indexed 1980=1) of this section are drawn from The Total Economy Database (Retrieved January 2014)


South Africa
South Africa GDP
South Africa GDPpc
Saudi Arabia
Saudi Arabia GDP
Saudi Arabia GDPpc
Iran
Iran GDP
Iran GDPpc
Mexico
Mexico GDP
Mexico GDPpc
Brazil
Brazil GDP
Brazil GDPpc
Argentina
Argentina GDP
Argentina GDPpc
South Korea
South Korea GDP
South Korea GDPpc
Japan
Japan GDP
Japan GDPpc
India
India GDP
India GDPpc
China
China GDP
China GDPpc
Russian Federation*
Russian Federation GDP
Russian Federation GDPpc
* Indexed 1980=1 . The strong decline after 1990s reflects the colapse of USSR
Australia
Australia GDP
Australia GDPpc
USA
United States GDP
United States GDPpc
Canada
Canada GDP
Canada GDPpc
UK
United Kingdom GDP
United Kingdom GDPpc
Turkey
Turkey GDP
Turkey GDPpc
Italy
Italy GDP
Italy GDPpc
France
France GDP
France GDPpc
Germany
Germany GDP
Germany GDPpc
Taiwan
Taiwan GDP
Taiwan GDPpc