ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΡΗΤΗΣ
ΣΧΟΛΗ ΚΟΙΝΩΝΙΚΩΝ ΕΠΙΣΤΗΜΩΝ
ΤΜΗΜΑ ΟΙΚΟΝΟΜΙΚΩΝ ΕΠΙΣΤΗΜΩΝ

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Αειφόρος Ανάπτυξη και Μεγέθυνση της Συνολικής Παραγωγικότητας των Συντελεστών Παραγωγής κάτω από την επίδραση Εξωτερικοτήτων: Θεωρητική Θεμελίωση και Εμπειρικές Ενδείξεις

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Γ' ΚΟΙΝΟΤΙΚΟ ΠΛΑΙΣΙΟ ΣΤΗΡΙΞΗΣ
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Η εκπόνηση της παρούσας διδακτορικής διατριβής ξεκίνησε τον Ιανουάριο του 2005 και ολοκληρώθηκε τον Ιανουάριο του 2008.
Εκπονήθηκε από την **Δήμητρα Βουβάκη**, υποψήφια Διδάκτορα του Τμήματος Οικονομικών Επιστημών του Πανεπιστημίου Κρήτης και Επόπτης της παρούσας Διατριβής ήταν ο καθηγητής Οικονομικών Επιστημών, **Αναστάσιος Ξεπαπαδέας**. Μέλη της τριμελούς επιτροπής ήταν ο αναπληρωτής καθηγητής Οικονομικών Επιστημών, Παντελής Καλαιτζιδάκης και ο επίκουρος καθηγητής Οικονομικών επιστημών, Βαγγέλης Τζουβελέκας, τους οποίους και ευχαριστώ πολύ για την βοήθεια που μου προσέφεραν κατά την διάρκεια συγγραφής της διατριβής.

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- 75% της Δημόσιας Δαπάνης από την Ευρωπαϊκή Ένωση – Ευρωπαϊκό Κοινωνικό Ταμείο
- 25% της Δημόσιας Δαπάνης από το Ελληνικό Δημόσιο – Υπουργείο Ανάπτυξης – Γενική Γραμματεία Έρευνας και Τεχνολογίας
- και από τον Ιδιωτικό Τομέα

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Περίληψη Διδακτορικής Διατριβής

Περιεχόμενα:

Περίληψη στα ελληνικά

1. Εισαγωγή

Η παρούσα διατριβή ασχολείται με την έννοια της αειφόρου ανάπτυξης με σκοπό να θεμελιώσει έναν θεωρητικό ορισμό ο οποίος θα μπορεί να χρησιμοποιηθεί αποτελεσματικά σαν ένας δείκτης αειφορίας και θα μπορεί να παρέχει εμπειρικές μετρήσεις των συνθηκών αειφορίας σε δεδομένες οικονομίες.

Σε αυτό το πλαίσιο, *στο πρώτο μέρος της διατριβής*, χρησιμοποιούνται ανατροφοδοτούμενοι και αυθαίρετοι κανόνες πολιτικής με βάση τους οποίους επιλέγονται μεταβλητές πολιτικής σε μη βέλτιστες οικονομίες. Ορίζονται οι λογιστικές τιμές και αποτιμώνται οι μεταβολές στις συνθήκες τρέχουσας κοινωνικής ευημερίας.

Η κατάσταση του περιβάλλοντος, με έμφαση στο φαινόμενο του θερμοκηπίου και την κλιματική αλλαγή, που θεωρείται ένα από τα πιο επείγοντα και σοβαρά περιβαλλοντικά προβλήματα της διεθνούς ατζέντας σήμερα, εισάγεται στο μοντέλο που αναπτύσσουμε σαν βασικός καθοριστικός παράγοντας της αειφορίας της παραγωγικής βάσης (productive base sustainability) μαζί με το παραγόμενο και το ανθρώπινο κεφάλαιο.

Το περιβάλλον προσεγγίζεται στην ανάλυση μας από το στοκ του διοξειδίου του άνθρακα, που αποτελεί τον κύριο παράγοντα της δημιουργίας του φαινόμενου του θερμοκηπίου. Διαφορετικά σενάρια πολιτικής για την εξέλιξη των παγκόσμιων εκπομπών του διοξειδίου του άνθρακα επιλέγονται και εφαρμόζονται και επιβεβαιώνουν την ισχυρή σχέση του περιβάλλοντος με το κριτήριο της αειφορίας της παραγωγικής βάσης της οικονομίας (productive base sustainability) και δημιουργούνται τα θεμέλια για την δημιουργία αειφόρων πολιτικών.

Το κριτήριο της αειφορίας της παραγωγικής βάσης (productive base sustainability) της οικονομίας, όπως ορίζεται και υπολογίζεται στο πρώτο μέρος της διατριβής, εξαρτάται και από τον παράγοντα της μεγέθυνσης της συνολικής παραγωγικότητας των συντελεστών (Total Factor Productivity Growth (TFPG)). Αν οι μετρήσεις της αειφορίας, δεν λαμβάνουν υπόψη τους την συνεισφορά του περιβάλλοντος στην συνολική μεγέθυνση του προϊόντος και αυτή η συνεισφορά αποδίδεται λανθασμένα στη μεγέθυνση της συνολικής παραγωγικότητας των συντελεστών – κατάλοιπο - τότε οι μετρήσεις του κριτηρίου της αειφορίας της παραγωγικής βάσης μπορεί να αποδειχθούν μεροληπτικές.

Αυτό το θέμα αναλύεται στο *δεύτερο μέρος της διατριβής* που αναγνωρίζει ότι η χρήση του περιβάλλοντος σαν συντελεστής παραγωγής συνεισφέρει μαζί με άλλους παραγωγικούς συντελεστές στη μεγέθυνση του συνολικού προϊόντος μίας οικονομίας και θα έπρεπε να υπολογίζεται στις μετρήσεις της παραγωγικότητας και να αφαιρείται από το παραδοσιακό «κατάλοιπο» του Solow.

Η παραδοσιακή μεθοδολογία του «υπολογισμού της μεγέθυνσης» (growth accounting methodology) επεκτείνεται και αναπτύσσεται θεωρητικά, λαμβάνοντας υπόψη το

περιβάλλον σαν νέος συντελεστής παραγωγής που είναι απλήρωτος (unpaid) ή πληρώνεται εν μέρει λόγω της έλλειψης περιβαλλοντικής πολιτικής.
Η έννοια του «υπολογισμού της μεγέθυνσης» με την εισαγωγή του παράγοντα περιβάλλον, εφαρμόζεται εμπειρικά σε 23 χώρες του ΟΟΣΑ (αναπτυγμένες) και 21 αναπτυσσόμενες χώρες.
Τα αποτελέσματα των μετρήσεων μας, υποδεικνύουν ότι η χρήση του περιβάλλοντος (που προσεγγίζεται με τη μορφή των εκπομπών του διοξειδίου του άνθρακα, που θεωρείται εξτρα παραγωγικός συντελεστής στην συνάρτηση παραγωγής), συνεισφέρει μαζί με τους παραδοσιακούς παραγωγικούς συντελεστές (κεφάλαιο, εργασία) στην μεγέθυνση του συνολικού προϊόντος και θα έπρεπε να λαμβάνεται υπόψη στις μετρήσεις της παραγωγικότητας.
Ένας άλλος τρόπος προσέγγισης του παράγοντα περιβάλλον στην μεθοδολογία που ακολουθείται για τον «υπολογισμό της μεγέθυνσης» (growth accounting methodology), είναι με τη χρήση της ενέργειας σαν συντελεστή παραγωγής. Οι παραδοσιακές μετρήσεις της παραγωγικότητας (σύμφωνα με τον Solow), αλλάζουν δραστικά για 23 αναπτυγμένες χώρες (ΟΟΣΑ), όταν το μέρος εκείνο της ενέργειας που περιλαμβάνει τις εκπομπές του διοξειδίου του άνθρακα (που δημιουργεί εξωτερικότητα) και παραμένει απλήρωτο στην παραγωγική διαδικασία, εσωτερικεύεται, δηλαδή οι εκπομπές του διοξειδίου του άνθρακα αποκτούν μία τιμή μέσω της επιβολής περιβαλλοντικών φόρων επάνω στις εκπομπές αυτές.
Το κατάλοιπο που υπολογίζεται μετά την συνεισφορά της ενέργειας σαν νέου συντελεστή παραγωγής, (externality adjusted TFPG), γίνεται σχεδόν μηδέν, γεγονός που μεταφράζεται ως εξής: όταν λάβουμε υπόψη μας την συνεισφορά του περιβάλλοντος στην μέτρηση της συνολικής παραγωγικότητας των συντελεστών και το αμείψουμε σαν εξτρα συντελεστή παραγωγής, δεν φαίνεται να υπάρχει παραγωγικότητας η οποία να δημιουργεί μεγέθυνση.

1.1 Ανασκόπηση της Βιβλιογραφίας

1.1.1. Η έννοια της Αειφόρου Ανάπτυξης

Σύμφωνα με τον ορισμό της Brundtland Commission Report (WCED 1987, σελ. 43), «Αειφόρος Ανάπτυξη είναι η ανάπτυξη που καλύπτει τις ανάγκες του σήμερα χωρίς να υποσκάπτει την δυνατότητα των μελλοντικών γενεών να ικανοποιήσουν τις δικές τους ανάγκες». Βασιζόμενοι σε αυτόν τον ορισμό που αποτελεί τον ακρογωνιαίο λίθο της έννοιας της αειφόρου ανάπτυξης, η παρούσα διατριβή έχει στόχο να αναλύσει την έννοια της αειφόρου ανάπτυξης αναπτύσσοντας ένα καλώς ορισμένο θεωρητικό πλαίσιο το οποίο θα μπορεί να παρέχει εμπειρικές μετρήσεις που θα χαρακτηρίζουν αν μία οικονομία είναι ή όχι αειφόρος.

Η προσπάθεια μετατροπής του ορισμού της Brundtland σε ένα λειτουργικό και εμπειρικά εφαρμόσιμο ορισμό, δεν είναι εύκολη υπόθεση. Σκοπός της έννοιας της Αειφόρου Ανάπτυξης είναι να λαμβάνει υπόψη της την ευημερία των μελλοντικών γενεών χωρίς να μειώνεται η ευημερία της παρούσας γενιάς. Αυτή η έννοια, απαιτεί μεγάλη προσπάθεια για να μετατραπεί σε κάτι που θα μπορεί να αποτιμηθεί οικονομικά. Αυτό συμβαίνει επειδή η έννοια της Αειφόρου Ανάπτυξης είναι μια περίπλοκη έννοια που περιλαμβάνει κοινωνικές, οικονομικές και περιβαλλοντικές παραμέτρους και προεκτάσεις.

Συγκεκριμένα η αειφόρος ανάπτυξη χωρίζεται σε τρία διαφορετικά είδη τα οποία και είναι και τα ακόλουθα: Κοινωνική αειφορία, περιβαλλοντική αειφορία και οικονομική αειφορία. Η κοινωνική, περιβαλλοντική και η οικονομική αειφορία δεν μπορούν να διαχωριστούν εντελώς. Υπάρχουν πολύ δυνατές συνδέσεις μεταξύ τους. Συγκεκριμένα, η κοινωνική αειφορία μπορεί να επιτευχθεί μόνο με συστηματική συμμετοχή της κοινωνίας και ισχυρή αστική κοινωνία. Το κοινωνικό κεφάλαιο απαρτίζεται από την ενότητα της κοινωνίας, την μορφωτική ταυτότητα, τον πλουραλισμό, τους θεσμούς, τους νόμους, την πειθαρχία κλπ. Goodland R., (1995).

Η Οικονομική Αειφορία απαιτεί την διατήρηση του οικονομικού κεφαλαίου. Η διατήρηση του οικονομικού κεφαλαίου ή το να διατηρηθεί το οικονομικό κεφάλαιο «ανέπαφο» είναι μία από τις βασικές έννοιες της οικονομικής αειφορίας. Goodland R., (1995).

Περιβαλλοντική Αειφορία, σημαίνει ότι το φυσικό κεφάλαιο πρέπει να διατηρηθεί και να διαφυλαχθεί για τις μελλοντικές γενιές. Η περιβαλλοντική Αειφορία αναζητά να βελτιώσει την ανθρώπινη ευημερία προφυλάσσοντας ταυτόχρονα τις περιβαλλοντικές πηγές υλικών που χρησιμοποιούνται για την κάλυψη των ανθρωπίνων αναγκών. Το φυσικό κεφάλαιο (φυσικό περιβάλλον), ορίζεται σαν το στοκ των περιβαλλοντικών πόρων που δημιουργούν μία ροή χρήσιμων αγαθών και υπηρεσιών. Αυτό το φυσικό κεφάλαιο μπορεί να αποτελείται από ανανεώσιμες ή μη ανανεώσιμες πηγές ενέργειας και αγαθά αγοραία ή μη αγοραία και η περιβαλλοντική αειφορία σημαίνει αειφόρος κατανάλωση και παραγωγή. Goodland R., (1995).

Αυτές οι τρεις διαφορετικές έννοιες αειφορίας σχετίζονται και αποτελούν τη βάση της αειφόρου ανάπτυξης. Η ιδέα της διατήρησης της ευημερίας της παρούσας και της μελλοντικής γενιάς είναι ο απόλυτος στόχος για ένα αειφόρο μέλλον. Για να είναι αυτή η ιδέα εφαρμόσιμη πολλά είδη κεφαλαίων (παραγόμενο κεφάλαιο, ανθρώπινο κεφάλαιο, κοινωνικό κεφάλαιο και φυσικό κεφάλαιο) πρέπει να διατηρηθούν για τις μελλοντικές γενιές.

Ένας ορισμός που μπορεί να περιλάβει όλες αυτές τις πτυχές και να τις εκφράσει σε οικονομικούς όρους μπορεί να θεωρηθεί σαν αποτελεσματικός ορισμός ο οποίος θα μπορεί να μετρήσει αν η ανάπτυξη είναι αειφόρος. Ένα βασικό ερώτημα που δημιουργείται είναι το κατά πόσον η προσπάθεια για όμοια μεταχείριση μίας σειράς μελλοντικών γενεών, είναι ένας στόχος εφικτός και κατά πόσον είναι εφικτό ένας τέτοιος ορισμός να μεταφραστεί σε οικονομικούς όρους.

Πέρα από τα τρία διαφορετικά είδη αειφορίας που υπάρχουν, η αειφορία εμφανίζεται επίσης και σε τέσσερις «βαθμούς» στη διεθνή βιβλιογραφία. Υπάρχουν τα παρακάτω είδη: «ασθενής» (weak), «ενδιάμεση» (intermediate), «ισχυρή» (strong) και «υπερβολικά ισχυρή» (absurdly strong or superstrong) αειφορία. Κάθε ένας από τους τέσσερις βαθμούς υπονοεί τον βαθμό διατήρησης και προφύλαξης των τεσσάρων ειδών κεφαλαίου από τα οποία απαρτίζεται το συνολικό κεφάλαιο, η διατήρηση του οποίου είναι αναγκαία για μία αειφόρο ανάπτυξη. (Τα τέσσερα είδη κεφαλαίου είναι τα εξής: παραγόμενο κεφάλαιο, ανθρώπινο κεφάλαιο, κοινωνικό κεφάλαιο και φυσικό κεφάλαιο).

«Ασθενής» περιβαλλοντική αειφορία σημαίνει διατήρηση της αξίας του συνολικού κεφαλαίου αμείωτου, χωρίς ωστόσο να δίνεται βάση στο ποσοστό συμμετοχής καθενός από τα τέσσερα ειδών κεφαλαίου στο συνολικό κεφάλαιο.
Η «ενδιάμεση» περιβαλλοντική αειφορία απαιτεί ότι για να διατηρηθεί η συνολική αξία του κεφαλαίου σταθερή, θα πρέπει να δοθεί προσοχή στην σύνθεση αυτού του κεφαλαίου, δηλαδή στη συμμετοχή καθενός από τα τέσσερα είδη κεφαλαίου στο συνολικό κεφάλαιο.
Η «ισχυρή» περιβαλλοντική αειφορία προϋποθέτει ότι θα διατηρούμε όλα τα είδη κεφαλαίου άθικτα, ενώ η «υπερβολικά ισχυρή» περιβαλλοντική αειφορία προϋποθέτει ότι δεν θα πρέπει να μειώνουμε ή να εξαντλούμε τίποτα. Αυτό σημαίνει ότι οι μη ανανεώσιμες πηγές δεν θα μπορούν να χρησιμοποιηθούν καθόλου. Goodland R., (1995).

1.1.2 Ιστορική Αναδρομή και Ορισμοί της Αειφορίας

Αυτή η ενότητα παραθέτει μία σύντομη ιστορική αναδρομή. Ξεκινώντας, παρατηρούμε ότι η έννοια της αειφορίας έχει την βάση της στους κλασικούς οικονομολόγους. Η ιδέα της αειφόρου ανάπτυξης ήταν ήδη παρούσα στην συζήτηση για την στενότητα και την μεγέθυνση. Οι Malthus, Ricardo, Mill, Hicks, Pigou και πολλοί άλλοι είχαν προβλέψει ότι η έλλειψη των φυσικών πόρων θα οδηγήσει σε επιβράδυνση και τελικά σε παύση της οικονομικής μεγέθυνσης. (Barnett and Morse, (1963, p. 2), in Pezzey, J., C.V, and Toman A., Michael (2004)).
Ο Hicks, ορίζει το εισόδημα σαν τη μέγιστη ποσότητα που μπορεί να ξοδευτεί στην κατανάλωση σε μία περίοδο, χωρίς να μειώνονται οι ευκαιρίες πραγματικής κατανάλωσης στο μέλλον. Hicks J., (1946). Άρα σε όρους ανάλυσης του Hicks, η Brutland Report μπορεί να λέει ότι στο παρόν θα πρέπει να καταναλώνουμε μέχρι και το εισόδημά μας. Μπορούμε επίσης να πούμε ότι το εισόδημα μπορεί να αποτελείται από όλα τα είδη κεφαλαίων και όχι μόνο το παραγόμενο κεφάλαιο και την εργασία αλλά και το ανθρώπινο κεφάλαιο, τη γνώση, το περιβαλλοντικό κεφάλαιο, το κοινωνικό κεφάλαιο κλπ. Heal, G. M. (1998).
Ο Solow και Hartwick στήριξαν την ιδέα ότι η αειφορία μπορεί να εκφραστεί μέσω του κριτηρίου maxmin, που σημαίνει: μεγιστοποίηση της ευημερίας της χειρότερης, σε όρους ευημερίας, γενιάς. Το κριτήριο μπορεί να εκφραστεί όπως παρακάτω:

$$\left\{ \max\left\{ \min\left\{ \text{welfare}_t \right\} \right\} \right\}$$

όπου welfare_t, είναι το επίπεδο ευημερίας της γενιάς t. Είναι απαραίτητο να βρεθεί το επίπεδο εκείνο ευημερίας της γενιάς που ευημερεί λιγότερο και έπειτα να αναζητηθεί το εφικτό μονοπάτι που παρέχει την υψηλότερη αξία σε αυτό το ελάχιστο επίπεδο ευημερίας. Heal, G. M. (1998).

Οι μετακλασικοί οικονομολόγοι ανέλυσαν το φυσικό περιβάλλον και την άριστη πολιτική στο πλαίσιο των εξωτερικοτήτων που δημιουργούνται από μόλυνση του περιβάλλοντος και έδωσαν έμφαση στην ανάγκη της περιβαλλοντικής συνειδητοποίησης. Ο Weitzman το 1976 ήταν ο πρώτος που έθεσε τα θεμέλια ενός «περιβαλλοντικού ή πράσινου» Καθαρού Εθνικού Προϊόντος (Green Net National Product). Απέδειξε ότι το συμβατικό μέτρο εισοδήματος είναι το επίπεδο της κατανάλωσης που αν διατηρούνταν μόνιμα θα είχε μία παρούσα αξία ίση με τον πλούτο της οικονομίας. Το καθαρό εθνικό προϊόν είναι η Χαμιλτονιανή ενός γενικού προβλήματος μεγιστοποίησης. Η μέγιστη εφικτή ευημερία από τον χρόνο *t* και μετά θα ήταν:

$$\int_t^{\infty} C^*(s)e^{-r(s-t)}ds$$

Υπό αυτή την έννοια το Net National Product είναι αυτό που αποκαλούμε σταθερό ισοδύναμο της μελλοντικής κατανάλωσης. Weitzman , M., L., (1976).
Το 1988 οι Markandya και Pearce υποστήριξαν ότι η έννοια της αειφόρου ανάπτυξης στηρίζεται στο πλαίσιο των φυσικών πόρων και του περιβάλλοντος. Αν η ιδέα αυτή εφαρμοστεί στους φυσικούς πόρους, αειφορία θα πρέπει να σημαίνει ότι ένα δεδομένο στοκ πόρων (δέντρα, νερό κλπ) δεν θα πρέπει να μειώνεται διαχρονικά. Ο Robert Haveman στα 1989, υποστήριξε ότι η αειφόρος ανάπτυξη είναι η διατήρηση ή η μεγέθυνση του συνολικού επιπέδου οικονομικής ευημερίας και ορίζεται σαν το επίπεδο της κατά κεφαλήν οικονομικής ευημερίας.
Ο John Pezzey το 1989, ορίζει την αειφόρο ανάπτυξη σαν την μη φθίνουσα χρησιμότητα. Ο Maler το 1991 δηλώνει ότι «η οικονομική ανάπτυξη είναι αειφόρος αν και μόνο αν η χρησιμότητα είναι μη φθίνουσα διαχρονικά». Επίσης ο Solow το 1992, δηλώνει τα παρακάτω: «το καθήκον που τίθεται από την αειφορία είναι να κληροδοτήσεις και να προικίσεις τους απογόνους με ότι χρειάζεται για να επιτύχουν ένα επίπεδο ζωής τόσο καλό όσο και το δικό μας. (Διατήρηση σταθερής χρησιμότητας).
Οι Pemberon and Ulph (2001) στήριξαν την ιδέα ότι μία οικονομία λειτουργεί με έναν αειφόρο τρόπο οικονομικής ανάπτυξης σε δεδομένη χρονική στιγμή, αν η αξία από την ροή του στοκ του κεφαλαίου που θα κληροδοτούσε στις μελλοντικές γενιές, ήταν η ίδια με την αξία το στοκ του κεφαλαίου που κληρονόμησε. Εναλλακτικά, μία οικονομία μπορούσε να θεωρηθεί αειφόρος στιγμιαία εάν η στιγμιαία μεταβολή της αξίας σε ένα δεδομένο χρονικό σημείο ήταν μηδέν[1]. Οι Pemberon και Ulph ολοκληρώνουν δηλώνοντας ότι το συμπεριλαμβανόμενο εισόδημα[2] (inclusive income), ισούται με τη στιγμιαία σταθερή αξία του εισοδήματος παρόλο που το συμπεριλαμβανόμενο εισόδημα δεν μετράει το επίπεδο της ευημερίας ή αξίες. Το συμπεριλαμβανόμενο εισόδημα είναι χρήσιμο στο να καθορίζει κατά πόσο μια οικονομία επιτυγχάνει στιγμιαία αειφορία. Η διαφορά μεταξύ του συμπεριλαμβανομένου εισοδήματος και της κατανάλωσης ορίζει τον ρυθμό μεταβολής της αξίας.
Υπάρχει επίσης η ιδέα της διατήρησης σταθερής χρησιμότητας από τώρα και μετά. Solow (1974), Hartwick (1977) και η ιδέα του να μην υπερβαίνει η χρησιμότητα $U(t)$

[1] Η στιγμιαία αειφορία προϋποθέτει ότι η παρούσα αξία της μελλοντικής χρησιμότητας παραμένει σταθερή σε ένα δεδομένο χρονικό σημείο. (Βλ. Pemberon M., & Ulph D., 2001)

[2] Το συμπεριλαμβανόμενο εισόδημα είναι το «περιβαλλοντικό ή πράσινο» εθνικό εισόδημα που είναι ίσο με την μέγιστη αξία της κατανάλωσης και της καθαρής μεταβολής σε όλα τα σχετικά στοκ κεφαλαίου που είναι εφικτά δεδομένων του στοκ των κεφαλαίων. Βλ. Pemberon M., & Ulph D., (2001).

ένα μέγιστο επίπεδο χρησιμότητας $U^m(t)$, (όπου U^m είναι η μέγιστη χρησιμότητα) που μπορεί να διατηρηθεί για πάντα δεδομένου του στοκ του κεφαλαίου που υπάρχει στον χρόνο t. Pearce et al., (1990), Pezzey, (1992, 1997).
Με βάση τους Arrow et al. (2003), η αειφόρος ανάπτυξη η οποία ορίζεται σαν την μη φθίνουσα κοινωνική ευημερία (Non-Declining Social Welfare (NDSW)), υπονοεί και προϋποθέτει την διατήρηση της παραγωγικής βάσης της οικονομίας[3]. Η κεντρική ιδέα είναι ότι η κάθε γενιά πρέπει να κληροδοτήσει στους διαδόχους της τουλάχιστον την παραγωγική βάση που κληρονόμησε από τους προγόνους της. Για να επιτευχθεί αυτό η παραγωγική βάση μίας οικονομίας θα πρέπει να διατηρηθεί για τις μελλοντικές γενιές. Αυτή η διατήρηση των ειδών κεφαλαίου που αποτελούν την παραγωγική βάση της οικονομίας μπορούν να εξασφαλίσουν με βάση τους Arrow et al. (2003), ένα αειφόρο μέλλον.
Ο Dasgupta το (2002) ακολουθώντας την ίδια προσέγγιση με τους Arrow et al, υποστηρίζει επίσης την ιδέα ότι η αξία του κεφαλαίου μίας οικονομίας είναι ο συνολικός συμπεριλαμβανόμενος πλούτος (inclusive wealth) που περιλαμβάνει παραγόμενο κεφάλαιο, ανθρώπινο κεφάλαιο, και φυσικό κεφάλαιο. Αν θέλουμε να πούμε ότι ο πλούτος αυξάνεται τότε πρέπει να πούμε ότι συνολικά υπήρξε μία καθαρή συσσώρευση κεφαλαίου. Η καθαρή αυτή συσσώρευση κεφαλαίου που ονομάζεται θετική γνήσια επένδυση σημαίνει ότι η ανάπτυξη μπορεί να χαρακτηριστεί αειφόρος με λαμβάνοντας υπόψη την παραγωγική βάση της οικονομίας, ενώ η αρνητική γνήσια επένδυση υπονοεί μη αειφορία της παραγωγικής βάσης της οικονομίας. Με άλλα λόγια αν:

$$\dot{V}_t = \frac{dV_t}{dt} \geq 0$$

όπου το $\dot{V}_t$ την χρονική στιγμή t, είναι η μεταβολή μίας Ramsey-Koopsman συνάρτησης κοινωνικής ευημερίας που υπονοεί μη φθίνουσα κοινωνική ευημερία μίας οικονομίας. Τότε η οικονομία μπορεί να χαρακτηριστεί αειφόρος με βάση το κριτήριο της παραγωγικής βάσης της οικονομίας και τον ορισμό του συμπεριλαμβανομένου πλούτου.

Οι Dasgupta και Mäler απέδειξαν ότι όταν το $\dot{V}$ εκτιμάται με βάση τις λογιστικές τιμές[4], ο πλούτος μετράει όχι μόνο την τρέχουσα αλλά και την μελλοντική ευημερία.

Η κοινωνική ευημερία πλήττεται από διάφορα φαινόμενα περιβαλλοντικά και μη που απασχολούν την διεθνή ατζέντα σήμερα και μπορούν να βάλουν φρένο στην όποια έννοια αειφόρου ανάπτυξης. Το φαινόμενο του θερμοκηπίου και η κλιματική αλλαγή είναι φαινόμενα που έχουν αποκτήσει αυξημένο ενδιαφέρον σε εθνικό και διεθνές επίπεδο και δημιουργούν την ανάγκη για την ανάπτυξη ενός καλώς ορισμένου θεωρητικού πλαισίου το οποίο θα μπορεί να εφαρμοστεί εμπειρικά και να μας

[3] Η παραγωγική βάση της οικονομίας περιλαμβάνει τα παρακάτω είδη κεφαλαίων: παραγόμενο κεφάλαιο, ανθρώπινο κεφάλαιο, φυσικό κεφάλαιο και γνώση.
[4] Λογιστική τιμή ενός πόρου είναι η βελτίωση στην ποιότητα ζωής (κοινωνική ευημερία) που θα επερχόταν αν μία μονάδα από αυτό τον πόρο γινόταν διαθέσιμη χωρίς κόστος. Αντίθετα: η υποβάθμιση στην ποιότητα ζωής που θα επερχόταν αν υπήρχε μία μονάδα λιγότερη από αυτό τον πόρο. Dasgupta P., & Mäler K., (2001).

παρέχει εκτιμήσεις για την αειφορία ή μη σύγχρονων οικονομιών. Μελέτες όπως η IPCC report, η Stern Report κ.α τονίζουν το γεγονός ότι ένα αειφόρο μέλλον θα είναι ένας άπιαστος στόχος για τα μελλοντικά χρόνια αν δεν ρυθμίσουμε το φαινόμενο του θερμοκηπίου σήμερα.

Μία προσέγγιση ικανή να μετρήσει την επίδραση της περιβαλλοντικής υποβάθμισης που σχετίζεται με τις ανθρώπινες πράξεις όπως η κλιματική μεταβολή, είναι αυτό που αποκαλούμε σε αυτή την διατριβή κριτήριο της αειφόρου παραγωγικής βάσης. Το κριτήριο αυτό βασίζεται στην μεταβολή μίας Ramsey-Koopman συνάρτησης κοινωνικής ευημερίας. Αν αυτή η συνάρτηση στον χρόνο t είναι θετική αυτό υπονοεί ότι η γνήσια επένδυση είναι επίσης θετική και ο συνολικός πλούτος αυξάνεται και άρα πολιτικές οι οποίες οδηγούν σε διαρκή θετική γνήσια επένδυση θεωρούνται αειφόρες.

1.1.3 Μέτρηση της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής και Αειφορία

Ένα σημαντικό θέμα που προκύπτει από την ανάλυση του κριτηρίου της αειφορίας της παραγωγικής βάσης μίας οικονομίας, είναι το πώς μετράμε την συνεισφορά κάθε παραγωγικού συντελεστή στην μεγέθυνση του συνολικού προϊόντος.

Η μεθοδολογία που χρησιμοποιούμε στην παρούσα διατριβή είναι η λεγόμενη μεθοδολογία της μέτρησης της παραγωγικότητας (growth accounting methodology) που μετράει την συνεισφορά του κάθε συντελεστή παραγωγής στην παραγωγή του συνολικού προϊόντος. Με βάση την μεθοδολογία αυτή, οι παραγωγικοί συντελεστές πληρώνονται το οριακό τους προϊόν σε ένα πλαίσιο μίας ανταγωνιστικής ισορροπίας και το μέρος της μεγέθυνσης που απομένει και δεν αποδίδεται στην χρήση αυτών των συντελεστών ονομάστηκε από τον Solow «κατάλοιπο» και παρουσιάζεται σαν τεχνολογική πρόοδος (Solow, 1956).

Η θεωρία της μέτρησης της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής, δημιουργήθηκε από τους Solow (1957), Kendrick (1961), Denison (1962), Jorgenson and Griliches (1967) and Griliches (1997), οι οποίοι έθεσαν τα θεμέλια της και όρισαν τους καθοριστικούς παράγοντες του καταλοίπου. Barro, (1999).

Ξεκινώντας με το μοντέλο του Solow, η συνάρτηση παραγωγής που χρησιμοποιείται είναι η ακόλουθη:

$$Y = F(K, A, L)$$

όπου K είναι το στοκ του κεφαλαίου, A είναι το επίπεδο της τεχνολογίας και το L είναι η ποσότητα εργασίας που χρησιμοποιούνται στην παραγωγή. Ο ρυθμός μεγέθυνσης του συνολικού προϊόντος μπορεί να μοιραστεί ανάμεσα στα συστατικά του που σχετίζονται με την συσσώρευση των συντελεστών (K, L) και την τεχνολογική πρόοδο (A).

Αν οι συντελεστές παραγωγής αμείβονται το οριακό τους προϊόν, έτσι ώστε $\frac{\partial F}{\partial K} = R_K$ η αμοιβή του κεφαλαίου και $\frac{\partial F}{\partial L} = w$ η αμοιβή του μισθού, τότε το κατάλοιπο του Solow μπορεί να οριστεί σαν:

$$g_S = s_L\left(\frac{\dot{A}}{A}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_L\left(\frac{\dot{L}}{L}\right)$$

Όπου το g_S είναι το κατάλοιπο ή μέτρηση της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής (TFPG). Τα s_L και s_K είναι τα μερίδια της εργασίας και του κεφαλαίου αντίστοιχα και τα $\left(\frac{\dot{K}}{K}\right)$, $\left(\frac{\dot{L}}{L}\right)$ και $\left(\frac{\dot{A}}{A}\right)$ είναι οι ρυθμοί μεταβολής της μεγέθυνσης του κεφαλαίου της εργασίας και της τεχνολογικής προόδου αντίστοιχα (Barro, 1999).

Εκτός από τον παραδοσιακό τρόπο που χρησιμοποίησε ο Solow, υπάρχουν και άλλοι τρόποι για να μετρηθεί το κατάλοιπο και ένας από αυτούς είναι να υπολογιστεί από τις τιμές των συντελεστών παραγωγής και όχι από τις ποσότητες (προσέγγιση του Solow). Αυτή η μεθοδολογία, (μέτρηση του καταλοίπου από τις τιμές των συντελεστών παραγωγής) εισήχθη από τον Hsieh το (1998), και ονομάζεται δυτή προσέγγιση στην μέτρηση της παραγωγικότητας, (a dual approach to growth accounting). Αυτή η ιδέα ξεκινάει από τον Jorgenson και τον Griliches στα 1967.
Πέρα από αυτές τις δύο βασικές μεθοδολογίες για την μέτρηση του κατάλοιπου, υπάρχουν και άλλα μοντέλα που προσπάθησαν να ασχοληθούν με το θέμα αυτό. Πιο συγκεκριμένα οι Griliches (1979), Romer (1986), και Lucas (1988), δημιούργησαν μοντέλα οικονομικής μεγέθυνσης με αυξανόμενες αποδώσεις και διάχυση (increasing returns and spillovers).
Ο Romer έδωσε τη δική του προσέγγιση για το θέμα παρουσιάζοντας το μοντέλο «μαθαίνω-κάνοντας» (learning-by-doing). Η βασική ιδέα είναι ότι οι παραγωγοί μαθαίνουν να παράγουν πιο αποτελεσματικά και αυτή η γνώση διαχέεται αμέσως έτσι ώστε η παραγωγικότητα κάθε κλάδου να εξαρτάται από την συνολική μάθηση η οποία και αντικατοπτρίζεται στο συνολικό στοκ του κεφαλαίου. Σε αυτή την περίπτωση, η μέτρηση του κατάλοιπου (TFPG) περιλαμβάνει την επίδραση της μεγέθυνσης από την διάχυση (spillovers) και τις αυξημένες αποδώσεις (increasing returns) μαζί με την μεταβολή της εξωγενούς τεχνολογικής προόδου του καταλοίπου του Solow και αντικατοπτρίζεται στην εξίσωση που ακολουθεί:

$$g_{IRS} = \frac{\dot{A}}{A} + \beta\left(\frac{\dot{K}}{K}\right) = \frac{\dot{Y}}{Y} - \alpha\left(\frac{\dot{K}}{K}\right) - (1-\alpha)\left(\frac{\dot{L}}{L}\right)$$

Κατά την διάρκεια των τελευταίων δεκαετιών, διαφορετικές προσεγγίσεις έχουν χρησιμοποιηθεί για να μετρηθεί το κατάλοιπο που περιλαμβάνουν σπάσιμο και διαχωρισμό των συντελεστών της συνάρτησης παραγωγής. Π.χ Barro (1999), Barro and Sala-i-Martin (2005). Επίσης, οι Romer (1990), Grossman και Helpman (1991, ch. 3) και οι Spence (1976), Dixit and Stiglitz (1977) παρουσίασαν μοντέλα διαφοροποιημένου προϊόντος (Product varieties models). Οι Aghion και Howitt

(1992) και οι Grossman and Helpman (1991, ch. 4), παρουσίασαν τα λεγόμενα quality-ladders models of technological change στην βιβλιογραφία της ενδογενούς οικονομικής μεγέθυνσης.

Βασιζόμενοι σε όλα τα παραπάνω, επιλέγουμε σε αυτή την διατριβή να αναπτύξουμε μία «περιβαλλοντική ή πράσινη» μεθοδολογία μέτρησης της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής (green TFPG methodology), που βασίζεται στην παράδοση του Solow και αποδεικνύει την συνεισφορά του παράγοντα περιβάλλον (φυσικό κεφάλαιο) στο συνολικό προϊόν. Με αυτό τον τρόπο αποκαλύπτεται η σχέση μεταξύ της έννοιας της αειφόρου ανάπτυξης και της μέτρησης της συνολικής παραγωγικότητας.
Για να γίνει αυτό περισσότερο ξεκάθαρο, αυτό που κάνουμε είναι να εισάγουμε το φυσικό κεφάλαιο στην διαδικασία παραγωγής και να υποστηρίζουμε ότι αυτό το είδος κεφαλαίου το οποίο προσεγγίζεται με την μορφή εκπομπών του διοξειδίου του άνθρακα, (CO_2 emissions) ή με την μορφή της ενέργειας, (τα οποία και θεωρούνται παραγωγικοί συντελεστές στην παραγωγική διαδικασία), μπορούν να αποτελούν πηγές μεγέθυνσης. Παρατηρούμε ότι αυτός ο εξτρα περιβαλλοντικός παραγωγικός συντελεστής, συνεισφέρει στην συνολική μεγέθυνση του προϊόντος μαζί με τους παραδοσιακούς παραγωγικούς συντελεστές όπως το κεφάλαιο, και η εργασία.

Σε αυτή την διατριβή αναλύουμε την συνεισφορά του περιβαλλοντικού παράγοντα ο οποίος είναι είτε απλήρωτος είτε πληρώνεται εν μέρει κατά την χρήση του και τα αποτελέσματα των μετρήσεων μας παρέχουν πιθανά σημαντικές προεκτάσεις πολιτικής. Όπως αναφέρθηκε και παραπάνω, το κριτήριο της αειφορίας της παραγωγικής βάσης της οικονομίας, σχετίζεται με την μη φθίνουσα κοινωνική ευημερία (non-declining social welfare) στον χρόνο *t*. Μία από τις βασικές προϋποθέσεις για αυτό είναι διατήρηση όλων των ειδών του κεφαλαίου για τις μελλοντικές γενιές (διατήρηση της παραγωγικής βάσης της οικονομίας). Η έννοια της αειφόρου ανάπτυξης μπορεί να αναλυθεί περισσότερο χρησιμοποιώντας το πλαίσιο της μεθοδολογίας της μέτρησης της παραγωγικότητας των συντελεστών που μετράει την συνεισφορά κάθε είδους κεφαλαίου στην μεγέθυνση του συνολικού προϊόντος και αποδεικνύει ότι το λεγόμενο κατάλοιπο του Solow δεν είναι ο μόνος παράγοντας που οδηγεί σε ανάπτυξη αλλά ότι και το περιβάλλον παίζει έναν πολύ σημαντικό ρόλο προς αυτή την κατεύθυνση.

1.2 Συνεισφορά στη βιβλιογραφία και Αποτελέσματα της Έρευνας

Μετά την παρουσίαση της έννοιας της αειφορίας και των διαφορετικών ορισμών που χρησιμοποιούνται για να εκφραστεί αυτή η έννοια, παρατίθεται αυτό το κεφάλαιο για να παρουσιαστεί η μεθοδολογική προσέγγιση που διαμορφώθηκε και ακολουθήθηκε στην παρούσα διατριβή, καθώς και τα πρωτότυπα θεωρητικά και εμπειρικά αποτελέσματα που συνεισφέρουν στη βιβλιογραφία της αειφόρου ανάπτυξης και της μέτρησης της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής.

Ο βασικός μας στόχος στο πρώτο μέρος της διατριβής είναι να αναπτυχθεί ένα θεωρητικό μοντέλο που θα μπορούσε να εφαρμοστεί και εμπειρικά και να χαρακτηρίσει κατά πόσον η ανάπτυξη είναι αειφόρος ή όχι. Ένα μοντέλο που θα μπορεί να εφαρμοστεί σε πραγματικές οικονομίες και τρέχουσες οικονομικές καταστάσεις.

Ξεκινώντας με την καταστροφική εξάντληση του φυσικού περιβάλλοντος, οι πιο συχνές έννοιες που χρησιμοποιούνται για να εκφράσουν την έννοια της αειφόρου ανάπτυξης είναι οι έννοιες της διαχρονικής διανομής (intertemporal distribution) και της διαχρονικής ισότητα ανάμεσα στις γενιές (intergenerational equity).

Με βάση τους Arrow et al. (2003), η αειφόρος ανάπτυξη ορίζεται σαν την μη φθίνουσα κοινωνική ευημερία (Non-Declining Social Welfare - NDSW), η οποία εκφράζεται με την διαχρονική διατήρηση της παραγωγικής βάσης της οικονομίας. Η ιδέα είναι ότι η παραγωγική βάσης μίας οικονομίας που περιλαμβάνει μια σειρά κεφαλαίων όπως παραγόμενο κεφάλαιο, ανθρώπινο κεφάλαιο, φυσικό κεφάλαιο και γνώση, θα πρέπει να διατηρηθεί και να διαφυλαχθεί για τις μελλοντικές γενιές. Arrow et al., 2003. Αν η γνήσια επένδυση, η οποία ορίζεται σαν το άθροισμα των επενδύσεων στις παραπάνω μορφές κεφαλαίου και μετριέται με τις λογιστικές τιμές, είναι μη φθίνουσα διαχρονικά, τότε η συνολική κοινωνική ευημερία είναι επίσης μη φθίνουσα. Σε αυτή την περίπτωση μεταβολή της συνάρτηση κοινωνικής ευημερίας στον χρόνο t θα είναι μη αρνητική και η ανάπτυξη θα μπορεί να θεωρηθεί σαν αειφόρος με βασιζόμενη στο κριτήριο της παραγωγικής βάσης της οικονομίας. Αυτή η έννοια της μη φθίνουσας κοινωνικής ευημερίας ή της θετικής γνήσιας επένδυσης στον χρόνο t, δεν υπονοεί αειφορία με βάση την χρησιμότητα, (δηλαδή διατήρηση του επιπέδου της χρησιμότητας σταθερό διαχρονικά, Pezzey 2004b)[5]. Ακολουθώντας τον ορισμό των Arrow et al., (2003) αναπτύσσουμε ένα θεωρητικό μοντέλο που βασίζεται στην παράγωγο μίας συνάρτησης κοινωνικής ευημερίας στον χρόνο t, η οποία μετράει την μεταβολή της κοινωνικής ευημερίας μίας οικονομίας. Η κοινωνική ευημερία σε μια δεδομένη στιγμή t ορίζεται ως ακολούθως:

$$V_t = \int_t^{\infty} e^{-\rho(\tau - t)} U(\mathbf{x}(\tau), \mathbf{u}(\tau))d\tau \, , \tau \geq t$$

Όπου $\mathbf{x} = (x_1, \ldots, x_n)$ είναι ένα διάνυσμα μεταβλητών κατάστασης (state variables) και $\mathbf{u} = (u_1, \ldots, u_m)$ είναι ένα διάνυσμα μεταβλητών ελέγχου, (control variables) που αποτελούν και τα εργαλεία πολιτικής. Η συνάρτηση, $U(\mathbf{x}(\tau), \mathbf{u}(\tau))$ μπορεί να μεταφραστεί σαν την ευημερία της γενιάς που ζει στον χρόνο τ. Χρησιμοποιώντας ένα μη βέλτιστο θεωρητικό πλαίσιο[6], χαρακτηρίζουμε την μεταβολή στην τρέχουσα κοινωνική ευημερία στον χρόνο t, όταν οι μεταβλητές ελέγχου επιλέγονται με βάση κάποιον κανόνα ανατροφοδότησης ή με βάση κάποιον αυθαίρετο κανόνα πολιτικής. (Ο κανόνας ανατροφοδότησης είναι για παράδειγμα ένας κανόνας τακτικής με βάση τον οποίο τα εργαλεία καθορίζονται σε σχέση με τις τιμές των μεταβλητών

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[5] Όπως αποδείχθει από τους Asheim (1994) και Pezzey (2004b), υπάρχουν βέλτιστες οικονομίες όπου η μη φθίνουσα κοινωνική ευημερία στον χρόνο t, μπορεί να υπονοεί ότι η αειφορία με βάση το κριτήριο της χρησιμότητα είναι μη αειφόρος για μια πεπερασμένη χρονική περίοδο.

[6] Ως μη βέλτιστη οικονομία χαρακτηρίζεται η οικονομία όπου η κυβέρνησή της είτε από σχεδιασμό είτε από ανικανότητα, δεν επιλέγει πολιτικές που μεγιστοποιούν την διαχρονική ευημερία.

κατάστασης του συστήματος. Ο αυθαίρετος κανόνας πολιτικής επιλέγεται αυθαίρετα).

Επίσης εξάγουμε το νέο αποτέλεσμα ότι όταν οι μεταβλητές ελέγχου ή τα εργαλεία πολιτικής επιλέγονται αυθαίρετα, η τρέχουσα μεταβολή στην κοινωνική ευημερία βασίζεται όχι μόνο στη μεγέθυνση των συντελεστών και των λογιστικών τους τιμών, αλλά και στις αυθαίρετες διαδρομές (paths) των μεταβλητών ελέγχου. Σε αυτή την περίπτωση η συνάρτηση αξίας (value function) μίας οικονομίας βασίζεται και στα τρέχοντα στοκ (current stocks) και στις τρέχουσες ροές (current flows) και μπορεί να γραφεί κάτω από τον κανόνα ανατροφοδότησης και τον αυθαίρετο κανόνα ως εξής:

$$V_t(\mathbf{x}_t;\mathbf{b}) = \int_t^{\infty} e^{-\rho(\tau-t)} U(\mathbf{g}(\boldsymbol{\phi}(\tau-t,\mathbf{x}_t,\mathbf{b})),\boldsymbol{\phi}(\tau-t,\mathbf{x}_t,\mathbf{b}))d\tau$$

$$V_t(\mathbf{x}_t,\bar{\mathbf{u}}_t;\mathbf{b}) = \int_t^{\infty} e^{-\rho(\tau-t)} U(\boldsymbol{\psi}(\tau-t,\mathbf{x}_t,\bar{\mathbf{u}}_0(\tau),\mathbf{b}),\bar{\mathbf{u}}_0(\tau))d\tau \qquad (1)$$

Οι λογιστικές τιμές για τους συντελεστές x_i και τις μεταβλητές ελέγχου $\bar{u}_j$ τον χρόνο t, ορίζονται ως εξής:

$$p_{tx_i} = \frac{\partial V_t}{\partial x_{it}},\ p_{tu_j} = \frac{\partial V_t}{\partial \bar{u}_{jt}}$$

Το $\dot{V}_t \equiv \frac{dV_t}{dt}$ δηλώνει τον ρυθμό μεταβολής της συνάρτησης κοινωνικής ευημερίας στον χρόνο t.

Όταν το $\dot{V}_t \geq 0$, αυτό σημαίνει *μη αρνητική γνήσια επένδυση* που στο πλαίσιο των Arrow et al. (2003), θεωρείται ένας δείκτης τρέχουσας αειφορίας της παραγωγικής βάσης της οικονομίας.

Όταν το $\dot{V}_t < 0$, ή η μεταβολή της συνάρτησης κοινωνικής ευημερίας είναι αρνητική, αυτό σημαίνει *αρνητική γνήσια επένδυση* και άρα έλλειψη αειφορίας σε όρους της παραγωγικής βάσης της οικονομίας. Αυτή η προσέγγιση του υπολογισμού της τρέχουσας μεταβολής της κοινωνικής ευημερίας μπορεί να είναι χρήσιμη για να παρέχει μία μέτρηση της αειφορίας σε όρους γνήσιας επένδυσης σε ένα μη βέλτιστο οικονομικό πλαίσιο. Η αρνητική γνήσια επένδυση μπορεί να υπονοεί ότι αφήνουμε λιγότερη παραγωγική ικανότητα στις μελλοντικές γενιές για να καλύψουν τις ανάγκες τους. Πιο συγκεκριμένα, αν μια οικονομία δεν θεωρείται αειφόρος με βάση το κριτήριο της παραγωγικής βάσης, τότε η μεταβολή της συνάρτησης κοινωνικής ευημερίας τον χρόνο *t* είναι αρνητική και η γνήσια επένδυση είναι επίσης αρνητική. Αυτό σημαίνει ότι ο συνολικός πλούτος θα μειώνεται και οι πολιτικές που θα οδηγούν σε συνεχώς αρνητική γνήσια επένδυση θεωρούνται μη αειφόρες[7].

Αυτή η μεθοδολογική προσέγγιση μπορεί να θεωρηθεί ως μία προσέγγιση αειφορίας της παραγωγικής βάσης της οικονομίας. Οι συναρτήσεις αξίας (1) σε κάθε δεδομένο χρονικό σημείο t παριστάνουν την κοινωνική ευημερία από τον χρόνο t και μετά και αυτό κάνει πιθανό τον χαρακτηρισμό της μεταβολής των συνθηκών της τρέχουσας

[7] Η Παγκόσμια Τράπεζα, (2006, Ch. 3), οι Asheim (1994), Hamilton and Clemens (1999), Pezzey (2004b), δείχνουν ότι η αρνητική γνήσια επένδυση τον χρόνο t, δηλαδή η φθίνουσα κοινωνική ευημερία, υπονοεί έλλειψη αειφορίας σε όρους χρησιμότητας σε βέλτιστες οικονομίες. Αυτό το αποτέλεσμα πάντως δεν έχει αποδειχθεί ότι ισχύει σε ένα γενικό μη βέλτιστο πλαίσιο.

κοινωνικής ευημερίας σε ένα γενικό πλαίσιο και παρέχει την βάση για μία εμπειρική εκτίμηση αυτών των μεταβολών.
Ο ρυθμός μεταβολής μιας συνάρτησης κοινωνικής ευημερίας δεν είναι μόνο το άθροισμα της γνήσιας επένδυσης, αλλά μπορεί επίσης να περιλαμβάνει και τον ρυθμό μεταβολής των εργαλείων πολιτικής που αμείβονται με βάση τις λογιστικές τους τιμές. Άρα σε συγκεκριμένες περιπτώσεις μη βέλτιστων οικονομιών με αυθαίρετες επιλογές μεταβλητών ελέγχου, η γνήσια επένδυση μπορεί να μην είναι ο πιο κατάλληλος ορισμός τον χαρακτηρισμό των συνθηκών αειφορίας. Σε αυτές τις περιπτώσεις, η γνήσια επένδυση θα πρέπει να προσαρμοστεί και για την μεγέθυνση των αυθαίρετα επιλεγμένων μεταβλητών πολιτικής, όπως για παράδειγμα τα όρια στις εκπομπές. Το θεωρητικό μας μοντέλο, συνεισφέρει στην τρέχουσα βιβλιογραφία τόσο στο θεωρητικό, όσο και στο εμπειρικό μέρος καθώς η συνάρτηση αξίας (value function) μπορεί να χρησιμοποιηθεί για να παρέχει εμπειρικές ενδείξεις για συνθήκες αειφορίας. Το μοντέλο μας εφαρμόστηκε στην περίπτωση της ελληνικής οικονομίας και εκτιμήθηκε η τρέχουσα μεταβολής της κοινωνικής ευημερίας στην περίπτωση της Ελλάδας.

Μετά τον καθορισμό του κριτηρίου της αειφόρου παραγωγικής βάσης και έχοντας εμπειρικά αποτελέσματα για την ελληνική οικονομία, επεκτείναμε το μοντέλο μας σε ένα γκρουπ αναπτυγμένων και αναπτυσσόμενων χωρών θέτοντας το θέμα ενός από τα πιο σημαντικά προβλήματα που υπάρχουν σήμερα στην διεθνή ατζέντα, το πρόβλημα του φαινομένου του θερμοκηπίου και της υπερθέρμανσης του πλανήτη στο πλαίσιο της αειφορίας της παραγωγικής βάσης μίας οικονομίας. Το φαινόμενο του θερμοκηπίου (global warming phenomenon) αποτελεί έναν από τους βασικούς παράγοντες που μπορούν να καθορίσουν ένα μη αειφόρο μέλλον. Οι εκπομπές του διοξειδίου του άνθρακα, (Carbon dioxide (CO_2) emissions), μαζί με άλλα αέρια του θερμοκηπίου θεωρούνται ως κάποιοι από τους βασικούς ανθρωποκεντρικούς παράγοντες που προκαλούν και ενισχύουν το φαινόμενο της πλανητικής υπερθέρμανσης που πλήττει την ευημερία τωρινών και μελλοντικών γενεών και απειλεί την αειφόρο ανάπτυξη.

Βασικός μας στόχος είναι να σχετίσουμε τις παγκόσμιες εκπομπές του διοξειδίου του άνθρακα (global CO_2 emissions) με την έννοια της αειφορίας της παραγωγικής βάσης και να προσεγγίσουμε εμπειρικά την επίδραση της περιβαλλοντικής υποβάθμισης που προκαλείται εν μέσω άλλων και από το φαινόμενο του θερμοκηπίου με τις συνθήκες μεταβολής της τρέχουσας κοινωνικής ευημερίας.

Για αυτό το σκοπό, αναπτύξαμε ένα θεωρητικό μεθοδολογικό πλαίσιο και εξήγαμε εμπειρικά αποτελέσματα υποδεικνύοντας μία σύνδεση ανάμεσα στην τρέχουσα μεταβολή της κοινωνικής ευημερίας και το φαινόμενο του θερμοκηπίου.

Χρησιμοποιήσαμε την μεταβολή μίας συνάρτησης κοινωνικής ευημερίας ($\dot{V}_t$) και ορίσαμε ένα κριτήριο που μετράει την αειφορία της παραγωγικής βάσης κάτω από την επίδραση του φαινομένου του θερμοκηπίου. Χρησιμοποιήσαμε την παρακάτω συνάρτηση κοινωνικής ευημερίας:

$$\dot{V}_t = p_{K_t}\dot{K} + p_{N_t}\dot{N} + p_{A_t}\dot{A} + p_{\bar{Z}_t}\dot{\bar{Z}}_\tau + p_{P_t}\dot{P}_\tau \gtreqless 0$$

όπου $\dot{V}_t$ είναι η συνάρτηση κοινωνικής ευημερίας και $p_{K_t}, p_{N_t}, p_{A_t}, p_{\bar{Z}_t}, p_{P_t}$ είναι οι λογιστικές τιμές του κεφαλαίου, του πληθυσμού, της τεχνολογίας, του ορίου των εκπομπών του διοξειδίου του άνθρακα και του στοκ των ρύπων αντίστοιχα και $\dot{K}, \dot{N}, \dot{A}, \dot{\bar{Z}}_\tau$, $\dot{P}_\tau$, είναι οι ρυθμοί μεταβολής του κεφαλαίου, του πληθυσμού, της τεχνολογικής προόδου, του ορίου των εκπομπών του διοξειδίου του άνθρακα και του στοκ των ρύπων.

Αν η μεταβολή του $\dot{V}_t$ είναι θετική, τότε μία οικονομία μπορεί να θεωρηθεί ότι είναι την χρονική στιγμή *t* αειφόρα με βάση το κριτήριο της παραγωγικής βάσης και άρα η γνήσια επένδυση είναι θετική.

Αν το $\dot{V}_t$ είναι αρνητικό τότε η οικονομία δεν είναι αειφόρα με βάση το κριτήριο της παραγωγικής βάσης και η γνήσια επένδυση θα είναι αρνητική.

Εφαρμόσαμε το θεωρητικό μας μοντέλο σε 23 αναπτυγμένες χώρες[8] και σε 21 αναπτυσσόμενες χώρες[9] και υπολογίζουμε την μεταβολή στην τρέχουσα κοινωνική ευημερία και στα δύο γκρουπ αναπτυγμένων και αναπτυσσόμενων χωρών. Τα αποτελέσματά μας δείχνουν ότι οι ζημιές από τις εκπομπές του διοξειδίου του άνθρακα είναι ένας σημαντικός παράγοντας που επηρεάζει αρνητικά την αειφορια της παραγωγικής βάσης μίας οικονομίας και παίζει σημαντικό ρόλο στην τρέχουσα και μελλοντική ευημερία των οικονομιών αυτών.

Αυτό το συμπέρασμα, επιβεβαιώνεται στο δεύτερο μέρος του διδακτορικού, όπου αναλύουμε το θέμα της μέτρησης της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής (Total factor Productivity Growth - TFPG).

Η μεθοδολογία του υπολογισμού της μεγέθυνσης (Growth Accounting) είναι η εμπειρική μεθοδολογία που επιτρέπει το «σπάσιμο» του τελικού προϊόντος στα συστατικά που το δημιουργούν και μετράει την συνεισφορά κάθε παράγοντα – παραγωγικού συντελεστή (ΠΣ) – στην μεγέθυνση του τελικού προϊόντος. Η έννοια της μέτρησης της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής (TFPG) που ονομάζεται και κατάλοιπο, μετράει το κομμάτι της μεγέθυνσης του προϊόντος που δεν αποδίδεται στους παραγωγικούς συντελεστές που απαρτίζουν μία νεοκλασική συνάρτηση παραγωγής, αλλά αποδίδεται στην τεχνολογική πρόοδο. Βασιζόμενοι σε αυτή τη θεωρία, επεκτείνουμε το παραδοσιακό κατάλοιπο του Solow, χρησιμοποιώντας το περιβάλλον σαν έναν εξτρα παραγωγικό συντελεστή σε μία νεοκλασική συνάρτηση παραγωγής και αποδεικνύουμε ότι το παραδοσιακό κατάλοιπο του Solow στο οποίο ο παράγοντας περιβάλλον δεν λαμβανόταν υπόψη, μπορεί να παρέχει παραπλανητικές μετρήσεις και αποτελέσματα, λόγω της απαλοιφής από τις μετρήσεις ενός σημαντικού όπως αποδεικνύουν τα αποτελέσματα μας ΠΣ, του περιβάλλοντος, που προσεγγίζεται στην ανάλυσή μας με τις εκπομπές διοξειδίου του άνθρακα και την ενέργεια.

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[8] Οι 23 αναπτυγμένες χώρες που χρησιμοποιούμε στη ανάλυσή μας είναι οι εξής: Καναδάς, Η.Π.Α, Αυστρία, Βέλγιο, Δανία, Φιλανδία, Γαλλία, Ελλάδα, Ιταλία, Πορτογαλία, Ισπανία, Σουηδία, Ελβετία, Ηνωμένο Βασίλειο, Ιαπωνία, Ισλανδία, Ιρλανδία, Ολλανδία, Νορβηγία, Αυστραλία, Μεξικό, Τουρκία, Λουξεμβούργο.

[9] Οι 21 αναπτυσσόμενες χώρες που χρησιμοποιούμε στη ανάλυσή μας είναι οι εξής: Περού, Ταϊλάνδη, Παραγουάι, Μορόκο, Δομινικανή Δημοκρατία, Γουατεμάλα, Χόνδουρας, Τζαμάικα, Βολιβία, Κολομβία, Εκουαδόρ, Ιράν, Σρι Λάνκα, Συρία, Γιουγκοσλαβία, Ινδία, Κένυα, Μαδαγασκάρη, Μαλάουι, Σιέρα Λεόνε, Ζιμπάμπουε.

Πιο συγκεκριμένα, βασιζόμενοι στην παρακάτω συνάρτηση παραγωγής:

$$Y = F(K, H, E, X)$$

όπου K είναι το παραγόμενο κεφάλαιο, H είναι το ανθρώπινο κεφάλαιο, E=AL είναι η ενεργός εργασία, (L είναι ο συντελεστής εργασία και A είναι η τεχνολογική πρόοδος της εργασίας) και X=BZ είναι οι ενεργοί ρύποι, (το B αντικατοπτρίζει την τεχνολογική πρόοδο των ρύπων και το Z να είναι οι ρύποι του διοξειδίου του άνθρακα σε φυσικές μονάδες), εισάγουμε το περιβάλλον στην συνάρτηση παραγωγής σαν ένα πρόσθετο παράγοντα που οδηγεί σε οικονομική μεγέθυνση.

Ορίζουμε τα μερίδια των παραγωγικών συντελεστών στο συνολικό προϊόν, σε ένα πλαίσιο μεγιστοποίησης των κερδών. Το κατάλοιπο (γ) επαυξημένο με την χρήση του περιβάλλοντος στην παραγωγική διαδικασία να ορίζεται όπως ακολουθεί:

$$\gamma = s_L\left(\frac{\dot{A}}{A}\right) + s_Z\left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_H\left(\frac{\dot{H}}{H}\right) - s_L\left(\frac{\dot{L}}{L}\right) - s_Z\left(\frac{\dot{Z}}{Z}\right) \qquad (2)$$

Συγκρίνοντας το παραδοσιακό κατάλοιπο του Solow που ακολουθεί:

$$g_S = s_L\left(\frac{\dot{A}}{A}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_L\left(\frac{\dot{L}}{L}\right) \qquad (3)$$

με το επαυξημένο κατάλοιπο με το περιβάλλον (2), παρατηρούμε ότι υπάρχουν δύο εξτρα παραγωγικοί συντελεστές – το ανθρώπινο κεφάλαιο και το περιβάλλον – που προσεγγίζονται από τις εκπομπές του διοξειδίου του άνθρακα- που δεν έχουν υπολογιστεί στις μετρήσεις του παραδοσιακού καταλοίπου (3).
Η εισαγωγή του περιβάλλοντος στην ανάλυσή μας, μπορεί να αλλάξει τον τρόπο με τον οποίο αναλύουμε το TFPG και μπορεί να αποτελέσει έναν σημαντικό παράγοντα της συνολικής μεγέθυνσης του προϊόντος. Παρόλα αυτά, η συνεισφορά του παράγοντα περιβάλλον στην μεγέθυνση του συνολικού προϊόντος δεν μπορεί να μετρηθεί σωστά λόγω της έλλειψης περιβαλλοντικής πολιτικής επάνω στους ρύπους. Εφόσον δεν υπάρχει περιβαλλοντική πολιτική επάνω στους ρύπους (π.χ η ύπαρξη ενός φόρου), τότε μέρος της μεγέθυνσης του συνολικού προϊόντος που θα έπρεπε να αποδίδεται στην χρήση του περιβάλλοντος αποδίδεται εσφαλμένα στην τεχνολογική πρόοδο. Παράλληλα, αν υπάρχει τεχνολογική πρόοδος στους ρύπους, αυτό μπορεί να θεωρηθεί άλλος ένας παράγοντας μεγέθυνσης παράλληλα με τη τεχνολογική πρόοδο της εργασίας που κατά τον Solow ήταν ο παράγοντας που δημιουργούσε μεγέθυνση.

Μετά την ανάπτυξη του θεωρητικού αυτού πλαισίου, εξετάζουμε εμπειρικά αυτή την υπόθεση χρησιμοποιώντας στοιχεία από ένα γκρουπ 23 χωρών του ΟΟΣΑ. Τα αποτελέσματά μας δείχνουν ότι ο «απλήρωτος», λόγω της έλλειψης ενός φόρου περιβαλλοντικός παράγοντας, ο οποίος προσεγγίζεται από τους ρύπους του διοξειδίου του άνθρακα, μπορεί να θεωρείται πηγή μεγέθυνσης και ένας σημαντικός παράγοντας που προκαλεί μεγέθυνση. Παρόλα αυτά, αν η χρήση του περιβάλλοντος αποτελεί πηγή μεγέθυνσης, όπως δείχνουν τα αποτελέσματά μας, αλλά το περιβάλλον χρησιμοποιείται σαν ένας απλήρωτος παραγωγικός συντελεστής στην παραγωγική διαδικασία, τότε οι περιβαλλοντικές ζημιές παραμένουν απλήρωτες. Όμως παραμένοντας απλήρωτες, δεν διατηρούνται σε ένα κοινωνικά «άριστο» επίπεδο κατά την διάρκεια της παραγωγικής διαδικασίας και αυτό μπορεί τελικά να διαβρώσει την

αειφορία της ίδιας της διαδικασίας μεγέθυνσης του προϊόντος. Ο λόγος για τον οποίο οι περιβαλλοντικές ζημιές μένουν απλήρωτες, είναι ότι δεν υπάρχει θεσμοθετημένη φορολογία για τις εκπομπές του διοξειδίου του άνθρακα. Προσπαθούμε να λύσουμε αυτό το πρόβλημα στην ανάλυσή μας, εξισώνοντας το μερίδιο των ρύπων στο συνολικό προϊόν, με το μερίδιο των περιβαλλοντικών ζημιών στο συνολικό προϊόν, χρησιμοποιώντας ανεξάρτητες εκτιμήσεις για τις ζημιές του διοξειδίου του άνθρακα. Εκτιμάμε επίσης απευθείας τα μερίδια των ΠΣ από μια συνολική συνάρτηση παραγωγής όπου οι εκπομπές του διοξειδίου του άνθρακα αποτελούν παραγωγικό συντελεστή στην παραγωγή μαζί με το κεφάλαιο και την εργασία.
Τα αποτελέσματά μας υποδεικνύουν ότι η χρήση του περιβάλλοντος μοιάζει να είναι ένας στατιστικά σημαντικός παράγοντας στην εξήγηση της μεγέθυνσης του συνολικού προϊόντος και υπάρχει επίσης και τεχνολογική πρόοδος στους ρύπους.

Ακολουθώντας την ίδια ανάλυση, εφαρμόζουμε το ίδιο θεωρητικό μοντέλο σε ένα γκρουπ 21 αναπτυσσόμενων χωρών[10] και τα αποτελέσματά μας επιβεβαιώνουν την πεποίθησή μας, ότι ο εξτρα παραγωγικός συντελεστής περιβάλλον συνεισφέρει στην μεγέθυνση του συνολικού προϊόντος.
Η τελευταία μας συνεισφορά σε αυτή τη διατριβή στο πλαίσιο του «περιβαλλοντικού ή πράσινου» κατάλοιπου, ήταν να διευρύνουμε ακόμα περισσότερο την θεωρία του παραδοσιακού κατάλοιπου εισάγοντας σαν συντελεστή παραγωγής ξανά το περιβάλλον το οποίο όμως αυτή τη φορά προσεγγίστηκε από την χρήση της ενέργειας. Η νεοκλασική συνάρτηση παραγωγής που χρησιμοποιήθηκε ήταν η εξής:

$$Y = F(K, H, W, X)$$

όπου K είναι το παραγόμενο κεφάλαιο, H είναι το ανθρώπινο κεφάλαιο, W=AL είναι η ενεργός εργασία, (L είναι ο συντελεστής εργασία και A είναι η τεχνολογική πρόοδος της εργασίας) και X=BE είναι η ενεργοί ρύποι, (το B αντικατοπτρίζει την τεχνολογική πρόοδο της ενέργειας και το E να είναι η ενέργεια σε φυσικές μονάδες). Το επαυξημένο με την ενέργεια κατάλοιπο ορίζεται ως εξής:

$$\gamma = s_L\left(\frac{\dot{A}}{A}\right) + s_E\left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_H\left(\frac{\dot{H}}{H}\right) - s_L\left(\frac{\dot{L}}{L}\right) - s_E\left(\frac{\dot{E}}{E}\right)$$

Χρησιμοποιούμε την ενέργεια σαν μία προσέγγιση για τον παράγοντα περιβάλλον αντί τους ρύπους του διοξειδίου του άνθρακα, παρατηρώντας ότι υπάρχει μία ευθεία και άμεση σχέση ανάμεσα στην ενέργεια και τους ρύπους αφού τα στοιχεία των ρύπων κατασκευάζονται από την χρήση στοιχείων ενέργειας.
Παρόλο που η ενέργεια πληρώνεται σαν ένας ΠΣ στην παραγωγή, υπάρχει επίσης ένα απλήρωτο μέρος της χρήσης της και αυτό είναι οι εκπομπές του διοξειδίου του άνθρακα που δημιουργούνται από την χρήση της και αυτό το μέρος παραμένει απλήρωτο, λόγω της έλλειψης πολιτικής για τους ρύπους τόσο στις αναπτυγμένες

[10] Οι 21 αναπτυσσόμενες χώρες που χρησιμοποιούμε στη ανάλυσή μας είναι οι εξής: Περού, Ταϊλάνδη, Παραγουάι, Μορόκο, Δομινικανή Δημοκρατία, Γουατεμάλα, Χόνδουρας, Τζαμάικα, Βολιβία, Κολομβία, Εκουαδόρ, Ιράν, Σρι Λάνκα, Συρία, Γιουγκοσλαβία, Ινδία, Κένυα, Μαδαγασκάρη, Μαλάουι, Σιέρα Λεόνε, Ζιμπάμπουε.

(OECD), όσο και στις αναπτυσσόμενες χώρες, (χώρες που δεν ανήκουν στον ΟΟΣΑ) και ιδιαίτερα για την περίοδο που εξετάζουμε (1965-1990).

Αναλύοντας το κατάλοιπο για ένα γκρουπ 23 αναπτυγμένων (ΟΟΣΑ) χωρών παρατηρούμε ότι υπάρχει μία ισχυρή αναλογική σχέση μεταξύ της ενέργειας και των ρύπων του διοξειδίου του άνθρακα. Κατασκευάζουμε ένα μοντέλο που μελετάει την ισοδυναμία του μοντέλου που βασίζεται στις εκπομπές ρύπων διοξειδίου του άνθρακα και του μοντέλου που βασίζεται στην χρήση της ενέργειας[11] κάτω από το πλαίσιο ενός άριστου φόρου στους ρύπους και εξωγενών τιμών της ενέργειας και εκτιμάμε την συνεισφορά του απλήρωτου μέρους των ρύπων που δημιουργούνται από την χρήση της ενέργειας στις μετρήσεις του καταλοίπου. Τα αποτελέσματά μας δείχνουν ότι οι παραδοσιακές μετρήσεις του κατάλοιπου αλλάζουν δραστικά όταν εισάγουμε τον εν μέρει πληρωμένο παραγωγικό συντελεστή (ενέργεια) στην συνάρτηση παραγωγής και κυρίως όταν αποδίδουμε μία συγκεκριμένη τιμή στο απλήρωτο μέρος της χρήσης της ενέργειας που είναι οι ρύποι του διοξειδίου του άνθρακα. Τα αποτελέσματά μας μπορούν να μεταφραστούν σαν μετρήσεις του καταλοίπου όταν οι ΠΣ που χρησιμοποιούνται στην παραγωγή δημιουργούν εξωτερικότητες. Με την εισαγωγή αυτής της εξτρα εισροής στην διαδικασία παραγωγής, της ενέργειας, οι ρύποι που δημιουργούνται υπολογίζονται στις μετρήσεις του καταλοίπου, αυτό μπορεί να πάρει ακόμα και αρνητικές τιμές. Αυτό μας δείχνει ότι όταν εσωτερικεύουμε το κόστος των ρύπων που δημιουργούνται από την χρήση της ενέργειας το κατάλοιπο γίνεται αρνητικό. Ένα αρνητικό κατάλοιπο, μπορεί να υπονοεί ότι κάθε εισροή που χρησιμοποιείται στην παραγωγική διαδικασία αμείβεται πλήρως για την συνεισφορά της στη μεγέθυνση του συνολικού προϊόντος και δεν υπάρχει τεχνολογική πρόοδος που οδηγεί σε οικονομική μεγέθυνση.

Τα αποτελέσματα του δεύτερου μέρους της διατριβής δείχνουν ότι οι παραδοσιακές μετρήσεις της παραγωγικότητας μπορεί να αποτελούν έναν παραπλανητικό δείκτη μεγέθυνσης ιδιαίτερα για τις αναπτυσσόμενες χώρες. Αυτό μπορεί να συμβεί επειδή ένας από τους παράγοντες που δημιουργούν μεγέθυνση, το περιβάλλον, δεν υπολογίζεται όπως θα έπρεπε στις μετρήσεις της παραγωγικότητας και αυτό μπορεί να οδηγήσει σε λάθος μετρήσεις σε αυτές τις χώρες. Βασιζόμενοι σε αυτή την διαπίστωση, παρέχουμε μετρήσεις του «πράσινου ή περιβαλλοντικού» κατάλοιπου για αυτές τις χώρες και συγκρίσεις με παρελθούσες μελέτες. Πιστεύουμε ότι αυτού του είδους η ανάλυση απευθύνεται στο πρόβλημα της περιβαλλοντικής υποβάθμισης με έναν αποτελεσματικό τρόπο επειδή τονίζει και αναδεικνύει την συνεισφορά του περιβάλλοντος στη συνολική μεγέθυνση του προϊόντος και αντικατοπτρίζει την χρήση των εκπομπών του διοξειδίου του άνθρακα σαν τρόπο προσέγγισης του περιβαλλοντικού παράγοντα στην συνολική παραγωγή τελικού προϊόντος. Αν μετατρέψουμε τον απλήρωτο (ελεύθερο προς χρήση) περιβαλλοντικό συντελεστή σε έναν συντελεστή με τιμή, αυτό θα οδηγούσε σε μία πολύ περισσότερο συντηρητική χρήση αυτού του ΠΣ.

[11] Σε ένα μοντέλο που βασίζεται στους ρύπους οι ρύποι θεωρούνται σαν εισροή στην παραγωγική διαδικασία, ενώ σε ένα μοντέλο που βασίζεται στη χρήση της ενέργειας, η ενέργεια θεωρείται εισροή στην παραγωγική διαδικασία.

Μπορούμε να σημειώσουμε επίσης ότι υπάρχει μία σημαντική σχέση ανάμεσα στα αποτελέσματα που παρήχθησαν από το πρώτο και το δεύτερο μέρος της διατριβής. Το κριτήριο της αειφόρου παραγωγικής βάσης είναι πολύ στενά συνδεόμενο με το πλαίσιο της μέτρησης της μεγέθυνσης και του καταλοίπου, όπου ο παράγοντας περιβάλλον μπορεί να θεωρηθεί σαν εισροή στην παραγωγή με σημαντική συνεισφορά και η τεχνολογική πρόοδος των ρύπων μπορεί επίσης να είναι παρούσα και να οδηγεί την μεγέθυνση μαζί με την τεχνολογική πρόοδο της εργασίας. Η σχέση μεταξύ του κριτηρίου της αειφόρου παραγωγικής βάσης και του πλαισίου της μέτρησης της μεγέθυνσης μπορεί να περιγραφεί όπως ακολουθεί.

Ένας σημαντικός παράγοντας στην εκτίμηση του κριτηρίου της αειφορίας είναι η μεταβολή της τεχνολογικής προόδου $\dot{A}$ που κατά τον Solow οδηγεί σε μεγέθυνση του συνολικού προϊόντος. Η εκτίμηση του παράγοντα της τεχνολογικής προόδου γίνεται μετρώντας τη συνολική μεγέθυνση της παραγωγικότητας των συντελεστών παραγωγής. Αν παρόλα αυτά το περιβάλλον δεν λαμβάνεται υπόψη στις παραδοσιακές μετρήσεις του καταλοίπου σαν ΠΣ, οι εκτιμήσεις αυτές θεωρούνται μεροληπτικές. Η συνεισφορά μας στην μέτρηση της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής, λαμβάνοντας υπόψη την συνεισφορά του περιβάλλοντος, όχι μόνο παρέχει τα μέσα για να διορθωθούν πιθανώς μεροληπτικά αποτελέσματα της μέτρησης του καταλοίπου, αλλά παρέχει επίσης και αμερόληπτες εκτιμήσεις του καταλοίπου που είναι απαραίτητες για την εκτίμηση του κριτηρίου της αειφορίας της παραγωγικής βάσης. Αυτή η σύνδεση αποκαλύπτει τη σχέση μεταξύ της αειφορίας της παραγωγικής βάσης και του κατάλοιπου ώστε να αποκτηθούν ορθές εκτιμήσεις του κριτηρίου της αειφορίας της παραγωγικής βάσης.

2. Συμπεράσματα

Στο πρώτο μέρος της διατριβής, ορίσαμε την έννοια της αειφορίας και μετρήσαμε τις συνθήκες αειφορίας σε αναπτυγμένες και αναπτυσσόμενες χώρες, ενώ στο δεύτερο μέρος επεκτείναμε το θέμα της μέτρησης της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής εισάγοντας τον παράγοντα περιβάλλον στην συνάρτηση παραγωγής.

Το παρόν κεφάλαιο, είναι μία προσπάθεια να συνοψιστούν όλα τα νέα θεωρητικά και εμπειρικά αποτελέσματα και ευρήματα της διατριβής.

Ξεκινώντας με το κεφάλαιο 3, ο σκοπός ήταν να αναπτυχθεί ένα μοντέλο ικανό να προσεγγίσει την έννοια της αειφορίας μετρώντας τις μεταβολές στις συνθήκες τρέχουσας κοινωνικής ευημερίας. Βασιζόμενοι σε μη βέλτιστες οικονομίες, αναπτύξαμε ένα μοντέλο που μας επέτρεπε να επιλέγουμε πολιτικές με βάση την επίδρασή τους στις συνθήκες τρέχουσας κοινωνικής ευημερίας. Θεμελιώσαμε δυο διαφορετικές προσεγγίσεις για την επιλογή εργαλείων πολιτικής. Έναν κανόνα ανατροφοδότησης (feedback rule) και έναν αυθαίρετο κανόνα (arbitrary rule) και ορίσαμε δύο κριτήρια για καθέναν από αυτούς τους κανόνες που μετράνε την μεταβολή στις συνθήκες τρέχουσας κοινωνικής ευημερίας. Το θεωρητικό πλαίσιο αυτό εφαρμόστηκε εμπειρικά και έδωσε αποτελέσματα για πραγματικές οικονομίες. Θετικές μεταβολές στην κοινωνική ευημερία υπονοούσαν θετική γνήσια επένδυση και αειφορία με βάση το κριτήριο της παραγωγικής βάσης. Αρνητικές μεταβολές στην κοινωνική ευημερία υπονοούν αρνητική γνήσια επένδυση και έλλειψη αειφορίας με βάση το κριτήριο της παραγωγικής βάσης. Όταν οι κανόνες πολιτικής επιλέγονται αυθαίρετα, τότε και η γνήσια επένδυση θα πρέπει να προσαρμόζεται ανάλογα. Έτσι θεωρώντας μία οικονομία του "Solow" όπου η μεγέθυνση του εγχώριου πληθυσμού, η μετανάστευση, η τεχνολογική πρόοδος της εργασίας και οι περιβαλλοντικές ζημιές που σχετίζονται με αέριους ρύπους είναι παρούσες, καθορίζουμε τις συνθήκες τρέχουσας κοινωνικής ευημερίας, τις συναρτήσεις αξίας και τις λογιστικές τιμές. Η εφαρμογή του θεωρητικού μας μοντέλου στην περίπτωση της ελληνικής οικονομίας μας παρείχε αποτελέσματα που έδειξαν ότι η μετανάστευση, η εξωγενής τεχνολογική πρόοδος, η μεγέθυνση του κατά κεφαλή κεφαλαίου και οι ζημιές από τους ρύπους του διοξειδίου του θείου (SO_2 emission damages) είναι σημαντικοί παράγοντες που χαρακτηρίζουν τις συνθήκες τρέχουσας μεταβολής της κοινωνικής ευημερίας της ελληνικής οικονομίας. Τα βασικά μας συμπεράσματα είναι ότι η ελληνική οικονομία δείχνει να είναι αειφόρος με βάση το κριτήριο της παραγωγικής βάσης και με βάση τις τρέχουσες εκτιμήσεις των ζημιών από το διοξείδιο του θείου (SO_2 emission damages) που θεωρείται στην ανάλυσή μας ο μόνος αέριος ρυπαντής. Οι ζημίες από το διοξείδιο του θείου είχαν αρνητική επίδραση στις συνθήκες τρέχουσας κοινωνικής ευημερίας. Η προσέγγισή μας παρέχει τις εμπειρικές αποδείξεις αυτού του αρνητικού αποτελέσματος και μπορεί επίσης να χρησιμοποιηθεί για να προσδιορίσει ποσοτικά τις περιβαλλοντικές επιπτώσεις στην κοινωνική ευημερία.

Στο κεφάλαιο 4, εφαρμόσαμε εφαρμόστηκε το υπόδειγμα στην περίπτωση δύο μεγάλων γκρουπ χωρών αναπτυγμένων και αναπτυσσόμενων και προσδιορίσαμε τις συνθήκες αειφορίας της παραγωγικής βάσης, μετρώντας την μεταβολή στην τρέχουσα κοινωνική ευημερία. Παρατηρήσαμε ότι ένας από τους κύριους παράγοντες που επηρεάζουν τις συνθήκες τρέχουσας κοινωνικής ευημερίας, είναι οι εκπομπές του διοξειδίου του άνθρακα μαζί με άλλα αέρια του θερμοκηπίου όπως αποκαλούνται, που θεωρείται ότι συνεισφέρουν καίρια στην δημιουργία του φαινόμενου του θερμοκηπίου. Δημιουργήσαμε ένα μοντέλο ικανό να παρέχει εμπειρικά αποτελέσματα για το κριτήριο της αειφόρου παραγωγικής βάσης οικονομιών που επηρεάζονται αρνητικά από τις εκπομπές του διοξειδίου του άνθρακα και των λοιπών αερίων του θερμοκηπίου. Πήραμε αποτελέσματα για το κριτήριο της αειφόρου παραγωγικής βάσης σε ένα πλαίσιο μη βέλτιστης μεγέθυνσης για την περίπτωση 23 αναπτυγμένων και 21 αναπτυσσόμενων χωρών χρησιμοποιώντας τρία διαφορετικά σενάρια για την εξέλιξη – μεγέθυνση - των παγκόσμιων ρύπων του διοξειδίου του άνθρακα. Τα βασικά μας αποτελέσματα δείχνουν ότι όταν οι παγκόσμιοι ρύποι του διοξειδίου του άνθρακα αυξάνονται, το κριτήριο της αειφορίας της παραγωγικής βάσης είναι αρνητικό για όλες τις χώρες της ανάλυσής μας[12], ενώ όταν οι παγκόσμιοι ρύποι του διοξειδίου του άνθρακα παραμένουν σταθεροί (μηδενική αύξηση), το κριτήριο της αειφορίας της παραγωγικής βάσης είναι θετικό για όλες τις χώρες της ανάλυσής μας.

[12] Για την περίπτωση του Μεξικό (αναπτυγμένες χώρες) το κριτήριο της αειφορίας της παραγωγικής βάσης είναι θετικό αντίθετα με όλες τις άλλες χώρες που αναλύουμε όπου το πρόσημο του V είναι αρνητικό όταν οι παγκόσμιοι ρύποι του διοξειδίου του άνθρακα αυξάνονται.

Το δεύτερο μέρος της διατριβής, αναλύει και εμβαθύνει στην έννοια της μέτρησης της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής ή του λεγόμενου καταλοίπου. Βασικός μας στόχος, είναι να δημιουργήσουμε μία νέα προσέγγιση στην μέτρηση της συνολικής μεγέθυνσης της παραγωγικότητας των συντελεστών παραγωγής (TFPG measurement) που θα λαμβάνει υπόψη της την χρήση του παράγοντα περιβάλλον, με τη μορφή των εκπομπών του διοξειδίου του άνθρακα και της ενέργειας, στις μετρήσεις του καταλοίπου σε ένα γκρουπ αναπτυγμένων και αναπτυσσόμενων χωρών.

Με βάση αυτό το στόχο, ξεκινήσαμε την ανάλυση μας στο κεφάλαιο 6, προσεγγίζοντας την χρήση του περιβάλλοντος με τους ρύπους του διοξειδίου του άνθρακα σαν εισροή στην παραγωγική διαδικασία και ορίσαμε ένα θεωρητικό μοντέλο που περιλάμβανε ρύπους ως εισροή στην συνάρτησης παραγωγής. Μεταφράσαμε το μερίδιο των ρύπων στο συνολικό προϊόν σε ένα πλαίσιο ανταγωνιστικής ισορροπίας υπό έναν άριστο φόρο, αφού οι ρύποι είναι μία «απλήρωτη» εισροή στην παραγωγική διαδικασία, λόγω της έλλειψης φορολογίας στους ρύπους. Στην συνέχεια εφαρμόσαμε το θεωρητικό μοντέλο μας σε ένα γκρουπ 23 αναπτυγμένων (OECD) χωρών και πήραμε άμεσες προσαρμογές του καταλοίπου, όταν οι ζημιές από τις εκπομπές του διοξειδίου του άνθρακα λαμβάνονταν υπόψη στην συνολική συνάρτηση παραγωγής. Επίσης διασπάσαμε την τεχνολογική πρόοδο, που κατά τον Solow οδηγεί σε ανάπτυξη, σε τεχνολογική πρόοδο της εργασίας και στην εξοικονόμηση των ρύπων. Τα αποτελέσματά μας δείχνουν ότι όταν οι εκπομπές των ρύπων αυξάνονται, οι παραδοσιακές μετρήσεις του κατάλοιπου υπερεκτιμούν το κατάλοιπο σε σχέση με τα δικά μας αποτελέσματα, αποδίδοντας μέρος της συνεισφοράς του περιβάλλοντος στην τεχνολογική πρόοδο. Το αντίθετο συμβαίνει όταν οι εκπομπές των ρύπων μειώνονται, δηλαδή όταν υπάρχουν αποθέματα του ΠΣ περιβάλλον, τότε οι παραδοσιακές μετρήσεις του καταλοίπου υποτιμούν το κατάλοιπο σε σχέση με τα δικά μας αποτελέσματα. Το μέγεθος της απόκλισης, βασίζεται στο μέγεθος της εκτίμησης της ζημιάς των εκπομπών του διοξειδίου του άνθρακα. Με βάση τα παραπάνω η προσέγγιση μας μπορεί να θεωρηθεί σαν μία «περιβαλλοντική ή πράσινη» μεθοδολογία μέτρησης της μεγέθυνσης της συνολικής παραγωγικότητας των ΠΣ.

Οι οικονομετρικές εκτιμήσεις τις οποίες εφαρμόσαμε σαν μία περισσότερο αξιόπιστη μέθοδο μέτρησης του «πράσινου» καταλοίπου, μας δείχνουν ότι για την περίοδο 1965-1990 που αναλύουμε, ο μέσος όρος του εκτιμώμενου καταλοίπου βρισκόταν περίπου στο 1%, ή χαμηλότερα. Επίσης οι εκτιμήσεις μας έδειξαν ότι οι εκπομπές του διοξειδίου του άνθρακα είναι στατιστικά σημαντική εισροή στην συνάρτηση και ότι η τεχνολογική πρόοδος των ρύπων συνυπάρχει με την τεχνολογική πρόοδο της εργασίας. Αυτό υπονοεί ότι η χρήση του περιβάλλοντος που προσεγγίζεται από τις εκπομπές του διοξειδίου του άνθρακα που είναι «απλήρωτος» συντελεστής στην παραγωγική διαδικασία, συνεισφέρει στην μεγέθυνση του συνολικού προϊόντος μαζί με το παραγόμενο κεφάλαιο, το ανθρώπινο κεφάλαιο και την εργασία και η συνεισφορά του θα έπρεπε να υπολογίζεται στις μετρήσεις του κατάλοιπου. Στην περίπτωση που καθοριζόταν ένας «άριστος» φόρος επάνω στις εκπομπές, αυτό θα εσωτερίκευε τις εξωτερικότητες που δημιουργούνται από την χρήση του απλήρωτου περιβαλλοντικού ΠΣ και αυτός ο συντελεστής θα αποκτούσε τιμή. Παρόλα αυτά, υπάρχει πάντα ο κίνδυνος να υπερεκτιμηθεί ή να υποτιμηθεί η «κοινωνικά άριστη» χρήση του παράγοντα περιβάλλον. Τα αποτελέσματά μας έδειξαν ότι αν οι οριακές ζημιές ήταν σχετικά υψηλές, η κοινωνικά άριστη χρήση του περιβάλλοντος στην διαδικασία μεγέθυνσης, θα ήταν σχετικά μικρή, ενώ το αντίθετο θα ίσχυε για χαμηλές οριακές ζημιές.

Η συνεισφορά του περιβάλλοντος είναι μετρήσιμη και τα αποτελέσματα μας καταδεικνύουν ότι η συνεισφορά των εκπομπών του διοξειδίου του άνθρακα είναι στατιστικά σημαντική, με ένα μερίδιο του περιβάλλοντος στο συνολικό προϊόν της τάξεως του 14%. Αν από τη λύση του προβλήματος του κοινωνικού σχεδιαστή είχαμε μία εκτίμηση του λ, που είναι η λογιστική τιμή των εκπομπών του διοξειδίου του άνθρακα και υπολογίζαμε το μερίδιο των ρύπων, τότε το κατάλοιπο μπορεί να έδινε και αρνητικά αποτελέσματα. Αυτό μπορεί να εξηγηθεί ως εξής: η συνολική χρήση των εισροών στην παραγωγική διαδικασία συμπεριλαμβανομένης και της περιβαλλοντικής εισροής σωστά αποτιμημένης, υπερβαίνει την μεγέθυνση του συνολικού προϊόντος που δημιουργείται από αυτές τις εισροές. Σε αυτή την περίπτωση, η ανάπτυξη που χρησιμοποιεί απλήρωτους ΠΣ, δεν μπορεί να θεωρηθεί αειφόρος.

Το μοντέλο που εφαρμόσαμε για να μετρήσουμε το κατάλοιπο στην περίπτωση των 23 αναπτυγμένων χωρών του ΟΟΣΑ με την εισαγωγή του περιβάλλοντος, επεκτάθηκε και εφαρμόστηκε στην περίπτωση 21 αναπτυσσόμενων χωρών στο κεφάλαιο 7. Σκοπός μας και εδώ είναι να μετρήσουμε ξανά την συνεισφορά του περιβάλλοντος, που προσεγγίζεται πάλι από τις εκπομπές του διοξειδίου του άνθρακα, στο γκρουπ των αναπτυσσόμενων χωρών και να πάρουμε αποτελέσματα για το κατάλοιπο και την συνεισφορά του εξτρα αυτού παραγωγικού συντελεστή στην μεγέθυνση του συνολικού προϊόντος. Βασιστήκαμε στην ίδια μεθοδολογία με αυτή του κεφαλαίου 6 και τα αποτελέσματα των μετρήσεων του καταλοίπου για την περίοδο 1965-1990 είναι πάλι της τάξεως του 1%. Η συνεισφορά των εκπομπών του διοξειδίου του άνθρακα, απεδείχθει ξανά στατιστικά σημαντικός παράγοντας με ένα μερίδιο στο συνολικό προϊόν της οικονομίας της τάξης του 33%.

Τέλος στο κεφάλαιο 8, γίνεται μία τελευταία επέκταση του παραδοσιακού καταλοίπου χρησιμοποιώντας αυτή την φορά σαν προσέγγιση για την χρήση του περιβάλλοντος στην παραγωγική διαδικασία την χρήση της ενέργειας. Χρησιμοποιούμε μία συνολική συνάρτηση παραγωγής επαυξημένη με την εισροή ενέργεια, ορίζουμε τα μερίδια των εισροών που χρησιμοποιούνταν στην παραγωγή σε ένα πλαίσιο μίας ανταγωνιστικής ισορροπίας. Σε αυτό το πλαίσιο η ενέργεια είναι ένας εν μέρει αμειβόμενος ΠΣ. Αυτό συμβαίνει επειδή το μερίδιο της ενέργειας μπορεί να θεωρηθεί ότι περιλαμβάνει ένα μέρος που δημιουργεί εξωτερικότητα, (εκπομπές διοξειδίου το άνθρακα) και αυτό το μέρος παραμένει απλήρωτο στην διαδικασία παραγωγής. Άρα και η χρήση της ενέργειας είναι μία εν μέρει αμειβόμενη εισροή στην παραγωγή. Πιο συγκεκριμένα, παρόλο που η ενέργεια έχει τιμή σαν παραγωγικός συντελεστής στην παραγωγή, υπάρχει επίσης ένα μέρος της ενέργειας που είναι οι εκπομπές διοξειδίου το άνθρακα που δημιουργούνται από την παραγωγή, που παραμένουν απλήρωτες αφού δεν υπάρχει πολιτική φορολόγησης των ρύπων κυρίως για την χρονική περίοδο που αναλύουμε (1965-1990). Προσπαθήσαμε να λύσουμε αυτό το πρόβλημα προσαρμόζοντας τις παραδοσιακές μετρήσεις του καταλοίπου με τις οριακές περιβαλλοντικές ζημιές από τις εκπομπές του διοξειδίου του άνθρακα που σχετίζονται με τη χρήση της ενέργειας. Χρησιμοποιήσαμε μία συνάρτηση παραγωγής για να εκτιμήσουμε το μερίδιο των ΠΣ και εκτιμήσαμε το συνολικό κατάλοιπο (για ένα γκρουπ 23 αναπτυγμένων χωρών) απευθείας από την συνολική συνάρτηση παραγωγής. Επίσης υπολογίσαμε τα μεμονωμένα κατάλοιπα ανά χώρα χρησιμοποιώντας τα μερίδα που υπολογίστηκαν από την εκτίμηση της συνάρτησης παραγωγής συνδυασμένα με τους μέσους όρους των αξιών των παραγωγικών συντελεστών και του τελικού προϊόντος ανά χώρα. Με αυτό τον τρόπο υπολογίσαμε τις μετρήσεις του «προσαρμοσμένου» κατάλοιπου αφαιρώντας από την μεγέθυνση του συνολικού προϊόντος την αξία του απλήρωτου μέρους της ενέργειας που σχετίζεται με τις εκπομπές του διοξειδίου του άνθρακα που δεν έχουν υπολογιστεί στις παραδοσιακές μετρήσεις του καταλοίπου λόγω της έλλειψης περιβαλλοντικής πολιτικής (φορολογία).

Επίσης, χρησιμοποιήσαμε τρέχουσες ζημιές από τις εκπομπές διοξειδίου του άνθρακα, για να προσεγγίσουμε την αξία του απλήρωτου μέρους της ενέργειας. Τα αποτελέσματα μας καταδεικνύουν ότι οι μετρήσεις του παραδοσιακού καταλοίπου αλλάζουν σημαντικά σε σχέση με τα νέα αποτελέσματα. Το νέο «προσαρμοσμένο» κατάλοιπο, μπορεί να πάρει ακόμα και αρνητικές τιμές εξαρτώμενες από την αξία που αποδίδουμε στις οριακές ζημιές που δημιουργούνται από τους ρύπους του διοξειδίου του άνθρακα. Αν αυτή η αξία είναι κοντά στους 20$/tCO_2$, τότε το κατάλοιπο παίρνει αρνητικές τιμές. Αυτό σημαίνει ότι όταν κάθε εισροή που χρησιμοποιείται στην παραγωγή αμείβεται πλήρως για την συνεισφορά της στην μεγέθυνση του συνολικού προϊόντος, δεν υπάρχει «κατάλοιπο». Όταν η αξία της οριακής ζημιάς από τους ρύπους του διοξειδίου του άνθρακα είναι κοντά στα 5$/tCO_2$, τότε το κατάλοιπο είναι θετικό. Τα αποτελέσματα μας υποστηρίζουν την ιδέα ότι μέρος αυτού που θεωρείται σαν κατάλοιπο είναι στην πραγματικότητα το απλήρωτο μέρος της χρήσης του περιβάλλοντος στην παραγωγή και οι εμπειρικές μετρήσεις μας υποστηρίζουν ότι τουλάχιστον ένα μέρος αυτού που θεωρείται παραδοσιακά σαν κατάλοιπο, είναι η ανυπολόγιστη χρήση του περιβάλλοντος στην διαδικασία της μεγέθυνσης. Τέλος στο κεφάλαιο 9, παρουσιάζονται όλα τα συμπεράσματα της Διδακτορικής Διατριβής.

Σε αυτή τη διατριβή αναλύθηκαν και αναπτύχθηκαν κριτήρια αειφορίας στα οποία η αειφορία σχετίζεται με την διατήρηση της παραγωγικής βάσης μιας οικονομίας. Ροές και στοκ εκπομπών του διοξειδίου του άνθρακα και διοξειδίου του θείου χρησιμοποιήθηκαν σαν παράγοντες που καθορίζουν την μεγέθυνση και έχουν επίπτωση στις συνθήκες αειφορίας της παραγωγικής βάσης. Έγινε εφαρμογή των θεωρητικών κριτήριων σε ένα μεγάλο αριθμό οικονομιών και θεμελιώθηκε εμπειρικά ότι το φαινόμενο του θερμοκηπίου έχει σημαντική αρνητική επίπτωση στις συνθήκες διατήρησης της παραγωγικής βάσης μια οικονομίας. Στο δεύτερο μέρος αναπτύχθηκε το υπόδειγμα μέτρησης της παραγωγικότητας όταν το περιβάλλον είναι παραγωγικός συντελεστής. Δείχτηκε εμπειρικά ότι οι παραδοσιακές μετρήσεις του καταλοίπου είναι μεροληπτικές στην περίπτωση αυτή και ότι μέρος της μεγέθυνσης το οποίο αποδίδεται στην τεχνολογική εξέλιξη οφείλεται στην χρήση του περιβάλλοντος ως μη αμειβόμενου παραγωγικού συντελεστή.

Αυτά τα αποτελέσματα συνοψίζουν την συνεισφορά της παρούσας διατριβής. Συγκεκριμένα η συνεισφορά της διατριβής έγκειται στα παρακάτω: (i) στην ανάπτυξη ενός καλώς ορισμένου θεωρητικού πλαισίου κριτηρίων αειφοριάς σε όρους διατήρησης της παραγωγικής βάσης μιας οικονομίας, τα οποία επιτρέπουν την εξαγωγή εμπειρικών συμπερασμάτων σχετικά με συνθήκες αειφορίας, (ii) στην εφαρμογή των κριτηρίων αυτών σε μεγάλες ομάδες οικονομιών και στην εξαγωγή εμπειρικών ενδείξεων σχετικά με την αειφοριά των οικονομιών αυτών κάτω από συνθήκες κλιματικής αλλαγής προκαλούμενης από το φαινόμενου του θερμοκηπίου, (iii) στην δημιουργία ενός εννοιολογικού πλαισίου διαμόρφωσης πολιτικών που θα προωθούν την αειφόρο ανάπτυξη, (iv) στη ανάπτυξη μεθοδολογίας προσδιορισμού της συνεισφοράς του περιβάλλοντος ως συντελεστή παραγωγής στην διαδικασία της οικονομικής μεγέθυνσης και στην μέτρηση της συνεισφοράς αυτής για μεγάλες ομάδες αναπτυγμένων και αναπτυσσομένων οικονομιών.

Ph. D Thesis

Title:

"Sustainability and Total factor Productivity Growth under Environmental Externalities: Theoretical issues and Empirical Evidence"

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1 Introduction

The present dissertation deals with sustainable development and seeks to arrive at a definition which can be effectively used as an indicator of sustainability. We want this definition to be theoretically sound, and at the same time useful for empirical assessment of sustainability conditions.

In this context, the first part of the thesis addresses theoretical and applied issues related to the concept of productive base sustainability. Feedback and arbitrary rules are used for selecting policy variables in non-optimizing economies, accounting prices are determined, changes in current social welfare conditions are theoretically defined and measured and the concept of productive base sustainability is defined and empirically estimated for a number of real economies. The state of the environment with particular reference to global warming and climate change, which is considered as one of the most urgent and severe problems of the international agenda today, is introduced in our model as a basic determinant of productive base sustainability along with produced and human capital. The state of the environment is proxied by the stock of Carbon Dioxide (CO_2) emissions, which is mostly responsible for the creation of the global warming phenomenon. Different policy scenaria for the evolution of global CO_2 emissions confirm empirically the strong association of the state of the environment with productive base sustainability and provide the foundations for the formulation of sustainability policy. Productive base sustainability, as defined and estimated in the first part of the thesis, depends among other factors, on Total Factor Productivity Growth (TFPG). If however, TFPG measurements do not take into account the contribution of environment to output growth and this contribution is wrongly attributed to TFPG, then productive base sustainability measurements might be biased.

This issue is addressed in the second part of the thesis, which explicitly acknowledges that the use of the environment as a factor of production contributes, in addition to conventional factors of production, to output growth and thus it should be accounted for in total factor productivity growth (TFPG) measurement and deducted from the traditional Solow 'residual'. The traditional growth accounting methodology is extended and a theoretical framework of green growth accounting is developed with the introduction of the environment as a new factor of production, which is unpaid or partly paid in the absence of environmental policy. The concept of "Green Growth Accounting", is empirically applied to the case of 23 developed OECD countries and 21 developing countries. The results strongly suggest that the use of the environment, in the form of CO_2 emissions as an input in production, contributes in addition to conventional factors of production, to output growth and should be accounted for in TFPG measurements. Approaching the use of the environment with the use of energy as an input in the production process is another way of approaching the green or externality adjusted TFPG. Traditional TFPG measurements change drastically for 23 OECD countries when the unpaid part of energy, which is associated with environmental externalities in the form of CO_2 emission's becomes internalized by taking into account in TFPG measurements, the environmental cost of CO_2 emissions, in which case externalities associated with production are "fully" paid and thus internalized. This externality adjusted TFPG is practically zero, meaning that hardly any TFP is left as a residual to drive output growth.

1.1 Review of the Literature

In order to provide an outline of the framework within this thesis is developed, we start with a brief review of the literature associated with Sustainability and Total Factor Productivity Growth measurements.

1.1.1 The Concept of Sustainability

"Sustainable development is development which meets the needs of the present without compromising the ability of future generations to meet their own needs"[1]. Based on this definition which constitutes the cornerstone of the concept of sustainable development, the current dissertation is an attempt to analyze sustainability. We develop a definition which is theoretically well founded and can provide empirical evidence regarding the sustainability conditions of an economy. The attempt to make the above definition of sustainability an operational and empirically tractable definition is not an easy task. Such an ethical concept which involves the idea of taking into account the well being of future generations without reducing the well being of current generations, is a concept that demands a great deal of effort to be transformed into something properly defined and measurable. This is because the idea of sustainable development is complex and encompasses different fields

[1] The Brundtland Commission Report - also known as "Our Common Future", (WCED 1987, pg 43).

and aspects: social, ecological and economical. Social, environmental and economic sustainability cannot be separated and distinguished completely. There are very strong linkages between the three and each definition cannot be completely separated from the other.

Social sustainability implies the maintenance of social capital[2]. A notion of economic sustainability requires that the economic capital should be maintained. Environmental sustainability means that natural capital should be maintained and preserved[3]. These three different concepts of sustainability are interlinked and constitute the foundation of sustainable development, *development that meets the needs of the present and by also taking into account future generation's needs*. The idea of preserving the well-being of current and future generations is the ultimate goal for a sustainable future. In order for this idea to be applicable in practice, several kinds of capital (human made capital, human capital, social capital and natural resources) have to be preserved and shared with future generations since they are seen as a common heritage of mankind to which every generation should have the same right of access. A definition, able to include all these aspects and express them in economic terms, can be considered as an efficient definition for measuring whether development is sustainable. Some of the basic questions that arise is whether the quest for an equal treatment of an infinite number of generations is an attainable and possible goal and how this concept can be expressed in economic terms.

Sustainability has also appeared in the literature in four "degrees". The weak, the intermediate, the strong and the absurdly strong or superstrong sustainability. Each one of these degrees imply the maintenance of four types of capital[4].

[2]Social sustainability can be achieved by systematic community participation and strong civil society. Social capital is constituted by cohesion of community, cultural identity, diversity, comity, tolerance, institutions, pluralism, laws, discipline, etc. Goodland R., (1995).

[3]Environmental sustainability (ES) seeks to improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded in order to prevent harm to humans. Natural capital (the natural environment), is defined as the stock of environmentally provided assets which provide a flow of useful goods or services. These can be renewable or non-renewable, marketed or non-marketed. ES means sustainable production and sustainable consumption. Goodland R., (1995).

[4]The four types of capital are natural capital, human capital, human made or produced capital and social capital.

Weak environmental sustainability means maintaining the value of total capital intact without regard to the partitioning of that capital among the four kinds. Intermediate environmental sustainability requires that in addition to maintain the total value of capital intact, attention should be given to the composition of that capital with regards to natural, manufactured and human capital. Strong environmental sustainability requires maintaining several kinds of capital and absurdly strong or supestrong environmental sustainability means that we should never deplete anything. In other words, non-renewable resources cannot be used at all[5].

1.1.2 Historical Retrospection and Definitions of Sustainability

Going back to the concept sustainable development, we provide a brief historical retrospection and observe that the idea of sustainable development has its origins in the classical economists.

Well before "Our Common Future" (WCED, 1987) made the concept of sustainability a very popular term, the idea of sustainable development was already present in the discussion about scarcity and growth. Malthus, Ricardo, Mill, Hicks, Pigou and many others had predicted that scarcity of natural resources would lead to retardation and eventually cessation of economic growth[6]. Hicks defines income as the maximum amount that can be spend on consumption in one period without reducing real consumption opportunities in future[7]. At the national level, national income can be defined as consumption that if kept constant would yield the same present value as the actual future consumption path[8]. Thus in Hicksian terms, "Our Common Future" may be saying that the present should consume within our income. If we further want to extend this, we can say that in this case income should be constituted by all types of capital and not just manufactured capital and labor but also human capital, knowledge, environmental capital, social capital, etc. This view can be also linked to the issue of growth accounting where we want to measure the contribution of each type of capital in total output growth[9].

Solow and Hartwick have argued that the idea of sustainability can be

[5] Goodland R., (1995).
[6] Barnett and Morse, (1963, p. 2), in Pezzey, J., C.V, and Toman A., Michael (2004).
[7] Hicks J., (1946).
[8] Asheim G., (1997).
[9] Heal, G. M. (1998).

expressed by the *minmax* criterion. Maximizing the welfare of the least well-off generations, can be expressed as follows:

$$\{\max\{\min\{\text{welfare}_t\}\}\}$$

where welfare_t is the welfare level of generation t. The requirements are to find the welfare level of the least well-off generation on a feasible path and then to seek the feasible path that can provide the highest value of this minimum level[10].

Post-classical economists analyzed the natural environment and optimal policy in the context of externalities caused by pollution and emphasized the need of environmental consciousness.

Weitzman in 1976, was the first to put the foundations of a green NNP (Net National Product) concept. He proved that the conventional measure of income product is precisely the level of consumption that if obtained permanently would have a present value equal to the economy's wealth. A clear notion of sustainability. Then, NNP is the Hamiltonian for a general optimization problem. If all investment were convertible into consumption at the given price transformation rates the maximum attainable level of consumption that could be maintained forever without running down capital stocks would appear to be NNP. The maximum welfare attainable from time t on, along a competitive trajectory would be:

$$\int_t^{\infty} C^*(s)e^{-r(s-t)}ds \tag{1}$$

In this sense NNP is what might be called the stationary equivalent of future consumption[11].

Many international agencies such as the United Nations Environment Program (UNEP), the International Union for Conservation of Nature and Natural Resources (IUCN), have dealt with the subject of sustainable development. The World Conservation Strategy published in 1980 (IUCN 1980), the World Commission on Environment and Development, the so called Brundtland Report in 1987 and many others have backed and further developed the idea of environmental concern and environmental limits. The fundamental point in Stockholm in 1972, was that development need not be

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[10] Heal, G. M. (1998).

[11] Weitzman , M., L., (1976).

impaired by environmental protection. Thus, the conflicts between environment and development should be resolved. Furthermore, development was needed in order to improve the environment. The Brundtland Report (1987), therefore starts from the premise that "development and environmental issues cannot be separated. The creation of degraded environments cannot be seen as simply an unfortunate by-product of the development process. It is an inherent part of that process itself and the way in which development projects are planned and executed"[12].

In 1988, Markandya and Pearce argued that the basic idea of sustainable development is simple in the context of natural resources (excluding exhaustible resources) and environment: the use made of these inputs to the development process should be sustainable through time. If we now apply the idea to resources, sustainability ought to mean that a given stock of resources - trees, soil quality, water and so on - should not decline. John Pezzey in 1989, defines sustainable development as the non-declining utility (U). Maler in 1991 states that "economic development is sustainable if and only if utility is non-decreasing over time". Also, Solow states that: "the duty imposed by sustainability is to bequeath to posterity not any particular thing but rather to endow them with whatever it takes to achieve a standard of living at least as good as our own". (Achievement of constant utility). The World Bank in 1992, argues that sustainable development means basing developmental and environmental policies on a comparison of costs and benefits and on careful economic analysis that will strengthen environmental protection and lead to rising and sustainable levels of welfare[13], etc.

During the Conference on Environment and Development which was held in 1992 by the United Nations (UNCED), the discussion was how individual countries and the whole world can achieve environmentally sound development. The *Rio Declaration on Environment and Development*, which was composed during this conference argued the following: "human beings are at the center of current concerns for sustainable development", "the right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations", and "in order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it". The World Bank and the World Development Report in 1992,

[12] W.M.Adams, (1990).

[13] World Development Report, (1992).

explains the notion of sustainability as follows: "Sustainable development means basing developmental and environmental policies on a comparison of costs and benefits and on careful economic analysis that will strengthen environmental protection and lead to rising and sustainable levels of welfare".

Pemberon and Ulph (2001), stated that an economy was acting in a sustainable fashion at a particular moment of time, if the value obtained from the vector of capital stocks it was passing on to the future, was the same as the value obtained from the vector of capital stocks it inherited. Alternatively, an economy was instantaneous value sustainable[14] if the instantaneous rate of change of its value at a particular moment of time, was zero. Pemberon and Ulph concluded by stating that inclusive income[15] equals instantaneous constant value income although inclusive income does not measure the level of welfare or value. Inclusive income is useful in determining whether or not the economy is achieving instantaneous value sustainability. The difference between inclusive income and consumption determines the rate of change of value.[16] There is also the idea of achieving constant utility from now onwards[17] and the idea of having the representative agent's utility $U(t)$ (well being) not exceeding a maximum level of utility $U^m(t)$, (where U^m is maximum utility) which can be sustained forever from t given the capital stocks existing at t[18].

In the context of the alternative approaches which have been developed for defining sustainable development, the idea of associating sustainability of the economy's productive base to Non-Declining Social Welfare (NDSW), that is avoiding any decline in the present value from time t and onwards defined in terms of a Ramsey-Koopmans Social Welfare Functional (R-K SWF)[19], is fundamental for this thesis.

According to Arrow et al. (2003), sustainable development, defined as non-declining social welfare (NDSW), implies and is implied by the mainte-

[14] Instantaneous value sustainability requires that the present value of future utility is constant at an instant of time. see. Pemberon M., & Ulph D., (2001).

[15] Inclusive income is green national income which is equal to the maximum value of consumption plus the net change in all the relevant stocks of capital that is feasible given the stocks of capital. see. Pemberon M., & Ulph D., (2001).

[16] Instantaneous value sustainability requires that the present value of all future utility be constant at an instant of time.

[17] Solow (1974), Hartwick (1977).

[18] Pearce et al., (1990), Pezzey, (1992, 1997).

[19] Riley (1980), Dasgupta and Mäler (2001), Pemberton and Ulph (2001), Arrow et al., (2003).

nance of the economy's productive-base[20]. The idea is that each generation should bequeath to each successor at least as large a productive base as it inherited from its predecessors. For this to be achieved, the productive base of the economy should be preserved for the future generations. This maintenance and preservation of specific types of capital can ensure according to Arrow et all. (2003) a sustainable future. In the same spirit Dasgupta (2002) argues that the value of an economy's capital assets is total inclusive wealth which includes manufactured capital, human capital and natural capital. To say that wealth increases is to say that in the aggregate there has been a net accumulation of capital assets. The net accumulation of capital assets is called genuine investment which can be either positive or negative. Positive genuine investment means that development can be considered as sustainable or productive base sustainable in our terminology while negative genuine investment implies unsustainability in terms of preserving the economy's productive base. If the productive base of an economy is growing, then according to Arrow et all, development can be characterized sustainable. In other words, if:

$$\dot{V}_t = \frac{dV_t}{dt} \geq 0 \tag{2}$$

where $\dot{V}_t$ at time t is the rate of change of a Ramsey-Koopsman Social Welfare Function (R-K SWF), this implies non declining social welfare of an economy. Then development can be characterized as productive base sustainable according to the definition of inclusive wealth. Dasgupta and Mäler have shown that when $\dot{V}$ is estimated on the bases of accounting prices[21], wealth measures not only current but also future well-being. Accounting prices reflect trade-offs among present and future well beings and among contemporaries too[22].

This variety of definitions and approaches, illustrates the increased interest associated with the subject of sustainable development, and also suggest the urgent need for the development and use of a well defined and measur-

[20] The productive base of an economy includes a list a assets such as manifuctured capital, human capital, natural capital and knowledge.

[21] "The accounting price of an asset, is the improvement in the quality of life (social welfare) that would be brought about if a unit more of that asset were made available costlessly. Alternatively, the deterioration in the quality of life that would occur if there were a unit less of that asset." Dasgupta P., & Mäler K., (2001).

[22] Dasgupta P., & Mäler K., (2001).

able definition able to provide empirical results of the so-called sustainable development process.

The global warming phenomenon and the associated climate change keep attracting increasing interest at the national and international level. This makes the need for a theoretically well defined and empirically tractable definition of sustainable development even more urgent. Reports such as the IPCC report[23], the Stern Report etc stresses the point that a sustainable future will be an unattainable goal for the years to come, if we will not change the way we handle the global warming phenomenon today. This phenomenon, which is closely interlinked with environmental sustainability, if not controlled by governments can cause irreversible damage to future generations.

An approach capable of defining and measuring the impact of environmental degradation associated with human actions, such as climate change, on sustainability is what we call in this dissertation a *productive base approach* to sustainable development. It is based on the time derivative of the Ramsey-Koopman Social Welfare Function (R-K SWF) introduced in (2). If the R-K SWF at time t is positive, this implies that genuine investment is also positive and total wealth increases. If on the other hand the R-K SWF at time t is negative, genuine investment is also negative and total wealth is in decline. Thus, policies that lead to persistently negative genuine savings or investment are considered unsustainable.

1.1.3 Total Factor Productivity Growth and Sustainability

An important issue that comes up during the analysis of productive base sustainability, is how we measure the contribution of each factor of production in output growth. The methodology we use is the growth accounting methodology that measures the contribution of each factor of production in total output growth. The factors of production are paid their marginal product in the production process in the context of a competitive equilibrium and the part of growth that remains and is not attributed to the use of those factors, is named after Solow[24] as the Solow "residual". The residual is the part of growth that cannot be explained through factor accumulation and appears as technological progress.

[23] IPCC Special Report on Emissions Scenarios

[24] Solow (1956).

The theory of growth accounting was first developed by Solow (1957), Kendrick (1961), Denison (1962), Jorgenson and Griliches (1967) and Griliches (1997) which provided the foundation of the theory of growth accounting and the determinants of the residual.[25]

Starting with Solow model, the basic production function used in growth accounting methodology is the following:

$$Y = F(K, A, L) \tag{3}$$

where K is the capital stock, A is the level of technology and L is the quantity of labor. The growth rate of output can be divided according (3) into components associated with the accumulation of the inputs (K, L) and technological progress (A). Then if the factors are paid their marginal products, so that $\frac{\partial F}{\partial K} = R_K$ (the rental price of capital) and $\frac{\partial F}{\partial L} = w$ (the wage rate), the Solow residual can be defined as:

$$g_S = s_L\left(\frac{\dot{A}}{A}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_L\left(\frac{\dot{L}}{L}\right) \tag{4}$$

where g_S is the Solow residual or the Total Factor Productivity Growth (TFPG). s_L and s_K are the shares associated with capital and labor and $\frac{\dot{K}}{K}$, $\frac{\dot{L}}{L}$, $\frac{\dot{A}}{A}$ are the rates of growth of capital, labor and technological progress respectively[26].

Apart from the traditional way Solow introduced for measuring TFPG from factor quantities, there is another way to measure the residual from factor prices. This methodology, introduced by Hsieh (1998), is called "a dual approach to growth accounting" and this idea goes back at least to Jorgenson and Griliches (1967)[27].

Using an equality between output and factor incomes we have:

$$Y = RK + wL \tag{5}$$

Differentiating both sides of (5) with respect to time, dividing by Y and rearranging the terms, we have:

$$\frac{\dot{Y}}{Y} = s_K\left(\frac{\dot{R}}{R} + \frac{\dot{K}}{K}\right) + s_L\left(\frac{\dot{w}}{w} + \frac{\dot{L}}{L}\right) \tag{6}$$

[25] Barro, (1999).
[26] Barro, (1999).
[27] Barro, (1999).

where s_K and s_L are again the factor income shares. If the terms involving the growth rates of factor quantities are placed on the left-hand side of the equation, then the estimated TFP growth rate is given by:

$$g = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_L\left(\frac{\dot{L}}{L}\right) = s_K\frac{\dot{R}}{R} + s_L\frac{\dot{w}}{w} \tag{7}$$

The dual estimate of TFPG (7) uses the same factor-income shares s_K and s_L as the primal estimate (4) but considers changes in factor prices, rather than quantities. In (7) rising factor prices can be sustained only if output is increasing for given inputs. Therefore, the appropriately weighted average of the growth of the factor prices measures the extent of TFP growth[28].

Apart from these two basic methodologies of approaching and measuring TFPG, there are also other models that tried to deal with the subject of TFPG. Griliches (1979), Romer (1986), and Lucas (1988), have constructed models of economic growth with increasing returns and spillovers.

Romer presents the learning-by-doing model. The basic idea is that producers learn by investing to produce more efficiently and the knowledge spills over immediately from one firm to others so that each firm's productivity depends on the aggregate of learning, which is reflected in the overall capital stock. In this case, the calculation of TFPG includes the growth effect from spillovers and increasing returns along with the rate of exogenous technological progress in the Solow residual and is reflected in the equation that follows:

$$g_{IRS} = \frac{\dot{A}}{A} + \beta\left(\frac{\dot{K}}{K}\right) = \frac{\dot{Y}}{Y} - \alpha\left(\frac{\dot{K}}{K}\right) - (1-\alpha)\left(\frac{\dot{L}}{L}\right) \tag{8}$$

During the last decades alternative approaches have been used to measure TFPG, which include approaches which basically involve disaggregations and refinement of inputs in the production function.[29] Product varieties models were presented by Romer (1990) and Grossman and Helpman (1991, ch. 3) and Spence (1976), Dixit and Stiglitz (1977) and quality-ladders models of technological change are present in the recent endogenous-growth literature from Aghion and Howitt (1992) and Grossman and Helpman (1991, ch. 4).

[28] Barro, (1999).

[29] See for example, Barro (1999), Barro and Sala-i-Martin (2005).

Based on all the above, we choose to develop a *green* TFPG methodology based on Solow's tradition, which can show the contribution of the environmental factor - natural capital - to output growth and this way reveal the link between sustainable development and TFPG.

To do this, we introduce natural capital in the production process and argue that this environmental capital proxied in the form of CO_2 emissions or energy (considered as inputs in production) can be sources of growth. We observe that this extra environmental inputs contribute in total output growth along with the traditional factors of production, capital and labor. We analyze the contribution of those environmental factors that are unpaid or partially paid in the production process and the results we obtain provide us potentially significant policy implications.

Productive base sustainability can be associated with non-declining social welfare at time t. One of the basic requirement for this, is the maintenance of all types of capital for future generations (preservation of the productive base of the economy). The concept of sustainable development can be further elaborated by using the growth accounting framework that measures the contribution of each type of capital used in the production of total output growth and show that the so called Solow residual or the labor augmenting technological progress is not the only determinant of growth but the environment also plays a crucial role towards this direction.

1.2 Contribution to the Literature and Main Results

After the presentation of the many different approaches and definitions used to capture the concept of sustainability, we use this section to describe the methodological approach we develop in this dissertation and the novel theoretical and empirical results that we believe that contribute to the current literature of sustainable development and TFPG measurements.

Our basic attempt in the first part of the thesis is to develop a theoretical model which could determine whether development can be characterized sustainable, a model that could fit current economic structures and could be used and applied to real economies. Beginning with the environmental concerns and the catastrophic depletion of the natural environment, the most commonly definition which addresses these problem is the definition of sustainable development which focuses on the ideas of intertemporal distribution and intergenerational equity.

According to Arrow et al. (2003), sustainable development is defined as Non-Declining Social Welfare (NDSW), which is expressed as the maintenance of the economy's productive-base. The idea is that the productive base of the economy, that includes a list of assets such as manufactured capital, human capital, natural capital and knowledge, should be preserved for future generations (Arrow et al., 2003). Thus, if genuine investment, defined as the sum of the investment in the above forms of capital, valued at accounting prices, is non-decreasing over time, then social welfare is also non-declining. In this case the time derivative of the Ramsey-Koopmans Social Welfare Function (R-K SWF) at time t is non negative and development can be regarded as "productive-base sustainable". This concept of NDSW or positive genuine investment at time t, does not imply 'utility-sustainability' - that is, utility at a level that can be sustained forever after t[30].

Following the definition of Arrow et al., (2003) we develop a theoretical model based on the time-derivative of a (R-K SWF) at a given time t, which provides a measure of the rate of change of the economy's current social welfare, or a measure of genuine investment at this time. Social welfare at any given time t is defined by the felicity functional:

$$V_t = \int_t^{\infty} e^{-\rho(\tau - t)} U\left(\mathbf{x}\left(\tau\right), \mathbf{u}\left(\tau\right)\right) d\tau \ , \tau \geq t \tag{9}$$

where $\mathbf{x} = (x_1, ..., x_n)$ is a vector of state variables (stocks of assets) and $\mathbf{u} = (u_1, ..., u_m)$ is a vector of control variables (policy instruments). The function $U\left(\mathbf{x}\left(\tau\right), \mathbf{u}\left(\tau\right)\right)$ can be interpreted as the welfare of the generation living at time τ. Using a non-optimizing theoretical framework[31], we characterize the current Change in Social Welfare (CSW) conditions at time t - when controls are chosen according to some feedback rule[32] or according to some arbitrary rule. We also derive the novel result that when controls (or

[30] Pezzey (2004b), introduced the definition of sustainability in utility terms by stating that if the utility of the representative agent at time t is at a level that can be sustained forever after t, this can been considered as a natural meaning of the economy been sustainable at time t. As shown by Asheim (1994) and Pezzey (2004b), there are optimizing economies where NDSW at time t could imply that utility is unsustainable for a finite time period.

[31] A non-optimizing economy is an economy in which the government, whether by design or incompetence, does not choose policies that maximize intergenerational welfare. The term sustainability acquires particular significance when it is put to work in imperfect economies, that is economies suffering from weak or even bad governance.

[32] A feedback rule in this context is, for example, a behavioral rule according to which instruments are determined in some relation to the values of the state variables.

policy instruments) are chosen in an arbitrary way, which is independent of the stock of assets,[33] the current CSW depends not only on the growth of the assets and their corresponding accounting prices, but also on the arbitrary paths of the controls. In this case the value function for the economy depends both on current stocks and current flows and can be written under a feedback or under an arbitrary -open loop- rule respectively, as:

$$V_t(\mathbf{x}_t;\mathbf{b}) = \int_t^{\infty} e^{-\rho(\tau-t)} U\left(\mathbf{g}\left(\boldsymbol{\phi}\left(\tau-t,\mathbf{x}_t,\mathbf{b}\right)\right),\boldsymbol{\phi}\left(\tau-t,\mathbf{x}_t,\mathbf{b}\right)\right) d\tau \quad (10)$$

$$V_t(\mathbf{x}_t,\bar{\mathbf{u}}_t;\mathbf{b}) = \int_t^{\infty} e^{-\rho(\tau-t)} U\left(\boldsymbol{\psi}\left(\tau-t,\mathbf{x}_t,\bar{\mathbf{u}}_0(\tau),\mathbf{b}\right),\bar{\mathbf{u}}_0(\tau)\right) d\tau \quad (11)$$

The accounting prices for asset x_i or control (instrument) $\bar{u}_j$ at time t, are defined respectively as:

$$p_{tx_i} = \frac{\partial V_t}{\partial x_{it}},\ p_{tu_j} = \frac{\partial V_t}{\partial \bar{u}_{jt}} \quad (12)$$

$\dot{V}_t \equiv \frac{dV_t}{dt}$ denotes the rate of change of the R-K SWF or the CSW at time t. When $\dot{V}_t \geq 0$, this implies non negative genuine investment and can be regarded, in the context of Arrow et al. (2003), as an indicator of current productive base sustainability or current non declining social welfare. When $\dot{V}_t < 0$, or CSW is negative, this implies negative genuine investment and thus unsustainability in productive base terms. This approach of measuring the current CSW could be useful in providing an indication of sustainability in terms of genuine investment in a non-optimizing context and maintenance of the economy's productive base and not in utility terms. Negative genuine investment implies that we leave less productive capacity to future generations to satisfy their needs. More specifically, if an economy is not currently productive base sustainable, then the time derivative of the R-K SWF at time t is negative and genuine investment is also negative. This means that total wealth is in decline and policies that lead to persistently negative genuine savings are unsustainable[34]. This methodological approach can be regarded as a productive base approach to sustainable development.

[33] This implies a non-feedback (arbitrary) way of choosing the controls.

[34] The World Bank (2006, Ch. 3). Asheim (1994), Hamilton and Clemens (1999), Pezzey (2004b), show that negative genuine savings at t, that is declining social welfare, implies unsustainability in individual utility terms in optimizing economy. This result however has not been shown to hold in a more general non-optimizing context.

The value function (10) or (11) at any given point t in time is taken to represent social welfare from time t onwards and this makes it possible to characterize current CSW conditions in a general context and to provide a basis for empirical estimation of these changes. The rate of change of the R-K SWF is not just the sum of genuine investments in specific assets, but it may also include the rate of change of policy instruments valued at their accounting prices. Thus, in certain cases of non-optimizing economies with arbitrarily choices of controls, genuine investment in assets might not be entirely appropriate as has been regarded in the relevant literature, for characterizing sustainability conditions. In these cases genuine investment should be adjusted for the growth of the arbitrary chosen policy variables, such as for example emission limits. Our theoretical model contributes to the current literature both at the theoretical level as pointed out above and the empirical level since the value function can be used to provide empirical evidence about sustainability conditions. Our model was applied to data from the Greek economy and estimates of the current CSW conditions in Greece were obtained.

After having defined the criterion of productive base sustainability and having obtained empirical results for the Greek economy, we extend our model to a group of countries, developed and developing by considering the issue of productive base sustainability in a context of one of the most urgent and severe problems that exist in the international agenda today, the global warming phenomenon. The global warming phenomenon is one of the basic factors able to affect a sustainable future. Carbon dioxide (CO_2) emissions along with other GHG's emissions are some of the basic anthropogenic drivers of the global warming phenomenon that can damage the well being of future generations and thus sustainability. Our main purpose is to relate global carbon dioxide (CO_2) emissions (that is mostly responsible for the global warming phenomenon and climate change) to the concept of productive base sustainability and empirically approximate the impact of environmental degradation on current Social Welfare (SW) conditions. We develop the conceptual framework and provide empirical results by establishing a link between current CSW and global warming.

We formulate our model using the time derivative of a social welfare function $\dot{V}_t$ and develop a criterion that measures sustainability in productive base terms under global warming.

We have the following definition:

$$\dot{V}_t = p_{K_t}\dot{K} + p_{N_t}\dot{N} + p_{A_t}\dot{A} + p_{\bar{Z}_t}\dot{\bar{Z}}_\tau + p_{P_t}\dot{P}_\tau \gtreqless 0 \tag{13}$$

where V is a R-K SWF and p_{K_t}, p_{N_t}, p_{A_t}, $p_{\bar{Z}_t}$, p_{P_t} are the accounting prices for capital, population, technology, the emission limit and the emission's stock respectively. $\dot{K}$, $\dot{N}$, $\dot{A}$, $\dot{\bar{Z}}_\tau$, $\dot{P}_\tau$ are the rates of change of capital, population, technological change, emission limit and the emission's stock. From (13) we observe that, if the time derivative of a R-K SWF at time t is positive, then an economy can be considered as currently productive base sustainable and genuine investment is also positive. If the time derivative of R-K SWF at time t is negative, then an economy cannot be considered as currently productive base sustainable and genuine investment is negative.

We then apply our theoretical model in 23 developed[35] and 21 developing countries[36] and estimate the current CSW conditions. Our results show that CO_2 damages are an important parameter in defining current CSW that plays an important role in current and future well being and productive base sustainability. This conclusion is further confirmed in the second part of the thesis where we analyze the topic that has drawn much attention in the literature of growth accounting, Total factor Productivity Growth (TFPG).

As pointed above, Growth Accounting is the empirical methodology that allows for the breakdown of output growth into its components and measures the contribution of each component in output growth. Thus, the concept of total factor productivity growth (TFPG) measures the part of output growth which is attributed to technological progress (according to Solow). We choose to extend the traditional Solow model by using the environment as an extra source of growth in an aggregate production function and prove that traditional TFPG estimates, which are estimates of TFPG when environment is not taken into account as an input in production, can provide misleading and insufficient results.

[35]The 23 countries used in our analysis are the following: Canada, U.S.A, Austria, Belgium, Denmark, Finland, France, Greece, Italy, Portugal, Spain, Sweden, Switzerland, U.K., Japan, Iceland, Ireland, Netherlands, Norway, Australia, Mexico, Turkey, Luxembourg.

[36]The 21 Developing countries used in our analysis are the following: Peru, Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Jamaica, Bolivia, Colombia, Ecuador, Iran, Srilanka, Syria, Yugoslavia, India, Kenya, Madagascar, Malawi, Sierra Leone, Zimbabwe.

Thus, based on an aggregate production function:

$$Y = F(K, H, E, X) \tag{14}$$

where K is physical capital, H is human capital, $E = AL$ is effective labour, with L being labour input and A reflecting labour augmenting (Harrod neutral) technical change and $X = BZ$ being the effective input of emissions, with B reflecting emissions augmenting technical change and Z being the input of CO_2 emissions, we introduce the use of the environment as an additional driver of economic growth. This provides a new dimension to the traditional theory of TFPG measurement.

We next define the factor shares in total output under profit maximization and the "residual" γ augmented to account for the use of the environment in the growth process is defined as follows:

$$\gamma = s_L\left(\frac{\dot{A}}{A}\right) + s_Z\left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_H\left(\frac{\dot{H}}{H}\right) - s_L\left(\frac{\dot{L}}{L}\right) - s_Z\left(\frac{\dot{Z}}{Z}\right) \tag{15}$$

Comparing the traditional Solow residual (4) with the augmented residual (15) we observe that there are two extra inputs in production - human capital and the environment, proxied by CO_2 emissions - which are not accounted in the traditional measurements. The introduction of the environment can change the way we analyze TFPG and can be identified as a significant determinant of total output growth. Since external emissions costs which are created during the production process are not taken into account in the measurement of total factor productivity growth, current measurements of TFP growth, or the Solow "residual", could provide biased results. Nevertheless, the contribution of the environmental factor in output growth cannot be properly measured due to the lack of environmental policy on emissions. Thus, output growth which should be attributed to the use of the environment is incorrectly attributed to TFPG or the residual. Furthermore, we show that if emissions saving technical change is present, this could be another source of growth in addition to the conventional labor augmented technical change.

After the development of this theoretical framework, we test our hypothesis empirically using data from a panel of 23 OECD countries[37]. Our results

[37] The 23 countries used in our analysis are the following: Canada, U.S.A, Austria, Bel-

suggest that the "unpaid"- due to absence of taxation - environmental factor, proxied by CO_2 emissions could be a source of growth, and an important component in the growth accounting methodology, supporting the case of a "Green Growth Accounting" approach. If the use of the environment is a source of growth, as our results seem to suggest, but environment is used as an unpaid factor, environmental damages remain 'unpaid'. By being 'unpaid' or not 'fully paid' however, they are not kept at a 'socially optimal level' during the growth process and this fact might eventually erode the sustainability of the growth process itself. The reason that the environmental damages remain 'unpaid', is because we don't have taxation for the emissions of CO_2. We attempt to solve this problem by equating the emission's share in total output with the share of environmental damages in total output, using independent estimates for CO_2 damages and also estimate the shares directly from an aggregate production function where CO_2 emissions is an input along with labor and capital. Our results suggest that the use of the environment seems to be a statistically significant factor in explaining output growth and labor augmenting technological progress is not the only factor that constitutes the 'true residual' but 'emission augmenting technical change' is also present.

Following the previous analysis of introducing CO_2 emissions as an input in an aggregate production function, estimating the shares of inputs in output and measuring the contribution of the environmental factor proxied by CO_2 emissions in total output growth, we apply the same theoretical methodology of TFPG measurement in a group of 21 developing countries[38] and confirm that the extra "unpaid" factor, the environment, contributes to the final output growth also in the case of developing countries.

In a context of a Green Growth Accounting framework, our final contribution is to further extend the traditional total factor productivity growth measurements by including again the environment as an extra input in the production process, but this time the environment will be approximated by the use of *energy* instead of CO_2 emissions, as an input in the production function.

gium, Denmark, Finland, France, Greece, Italy, Portugal, Spain, Sweden, Switzerland, U.K., Japan, Iceland, Ireland, Netherlands, Norway, Australia, Mexico, Turkey, Luxembourg.

[38] The 21 Developing countries used in our analysis are the following: Peru, Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Jamaica, Bolivia, Colombia, Ecuador, Iran, Srilanka, Syria, Yugoslavia, India, Kenya, Madagascar, Malawi, Sierra Leone, Zimbabwe.

The neoclassical production function we use is:

$$Y = F(K, H, W, X) \tag{16}$$

where K is physical capital, H is human capital, $W = AL$ is effective labour with A reflecting labor augmenting technical change or input augmenting technical change and L being labor in physical units, $X = BE$ is effective input of energy, with E being energy in physical units and B reflecting energy saving technical change.

Then, the augmented residual is defined as follows:

$$\gamma = s_L\left(\frac{\dot{A}}{A}\right) + s_E\left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_H\left(\frac{\dot{H}}{H}\right) - s_L\left(\frac{\dot{L}}{L}\right) - s_E\left(\frac{\dot{E}}{E}\right) \tag{17}$$

We use *energy* as a proxy for the use of the environment, instead of emissions and observe a direct functional relationship between energy and emissions since emissions data are constructed from energy data. Although energy is paid as an input in production, there is also an unpaid part of energy which is the CO_2 emission's created from the use of energy and this part is considered unpaid since no carbon tax policy is in general applied in the OECD or the non-OECD countries and more specifically no carbon tax policy was in use for the period we analyze (1965-1990). We empirically analyze the residual for a group of 23 OECD countries[39] where we observe a strong proportional relationship between energy and CO_2 emissions. We set up a model that examines the equivalence of the emission based model and the energy based model[40] under an optimal emission taxation and exogenous energy prices and we estimate the contribution of the unpaid part of emissions embodied into energy in TFPG measurements. Our results show that traditional TFPG measurements change drastically when we introduce this partially-paid input in the production function and especially when we assign a certain price to the unpaid part of the energy use - the emission's

[39] The 23 countries used in our analysis are the following: Canada, U.S.A, Austria, Belgium, Denmark, Finland, France, Greece, Italy, Portugal, Spain, Sweden, Switzerland, U.K., Japan, Iceland, Ireland, Netherlands, Norway, Australia, Mexico, Turkey, Luxembourg.

[40] In an emission based model, emissions are regarded as an input in the aggregate production function, while in an energy based model energy is regarded as an input in the aggregate production function.

part. Our results can be interpreted as TFPG measurements when inputs generate externalities.

When we introduce an extra input in the production process, energy and when the emission's part of energy is accounted for in the measurements by taking into account CO_2 damages, the residual can even take negative values. This indicates that when we internalize the cost of emissions created from the use of energy, (when this partially paid part of energy becomes fully compensated), the residual becomes negative. A negative residual could imply that each input used in the production process is fully paid for its contribution in total output growth and no technical change that can drive growth is present.

The results of the second part of the thesis suggest that the traditional growth accounting measurement might be a misleading indicator of growth especially for developing countries. That is because one of the production factors that create growth, the environment, is not properly accounted in growth accounting measurements and this might lead to incorrect TFPG results for these countries. Based on this ascertainment we provide measurements of the "Green" TFPG (GTFPG) for those countries and comparisons with prior estimates of other studies. We believe that this kind of analysis addresses the problem of environmental degradation in an effective way because it highlights the contribution of the environment in total output growth and reflects the use of CO_2 emissions as an environmental proxy in the aggregate output production. If we transform the unpaid-free to use- factor of production, environment into something costly, this would lead to a much more conservative use of this factor and would change the growth accounting measurement results.

It can be noted that an important relation exists between the results obtained in the first and the second part of the thesis. The productive base sustainability criterion (keeping the change of the social welfare function positive in a current point in time) is closely connected with a growth accounting framework where the parameter environment can be considered an input in production and emissions augmenting technical change can be present and can drive growth along with labor augmenting technical change. This connection between the productive base sustainability framework and the growth accounting framework can be shown as follows. An important factor in the estimation of the productive base sustainability criterion (13), or equivalently the time derivative of the R-K SWF, is the rate of change of technology $\dot{A}$. Estimate of this $\dot{A}$ imply estimate of TFPG. If however environment is not taken into account in traditional TFPG estimates, then it is most likely that traditional estimates of TFPG are biased upwards. This means that while the correct way to estimate TFPG is through equations like (15), equations like (4) when used, provide upwards biased estimates of productive base sustainability. So our contribution in estimating TFPG by taking into account the contribution of the environment, not only provides a means to correct possible biases in TFPG estimates but provides also unbiased estimates of the TFPG which are necessary for the correct estimation of the productive base sustainability criterion. This link reveals the connection between productive base sustainability and TFPG and points out to the need for unbiased TFPG estimates in order to obtain meaningful estimates about productive base sustainability. Therefore, the contribution in the second part of the thesis not only provides a way to correct TFPG for the use of the environment and make meaningful estimates, but also provide a way to correct for possible biases the productive base sustainability criterion.

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PART I: Productive Base Sustainability

2. Introduction

The development of a criterion capable to provide realistic measurements for whether an economy can be characterized as productive base sustainable or not, is the focus of the first part of this dissertation. According to Arrow et al. (2003), the time-derivative of a R-K SWF at a given time t provides a measure of the rate of change of the economy's current social welfare, or a measure of genuine investment at this time. Following this idea and using a context of non optimizing economies, thus economies where the government either by incompetence or by design does not choose policies that maximize intergenerational welfare, we formulate criteria that measure whether an economy is productive base sustainable or not. We apply our model to the case of a single developed country and also extend it in a group of developed and developing countries. We obtain measurable results for the case of three different policy scenaria that deal with the evolution of global CO_2 emissions and associate closely the environmental degradation with the current social welfare conditions of economies.

In chapter 3 entitled as: "Changes in Social Welfare and Sustainability: Theoretical Issues and Empirical Evidence", we analyze the time derivative of a Ramsey-Koopmans social welfare function (R-K SWF), as an indicator of genuine investment and current change in social welfare (CSW) conditions, when feedback or arbitrary rules are used for selecting policy variables in non-optimizing economies. When policy variables are selected arbitrarily, their accounting prices should determine current CSW in addition to the accounting prices of the economy's assets and genuine investment should be adjusted accordingly. We use our theoretical framework to characterize CSW conditions for non-optimizing economies, based on direct estimation of accounting prices. We use our theoretical model to provide empirical evidence regarding the CSW conditions for the Greek economy.

In chapter 4 entitled as: "Productive Base Sustainability and Global Warming", we deal with the phenomenon of climate change which is one of the most urgent and severe problems of the international agenda and one of the basic factors that determine sustainability conditions. This paper attempts to reveal the connection between productive base sustainability for two large groups of countries, developed and developing and the state of the environment which is proxied by the stock of CO_2 (mostly responsible for the creation of the global warming phenomenon). Three different policy scenaria for the evolution of global CO_2 emissions empirically confirm the strong association of the environment with productive base sustainability and provide the foundations for the formulation of sustainability policy.

3. Changes in Social Welfare and Sustainability: Theoretical Issues and Empirical Evidence

3.1 Introduction

Concerns about environmental deterioration and natural resource depletion have advanced sustainable development as a key concept in policy design both at the national and the international level. Sustainable development has been the central concept in the United Nations World Conservation Strategy and in the report of the World Commission on Environment and Development (United Nations, 1987), also known as the Brundtland Report. Sustainability has also become a central concept in the policy of the European Union.

The most commonly used definition of sustainable development is that of the Brundtland Report which defines sustainable development as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition stresses the aspects of intertemporal distribution and intergenerational equity, but since it embeds many complex economic ideas it suffers from a lack of tractability, especially when it comes to providing answers to applied questions regarding the sustainability of economies, or the design and evaluation of sustainable development policies.

In an attempt to make the definition of sustainable development operational and useful for the development of sustainability criteria or sustainability indicators and for the design of sustainable policies, some auxiliary definitions have been developed. These definitions identify conditions under which an economy can be regarded as following a sustainable development path. The most prevailing of these definitions, as reported by Pezzey (2004a), associate sustainability with:

1. Achieving constant utility (Solow, 1974; Hartwick, 1977).

2. Having the representative agent's utility (well being) $U(t)$, not exceeding the maximum level of utility $U^m(t)$ which can be sustained forever from t onwards given the capital stocks existing at t (Pezzey, 2004b). This definition is implied by, but does not imply, the well known condition that the agent's utility is forever non-declining from t onwards (Pearce et al., 1990; Pezzey, 1992, 1997).

3. Non-Declining Social Welfare (NDSW), that is, avoiding any decline in intergenerational social welfare defined in terms of a Ramsey-Koopmans social welfare functional (R-K SWF), either from time t forever onwards, or much less demandingly, just at time t (Riley, 1980; Dasgupta and Mäler, 2001; Pemberton and Ulph, 2001; Arrow et al., 2003).

Arrow et al. (2003, p. 653) define a sustainable development path at t as one with NDSW at t. Their Theorem 2 then shows that in an autonomous economy, this criterion implies the maintenance of the economy's "productive base" at t, in the sense that NDSW at t is equivalent to non-negative genuine investment at t, defined as the sum of investments, valued at accounting prices, in all productive assets such as manufactured capital, human capital, natural capital and knowledge.[41] So in this paper we call NDSW or non-negative genuine investment at time t "productive-base sustainability". This can also be regarded as corresponding to the weak sustainability concept (Pearce and Atkinson, 1993; Hediger, 1999, 2000).

However, NDSW or positive genuine investment at time t does not imply that the utility of the representative agent at time t is at a level that can be sustained forever after t, which has been considered as a natural meaning of the economy been sustainable at time t. As shown by Asheim (1994) and Pezzey (2004b), there are optimizing economies where NDSW, and yet utility being unsustainable, could occur together during a finite time period. Thus NDSW or positive genuine investment at time t, does not imply 'utility-sustainability' - that is, utility at a level that can be sustained forever after t.

In the present paper we choose to analyze both theoretically and empirically the concept of the time-derivative of a R-K SWF at a given time t, which provides, according to Arrow et al. (2003), a measure of the rate of change of the economy's current social welfare, or a measure of genuine investment at this time. Our interest in this time derivative stems from two facts: (i)

[41] The concept of genuine saving (also known as adjusted net saving) was introduced by Pearce and Atkinson (1993) and Hamilton (1994). Genuine saving provides a much broader indicator of sustainability by valuing changes in natural resources, environmental quality, and human capital, in addition to the traditional measure of changes in produced assets provided by net saving. (World Bank 2006, Chapter 3.) We use the term genuine investment interchangeably with genuine saving in this paper, since the former seems to be closer to the approach of valuing CSW in terms of changes in the values of the assets comprising the productive base of the economy.

If the time derivative is positive, this implies that currently CSW is positive and that genuine investment is positive,[42] without implying, as stated above, sustainability in individual utility terms, (ii) If the time derivative is negative, then genuine investment is negative. As suggested by the World Bank (2006, Ch. 3), negative genuine saving rates imply that total wealth is in decline and policies leading to persistently negative genuine savings are unsustainable.[43] Thus, using World Bank's terminology, we may interpret a negative current CSW, or a negative time derivative of the R-K SWF at a given time t, as an indication of currently unsustainable policies.

The approach of measuring the current CSW could be useful in providing an indication of sustainability in terms of genuine investment and maintenance of the economy's productive base, and not in utility terms, in a more general non-optimizing context. There is a clear distinction between an optimizing and a non-optimizing economy, as illustrated by Arrow et al. (2003).[44] In a non-optimizing economy, the paths of the state variables can also be used to define a value function for the economy through the R-K SWF at a given point in time. The value function at any given point t in time is taken to represent social welfare from time t onwards, and it is a function of the values of the economy's assets at time t.[45] This makes it possible to characterize current CSW conditions in a general context and to provide a basis for empirical estimation of these changes.

We also believe that since, especially for developing countries, there is no reason to assume that observed data are generated by optimizing processes, the non-optimizing framework, properly defined, will be useful both for purposes of theoretical foundations of the current CSW conditions under alter-

[42] Evidence provided by the World Bank (2006) suggest that investments in produced capital, human capital, and governance, combined with saving efforts aimed at offsetting the depletion of natural resources, can lead to future welfare increases in developing countries.

[43] Asheim (1994), Hamilton and Clemens (1999), Pezzey (2004b), show that negative genuine savings at t, that is declining social welfare, implies unsustainability in individual utility terms in optimizing economy. This result however has not been shown to hold in a more general non-optimizing context.

[44] A non-optimizing economy is an economy in which the government, whether by design or incompetence, does not choose policies that maximize intergenerational welfare. The term sustainability acquires particular significance when it is put to work in imperfect economies, that is economies suffering from weak or even bad governance.

[45] This is an interpretation of the value function similar to the one given in Dynamic Programming. The main difference is that no optimization needs to be assumed here.

native hypotheses about the structure and the objectives of the economy, and for empirical estimations.

By using the non-optimizing theoretical framework, we characterize CSW conditions at time t - when controls are chosen according to some feedback rule[46]. We also show that when controls (or policy instruments) are chosen in an arbitrary way, which is independent of the stock of assets,[47] the current CSW depends not only on the growth of the assets and their corresponding accounting prices, but also on the arbitrary paths of the controls. In this case the value function for the economy depends both on current stocks and current flows. These results suggest that the rate of change of the R-K SWF is not just the sum of genuine investments in specific assets, but that it may also include the rate of change of policy instruments valued at their accounting prices. Thus, in certain cases of non-optimizing economies with arbitrarily choices of controls, genuine investment in assets might not be entirely appropriate for characterizing CSW conditions. In these cases genuine investment should be adjusted for the growth of the arbitrary chosen policy variables, such as for example emission limits. This theoretical framework is applied to data from an actual economy with the purpose of providing estimates of the current CSW conditions. Our application refers to the Greek economy.

3.2 Changes in Current Social Welfare Conditions and Sustainability in Non-optimizing Economies

Following Arrow et al. (2003) we assume that social welfare at any given time t is defined by the felicity functional:

$$V_t = \int_t^{\infty} e^{-\rho(\tau - t)} U\left(\mathbf{x}\left(\tau\right), \mathbf{u}\left(\tau\right)\right) d\tau \ , \tau \geq t \tag{18}$$

where $\mathbf{x} = (x_1, ..., x_n)$ denotes a vector of state variables which can be interpreted as stocks of assets and $\mathbf{u} = (u_1, ..., u_m)$ denotes a vector of control variables which can be interpreted as policy instruments. The function $U\left(\mathbf{x}\left(\tau\right), \mathbf{u}\left(\tau\right)\right)$ can be interpreted as the welfare of the generation living at time τ, under appropriate assumptions about the growth of the population, as will become clear in the following sections.

[46] A feedback rule in this context is, for example, a behavioral rule according to which instruments are determined in some relation to the values of the state variables.

[47] This implies a non-feedback (arbitrary) way of choosing the controls.

The evolution of the economy is described by a system of transition equations linking the state and the control variables,

$$\dot{\mathbf{x}}_\tau = \mathbf{f}\left(\mathbf{u}\left(\tau\right), \mathbf{x}\left(\tau\right)\right) \ , \ \mathbf{x}\left(t\right) = \mathbf{x}_t \ , \tau \geq t \tag{19}$$

In an optimizing economy the control paths $\mathbf{u}(\tau)$ are chosen to maximize (18) subject to the constraints imposed by the transition equations (19). In a non-optimizing economy the choice of the controls could be determined by a feedback rule $\mathbf{u}(\tau) = \mathbf{g}(\mathbf{x}(\tau))$ which might reflect behavioral characteristics of the economy, such as learning rules or imitation rules, or some other intentional but not optimal feedback policy rule.[48] For example, in the Solow model of economic growth (Solow 1956), consumption, which can be interpreted as a control variable, is a constant fraction of output. Output is determined, through the aggregate production function, by the capital stock which is the state variable. This constant fraction is a behavioral parameter. Thus in Solow's model, consumption is determined by a feedback rule. In addition, feedback controls can be chosen to stabilize the economic system around some desirable steady state,[49] or can be chosen to steer the system to a certain state vector in finite time.[50]

Alternatively the choice of controls can be determined in a completely arbitrary way, by exogenous factors, such as domestic political conditions, historic trends or international conditions. In this case the control paths will be $\mathbf{u}(\tau) = \bar{\mathbf{u}}(\tau)$. An arbitrary control path could be, for example, a path for which consumption increases $x\%$ per year, or CO_2 emissions are reduced $z\%$ per year, without any relation to the evolution of a state variable[51]. To put it in another way that is closer to the recent discussion about the Kyoto protocol: choosing CO_2 emissions as a proportion of global CO_2 stock is a feedback (closed loop) rule, while keeping emissions at the 1990 levels is an arbitrary (open loop) rule. It seems that in actual economies most policy rules are arbitrary rather than feedback or optimal rules.

Consider the system of transition equations (19) under the feedback rule

[48] These types of controls could also be called *closed loop* controls.

[49] In this case the feedback function is chosen so that the steady state is stable in the Lyapunov sense.

[50] In this case the feedback function is chosen so that the system starting from the initial point $\mathbf{x}_0$, reaches the terminal state $\mathbf{x}_T$, at finite time T. It is assumed in this case that the rank conditions for controllability are satisfied.

[51] Such types of controls could also be called *open loop* controls.

or the arbitrary rule, respectively:

$$\dot{\mathbf{x}}_\tau = \mathbf{f}\left(\mathbf{g}\left(\mathbf{x}\left(\tau\right)\right), \mathbf{x}\left(\tau\right), \mathbf{b}\right) \ , \ \mathbf{x}\left(t\right) = \mathbf{x}_t \tag{20}$$

$$\dot{\mathbf{x}}_\tau = \mathbf{f}\left(\bar{\mathbf{u}}\left(\tau\right), \mathbf{x}\left(\tau\right), \mathbf{b}\right) \ , \ \mathbf{x}\left(t\right) = \mathbf{x}_t \tag{21}$$

where $\mathbf{b}$ is a vector of exogenous parameters. Solutions to these systems, provided they exist, will determine the paths of the state variables as functions of their initial values, the exogenous parameters and possibly the paths of the arbitrary (or open loop) controls. In general these solutions will be of the form:

$$\mathbf{x}_\tau = \boldsymbol{\phi}\left(\tau - t, \mathbf{x}_t, \mathbf{b}\right), \tag{22}$$

$$\mathbf{x}_\tau = \boldsymbol{\psi}\left(\tau - t, \mathbf{x}_t, \bar{\mathbf{u}}\left(\tau\right), \mathbf{b}\right) \tag{23}$$

Substituting the solutions (22) or (23) into (18), we obtain the value function of the system as a function of the initial state vector $\mathbf{x}_t$, and possibly the vector of arbitrary controls $\bar{\mathbf{u}}\left(\tau\right)$. If the arbitrary (or open loop) control path can be written as: $\bar{\mathbf{u}}_0\left(\tau\right) = \bar{\mathbf{u}}\left(\tau - t, \bar{\mathbf{u}}_t\right)$, [52] then the value function for the economy can be written for the feedback and the open loop rules respectively, as:

$$V_t^F\left(\mathbf{x}_t; \mathbf{b}\right) = \int_t^\infty e^{-\rho(\tau - t)} U\left(\mathbf{g}\left(\boldsymbol{\phi}\left(\tau - t, \mathbf{x}_t, \mathbf{b}\right)\right), \boldsymbol{\phi}\left(\tau - t, \mathbf{x}_t, \mathbf{b}\right)\right) d\tau \tag{24}$$

$$V_t^A\left(\mathbf{x}_t, \bar{\mathbf{u}}_t; \mathbf{b}\right) = \int_t^\infty e^{-\rho(\tau - t)} U\left(\boldsymbol{\psi}\left(\tau - t, \mathbf{x}_t, \bar{\mathbf{u}}_0\left(\tau\right), \mathbf{b}\right), \bar{\mathbf{u}}_0\left(\tau\right)\right) d\tau \tag{25}$$

Accounting prices for asset x_i or control (instrument) $\bar{u}_j$ at time t, are defined respectively as:

$$p_{tx_i} = \frac{\partial V_t^l}{\partial x_{it}}, \ l = F, A, \quad p_{tu_j} = \frac{\partial V_t^A}{\partial \bar{u}_{jt}}, \tag{26}$$

Let $\dot{V}_t^l \equiv \dfrac{dV_t^l}{dt}$, $l = F, A$ denote the rate of change of the R-K SWF or the CSW at time t. Then,

$$\dot{V}_t^l \geq 0, \ l = F, A \tag{27}$$

implies non negative genuine investment and can be regarded, in the context of Arrow et al. (2003) arguments as an indicator of current productive base

[52] This implies that the control is chosen according to some arbitrary time dependent rule, for example $z\%$ change relative to the previous year.

sustainability. $\dot{V}_t^l < 0,\ l = F, A$ or a negative CSW implies negative genuine investment.

Proposition 1 *Consider a non-optimizing economy with* $x_i,\ i = 1, ...n$ *assets and* $u_j,\ j = 1, ..., m$ *policy instruments.* (i) *If policy instruments are chosen following feedback rules associated with the assets of the economy, then* $\dot{V}_t^F$ *depends on the assets' growth and their corresponding accounting prices.* (ii) *If policy instruments are chosen arbitrarily then,* $\dot{V}_t^A$ *depends both on the assets' and the policy instruments' growth and their corresponding accounting prices.*

Proof. (i) Differentiating (24) totally with respect to time we obtain :

$$S_t^F \equiv \dot{V}_t^F = \sum_{i=1}^{n} \frac{\partial V_t^F}{\partial x_{it}} \frac{dx_{it}}{dt} + \frac{\partial V_t^F}{\partial t} \tag{28}$$

(ii) Differentiating (25) totally with respect to time we obtain:

$$S_t^A \equiv \dot{V}_t^A = \sum_{i=1}^{n} \frac{\partial V_t^A}{\partial x_{it}} \frac{dx_{it}}{dt} + \sum_{j=1}^{m} \frac{\partial V_t^A}{\partial \bar{u}_{jt}} \frac{d\bar{u}_{jt}}{dt} + \frac{\partial V_t^A}{\partial t} \tag{29}$$

■

It should be noticed that part (ii) of the above proposition shows that in arbitrary (open loop) non-optimizing economies - that is, economies where instruments are chosen without any relationship to assets - $\dot{V}_t^A$ depends on the growth of these instruments too. Thus the growth of the instruments affects the change in social welfare in addition to the growth of the assets. Since the term $\sum_{i=1}^{n} \frac{\partial V_t^A}{\partial x_{it}} \frac{dx_{it}}{dt}$ represents genuine investment, our result implies that in time autonomous economies, where $\frac{\partial V_t^A}{\partial t} = 0$, positive genuine investment does not provide indications about the change in social welfare at time t. To fully assess this change, the impacts of instruments should also be taken into account. In this sense, part (ii) of Proposition 1 extends previous results about non-optimizing economies where the change in current social welfare depended on genuine investment alone. This result can be associated, for example, with the introduction of environmental policy, which in actual economies can be regarded most of the times as arbitrary. For example, let $\bar{u}_j$

denote an arbitrary upper limit on emissions, then $\frac{\partial V_t^A}{\partial \bar{u}_{jt}}$ can be interpreted as the accounting price for this limit and the term $\frac{\partial V_t^A}{\partial \bar{u}_{jt}} \frac{d\bar{u}_{jt}}{dt}$ can be interpreted as the impact of a changing emission limit on the current social welfare conditions.

If, in the arbitrary instrument choice case, instruments are constant so that $\frac{d\bar{u}_{jt}}{dt} = 0$, the value function (25) depends on the vector of parameters $\bar{\mathbf{u}}$ and is written as $V_t^A (\mathbf{x}_t; \bar{\mathbf{u}})$. In this case we can still define the accounting price for the instrument, although the current CSW does not depend directly on $\bar{\mathbf{u}}$ but indirectly, through the accounting prices for the assets, which can be written as: $p_{tx_i} (\bar{\mathbf{u}}) = \partial V_t^A (\mathbf{x}_t; \bar{\mathbf{u}}) / \partial x_{it}$.

Criteria (28) and (29) along with the definitions of accounting prices (26) can be used to suggest a broad rule for evaluating current policies according to their impact on changes in current social welfare.

Consider two alternative feedback policies (rules) $(\mathbf{g}_1 (\mathbf{x}(\tau)), \mathbf{g}_2 (\mathbf{x}(\tau)))$, or two arbitrary policies $(\bar{\mathbf{u}}_1 (\tau), \bar{\mathbf{u}}_2 (\tau))$. The time derivative of the SWF at time t can be defined through (28) under the the feedback rule as $\left(S_{1t}^F, S_{2t}^F\right))$, or through (29) under the arbitrary rule as $\left(S_{1t}^A, S_{2t}^A\right)$ Then the following comparisons could be useful for policy evaluation:

1. If $S_{1t} > S_{2t} > 0$, policy 1 leads to higher change in social welfare at time t relative to policy 2.

2. If $S_{1t} > 0$, $S_{2t} < 0$, policy 1 can be regarded as consistent with 'current productive-base sustainability' at time t, while policy 2 implies negative genuine saving rates. S_{2t}-type policies leading to persistently negative genuine saving are unsustainable in the World Bank's (2006) context.

3. If policies 1, 2 result in welfare paths $V_1(t) \lesseqgtr V_2(t)$, but $\dot{V}_1(t) \gtreqless \dot{V}_2(t)$ then there is a potential conflict in ranking two policies, when one leads to a higher welfare path relative to the other, but is inferior, relative to the other, in terms of changes in current social welfare. This is part of a more general open issue in the evaluation of development criteria, which reflects a potential conflict between optimality and sustainability as criteria for development. The resolution of this conflict is beyond the purpose of the present paper.

3.3 Defining Value Functions and Accounting Prices in Non-optimizing Economies

Having defined the value function and the associated accounting prices at time t, we proceed to consider a structured model of an economy with the purpose of providing exact, and whenever possible, closed form representations of these concepts. These representations will provide more insights into our approach, as well as a basis for empirical estimations.

We consider therefore an aggregate model of a growing economy where output is produced by capital and labor. The production process is affected by exogenous labor augmenting technical change, while the total labor force is determined by domestic population growth and migration inflows (or outflows). Output is divided among consumption and investment and consumption generates utility. On the other hand output production generates emissions which affect utility negatively. Thus, although we are dealing with a stylized model, important characteristics of modern economies such as technical change, environmental pollution and migration are taken into account in exploring the CSW conditions at time t.[53]

Capital accumulation in our stylized economy is described by using the standard Solow model (Solow 1956). Assuming exogenous labor augmenting technical change, the aggregate production function can be written as $Y = F(K, AN)$, where as usual Y is aggregate output, K is capital stock, N is labor input, $\frac{\dot{A}}{A} = g$ is the rate of exogenous technical change so that $L = AN$ is effective labor. The standard Cobb-Douglas production function $Y = K^a (AN)^{1-a}$, $0 < a < 1$, can then be expressed in per effective worker terms as $\hat{y} = \hat{k}^a$, where $\hat{y} = \frac{Y}{AN}$, $\hat{k} = \frac{K}{AN}$.[54]

In our stylized economy we seek to incorporate the impact of migration into the change in the total labor force. Given the importance that migration

[53] In our stylized economy we do not consider natural resources and their contribution to production. This is because we want to keep the model relatively simple in order to obtain the representations of value functions and accounting prices which will help to provide some insights into the structure and the determinants of these concepts. The introduction of natural resources in this context is undoubtedly an area for further research.

[54] An alternative approach would be to specify the production function in the context of an endogenous growth model, by using an AK function or more generally a production function with knowledge externalities or human capital. This approach is another area of further research, once the structure of the value function and accounting prices is understood in the context of the traditional Solow model.

flows have played in the history of economic development, it is interesting to determine the contribution of migration to the current CSW conditions of an economy, along with technical change and environmental pollution. Migration is a phenomenon that affects an economy's population and labor supply. It represents gains in population for the destination economy and at the same time losses for the source economy. The movement of a person could also entail the movement of human capital and that is the reason why migration also implies some degree of capital mobility.[55]

Following Barro and Sala-i-Martin (2004, pp. 384-5), let $M(t) \gtreqless 0$ be the flow of migrants into the domestic economy. Let the domestic population and labor force, $N(t)$, grow at the constant rate n, then the overall growth rate of the domestic labor is:

$$\frac{\dot{N}}{N} = n + \frac{M}{N} = n + m = \tilde{n}$$

where $m = M/N$ is the net migration rate. Assuming that each migrant does not bring along any capital into the domestic economy[56] the accumulation of capital in the domestic economy, measured in per effective worker terms, is given by:

$$\dot{\hat{k}}_t = s\hat{k}_t^a - (n + \delta + g)\hat{k}_t - m\hat{k}_t \tag{30}$$

where s is the constant saving rate and δ is the depreciation rate. This is a Bernoulli differential equation which can be solved to obtain:[57]

$$\hat{k}_\tau = \left[\left(\hat{k}_t^{1-a} - \frac{s}{\omega}\right) e^{-(1-a)\omega(\tau-t)} + \frac{s}{\omega}\right]^{\frac{1}{1-a}} \ , \tau \geq t \ , \ \omega = (n + \delta + m + g) \tag{31}$$

Let C denote aggregate consumption and $\hat{c} = \dfrac{C}{AN}$ denote consumption per effective worker. Since in the Solow model consumption is a fixed proportion of output,[58] we have, in per effective worker terms:

$$\hat{c}_\tau = (1 - s)\hat{k}_\tau^a \tag{32}$$

Using (31) we obtain:

$$\hat{c}_\tau = (1 - s)\left[\left(\hat{k}_t^{1-a} - \frac{s}{\omega}\right) e^{-(1-a)\omega(\tau-t)} + \frac{s}{\omega}\right]^{\frac{a}{1-a}} \tag{33}$$

[55] See, for example, Barro and Sala-i-Martin (2004), pp. 384-5.

[56] This can be interpreted as migration which does not support any capital movement.

[57] For the solution, see Appendix 1.

[58] In the terminology of the previous section, consumption is a feedback control.

Environment is introduced into the model by assuming that pollution, denoted by P, which is a by-product of production, affects utility in a negative way. Then the utility function becomes a function of per capita consumption c_τ and total pollution P_τ and is assumed, as is common in this type of analysis, to have the following separable specification:

$$U\left(c_\tau, P_\tau\right) = -c_\tau^{-(\sigma-1)} - D\left(P_\tau\right) \tag{34}$$

In (34) $-\sigma$ is the elasticity of marginal utility, with $\sigma > 1$, and $D\left(P_\tau\right)$ can be interpreted as a damage function assumed strictly increasing and convex. We specify the damage function as $D\left(P_\tau\right) = \theta P_\tau^\gamma$ with $\theta > 0$ and $\gamma \geq 1$.[59] Since the production structure is determined in per effective worker terms, we need to specify the utility function (34) in per effective worker terms. Since $\hat{c} = C/AN$, from the definition of per capita consumption we obtain:

$$\frac{C_\tau}{N_\tau} \equiv c_\tau = \hat{c}_\tau A_t e^{g(\tau-t)}\ ,\ u\left(c_\tau\right) = -c_\tau^{-(\sigma-1)} = -\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)^{-(\sigma-1)}$$

where A_t is some initial technology level, and the utility function (34/) becomes:

$$U\left(c_\tau, P_\tau\right) = -\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)^{-(\sigma-1)} - \theta P_\tau^\gamma \tag{35}$$

We assume that pollution is of the flow type and that the flow of emissions, since it is a by-product of production, is related to output by a strictly increasing function $P_\tau = \mu\left(Y_\tau\right)$. In terms of the discussion in chapter 3.2, pollution can be regarded as a form of a feedback control, since by using the production function to substitute for output, emissions can be written as a function of the capital stock. This feedback rule can be associated with technical conditions and production practices which determine completely, in the absence of environmental policy, the evolution of emissions.[60] The $\mu(\cdot)$ function can be further specified as:

$$P_\tau = \mu Y_\tau^\beta e^{xt}, \mu > 0, \beta > 0 \tag{36}$$

[59] This specification is consistent with empirical work related to the formulation of damages from pollutants such SO_2, NO_x and particulates. (See for example Barker and Rosendahl, 2000; Eyckmans and Bertrand, 2000).

[60] For example in the absence of environmental policy or any other environmental constraint, a firm will emit as much as possible for a given level of output and technical conditions, since emissions can be regarded as an unpaid factor.

where x reflects technical change in pollution generation[61]. A negative x reflects pollution reducing technical change. In per effective worker terms, $Y_\tau = \hat{y}_\tau A_\tau N_\tau = \hat{k}_\tau^a A_t N_t e^{(g+\tilde{n})(\tau-t)}$, $\tilde{n} = n + m$, with N_t the initial value for the domestic labour force. By substituting Y_τ in (36) and using (31), (33), and (35), the utility flow in per effective worker terms is specified as:

$$U\left(\hat{k}_t, N_t, A_t\right) = -\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)^{-(\sigma-1)} - \theta\left[\mu\left(\hat{k}_\tau^a A_t N_t e^{(g+\tilde{n})(\tau-t)}\right)^\beta e^{x(\tau-t)}\right]^\gamma \tag{37}$$

The flow of total utility in the economy is $N_\tau U(c_\tau, P_\tau)$ and the value function for the economy can be defined, using (37), as:

$$V_t\left(\hat{k}_t, N_t, A_t\right) = \int_t^\infty e^{-\rho(\tau-t)} N_\tau U(\hat{k}_\tau, N_\tau, A_\tau)dt \ , \ N_\tau = N_t e^{\tilde{n}(\tau-t)} \tag{38}$$

where the value function depends only on the current values of state variables of the problem $\left(\hat{k}_t, N_t, A_t\right)$ and the parameters describing the structure of the economy.

This formulation of the social welfare, with utility of per capita consumption multiplied by the total number of individuals, which is the criterion function proposed by Arrow and Kurz (1970), should be contrasted to another possible formulation where per capita utilities are summed. There is an old controversy about the choice of the criterion (Koopmans, 1977). In our formulation, the growth of population helps welfare and this reflects the idea that "if more people benefit, so much the better". In this context migration helps welfare. On the other hand, if population size is a decision variable, and in our case this could have been the case if the migration rate was not exogenous but a control variable, then the choice of the criterion function would acquire more importance.

Using (38) the current accounting prices are defined as:

$$p_{t\hat{k}_t} = \frac{\partial V_t}{\partial \hat{k}_t}, p_{tN_t} = \frac{\partial V_t}{\partial N_t}, p_{tA_t} = \frac{\partial V_t}{\partial A_t} \tag{39}$$

Since $\hat{k} = \dfrac{k}{A} = \dfrac{K}{AN}$, $k = \dfrac{K}{N}$, the accounting price of capital in physical units and per capita units is defined respectively as:

[61] This type of technical change can be induced by environmental policy. We do not model this process here, but in the empirical application we try to make inferences about the existence of this type of technical change from data.

$$p_{tK_t} = \frac{\partial V_t}{\partial \hat{k}_t}\frac{\partial \hat{k}_t}{\partial K_t} = \frac{1}{A_t N_t} p_{t\hat{k}_t} \tag{40}$$

$$p_{tk_t} = \frac{\partial V_t}{\partial \hat{k}_t}\frac{\partial \hat{k}_t}{\partial k_t} = \frac{1}{A_t} p_{t\hat{k}_t} \tag{41}$$

It should be noted that in this case there is no specific accounting price for pollution since pollution is not a stock, but the impact of pollution is realized through the accounting price of capital $p_{t\hat{k}_t} = \partial V_t / \partial \hat{k}_t$ which depends on the parameters of the damage function.

3.4 Changes in Current Social Welfare in the Presence of Environmental Policy

In the previous section emissions were considered as a by-product of output production, determined by technical conditions alone. In this section we explicitly introduce environmental policy which is expressed through a performance standard that determines an upper limit for the emissions of the firms. The emission function of the representative firm can be written as:

$$P_\tau = \mu Y_\tau^\beta e^{x(\tau-t)} = \mu \left(\hat{y}_\tau AN\right)^\beta e^{x(\tau-t)} = \phi\left(f\left(\hat{k}_\tau\right)AN\right)e^{x(\tau-t)} \tag{42}$$

where $f\left(\hat{k}_\tau\right) = \hat{y}_\tau$ is the production function in per effective worker terms. To simplify subsequent notation we set $\phi(\zeta) = \mu\zeta^\beta$, $\zeta = f\left(\hat{k}_\tau\right)AN$.

The emission limit will take the form:

$$P_\tau \leq \bar{P}_\tau \tag{43}$$

The profit function of the representative firm can be written in per effective worker terms as:

$$AN\left[f\left(\hat{k}_\tau\right) - (r+\delta)\hat{k}_\tau - we^{-g(\tau-t)}\right] \tag{44}$$

The firm considers the interest rate r and the wage rate w as fixed and chooses capital, for any fixed level of effective labor AN, to maximize (44) subject to (43). The Lagrangian for the problem is:

$$\mathcal{L} = AN\left[f\left(\hat{k}_\tau\right) - (r+\delta)\hat{k}_\tau - we^{-g(\tau-t)}\right] + \lambda\left[\bar{P}_\tau - \phi(\zeta)e^{x(\tau-t)}\right] \tag{45}$$

The Kuhn-Tucker conditions for an interior solution to the problem imply:

$$f^{'}\left(\hat{k}_{\tau}^{*}\right)\left[1-\lambda\phi^{'}e^{x(\tau-t)}\right] = r+\delta \ ,\hat{k}_{\tau}^{*}>0 \tag{46}$$

$$\lambda\left[\bar{P}_{\tau}-\phi\left(f\left(\hat{k}_{\tau}^{*}\right)AN\right)e^{x(\tau-t)}\right] = 0 \ ,\lambda\geq 0 \tag{47}$$

If the emission constraint is not binding then $\lambda = 0$ and the solution $\hat{k}_{\tau}^{*}$ is obtained by the usual condition $f^{'}\left(\hat{k}_{\tau}\right) = r+\delta$.[62] Under concavity of the production function and Inada conditions, a unique solution always exists.[63] If $\lambda > 0$ then the constraint is binding and the capital stock is determined as a function of the emission limit by the solution of:

$$\bar{P}_{\tau} = \phi\left(f\left(\hat{k}_{\tau}\right)AN\right)e^{x(\tau-t)} \text{ , as} \tag{48}$$

$$\hat{k}_{\tau}^{*} = \psi\left(\bar{P}_{\tau};AN,e^{x(\tau-t)}\right)=\hat{k}_{\tau}^{*}\left(\bar{P}_{\tau}\right) \text{ , with } \frac{d\hat{k}_{\tau}}{d\bar{P}_{\tau}}>0 \tag{49}$$

Thus a more stringent emission limit will reduce the equilibrium stock of capital. This can also be seen from (46). A positive λ shifts the marginal product curve $f^{'}\left(\hat{k}_{\tau}\right)$ to the left. As a result, $\hat{k}_{\tau}^{*}<\hat{k}_{\tau}$ and the binding performance standard reduces the equilibrium stock of capital. It can also be noticed that if $x<0$ so that we have emission saving technical change then the reduction of the equilibrium stock of capital under the performance standard will be smaller, the larger this type of technical change is. Since capital stock is reduced from a binding performance standard or equivalently from a more stringent performance standard, output is also reduced *ceteris paribus*. This reduction is determined as $f\left(\hat{k}_{\tau}\right)-f\left(\hat{k}_{\tau}^{*}\left(\bar{P}_{\tau}\right)\right)$, where $f\left(\hat{k}_{\tau}\right)$ is the output of the economy without the performance standard, and $f\left(\hat{k}_{\tau}^{*}\left(\bar{P}_{\tau}\right)\right)$ is the output of the economy under the binding performance standard $\bar{P}_{\tau}$.

[62] Zero profits for any given wage w require that

$$\left[f\left(\hat{k}_{\tau}\right)-\hat{k}_{\tau}f^{'}\left(\hat{k}_{\tau}\right)+\lambda\phi^{'}f^{'}\left(\hat{k}_{\tau}\right)e^{x(\tau-t)}\right]e^{-g(\tau-t)}=w$$

[63] Inada conditions state that $lim_{k\rightarrow 0}f^{'}(k)=+\infty$ and $lim_{k\rightarrow\infty}f^{'}(k)=0$. When they are combined with a concave production function then $f^{'}(k)$ is monotonically declining and intersects $r+\delta$ only once, providing a unique solution.

Consumption in per effective worker terms is defined as $\hat{c}_\tau = (1-s)\, y_t$, and since $y = f\left(\hat{k}^*_\tau\left(\bar{P}_\tau\right)\right)$,we have:

$$\hat{c}_\tau = (1-s)\, f\left(\hat{k}^*_\tau\left(\bar{P}_\tau\right)\right) = \hat{c}_\tau(\bar{P}_\tau) \tag{50}$$

Thus the per capita utility flow in the economy under the performance standard will be:

$$U\left(\hat{c}_\tau, \bar{P}_\tau\right) = \left[-\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)^{-(\sigma-1)} - \theta \bar{P}^\gamma_\tau\right] \tag{51}$$

with $\hat{c}_\tau$ determined by (50). In empirical applications, where the main purpose is to examine the impact of a performance standard on the current CSW conditions of the economy, a reliable estimate of $f\left(\hat{k}^*_\tau\left(\bar{P}_\tau\right)\right)$ is unlikely due to data limitations. In this case one approach could be to assume that the reduced output under the binding standard is approximately proportional to the output obtained without a limit on emissions. This means that we set:

$$f\left(\hat{k}^*_\tau\left(\bar{P}_\tau\right)\right) \approx (1-z_{\bar{P}})\, f\left(\hat{k}_\tau\right) \tag{52}$$

which implies that $f\left(\hat{k}_\tau\right)$ can be interpreted as full capacity output without environmental constraints and $z_{\bar{P}}$ is a new parameter introduced here which reflects the reduction in output due to the upper emission limit $\bar{P}_\tau$.[64] Under the Cobb-Douglas assumption, we have, $\hat{y} = (1-z_{\bar{P}})\, \hat{k}^a$. In this case the accumulation of capital equation in per effective worker terms is:

$$\dot{\hat{k}}_t + (n+\delta+m+g)\, \hat{k}_t = s(1-z_{\bar{P}})\hat{k}^a_t \tag{53}$$

The solution of this Bernoulli equation is:[65]

$$\hat{k}_\tau = \left[\left(\hat{k}^{1-a}_t - \frac{s(1-z_{\bar{P}})}{\omega}\right) e^{-(1-a)\omega(\tau-t)} + \frac{s(1-z_{\bar{P}})}{\omega}\right]^{\frac{1}{1-a}} \tag{54}$$

$$\omega = n+\delta+m+g \tag{55}$$

[64] For an estimate of the proportion of output loss due to environmental regulation in the US economy see Jorgenson and Wilcoxen (1998).

[65] See Appendix 1 for details.

Therefore $\hat{c}_\tau = (1-s)(1-z_{\bar{P}})\hat{k}_\tau^a = \hat{c}_\tau\left(\hat{k}_\tau; z_{\bar{P}}\right)$, and the value function for the economy becomes:

$$V_t = \int_t^\infty e^{-\rho(\tau-t)} N_t U(\hat{k}_\tau, N_\tau, A_\tau, \bar{P}_\tau; z_{\bar{P}}) d\tau \text{ , or} \tag{56}$$
$$V_t = -\int_t^\infty e^{-\rho(\tau-t)} N_t \left[\left(\hat{c}_\tau\left(\hat{k}_\tau; z_{\bar{P}}\right) A_t e^{g(\tau-t)}\right)^{-(\sigma-1)} - \theta \bar{P}_\tau^\gamma\right] d\tau$$

The current accounting price for the performance standard $\bar{P}_t$ can be calculated as:

$$p_{t\bar{P}} = \frac{\partial V_t}{\partial \bar{P}_t} = \int_t^\infty e^{-\rho(\tau-t)} \frac{\partial}{\partial \bar{P}_t}\left[N_t U(\hat{k}_\tau, N_\tau, A_\tau, \bar{P}_\tau; z_{\bar{P}})\right] d\tau \tag{57}$$

Thus there is a specific accounting price for the arbitrary control $\bar{P}_t$, as was anticipated by Proposition 1. There is also an accounting price associated with the parameter $z_{\bar{P}}$, which is defined as:

$$p_{tz_{\bar{P}}} = \frac{\partial V_t}{\partial z_{\bar{P}}} \tag{58}$$

3.5 Current Changes in Social Welfare in a Non-optimizing Economy

The previous section obtained representations of value functions and accounting prices. Combining these representations with Proposition 1, it follows that our stylized economy is characterized by non-declining current CSW when feedback rules are followed, if:

$$\dot{V}_t^F = p_{K_t}\dot{K} + p_{N_t}\dot{N} + p_{A_t}\dot{A} \geq 0$$

Dividing by Nk where $k = \frac{K}{N}$, using the fact that $\dot{k} = \frac{d(K/N)}{dt} = \frac{\dot{K}}{N} - \frac{\dot{N}}{N}k$ and that the accounting price for capital in physical terns is related to the accounting price of capital in per effective worker terms, by (40) we obtain:

$$\hat{S}_t^F = \frac{\dot{V}_t^F}{N_t k_t} = \frac{p_{t\hat{k}_t}}{A_t N_t}\left(\frac{\dot{k}}{k} + \frac{\dot{N}}{N}\right) + p_{tN_t}\frac{\dot{N}}{N}\frac{1}{k_t} + p_{tA_t}\frac{\dot{A}}{A}\frac{A_t}{N_t k_t}$$

where $\hat{S}_t^F$ measures the change in the value of the economy per unit of produced capital stock at time t. Thus $\hat{S}_t^F$ could be interpreted as the rate of return on produced capital measured in terms of social welfare. It is clear that by multiplying $\hat{S}_t^F$ by the current stock of capital we obtain a measure of current genuine investment. Using as before $\dot{A}/A = g$, $\tilde{n} = n + m$, with $m \gtreqless 0$, and denoting the rate of growth of capital per worker by $\dot{k}/k = v$, we have that social welfare is currently non-declining if:

$$\hat{S}_t^F = \frac{p_{t\hat{k}_t}}{A_t N_t}(v + \tilde{n}) + p_{t_{N_t}}\tilde{n}\frac{1}{k_t} + p_{t_{A_t}} g \frac{1}{k_t}\frac{A_t}{N_t} \geq 0 \tag{59}$$

When an arbitrary environmental policy in the form of the emission limit $\bar{P}_\tau$ is present, the criteria become:

$$\dot{V}_t^A = p_{K_t}\dot{K} + p_{N_t}\dot{N} + p_{A_t}\dot{A} + p_{\bar{P}_t}\frac{d\bar{P}_\tau}{dt} \quad \text{or} \tag{60}$$

$$\hat{S}_t^A = \frac{p_{\hat{k}_t}}{A_t N_t}(v + \tilde{n}) + p_{Nt}\tilde{n}\frac{1}{k_t} + p_{A_t} g \frac{1}{k_t}\frac{A_t}{N_t} + p_{\bar{P}t}\pi\frac{1}{k_t}\frac{\bar{P}_t}{N_t} \tag{61}$$

where π is the rate of growth of the emission limit, with $\pi < 0$ indicating that environmental policy becomes gradually more stringent and $\pi > 0$ indicating that environmental policy is gradually becoming laxer. As before, by multiplying $\hat{S}_t^A$ by the current stock of capital we obtain a measure of current genuine investment. In this case genuine investment is adjusted for the changes in environmental policy, a required adjustment that has not been noticed in earlier literature.

Measures of current CSW (59) and (61) are basically short-term measures since they reflect measurements at time t. These conditions will change if basic parameters, such as growth rates of assets or choices of instruments, change. Since the economy is not on an optimal path these changes - especially in the case of arbitrary choice of controls - might actually take place. Therefore, if the basic parameters are likely to change, then recalculations and updating of (59) or (61) are necessary. We believe that this observation is important, especially for applied work.

3.6 Exploring Current Changes in Social Welfare Conditions for the Greek Economy

The stylized model developed above is used to explore the current social welfare conditions for the Greek economy. To apply the model we need estimates of the parameters required to define value functions like those defined in (38) or (56).

Our approach was to estimate, using econometric estimations, the parameters that correspond to structural relations and to assign plausible values to those parameters for which econometric estimation was not possible. For these parameters we used sensitivity analysis to explore the robustness of our results.

The parameters required in order to estimate measures (59) and (61) are: n the rate of growth of the domestic population and labor force, m the net migration rate; v the rate of growth of capital per worker; g the rate of growth of labor augmenting technological change; s which expresses savings as a proportion of the Greek GDP in the period analyzed; a which is the parameter of the production function reflecting the elasticity of capital input; ρ which represents the discount rate; σ the elasticity of marginal utility the value of which reflects intertemporal preferences towards equality in income distribution; δ which is the depreciation rate; θ and γ which are the parameters of the postulated damage function $D(P_\tau) = \theta P_\tau^\gamma$; μ, β and x which are the parameters of the emission function $P_\tau = \mu Y_\tau^\beta e^{xt}$; and finally, when we need to examine the impact of an emission limit, the potential reduction in GDP due to this emission limit is required, which is the parameter $z_{\bar{P}}$.

The fundamental data for the Greek economy were GDP, capital, and labor, measured in 1990 million \$ and thousands of workers respectively, taken from the Penn World Table (Mark 5.6) for the period 1965-1990. We obtain the average annual growth rates of these variables in physical units and in per capita terms during the sample period by estimating the relationship $\ln x_t = a_o + a_1 t$, where x_t is the variable of interest and t takes values $t = 1, ..., T^S$ during the sample period, with $T^S = 26$.[66]

The estimates of the growth rates for the variables of interest in physical and in per worker terms are shown in the table below.

Table 1: Average growth rates of capital, output and labor force for the Greek economy, 1965-1990

[66] Relationship $\ln x_t = a_o + a_1 t$ corresponds to the standard exponential growth model $x_t = A_o e^{a_1 t}$.

	% per year	Per worker terms	% per year
Capital ($\dot{K}/K$)	5.55	Capital $\left(\dot{k}/k\right)$	4.95
GDP ($\dot{Y}/Y$)	3.64	GDP ($\dot{y}/y$)	3.035
labor force (n)	0.60	—	—

The basic structural relationship for the Greek economy is the aggregate production function (36), since estimates from the production function will be used to determine the elasticity of capital with respect to output, which is the parameter a, and the rate of labor augmenting technical change g. For this estimation we assume the existence of a constant returns to scale Cobb-Douglas long run aggregate production function for the Greek economy, defined over man made capital and effective labor input, which takes the form:

$$Y_t = BK^a \left(Ne^{gt}\right)^{1-a}$$

or in per worker terms:[67]

$$y_t = Bk_t^a e^{qt} \ , q = g\left(1-a\right))$$

The statistical model can be written as:

$$\ln y_t = \ln B + a \ln k_t + qt + \varepsilon_t \ , t = 1, ..., T^S \tag{62}$$

where ε_t is the usual error term. The production function (62) can be interpreted as a long run equilibrium relationship that shifts in time as it is affected by technical change. To test for the existence of such an equilibrium relationship we test for the existence of a cointegrating relationship. The Johansen cointegration test suggests that both the trace and the maximum eigenvalue tests indicate one cointegrating relationship with constant and deterministic trend at the 5% level. When a cointegrating relationship exists, ordinary least square (OLS) estimation is superconsistent, that is the estimated coefficients are consistent and asymptotically normal (Stock, 1987). Using therefore OLS to estimate (62) we obtain that the elasticity of capital input is $a = 0.4025$, [68] while the rate of labor augmenting technical change is

[67] It is clear that in per worker terms this function becomes $\hat{y}_t = B\hat{k}_t^a$, which is the function used in the previous sections with $B \equiv 1$

[68] We did not include human capital in our production function. However, the value of estimated a can be regarded, under certain assumptions, as incorporating human capital effects (Barro and Sala-i-Martin, 2004).

$g = \dfrac{q}{1-a} = 0.009$ or 0.9% annually.[69] The details of the cointegration test and the OLS estimation results are presented in Appendix 2[70].

To model environmental pollution we consider sulfur dioxide emissions (SO_2) as the main flow pollutant. Sulfur dioxide emissions in Greece are mainly localized because the majority of them are created in the processes of power generation[71]. These emissions were related to output, assuming an emission function of the constant elasticity form (36), which was regarded as a technological relationship and was estimated using data of annual emissions in kilotons covering the period $1980-1999$[72]. The estimated elasticity of SO_2 emissions with respect to aggregate output was 0.225. A trend term which could indicate technical change associated with SO_2 emissions was highly insignificant[73].

For the migration rate, a recent study (Lianos, 2003) indicates that between 1991 and 2001 the number of immigrants who entered the Greek economy was around $630,000$. Assuming an average annual flow of $60,000$ immigrants, the average net migration rate is approximately 1.5%, and $n + m = 0.021$. For the marginal propensity to save, we use the average value for the period $1970 - 1990$ of savings as a proportion of GDP, with $s = 0.21$[74]. The depreciation rate was set at $\delta = 3\%$ following Mankiw et al. (1992); the utility discount rate at $\rho = 3\%$;[75] and the elasticity of marginal utility at $\sigma = 3$ which reflects relatively strong preferences towards equal

[69] This method of estimating the labour augmenting technical change from a Cobb-Douglas production function is similar to what is proposed by Barro and Sala-i-Martin (2004).

[70] All estimations were performed using the sofware package EViews 5.0.

[71] Lignite fired power plants in Greece produced 63% of total electricity in 2003, and are concentrated mainly in two locations in the Northern and in the Southern part of the country.

[72] The source of the data was the European Environment Agency (http://www.eea.europa.eu/).

[73] Estimates were corrected for first order serial correlation, which turned out to be highly significant. Details are presented in Appendix 2.

[74] Data were taken from "The Greek Economy in Figures," (2002, page 105).

[75] The value of 3% has been used by a number of researchers for the estimation of marginal social costs of CO_2 emissions (see, for example, surveys by Fankhauser and Tol, 1997, Tol, 2005). The values of 1% and 2%, along with time declining rates, have also been used in these studies. We perform a sensitivity analysis of our results by using a value of 1% for the utility discount rate. There is an increase in the absolute values of the accounting prices reported in tables 2 and 3, but there is no change in the signs of the criteria $\hat{S}_t^F$ and $\hat{S}_t^A$.

income distribution. The parameter γ of the damage function was set at $\gamma = 1$. This implies a linear damage function in which θ, the damage cost coefficient, reflects constant marginal damages from SO_2. Since the units of output and consumption were million $US\$$, θ reflects the environmental damages in Greece, in million $US\$$, from the emissions of one kiloton of sulphur dioxide in a year. Because, as mentioned above, SO_2 emissions are mainly localized, the value of θ in our model can be interpreted as capturing marginal damages averaged over the whole population. As noted by Sáez and Linares (1999), damages from SO_2 emissions are associated with health damages from SO_2 and sulfates exposure along with damages inflicted on buildings, crops and natural habitats. Estimates of SO_2 damages and associated damage cost coefficients, θ, obtained by Sáez and Linares (1999) and Barker and Rosendahl (2000) for Greece, range from 0.12946 to 0.5128 $US\$$ per kiloton of SO_2 a year[76]. In our estimations we considered values of θ in the interval $[0.2856 \cdot 10^{-6}, 10^{-3}]$ indicating damages from 0.28256 $US\$$ to 1000 $US\$$ per kiloton of SO_2 a year.[77] For the parameter $z_{\bar{P}}$ there is no information for the Greek economy. Jorgenson and Wilcoxen (1998), using a computable general equilibrium approach, estimated the cost of all environmental restrictions for the US economy to be 2.592% of real GNP, so we set $z_{\bar{P}}$ at a conservative value of 1%.

The parameter values used are summarized in the following table:

Parameter	$\tilde{n}$	v	g	s	a	ρ	δ	σ
Value	0.021	0.0495	0.009	0.21	0.4025	0.03	0.03	3
Parameter	β	μ	x	γ	θ	$z_{\bar{P}}$		
Value	0.225	4.146	0	1	$[0.2856 \cdot 10^{-6}, 10^{-3}]$	0.01		

Using the above parameters, accounting prices were calculated with numerical integration of the derivatives of the value function.[78] We used a time horizon of 100 years as a necessary approximation for the numerical estima-

[76] Estimates in euros were converted to 1990 $US\$$.

[77] The value of 0.2856 is the point estimate of Barker and Rosendahl (2000) of the damage coefficient for Greece. It should also be noticed that in these estimates premature mortality has been estimated as the value of years lost (VOYL). Use of the value of statistical life (VOSL) could have increased these estimates by 50%. We use higher values of θ, in addition to the available estimates, in order to check the sensitivity of our results. The extreme value of 1000 US\$ for θ is used to identify a switch point, that is the value of θ for which criteria $\hat{S}_t^F$ and $\hat{S}_t^A$ turn negative.

[78] Numerical results were obtained by using *Mathematica*.

tion.[79] Two sets of results were obtained. The first set which corresponds to emissions determined by a feedback rule through the emission function is obtained using (59). The second set is obtained using the 1999 sulphur dioxide emissions as an upper emission limit and (61). Table 2 below shows accounting prices and the estimated changes in social welfare for different marginal damages in Greece in 1990.

Table 2: Accounting Prices and Changes in Social Welfare for Greece in 1990*

m	θ	p_K	p_N	p_A	$\hat{S}_t^F$
0	0	0.0011216	-0.0464493	315.511	0.00007839
0.015	0	0.00238486	-0.125464	852.225	0.00142968
0.015	$0.2856 \cdot 10^{-6}$	0.00238306	-0.12792	850.693	0.0001406
0.015	10^{-5}	0.00237046	-0.134064	846.860	0.00013461
0.015	10^{-4}	0.00224252	-0.21147	798.574	0.00005950
0.015	10^{-3}	0.00096316	-0.985523	315.712	-0.0006916

(*)The accounting prices p_K, p_N, p_A, are defined in (39), while $\hat{S}_t^F$ is defined in (59)

We can observe from table 2 that for marginal environmental damages below 1000 $US\$$ per kiloton of SO_2 the Greek economy was characterized by a positive change in social welfare in 1990. Given the very high value of θ relative to the estimates for Greece, for which criterion $\hat{S}_t^F$ changes sign, it seems that in the context of our analysis it might be claimed that the evolution, for the examined sample period, of the Greek economy is characterized by positive changes in social welfare, which can be regarded as an indication that it is currently productive-base sustainable. Furthermore, it is clear that migration has played an important role in the current conditions of the Greek economy, since the positive change in social welfare is reduced substantially when we set $m = 0$[80]. In addition, the accounting prices have

[79]The fundamental parameters of the Greek economy imply that convergence to a steady state will take place in approximately 70 years. Thus, the time horizon chosen extends well into the steady state period. The results are robust to changes in the time horizon. Of course as noted above accounting prices need to be recalculated, if the fundamental growth rates used in the estimations change.

[80]It should be noticed that the positive effect of migration is associated with the choice of criterion function (38). The alternative formulation of using per capita utility in the criterion function and the impact on the estimated accounting prices changes in social welfare could be an area for further research.

the expected signs and the rate of change of social welfare is declining in environmental damages as expected.

In table 3 we present accounting prices and estimated changes in social welfare under a binding environmental policy. Thus table 3 shows accounting prices and changes in social welfare for different marginal damages in Greece in 1990 as if the emission limit for sulphur dioxide had been set at the 1999 emission level, which was 541 kilotons. Values have been calculated for $m = 0.015$ and $z_{\bar{P}} = 0.01$.

Table 3: Accounting Prices and Changes in Social Welfare for Greece in 1990 under an Emission Limit*

θ	p_K	p_N	p_A	$p_{\bar{P}}$	$p_{z_{\bar{P}}}$	$\hat{S}_t^A$
$0.2856 \cdot 10^{-6}$	0.002449	-0.144	873.9	-0.09694	-1107.6	0.00013
10^{-3}	0.002449	-54.23	873.9	-339.6	-1107.6	-0.0409

(*)Accounting Prices $(p_K,\ p_N,\ p_A)$ are defined in (39) , $\left(p_{\bar{P}}, p_{z_{\bar{P}}}\right)$ are defined in (57),(58) respectively, while $\hat{S}_t^A$ is defined in (61)

In table 3 the column $p_{\bar{P}}$ refers to $\dfrac{\partial V}{\partial \bar{P}_\tau}$ which is the accounting price for the emission standard. This price is negative as expected, since an increase in $\bar{P}_\tau$, that is a laxer environmental policy, is expected to reduce the economy's social welfare, when $z_{\bar{P}}$ remains constant. The column $p_{z_{\bar{P}}}$ refers to $\dfrac{\partial V}{\partial z_{\bar{P}}}$ which is negative as expected. This means that if the cost of the standard in terms of output foregone increases, then the economy's social welfare is reduced *ceteris paribus*. Since a lax standard is expected to reduce $z_{\bar{P}}$, the final effect of a change in the performance standard on social welfare depends on the expression $\frac{\partial V}{\partial \bar{P}_\tau} d\bar{P}_\tau + \frac{\partial V}{\partial z_{\bar{P}}} dz_{\bar{P}}$. Again, as expected, the criterion is declining in marginal environmental damages.

3.7 Concluding Remarks

This chapter analyzed current change in social welfare (CSW) conditions under a non-optimizing framework. The main purpose was to develop an applicable and operational approach to measure current CSW and to contribute to the development of a framework for the evaluation of policies with respect to their impact on current social welfare conditions. For this purpose we tried to determine a measure for CSW which would fit into a non-optimizing economic framework, since we consider such a framework to adequately represent current economic conditions, at least in developing countries. By considering two different approaches for choosing policy instruments, a feedback rule and an arbitrary rule, we determined two corresponding criteria for measuring changes in current social welfare conditions which can provide numerical results for actual economies and could be applied in empirical work. Since current changes in social welfare can be associated with current changes in the productive base of the economy valued at accounting prices, positive changes imply positive genuine investment and current productive-base sustainability. On the other hand negative changes in social welfare and therefore negative genuine investment can be regarded as an indicator of currently unsustainable policies. In doing this, we extended current results about genuine investment by showing that when policy rules are chosen in an arbitrary way, then genuine investment should be adjusted accordingly. Given the arbitrary nature of most government policies in practice - environmental policies included - this observation might have important implications for empirical applications. We provide exact representations and closed form solutions for value functions and accounting prices, by considering a "Solow" economy, where domestic population growth, migration, labor augmenting technical change, and environmental damages associated with pollutant flows generated by economic activities are taken into account in determining the current social welfare conditions.

The criteria developed in this paper were applied to the case of the Greek economy and empirical estimates were obtained. Our findings seem to support the idea that our theoretical framework can be used for empirical purposes. In particular, our results show that migration inflows, exogenous technical change, growth of capital per worker, and SO_2 emissions damages, are important factors characterizing the current changes in social welfare conditions of the Greek economy. Our approach allows for the estimation of the contribution of these factors which is undoubtedly useful information for the design and evaluation of policies. The main empirical finding is that the Greek economy seems to be currently 'productive-base sustainable', given the current estimates of SO_2 emission damages, which was the only pollutant considered in our analysis. Furthermore, and as expected, taking into account environmental damages has a negative effect on the current social welfare conditions. Thus, our empirical results for the case of Greece support the perception that pollution damages are a factor affecting conditions associated with changes in social welfare conditions. Our approach not only provides an empirical confirmation of this result, but can be used to quantify, at least approximately, environmental impacts on social welfare, another important piece of information for policy design. A more precise quantification of these effects is an open research area.

Admittedly sustainable development as a general definition does not provide a systematic framework for empirical estimations and for policy design. This attempt is a modest attempt to make the definition operational and capable of providing empirical estimates which are based on the structure of the economy, and which can be associated with concepts of current changes in social welfare and current productive-base sustainability. Thus important fundamentals, such as the elasticity of the production function, the rate of technical change, migration, environmental damages, and assets' rates of growth, play a key role in the measurement of current CSW conditions. The model developed here can be extended and made more realistic by including transition equations for stocks of pollutants, natural resources (depletable or renewable), human capital, or by introducing uncertainty in the evolution of the economy. These extensions will provide better insights regarding the changes in social welfare conditions of economies and will enhance our ability to provide meaningful estimates of such changes.

Appendix 1

Solutions of the Bernoulli equations for the capital stock.

Solution of Equation (30)

The Bernoulli equation is solved in the following way: Multiplying by $\hat{k}_t^{-a}$ we have:

$$\dot{\hat{k}}_t \hat{k}_t^{-a} + (n + \delta + m + g) \hat{k}_t \hat{k}_t^{-a} = s \hat{k}_t^{-a} \hat{k}_t^{a} \tag{63}$$

$$\dot{\hat{k}}_t \hat{k}_t^{-a} + (n + \delta + m + g) \hat{k}_t^{1-a} = s \tag{64}$$

If $\gamma = \hat{k}_t^{1-a}$ and $\dot{\gamma} = (1-a)\left(\dot{\hat{k}}_t \hat{k}_t^{-a}\right)$, then we have:

$$\dot{\gamma} + (n + \delta + m + g) \gamma (1-a) = (1-a)s, \text{ which is linear in } \gamma \tag{65}$$

with solution:

$$\gamma_t = \left(\gamma_o - \frac{s}{n + \delta + m + g}\right) e^{-(1-a)(n+\delta+m+g)t} + \frac{s}{n + \delta + m + g} \tag{66}$$

Setting $\gamma_t = \hat{k}_t^{1-a}$, we have:

$$\hat{k}_t = \left[\left(\hat{k}_o^{1-a} - \frac{s}{n+\delta+m+g}\right) e^{-(1-a)(n+\delta+m+g)t} + \frac{s}{n+\delta+m+g}\right]^{\frac{1}{1-a}}$$

$$\hat{k}_\tau = \left[\left(\hat{k}_t^{1-a} - \frac{s}{\eta+\delta+m+g}\right) e^{-(1-a)(n+\delta+m+g)(\tau-t)} + \frac{s}{n+\delta+m+g}\right]^{\frac{1}{1-a}}$$

Solution of Equation (53)

Using function $\hat{y} = (1 - z_{\bar{P}})\,\hat{k}^a$ instead of $\hat{y} = \hat{k}^a$, the accumulation of capital in per effective worker terms becomes:

$$\dot{\hat{k}}_t = s(1 - z_{\bar{P}})\hat{k}_t^a - (n + \delta + g)\,\hat{k}_t - m\hat{k}_t + z$$

Working as before we obtain:

$$\hat{k}_t = \left[\left(\hat{k}_o^{1-a} - \frac{s(1-z_{\bar{P}})}{n+\delta+m+g}\right) e^{-(1-a)(n+\delta+m+g)t} + \frac{s(1-z_{\bar{P}})}{n+\delta+m+g}\right]^{\frac{1}{1-a}}$$

Appendix 2

Johansen Cointegration Test

Trend assumption: Linear deterministic trend (restricted)

Series: $lny_t, \ln k_t$

Lags interval (in first differences): 1:1

Unrestricted Cointegration Rank Test (Trace)

Hypothesized No of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob**
None*	0.649227	30.97507	25.87211	0.0106
At most 1	0.347789	8.975136	12.51798	0.1819

Trace test indicates 1 cointegrating eqn(s) at he 0.05 level

*denotes rejection of the hypothesis at the 0.05 level

**MacKinnon-Haug-Michelis (1999) p-values

Unrestricted Cointegration Rank Test (maximum Eigenvalue)

Hypothesized No of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob**
None*	0.649227	21.99993	19.38704	0.0204
At most 1	0.347789	8.975136	12.51798	0.1819

Max-Eigenvalue test indicates 1 cointegrating eqn(s)
at he 0.05 level

*denotes rejection of the hypothesis at the 0.05 level

**MacKinnon-Haug-Michelis (1999) p-values

Econometric Estimations

The Production Function

Variable	**Coefficient**	**Std. Error**	**t-Statistic**
$\ln B$	1.438115	0.187444	7.672226
$\ln k$	0.402501	0.080129	5.023150
t	0.005392	0.003080	1.750943

R-squared	0.957372
Adjusted R-squared	0.952636
Durbin-Watson stat	1.175040

The Emission Function

Variable	Coefficient	Std. Error	t-Statistic
constant	4.156018	2.289511	1.815243
$\ln Y$	0.225308	0.241803	1.931786
AR(1)	0.745520	0.084558	8.816671
R-squared	0.906529		
Adjusted R-squared	0.894845		
Durbin-Watson stat	2.176287		

4. Productive Base Sustainability and Global Warming

4.1 Introduction

One of the most urgent and severe problems that occupy the international agenda today, is the rapid climate change and the global warming phenomenon. Global temperature increase, is associated with the greenhouse effect and is likely to trigger serious consequences for the state of the earth and for humankind[81]. The European Commission reports that during the last century, the Earth's average surface temperature rose by around 0.6 degrees Centigrade[82]. This generates a number of problems in all aspects of life and activities. Extreme weather events, endangerment of species, the rise of the sea level which will endanger coastal areas and small islands, important effects for agriculture, the farming sector etc. It is nowadays's general knowledge th at most of the global warming is attributable to human activities[83]. This includes the burning of fossil fuels which cause carbon dioxide (CO_2) emissions which is considered to be the main factor responsible for climate change, as well as the emissions of other 'greenhouse' gases[84]. This direct link between the environment and economic activity points out the destructive results of the inconsiderate use of the environmental resources by humans. Current reports (IPCC report[85], the Stern Report) present different possible future scenaria that include more or less pessimistic predictions for the years to come, depending on the way we decide to handle and control the global warming phenomenon today and in the immediate future[86]. The prospects

[81] The IPCC Report, European Commission Report 2006, The Stern Report.

[82] NASA reports that 2006 was the fifth warmest year on record and 2007 will likely be even warmer - possibly the warmest year in the history of instrumental measurements. Over the past 30 years Earth has warmed by about 0.6 degrees Centigrade or 1.08 degrees Fahrenheit.

[83] The IPCC Report, Technical Summary

[84] As has been indicated by the European Commission Report, 2006.

[85] IPCC Special Report on Emissions Scenarios

[86] "The current level or stock of greenhouse gases in the atmosphere is equivalent to around 430 parts per million (ppm) CO_2, compared with only 280ppm before the Industrial Revolution. These concentrations have already caused the world to warm by more than half a degree Celsius and will lead to at least a further half degree warming over the next few decades, because of the inertia in the climate system". The Stern Review: The Economics of Climate Change, Executive Summary pg. iii.

are not very optimistic if action is not taken now. If the implementation of current policies that do not pay any attention to the global warming is continued, this phenomenon will be intensified. The various reports[87] on this issue identify the urgent need for action now in order to build and maintain a development process that could be characterized as sustainable. Thus the global warming phenomenon which is clearly interlinked with environmental sustainability, if not controlled by governments and policy makers, can cause irreversible damage to future generations.

Based on these concepts, the paper's main objective is to relate global carbon dioxide (CO_2) concentration and emissions that lead to global warming and climate change, to a concept of productive base sustainability and to approximate empirically the impact of environmental degradation on current social welfare (CSW). Sustainability though, has been regarded as the current and future goal to be achieved. The idea that each generation should bequeath to each successors at least the productive base it inherited from its predecessors, is the cornerstone of sustainable development. Thus, this paper has two basic goals. First, it attempts to model the Brutland Report's concept[88] in terms of changes in current social welfare (CCSW) conditions by taking into account the way the climate change contributes to current social welfare. The second aim is to provide empirical results for two large groups of countries (developed and developing) obtained directly from the application of our theoretical model and this way to establish and estimate a link between CCSW and global warming. Social welfare (SW) measures the current and future state of human well being which is closely associated with the state of the earth and sustainable development. In order to define a measure of CCSW conditions we use the time derivative of social welfare function which provides, according to Arrow et al. (2003), a measure of the rate of change of the economy's current social welfare or a measure of genuine investment at this time. In order to measure whether an economy is currently characterized by *positive* changes in social welfare and thus positive genuine investment, we formulate a criterion that measures sustainability in productive base terms. If the time derivative of a Ramsey-Koopmans Social Welfare Function (R-K SWF) at time t is positive, then an economy is currently productive base sus-

[87] Kyoto Protocol, IPCC report, the Stern Report

[88] "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The Brutland Report.

tainable and genuine investment is also positive[89]. In this sense, sustainable development is measured as the change in productive capacity. Reductions in productive capacity can be captured by negative genuine investment and imply that we leave less productive capacity to future generations to satisfy their needs. More specifically, if an economy is not currently productive base sustainable, then the time derivative of the R-K SWF at time t is negative and genuine investment is also negative. Negative genuine investment (or savings) imply that total wealth is in decline and policies that lead to persistently negative genuine savings are unsustainable[90]. This can be considered as a *productive base approach* to sustainable development.

Following this methodological approach, we develop our model based on the case of non optimizing economies[91] that we believe fits best current economic structures. We estimate CCSW conditions for two large groups of 23 developed[92] and 21 developing economies[93] by taking into account one of the basic environmental factors that can be held accountable for the global warming phenomenon, namely CO_2 emissions[94]. Given the damages that CO_2 emissions and other GHG's create, our goal is first to define theoretically and then to estimate the CCSW for each one of the countries we analyze (developed and developing). Under the current production structure, the realized CO_2 emission time paths, the currently estimated CO_2 damages and

[89] Arrow et all., (2003).

[90] The World Bank (2006, Ch. 3). Asheim (1994), Hamilton and Clemens (1999), Pezzey (2004b), show that negative genuine savings at t, that is declining social welfare, implies unsustainability in individual utility terms in optimizing economy. This result however has not been shown to hold in a more general non-optimizing context.

[91] A non-optimizing economy is an economy where goverment whether by design or by incompetence does not choose policies that maximize intergenerational welfare. (Arrow et all., 2003).

[92] The 23 countries used in our analysis are the following: Canada, U.S.A, Austria, Belgium, Denmark, Finland, France, Greece, Italy, Portugal, Spain, Sweden, Switzerland, U.K., Japan, Iceland, Ireland, Netherlands, Norway, Australia, Mexico, Turkey, Luxembourg.

[93] The 21 Developing countries used in our analysis are the following: Peru, Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Jamaica, Bolivia, Colombia, Ecuador, Iran, Srilanka, Syria, Yugoslavia, India, Kenya, Madagascar, Malawi, Sierra Leone, Zimbabwe.

[94] There are two basic reasons why we use CO_2 emissions in this paper as the basic contributant to the global warming phenomenon. The first reason is that CO_2 emissions is the most important of all the other GHGs such as methane, nitrous oxides etc in terms of percentage contribution in the global warming phenomenon. The second reason has to do with the avaliability of data on CO_2 emissions for those two large groups of countries.

the projected emission time paths[95], the CCSW obtained are negative. When CO_2 emission time paths are considered as a policy parameter and when we change them so that emissions do not increase over time, CCSW becomes positive. We believe that this theoretical framework is capable of providing policy suggestions regarding the productive base sustainability implied directly or indirectly from the empirical implementation of the model.

The next of chapter 4 is organized as follows. Chapter 4.2, describes our basic model. This model allows us to define a productive base sustainability criterion or the current change in social welfare conditions. We use a production function that includes capital along with technical change and CO_2 emissions as inputs in production. Chapter 4.3 defines the value function and the accounting prices of our model under the assumption of the global warming phenomenon. Chapter 4.4 defines the productive base sustainability criterion or the current change on social welfare conditions criterion and the next chapter 4.5 presents the parameters and the empirical results for each one of the two large group of countries we analyze. Chapter 4.6 presents our empirical estimations and chapter 4.7 presents some policy implications that arise from the empirical application and the results of our model. The last chapter concludes.

4.2 Descriptive Growth with Emissions as an Input

Starting from the concept of a non-optimizing economy in the sense that while firms maximize profits, consumers save a fixed proportion of their income, our attempt is to provide a measure of current changes in social welfare. We consider a stylized economy where the productive base includes a list of assets such as physical capital, human capital, and natural capital, along with labor augmenting (Harrod neutral) technical change and emission augmenting technical change. We consider the earth's atmosphere as a component of social overhead capital (Uzawa, 2003) which can play the role of natural capital. In this case natural capital is associated with the stock of accumulated GHG's and CO_2 emissions along with other GHG's can be thought as a reduction of this social capital - a form of disinvestment. Thus the impact of natural capital in our model is captured by two factors: emissions of CO_2 and other GHGs which are considered as an input into the aggregate production function. Environmental damages that are associated with the

[95] The Stern Report scenario corresponds to 2.5% annual increase of CO_2 emissions.

global stock of CO_2 and GHGs, which accumulate globally and cause global warming and climate change[96].

Capital accumulation in our stylized economy is described by using the standard Solow model. We assume that exogenous technical change of labour augmenting type and technical change associated with emissions are present. The production function we use is of the form:

$$Y = F(K, H, AL, BZ) \tag{67}$$

where K is physical capital, H is human capital, AL is effective labour with L being labor in physical units, A reflecting labor augmenting technical change[97] and BZ is effective input of emissions, with Z being emissions in physical units and B reflecting emission saving technical change, or input augmenting technical change[98]. Using the Cobb-Douglas assumption, the production function (67) becomes:

$$Y = K^{a_1} H^{a_2} (AL)^{a_3} (BZ)^{a_4}$$

Assuming the existence of constant returns to scale: $a_1 + a_2 + a_3 + a_4 = 1$, and expressing output in per worker terms, where $y = \frac{Y}{L}, k = \frac{K}{L}$, $z = \frac{Z}{L}$and $h = \frac{H}{L}$, we obtain:

$$\begin{aligned}
\frac{Y}{L} &= \left(\frac{K}{L}\right)^{a_1} \left(\frac{H}{L}\right)^{a_2} \left(\frac{AL}{L}\right)^{a_3} \left(\frac{BZ}{L}\right)^{a_4}, \\
y &= \left(e^{gt}\right)^{a_3} \left(e^{bt} z\right)^{a_4} k^{a_1} h^{a_2}, \\
y &= e^{(ga_3 + a_4 b)t} k^{a_1} h^{a_2} z^{a_4} \ , \ ga_3 + a_4 b = \lambda \\
y &= e^{\lambda t} k^{a_1} h^{a_2} z^{a_4}
\end{aligned}$$

Capital accumulation in per worker terms, assuming that the two capital goods (produced and human) depreciate at the same constant rate[99] is given by:

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[96] CO_2 emissions is the basic contributor to the global warming phenomenon and thus is used in this paper as the fundamental environmental factor in the production function.

[97] $A(t)$: *the level of* labor augmented technical change *is defined as* $A_0 e^{gt}$.

[98] $B(t) = B_0 e^{bt}$. We normalize the initial level of emission augmented technical change, by setting $B_0 = 1$ assuming that each of the groups of the countries we examine started at the beginning of our data period (1965) approximately at the same level of emissions augmenting technical change.

[99] For this assumption see Barro and Sala-i-Martin, (2004).

$$\dot{k} + \dot{h} = sy - (\eta + \delta)(k + h) \tag{68}$$

Defining $k = \hat{k}e^{\xi t}$, $h = \hat{h}e^{\xi t}$, and $z = \hat{z}e^{\xi t}$ in efficiency units we have:

$$\dot{k} = \dot{\hat{k}}e^{\xi t} + \xi\hat{k}e^{\xi t}, \;\; \dot{h} = \dot{\hat{h}}e^{\xi t} + \xi\hat{h}e^{\xi t} \text{ and } \dot{z} = \dot{\hat{z}}e^{\xi t} + \xi\hat{z}e^{\xi t} \tag{69}$$

Substituting $\dot{k}$ and $\dot{h}$ in (68) we obtain:

$$\dot{\hat{k}}_t e^{\xi t} + \xi\hat{k}e^{\xi t} + \dot{\hat{h}}_t e^{\xi t} + \xi\hat{h}e^{\xi t} = se^{\lambda t}(\hat{k}_t e^{\xi t})^{a_1}(\hat{h}_t e^{\xi t})^{a_2}\left(\hat{z}e^{\xi t}\right)^{a_4} - (\eta+\delta)(\hat{k}_t e^{\xi t} + \hat{h}_t e^{\xi t})$$

dividing with $e^{\xi t}$ we obtain:

$$\dot{\hat{k}}_t + \dot{\hat{h}}_t = \frac{se^{\lambda t}\hat{k}_t^{a_1}e^{\xi t a_1}\hat{h}_t^{a_2}e^{a_2\xi t}z_t^{a_4 a_2}e^{a_4\xi t}}{e^{\xi t}} - (\eta + \delta + \xi)(\hat{k}_t + \hat{h}_t)$$

$$\dot{\hat{k}}_t + \dot{\hat{h}} = se^{(\lambda - \xi + a_1\xi + a_2\xi)t}\hat{k}_t^{a_1}\hat{h}_t^{a_2}\hat{z}_t^{a_4} - (\eta + \delta + \xi)(\hat{k}_t + \hat{h}_t) \tag{70}$$

Setting $\lambda - \xi + a_1\xi + a_2\xi = 0$ so that (70) becomes time autonomous we have $\xi = \frac{\lambda}{1-a_1-a_2} = \frac{ga_3+a_4b}{1-a_1-a_2}$, and

$$\dot{\hat{k}}_t + \dot{\hat{h}} = s\hat{k}_t^{a_1}\hat{h}_t^{a_2}\hat{z}^{a_4} - (\eta + \delta + \xi)(\hat{k}_t + \hat{h}_t) \tag{71}$$

Following (Barro and Sala-i-Martin, 1995) we assume that savings are allocated between physical and human capital so that the two marginal products of capital are equal if we use both forms of investment. For this to be achieved, the following conditions should be satisfied:

$$a_1\frac{\hat{y}_t}{\hat{k}_t} - \delta = a_2\frac{\hat{y}_t}{\hat{h}_t} - \delta$$

The equality between marginal products implies a one to one relationship between physical and human capital:

$$\hat{h}_t = \frac{a_2}{a_1}\hat{k}_t, \;\; \dot{\hat{h}}_t = \frac{a_2}{a_1}\dot{\hat{k}}_t$$

then (71) becomes:

$$\dot{\hat{k}}_t + \frac{a_2}{a_1}\dot{\hat{k}}_t = s\hat{k}^{a_1}\left(\frac{a_2}{a_1}\hat{k}_t\right)^{a_2}\hat{z}^{a_4} - (\eta + \delta + \xi)\left(\hat{k}_t\frac{a_2}{a_1}\hat{k}_t\right) \tag{72}$$

$$\left(1+\frac{a_2}{a_1}\right)\dot{\hat{k}}_t = s\hat{k}^{(a_1+a_2)}\hat{z}^{a_4}\left(\frac{a_2}{a_1}\right)^{a_2} - (\eta+\delta+\xi)\left(1+\frac{a_2}{a_1}\right)k \tag{73}$$

$$\dot{\hat{k}}_t = s\left(\frac{{a_2^{a_2}}a_1}{a_1^{a_2}\left(a_1+a_2\right)}\right)\hat{k}^{(a_1+a_2)}\hat{z}^{a_4} - (\eta+\delta+\xi)\,k \tag{74}$$

Setting: $\left(\frac{{a_2^{a_2}}a_1}{{a_1^{a_2}}(a_1+a_2)}\right) = \Psi$, where Ψ is a constant, we have:

$$\dot{\hat{k}}_t = s\Psi\hat{k}_t^{a_1+a_2}\hat{z}^{a_4} - (\eta+\delta+\xi)\,\hat{k}_t \tag{75}$$

Setting $a_1+a_2=\phi$, then we have:

$$\dot{\hat{k}}_t = s\Psi\hat{k}_t^{\phi}\hat{z}^{a_4} - (\eta+\delta+\xi)\,\hat{k}_t \tag{76}$$

where output in efficiency units is defined as:

$$\hat{y} = \Psi\hat{k}_t^{\phi}\hat{z}^{a_4}$$

(76) is a Bernoulli equation which can be solved in the following way:
Multiplying with $\hat{k}_t^{-\phi}$ we have:

$$\dot{\hat{k}}_t\hat{k}_t^{-\phi} = s\Psi\hat{k}_t^{\phi}\hat{k}_t^{-\phi}\hat{z}^{a_4} - (\eta+\delta+\xi)\,\hat{k}_t\hat{k}_t^{-\phi}$$

$$\dot{\hat{k}}_t\hat{k}_t^{-\phi} = s\Psi\hat{z}^{a_4} - (\eta+\delta+\xi)\,\hat{k}_t\hat{k}_t^{-\phi}$$

$$\dot{\hat{k}}_t\hat{k}_t^{-\phi} + (\eta+\delta+\xi)\,\hat{k}_t\hat{k}_t^{-\phi} = s\Psi\hat{z}^{a_4} \tag{77}$$

$$\dot{\hat{k}}_t\hat{k}_t^{-\phi} + (\eta+\delta+\xi)\,\hat{k}_t^{1-\phi} = s\Psi\hat{z}^{a_4}$$

Setting $\gamma = \hat{k}_t^{1-\phi}$, we have $\dot{\gamma} = (1-\phi)\dot{\hat{k}}_t\hat{k}_t^{-\phi}$. Then:

$$\dot{\gamma} + (\eta+\delta+\xi)\,\gamma(1-\phi) = (1-\phi)s\Psi\hat{z}^{a_4} \tag{78}$$

which is linear in γ and the solution is the following:

$$\gamma_t = \left(\gamma_o - \frac{s\Psi\hat{z}^{a_4}}{\eta+\delta+\xi}\right)e^{-(1-\phi)(\eta+\delta+\xi)t} + \frac{s\Psi\hat{z}^{a_4}}{\eta+\delta+\xi} \tag{79}$$

replacing $\gamma_t = \hat{k}_t^{1-\phi}$, we have:

$$\hat{k}_t = \left[\left(\hat{k}_o^{1-\phi} - \frac{s\Psi\hat{z}^{a_4}}{\eta+\delta+\xi}\right)e^{-(1-\phi)(\eta+\delta+\xi)t} + \frac{s\Psi\hat{z}^{a_4}}{\eta+\delta+\xi}\right]^{\frac{1}{1-\phi}}$$

$$\hat{k}_\tau = \left[\left(\hat{k}_t^{1-\phi} - \frac{s\Psi\hat{z}^{a_4}}{\eta+\delta+\xi}\right)e^{-(1-\phi)(\eta+\delta+\xi)(\tau-t)} + \frac{s\Psi\hat{z}^{a_4}}{\eta+\delta+\xi}\right]^{\frac{1}{1-\phi}}$$

by replacing $\hat{z} = ze^{-\xi\tau}$, the solution for the time path of the stock of capital is of the form:

$$\hat{k}_\tau = \left[\left(\hat{k}_t^{1-\phi} - \frac{s\Psi\left(z_t e^{\xi\tau}\right)^{a_4}}{\eta+\delta}\right)e^{-(1-\phi)(\eta+\delta+\xi)(\tau-t)} + \frac{s\Psi\left(z_t e^{\xi\tau}\right)^{a_4}}{\eta+\delta}\right]^{\frac{1}{1-\phi}}, \text{ for } \tau \geq t \tag{80}$$

Equation (80) express the time path of the physical capital stock in the economy as a function of the parameters of the economy and the time path of emissions per capita. We examine the way that the path of emissions might be determined in a market economy in the next section and the implication of the time paths of emissions on the economy's value function.

4.3 Value Functions and Policy Implications under Global Warming

In this chapter we define the choice of emissions and the implied time path in a context of profit maximizing firms. Assume a representative competitive firm which solves the following profit maximization problem:

$$\begin{aligned} \max \Pi &= F(K, H, AL, BZ) - R_K K - R_H H - wL \\ &\text{subject to} \quad Z \leq \bar{Z} \end{aligned} \tag{81}$$

Positive marginal products for the inputs and profit maximization implies that $Z = \bar{Z}$. Where $\bar{Z}$ is an upper emissions limit for the representative firm. The upper bound on emissions could reflect technical constraints associated with production technologies or an emission limit determined exogenously by a regulator or an international agreement such as Kyoto. In this case aggregate emissions are constrained by the emission limit and emissions in per effective worker terms are defined as:

$$\hat{z} = \bar{Z}e^{-(\xi+\eta)t} = \frac{\bar{Z}}{L}e^{-\xi t} = \bar{z}e^{-\xi t} \tag{82}$$

where $\bar{Z}$ denotes the aggregate emission limit on CO_2 emissions and $\bar{z}$ the emission limit in per capita terms.

Using the standard Sollow assumption, where consumption is a fixed proportion of output we have that consumption in per effective worker terms is defined as:

$$\hat{c}_\tau = (1-s)\,\hat{y} \tag{83}$$

where $\hat{y} = ye^{-\xi t}$. Thus (83) will take the form:

$$\hat{c}_\tau = (1-s)\,\Psi \hat{k}_\tau^{\phi} \hat{z}_\tau^{a_4}$$

and by replacing $\hat{k}_\tau$ by (80) in the consumption function we have:

$$\hat{c}_\tau = (1-s)\,\Psi \left[\left(\hat{k}_t^{1-\phi} - \frac{s\Psi \left(\bar{z}_t e^{\xi\tau}\right)^{a_4}}{\eta+\delta} \right) e^{-(1-\phi)(\eta+\delta+\xi)(\tau-t)} + \frac{s\Psi \left(\bar{z}_t e^{\xi\tau}\right)^{a_4}}{\eta+\delta}^{\frac{\phi}{1-\phi}} \left(\bar{z}e^{-\xi t}\right)^{a_4} \right] \tag{84}$$

The general state of the environment is introduced into the model by the variable P, which is interpreted as the *stock* of CO_2 emissions which affects utility in a negative way. Then the utility function becomes a function of per capita consumption c_τ and total pollution P_τ and is assumed, as it is common in this type of analysis, to have the following separable specification:

$$U(c_\tau, P_\tau) = \frac{c_\tau^{1-\sigma}}{1-\sigma} - D(P_\tau) \text{ for } 0 \leq \sigma < 1 \tag{85}$$

$$U(c_\tau, P_\tau) = \ln c_\tau - D(P_\tau) \text{ for } \sigma = 1 \tag{86}$$

In (85) σ is the elasticity of marginal utility, and P_τ is pollution stock which creates disutility. Therefore $D(P_\tau)$ can be interpreted as a damage function assumed strictly increasing and convex. We specify the damage function as $D(P_\tau) = \beta P_\tau^\gamma$ with $\beta > 0$ and $\gamma \geq 1$. Since the production structure is determined in per effective worker terms, we need to specify the utility function (85) in per effective worker terms. If we define consumption per effective worker as $\hat{c} = \dfrac{C}{AN}$, from the definition of per capita consumption we have:

$$\frac{C_\tau}{N_\tau} = c_\tau = \hat{c}_\tau A_t e^{g(\tau-t)}$$

then we have:

$$u\left(c_\tau\right)=\frac{1}{1-\sigma}\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)^{1-\sigma}$$

and the utility function (85) becomes:

$$U\left(c_\tau,P_\tau\right)=\frac{1}{1-\sigma}\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)^{1-\sigma}-\beta P_\tau^\gamma \tag{87}$$

We assume that the evolution of CO_2 stock, denoted by P_τ, is determined by a first order linear differential equation:

$$\dot{P}_\tau=\sum_{j=1}^{J} Z_i - mP_\tau \ \ , P\left(t\right)=P_t \tag{88}$$

where $\sum_{j=1}^{J} Z_j = Z^T$ is the sum of aggregate emissions from $j=1,...,J$ countries which are possibly constrained under an international agreement, with m reflecting exponential GHG's decay.

The solution of (88) is:

$$P_\tau=(P_t-\frac{Z^T}{m})e^{-m(\tau-t)}+\frac{Z^T}{m} \tag{89}$$

Then damages from CO_2 stock for country j can be determined as

$$D_j(P_\tau)=\beta_j\left[(P_t-\frac{Z^T}{m})e^{-m(\tau-t)}+\frac{Z^T}{m}\right]^{\gamma_j}$$

The utility flow in per effective worker terms for country j can be specified as:

$$U_j\left(\hat{k}_t,A_t,z,Z^T,P_t\right)=\frac{1}{1-\sigma}\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)_j^{1-\sigma}-\beta_j\left[(P_t-\frac{Z^T}{m})e^{-m(\tau-t)}+\frac{Z^T}{m}\right]^{\gamma_j} \tag{90}$$

The flow of total utility in the economy is $N_{j\tau}U_j(c_\tau,P_\tau)$, therefore the value function for the economy, using (90) becomes:[100]

[100] A more complex structure would require, additional transition equations for say, natural resources (depletable or renewable), stocks of pollutants, human capital and so on. In this case the value function would depend on the current values of the stocks for these assets. The development of such a dynamic system, so that the value function can be defined in an operational way, is an area for future research.

$$V_{jt} = \int_t^\infty e^{-\rho(\tau-t)} N_{j\tau} U_j(\hat{k}_t, A_t, \hat{z}, Z^T, P_t)dt \ , \quad N_\tau = N_{jt} e^{n_j(\tau-t)} \tag{91}$$

$$V_{jt}\left(\hat{k}_t, N_t, A_t, , z, Z^T P_t\right) = \int_t^\infty e^{-(\rho-n_j)(\tau-t)} N_{jt} \left[\frac{1}{1-\sigma}\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)_j^{1-\sigma} - \beta_j \left((P_t - \frac{Z^T}{m})e^{-m(\tau-t)} + \frac{Z^T}{m}\right)^{\gamma_j}\right] dt \tag{92}$$

It should be noted that under an effective emission limit $\hat{z}$ is defined in terms of emission limit $\bar{z}$ through (82). We do not examined how countries have reached these emissions limits. They might have been determined through an agreements such as Kyoto's or limits might have been determined unilaterally. The key assumption is however that irrespective of how the limits have been set, they are not the outcome of an explicit optimization either at a national or at a global level, but, as it is probably more realistic, they are the outcome of a non-optimizing political process. In the above formulation we could distinguish between small and large countries. A small country will consider Z^T as a fixed exogenous parameter. On the other hand, a large country might recognize its contribution in total emissions. In this case, aggregate emissions for the large country l will be defined as:

$$Z^T = \bar{Z}_l + \sum_{j \neq l} \bar{Z} = \bar{Z}_l + Z_{-l}^T \tag{93}$$

If we write $\bar{Z}_l = \bar{z}_l e^{(\xi+\eta)t}$, then accounting prices for any country l at time t can be defined as:

$$p_{\hat{k}_{lt}} = \frac{\partial V_t}{\partial \hat{k}_{lt}}, \ p_{N_{lt}} = \frac{\partial V_t}{\partial N_{lt}}, \ p_{A_{lt}} = \frac{\partial V_t}{\partial A_{lt}}, \ p_{P_{lt}} = \frac{\partial V_t}{\partial P_{lt}}, \ p_{\bar{z}_{lt}} = \frac{\partial V_t}{\partial \bar{z}_{lt}}, \ p_{\bar{Z}_{-lt}^T} = \frac{\partial V_t}{\partial \bar{Z}_{-lt}^T} \tag{94}$$

It should be noted that there is an accounting price for the emission limit $\bar{z}_l$, which is formed by two effects. The effect of the emission limit on consumption through the production function as reflected in (85), and the effect of the emission limit on environmental damages, through aggregate emissions as reflected in the second term of (90). There is also an accounting price for the aggregate emissions of all other countries since these aggregate emissions affect environmental damages.

Since for any variable $\omega = \left(\hat{k}, \hat{z}\right)$ we have:

$$\hat{\omega} = \omega e^{-\xi t} = \frac{\Omega}{N} e^{-\xi t} \tag{95}$$

accounting prices in total and per capita terms are defined as:

$$p_{t\Omega_t} = \frac{\partial V_t}{\partial \hat{\omega}_t} \frac{\partial \hat{\omega}_t}{\partial \Omega_t} = \frac{e^{-\xi t}}{N_t} p_{t\hat{\omega}_t} \tag{96}$$

$$p_{t\omega_t} = \frac{\partial V_t}{\partial \hat{\omega}_t} \frac{\partial \hat{\omega}_t}{\partial \omega_t} = e^{-\xi t} p_{t\hat{\omega}_t} \tag{97}$$

4.4 A Productive Base Sustainability Criterion

In our stylized economy, a positive change in current social welfare can be considered as an indicator of productive-base sustainability for the country analyzed. In other words if:

$$\dot{V}_t = p_{K_t} \dot{K} + p_{N_t} \dot{N} + p_{A_t} \dot{A} + p_{\bar{Z}_t} \dot{\bar{Z}}_\tau + p_{P_t} \dot{P}_\tau \geq 0 \tag{98}$$

then the economy is currently productive base sustainable. More analytically, if the time derivative of the social welfare function is positive, this implies that CCSW is positive and that genuine investment is also positive,[101] without implying sustainability in individual utility terms. If the time derivative is negative, then genuine investment is negative[102]. p_{K_t}, p_{N_t}, p_{A_t}, $p_{\bar{Z}_t}$, p_{P_t} are the accounting prices for capital, population, technology, the emission limit and the pollution stock and $\dot{K}$, $\dot{N}$, $\dot{A}$, $\dot{\bar{Z}}_\tau$, $\dot{P}_\tau$ are the rates of change of capital, population, technological change, emission limit and the pollution stock respectively.

[101] Evidence provided by the World Bank (2006) suggest that investments in produced capital, human capital, and governance, combined with saving efforts aimed at offsetting the depletion of natural resources, can lead to future welfare increases in developing countries.

[102] As suggested by the World Bank (2006, Ch. 3), negative genuine saving rates imply that total wealth is in decline and policies leading to persistently negative genuine savings are unsustainable.

Dividing by Nk where $k = \dfrac{K}{N}$, using the fact that $\dot{k} = \dfrac{d\,(K/N)}{dt} = \dfrac{\dot{K}}{N} - \dfrac{\dot{N}}{N}k$ and that the accounting price for capital in physical terns is related to the accounting price of capital in per effective worker terms, by (96) we obtain:

$$S_t = \frac{\dot{V}_t}{N_t k_t} = \frac{p_{t\hat{k}_t}}{A_t N_t}\left(\frac{\dot{k}}{k} + \frac{\dot{N}}{N}\right) + p_{tN_t}\frac{\dot{N}}{N}\frac{1}{k_t} + p_{tA_t}\frac{\dot{A}}{A}\frac{A_t}{N_t k_t} + p_{\bar{Z}_t}\frac{\dot{\bar{Z}}_\tau}{Z}\frac{Z}{N_t k_t} + p_{P_t}\frac{\dot{P}_\tau}{P}\frac{P}{N_t k_t} \quad (99)$$

where S_t measures the change in the value of the economy per unit of produced capital stock at time t and could be interpreted as the rate of return on produced capital measured in terms of social welfare. By multiplying S_t by the current stock of capital we obtain a measure of current genuine investment. Using as before $\dot{A}/A = g$; $\dot{N}/N = n$; and denoting the rate of growth of capital per worker by $\dot{k}/k = v$; by $\frac{\dot{\bar{Z}}_\tau}{Z} = \chi$; the rate of growth of the flow emission limit with $\chi < 0$ indicating that environmental policy becomes gradually more stringent and $\chi > 0$ indicating that environmental policy is gradually becoming laxer; and with $\pi = \frac{\dot{P}_\tau}{P}$ the rate of change of the GHGs stock, we have that social welfare increases currently and thus development can be considered as currently sustainable in productive base terms if:

$$S_t = \frac{p_{t\hat{k}_t}}{A_t N_t}(v+n) + p_{tN_t} n \frac{1}{k_t} + p_{tA_t} g \frac{A_t}{N_t}\frac{1}{k_t} + p_{\bar{Z}_t}\chi\frac{Z}{N_t k_t} + p_{P_t}\pi\frac{P}{N_t k_t} \geq 0 \quad (100)$$

4.5 Empirical Estimations - Parameters and Results

Based on the descriptive growth model of chapter 4.2 and the methodology developed to determine whether an economy is currently productive base sustainable, positive change on social welfare or not, we define in this section the parameters used and present the numerical values. The table that follows defines the parameters. The values correspond to the period 1965-1990.

Parameters	*Values in tables*
v : Average growth of capital per worker	$(1,3)$
n : Average growth of population	$(1,3)$
β : Marginal damages from CO_2 stock	$(1,3)$
s : Average saving rate	$(1,3)$
χ : Average growth of CO_2 emissions	$(1,3)$
k : Average value of capital per worker	$(1,3)$
N : Average value of population per country	$(1,3)$
Z : Average of CO_2 emissions per country	$(1,3)$
$\blacksquare$: Constant of the production function	$(1,3)$
$\phi = a_1 + a_2$	$(2,4)$
a_3 : Production elasticity with respect to labor	$(2,4)$
a_4 : Production elasticity with respect to emissions	$(2,4)$
g : Rate of growth of labor augmenting technical change	$(2,4)$
b : Rate of growth of emissions augmenting technical change	$(2,4)$
δ : Depreciation rate	$(2,4)$
σ : Elasticity of marginal utility	$(2,4)$
$\lambda = ga_3 + ba_4$	$(2,4)$
ρ : Utility discount rate	$(2,4)$
π : Growth rate of total stock of CO_2	$(2,4)$
γ : Parameter of the damage function	$(2,4)$
$\blacksquare = \frac{\lambda}{1-a_1-a_2}$	$(2,4)$

a_1 and a_2 are the production elasticities with respect to physical and human capital. In the competitive context all elasticities can be interpreted as the corresponding input share in output. In the context of Barro's assumption about the equality of marginal products of physical and human capital, we can interpret ϕ as the sum of share of each of these two types of capital. For the case of *developed countries*: a_3 is the share of labor and a_4 is the share of emissions. For the case of *developing countries* a_3 is the share of emissions and a_4 does not exists.

Tables 1, 2, 3 and *4* that follow, present the parameter values used in our analysis for each one of the *23 developed* and the *21 developing* countries we analyze in order to estimate the productive base sustainability criterion (100). All the data from *tables 1, 3*, are estimated using the Penn World tables 5.6. The estimated parameters in *tables 2* and *4*, are taken from

Tzouvelekas, Vouvaki and Xepapadeas, (2006)[103].

Table 1: Parameters for the group of the 23 *developed countries*

Countries	v	n	β
CANADA	0.032928687	0.021663857	0.00000000589025
U.S.A.	0.025689321	0.016860844	0.0000000170573
AUSTRIA	0.056128625	0.005204929	0.0000000112802
BELGIUM	0.033679182	0.006020976	0.0000000112802
DENMARK	0.032228406	0.009740526	0.0000000112802
FINLAND	0.038567052	0.007327035	0.0000000112802
FRANCE	0.041156021	0.008760808	0.0000000112802
GREECE	0.048409278	0.005288991	0.0000000112802
ITALY	0.038191952	0.004650733	0.0000000112802
LUXEMBOURG	0.024833593	0.00845968	0.0000000112802
PORTUGAL	0.048177233	0.009314411	0.0000000112802
SPAIN	0.059058156	0.007504434	0.0000000112802
SWEDEN	0.03556534	0.009562269	0.0000000112802
SWITZERLAND	0.033619931	0.007888075	0.00000000589025
U.K.	0.034014633	0.004932269	0.0000000112802
JAPAN	0.076563662	0.010002479	0.00000000589025
ICELAND	0.041646473	0.02103928	0.00000000589025
IRELAND	0.043979598	0.008039493	0.0000000112802
NETHERLANDS	0.030230736	0.013831165	0.0000000112802
NORWAY	0.007732509	0.014628489	0.00000000589025
AUSTRALIA	0.023857968	0.021364042	0.00000000589025
MEXICO	0.028233733	0.030730162	0.00000000589025
TURKEY	0.046517799	0.01948306	0.00000000589025

table 1 continued

[103] Tzouvelekas, E., Vouvaki, D. and A. Xepapadeas, "Total Factor Productivity Growth and the Environment: A Case for Green Growth Accounting", FEEM working paper 42, 2006.

Countries	s	χ
CANADA	0.192667465	−0.000268545
U.S.A.	0.154015995	−0.005307595
AUSTRIA	0.224252472	0.010731307
BELGIUM	0.237979369	−0.007877097
DENMARK	0.207586337	−0.009204111
FINLAND	0.233684447	0.017010918
FRANCE	0.198030225	−0.007721138
GREECE	0.167062284	0.051160436
ITALY	0.208762513	0.021453243
LUXEMBOURG	*0.208762513*	−0.015120024
PORTUGAL	0.202154111	0.04375945
SPAIN	0.218688333	0.034295707
SWEDEN	0.206691146	−0.02630012
SWITZERLAND	0.319314338	0.004782584
U.K.	0.158115522	−0.008363536
JAPAN	0.300260704	0.029049305
ICELAND	0.164227689	−0.008439755
IRELAND	0.201257546	0.020256859
NETHERLANDS	0.260411589	0.001596095
NORWAY	0.285949685	0.005501036
AUSTRALIA	0.200730732	0.011726163
MEXICO	0.197188633	0.024634313
TURKEY	0.201245619	0.044337772

table 1 continued

Countries	k	N	Z	■
CANADA	29053.44	23264538.46	34.7	0.972305717
U.S.A.	26868.12	222123115.4	43	1.110251982
AUSTRIA	22481.44	7513230.769	15.7	0.852257132
BELGIUM	28152.6	9769153.846	29.8	0.884707674
DENMARK	25440.36	5034653.846	21.9	0.801291883
FINLAND	31474.16	4758153.846	19.4	0.704514053
FRANCE	25789.96	53046269.23	17.9	0.932318299
GREECE	17145.92	9355846.154	12.3	0.610576308
ITALY	22957.64	55493192.31	15.1	0.919599527
LUXEMBOURG	37022.96	357807.6923	74.9	0.828567478
PORTUGAL	7720.64	9487769.231	5.7	0.640545578
SPAIN	16900.32	36152269.23	12.5	0.895747244
SWEDEN	27359.56	8204807.692	18	0.909050164
SWITZERLAND	53245.24	6344538.462	12.7	0.865843589
U.K.	15321.44	56133653.85	22.1	0.919075505
JAPAN	19857.68	112855269.2	11.7	0.639526001
ICELAND	13281.72	223307.6923	15.6	0.949797951
IRELAND	15612.68	3251692.308	18.5	0.723397077
NETHERLANDS	25850.72	13791192.31	24.9	0.996420422
NORWAY	41986.04	4021692.308	14.2	0.762167448
AUSTRALIA	29943.04	14228115.38	28.7	0.918414009
MEXICO	11906.36	63155307.69	9.5	0.804922725
TURKEY	5459.76	42756115.38	4	0.443093265

For *tables 1 - above-* and *3* - that follows- the parameters were obtained as follows: the average of the saving rates s for the case of the *developed countries* were obtained from the National Accounts of OECD database and for the case of the *developing countries* were obtained from the Economics, Business, and the Environment — National Savings: Gross savings as a percent of GNI. In estimating the production function we used fixed effects estimation so Ψ was the sum of the coefficient of the production function and the fixed effects of the production function. The shares of capital, labor, emissions and the rate of growth of labor augmenting and emission's augmenting technical change were obtained from Tzouvelekas, Vouvaki and Xepapadeas, 2006[104]. β which is the marginal damages from CO_2 stock was

[104] Tzouvelekas, E., Vouvaki, D. and A. Xepapadeas, "Total Factor Productivity Growth and the Environment: A Case for Green Growth Accounting", FEEM working paper 42,

estimated for the developed countries using Fankhauser and Tol (1997) who estimated damages from the doubling of CO_2 in different world regions. For the developing countries, marginal damages were obtained using Nordhaus (1998)[105].

Table 2: Common parameter values

$Parameter$	ϕ	a_3	a_4	g	b	ga_3	ba_4	δ
$Value$	0.325968	0.596	0.077	0.014	0.026	0.008	0.002	0.03

σ	$\lambda = ga_3 + ba_4$	ρ	γ	$\blacksquare = \frac{\lambda}{1-a_1-a_2}$
0.5	0.010675682	0.03	1	0.015838539

For *tables 2 - above-* and *4* - that follows, the parameters were obtained as follows: the depreciation rate δ was the same for the case of developed and developing countries and was obtained from Mankiw et all., (1992). The elasticity of marginal utility σ was also the same for both cases and suggests that the equal distribution of income does not have a significant weight in the utility function. The utility discount rate ρ was taken 3%[106] and $\gamma = 1$ which implies a linear damage function.

The parameter values for the group of *developing countries* are summarized in table 3 that follows.

Table 3: Parameters for the group of the 21 *developing countries*

2006.

[105] W. D. Nordhaus, 1998, Revised Estimates of the Impacts of Climate Change.

[106] The value of 3% has been used by a number of researchers for the estimation of marginal social costs of CO_2 emissions (see, for example, surveys by Fankhauser and Tol, 1997, Tol, 2005). The values of 1% and 2%, along with time declining rates, have also been used in these studies.

Countries	v	n	β
PERU	0.012155219	0.026573374	0.0000000907476
THAILAND	0.064312423	0.026938467	0.0000000529394
PARAGUAY	0.0599008	0.029792926	0.0000000907476
MOROCCO	0.01180978	0.030086627	0.0000000578675
DOMINICAN REP.	0.052249044	0.029116439	*0.0000000578675*
GUATEMALA	0.021661835	0.025445452	0.0000000907476
HONDURAS	0.016896959	0.031984921	0.0000000907476
JAMAICA	−0.00078736	0.021162102	*0.0000000907476*
BOLIVIA	0.030452654	0.021997488	0.0000000907476
COLOMBIA	0.02456555	0.025270989	0.0000000907476
ECUADOR	0.039715588	0.025793195	0.0000000907476
IRAN	0.069761428	0.034655315	0.0000000692038
SRILANKA	0.030501594	0.018220663	0.0000000529394
SYRIA	0.017400356	0.0300723	0.0000000692038
YUGOSLAVIA	0.050017192	0.008301377	*0.0000000692038*
INDIA	0.036262979	0.019425761	0.0000000529394
KENYA	−0.007093912	0.040524848	0.0000000578675
MADAGASCAR	0.007302069	0.020755864	0.0000000578675
MALAWI	0.056975768	0.025468426	0.0000000578675
SIERRALEONE	0.048099166	0.014407023	0.0000000578675
ZIMBABWE	−0.015083099	0.036904505	0.0000000578675

Table 3 continued

Countries	s	χ
PERU	0.1877	−0.002464966
THAILAND	0.2777297297	0.075204219
PARAGUAY	0.1564102564	0.026822542
MOROCCO	0.2085714286	0.038209517
DOMINICAN REP.	0.1932432432	0.043170423
GUATEMALA	0.11885	0.012405097
HONDURAS	0.1550263158	0.017557974
JAMAICA	0.1973	0.017935637
BOLIVIA	0.1459714286	0.029362691
COLOMBIA	0.1784285714	0.010349838
ECUADOR	0.145425	0.05290342
IRAN	0.2933793103	0.020324961
SRILANKA	0.17465	−0.003297832
SYRIA	0.1774857143	0.061044875
YUGOSLAVIA	*0.1774857143*	0.03099768
INDIA	0.20095	0.036739344
KENYA	0.167225	−0.006222883
MADAGASCAR	0.5808333333	0.000359423
MALAWI	0.028	−0.003835103
SIERRALEONE	0.3292	−0.007724857
ZIMBABWE	0.1395789474	0.009521261

Table 3 continued

Countries	k	N	Z	■
PERU	8648.615385	16312.34615	4.006080643	1.67630338
THAILAND	2866.730769	43799.96154	1.481421126	1.138801052
PARAGUAY	609.3076923	3010.769231	1.159184513	2.003815273
MOROCCO	2147.615385	18701.69231	2.280925304	1.487305361
DOMINICAN REP.	3836.615385	5408.153846	3.602092971	1.448813579
GUATEMALA	3298	6600.846154	1.701286795	2.021977514
HONDURAS	4286.192308	3492.384615	1.628043995	1.206198888
JAMAICA	4436.384615	2064.615385	7.004211969	0.984705172
BOLIVIA	5720.346154	5330.307692	2.174962904	1.303648667
COLOMBIA	10647.73077	25299.73077	4.818757212	1.438349103
ECUADOR	11560.53846	7690.538462	4.170708691	1.528243444
IRAN	8191.384615	37401.38462	11.59577103	1.966782581
SRILANKA	6924.961538	14127.73077	0.699531707	1.439297288
SYRIA	12150.84615	8287.5	7.553502822	1.993631799
YUGOSLAVIA	5422.346154	21765.53846	9.351693997	1.410042717
INDIA	1376.153846	656496.1154	1.269852887	0.740467897
KENYA	1130.076923	15803.53846	0.650252843	0.773179535
MADAGASCAR	1731.038462	8379.230769	0.258102064	1.05960691
MALAWI	365.7307692	5860.038462	0.200389063	0.735358606
SIERRALEONE	163.3076923	3162.692308	0.420699171	1.606222261
ZIMBABWE	5759.615385	6768.346154	3.451498869	0.569696794

Table 4: Common parameter values

Parameter	ϕ	$a_3 = s_z$	g	b	ga_2	ba_3
Value	0.095117	0.330547	0.00815	0.00405	0.004684	0.001339273

δ	σ	$\lambda = ga_2 + ba_3$	ϱ	γ	$\blacksquare = \frac{\lambda}{1-a_1-a_3}$
0.03	0.5	0.006023273	0.03	1	0.010487368

To determine (99) and (100), we also need values regarding the growth of CO_2 emissions and the growth of CO_2 stock. Treating the future growth of CO_2 emissions as a policy variable, the evolution of the CO_2 stock can be determined using (89) as:

$$P(t) = \frac{e^{xt} Z_0}{m + x} + e^{-mt}(P_0 - \frac{Z_0}{m + x}) \tag{101}$$

where m is the exponential pollution decay on emissions, x is the rate of growth of global CO_2 emissions, P_0 is the initial stock of CO_2 and Z_0 is the initial level of total CO_2 emissions globally. Regarding the parameters values, the initial stock of pollution from CO_2 emissions P_0 was 785.3 billion tons of CO_2 obtained from Guillerminet and Tol (2005) and the initial level of global total emissions (flow) Z_0 was 6.15 billion tons of CO_2 and was obtained from Guillerminet and Tol (2005). m, the exponential pollution decay on emissions taken at a value of 0.0083 from Reillly and Richards (1993). For the value of x we used three different scenaria regarding the evolution of CO_2 emissions. The first scenario, which was motivated by the Stern Report[107], follows the assumption that the global CO_2 emissions increase annually by 2.5% or $x = 0.025$ per year. The second scenario is a scenario of constant global CO_2 emissions $x = 0$, that enabled us to extract helpful results for the impact of the environmental factor on productive base sustainability. The third scenario is based on an annual increase of global emissions per 0.5% or $x = 0.005$ per year. This is a completely arbitrary scenario chosen to check whether for low rates of growth of annual global CO_2 emissions, the productive base sustainability criterion changes sign.

4.6 Accounting Prices and Productive Base Sustainability for Developed and Developing Countries

This chapter presents the results of our empirical estimations which are based on our empirical model and the parameter values described in chapter 4.5. The accounting prices for the two groups of countries and the signs of the CCSW or the productive base sustainability criterion of the economies analyzed were obtained under the three different scenaria of global CO_2 emissions described in chapter 4.5.

When we follow scenario 1 ($x = 0.025$), the results indicate that both for *developed* and *developing* economies the accounting prices of capital (APK), CO_2 emissions ($A.PCO_2$), technological change (APG) are positive while the accounting prices of global emissions of CO_2 ($APGz$) and of the stock of CO_2 (APP) are negative. The signs of the accounting prices can be interpreted as following: When capital, CO_2 emissions and technological change increase per one unit, then the social welfare also increases. On the other

[107] "Annual emissions are still rising. Emissions of carbon dioxide, which accounts for the largest share of greenhouse gases, grew at an average annual rate of around $2\frac{1}{2}$% between 1950 and 2000. In 2000, emissions of all greenhouse gases were around 42GtCO2e, increasing". The Stern Review, Part III: The Economics of Stabilisation, Chapter 7 pp. 169

hand, when global emissions and of the stock of CO_2 increases, this reduces social welfare and thus the sign of those accounting prices is negative. For the case of *scenario 1*, the sign of the current change on social welfare conditions $\left(\dot{V}\right)$ is *negative* which is something we expected due to the positive and high environmental degradation that the persistent increase of global annual CO_2 emissions create. Following *scenario 2* ($x = 0$), we observe that the results change significantly. As far as the signs of the accounting prices are concerned, we have the same pattern, but the CCSW criterion - $\left(\dot{V}\right)$ is now *positive* both for the case of *developed and developing* countries. This result confirms the hypothesis that the currently regarded as plausible path of global CO_2 emissions affects *negatively* productive base sustainability. Thus, our results indicate that by keeping emissions at a constant level, this environmental friendly but probably unrealistic scenario would provide positive results for the CCSWC and imply current productive base sustainability. *Scenario 3* ($x = 0.005$), provides the same *positive values* for the accounting prices of capital, CO_2 emissions, and technological change, *negative values* for the accounting prices of global emissions, the stock of CO_2 and the productive base sustainability criterion[108].[109] This pattern confirms our initial hypothesis and observation that even with a very small percentage annual increase of CO_2 emissions, the results are not optimistic for productive base sustainability. Those results are an indication of the need for a strict management of global CO_2 emissions in order to avoid the erosion of the sustainability of the productive base of the economy that the global warming phenomenon creates.

4.7 Policy Implications

As shown from the results of our empirical analysis, there are some basic parameters that affect the sign of the CCSW criterion. The basic one, is the accumulation of global CO_2 emissions in the atmosphere. We observe from our empirical analysis that when the annual growth of global CO_2 emissions increase from 0% to 0.5% or 2.5%, the current change in social

[108]For the case of Mexico (developed countries) in scenario 3, the result of the Current Changes on Social Welfare Conditions $\dot{V}$ is *positive* in contrast with all the other countries under analysis where the sign of $\dot{V}$ is negative for 0.5% global CO_2 emissions increasement.

[109]The calculations were performed using Mathematica. All the codes are available by the author at: http://www.soc.uoc.gr/vouvaki - Mathem. Code. Two of the calculations are presented in the appendix of the current chapter as an example.

welfare criterion changes sign and becomes negative ($\dot{V} < 0$). In particular, when we have 0% rate of growth of global emissions, then the growth of the stock of CO_2 emissions is negative and the growth of emissions of each country is zero. This means that the state of the environment has a positive impact on total social welfare and the criterion is positive both for the group of the developed and the developing economies. When we change the annual global emissions rate of growth to 0.5%, the growth of the stock of CO_2 is positive. This implies that the CO_2 accumulation has a negative impact on total social welfare and the criterion turns negative for developed and developing countries. When the global emissions rate of growth becomes 2.5%, the growth of the stock of CO_2 is also positive and the change in social welfare is "more negative" relative to the 0.5% CO_2 growth scenario. The global CO_2 emission's rate of growth can be adjusted by the use of specific policy tools such as emission limits ($\bar{Z}$) or emission taxes (τ). Those emission limits can be used on a country level so that global CO_2 emissions not to exceed a specific maximum level $Z^{global\max}$. Similar results can be obtained with the imposition of a tax as a policy tool. The Kyoto protocol can be regarded as an attempt to define $\bar{Z}$ and therefore the growth of emissions of the participating countries and globally. Our results suggests that in order to have productive base sustainability, the international agreements should set the limit of emission's growth very close to 0%.

From the results we obtained, we observe that there is a direct relationship between the growth of emissions of each country we analyze, the growth of global emissions, the growth of CO_2 stock and productive base sustainability criterion. The growth of emissions of each country affects the growth of global emissions which affects the growth of CO_2 stock. A result, a reduction of global CO_2 emissions could have two conflict impacts. The first is that reduced emissions will produce gains in terms of reduced CO_2 stock and this a positive effect for productive base sustainability. The second is that reduced emissions in a country may imply output reduction if other cleaner ways of production are not used. This implies reduced consumption and capital accumulation and a negative effect or productive base sustainability. Our results suggest that if emissions are kept constant the gains from the reduction of the global CO_2 stock outweights any losses in output in an individual country, for all the countries examined and promotes productive base sustainability in all countries.

It is well known that output growth has been connected to the environment and sometimes the perception exists that environmental consciousness, care and environmental friendly politics can harm growth. Nevertheless, studies as those related to the environmental Kuznets curve and the related literature seem to provide evidence that tend to change this hypothesis and delink output growth and the environment in terms of reduction of total output in the case where environmental friendly policies are used. From our model, a parameter that can play an important role toward this de linking is the parameter b - the emission's augmenting technological change. The significance of this parameter is that it can be used as a potential policy tool to compensate for the negative impact that a reduction in emissions can have on growth. This can be obtained for example by subsidies for the use of cleaner technologies or by international R&D cooperation.

The second question that arises is whether a single country is able to change the sign of CSW and whether unilateral policies can have results and how significant those results will be in terms of productive base sustainability both for the country that takes the unilateral action of reducing CO_2 emissions and also for other countries that might benefit from the unilateral actions, since global CO_2 emissions might be reduced. This is a hard issue to be addressed due to the reason that when we deal with the greenhouse effect and climate change, we refer to global magnitudes. What we measure in these cases, is the contribution of all countries in total emissions. Unilateral policies can lead to the reduction of emissions in certain countries if these policies are applicable and effective. The case where the contribution of a group of countries in total emissions is positive (which is the realistic case) but there is one country with negative contribution in total emissions, the question that arises is whether this reduction can counterbalance the total result on current CSW. For example, if USA reduces its annual emissions of CO_2 and the rest of the world keeps increasing annual CO_2 emissions, the question is whether and how much productive base sustainability for each country will be affected. The significant parameter here is the percentage (%) contribution of a single country to total emissions. When we deal with U.S.A for instance, we know that this country has large importance in the global warming phenomenon as implied by the large contribution of U.S.A emissions on global emissions. If U.S.A for example followed policies that reduced it's CO_2 emissions yearly by 2%, this could promote productive base sustainability both in the U.S.A and in the rest of the world. This final result however depends also on the reaction of other countries. If the unilateral action triggers more emissions by other countries since they might expect that their increased emissions will be counterbalanced by the unilateral action, then the final result might be overall negative CSW. To further examine this question we measured the productive base sustainability criterion for the case of U.S.A using the following assumptions. The rate of growth of CO_2 emissions for U.S.A was negative and at the same time we assumed an annual global CO_2 emissions increase of 2.5% (for the other countries). The productive base sustainability criterion was negative. This experiment means that eventhough U.S.A, a country with a large contribution in the global warming phenomenon, could follow policies leading to a negative rate of growth of its own CO_2 emissions, this does not imply that the productive base sustainability criterion will be positive with a rate of growth of CO_2 emissions for the rest of the world increasing at 2.5% per year. This result suggests that the final result about productive base sustainability depends on the reaction of other countries. Our model could help at tracing these effects since basically this implies the incorporation of alternative paths for CO_2 emissions for different countries. The last test we run in order to verify that our main results were robust, was to choose a logarithmic utility function[110] instead of (90) where elasticity of marginal utility was $\sigma = 0.5$, assuming therefore $\sigma = 1$ we obtain results for the productive base sustainability criterion both in developed and in developing countries. The results we obtained using the logarithmic utility function are summarized as follows: When we follow scenario 1 ($x = 0.025$), with a global CO_2 emissions increacement per 2.5% and a logarithmic utility function, the productive base sustainability criterion becomes negative and the accounting prices of capital, technical change and emissions are positive while the accounting prices of global emissions and CO_2 stock are negative. If we follow scenario 2 where global CO_2 emissions is zero ($x = 0$), we observe that the results remain the same as before when we used (90) with $\sigma = 0.5$, both for developed and developing countries. More analytically, the productive base sustainability criterion is positive and the accounting prices of capital, technical change and emissions are positive while the accounting prices of global emissions and CO_2 stock are negative. Thus, the same conclusions and implications regarding productive base sustainability can be derived for the case where we use the same utility function that the Stern Report assumes.

4.8 Concluding Remarks

[110] Such a function has been extensively used in the Stern report, so our results about productive base sustainability could be interpreted in the context of the utility function assumptions of the Stern report.

One of the basic variables that affect the current change on social welfare (CCSW) conditions is CO_2 emissions along with other GHG's emissions which are considered to be the basic contributors to the global warming phenomenon. This paper attempts to formulate a theoretical model to provide empirical results for the productive base sustainability of economies under global warming and can be characterized as a *productive base approach to sustainable development*. To achieve this, we tried to determine a criterion that measures the current change of the productive base of an economy by taking into account the environmental damage created from the global warming phenomenon. We considered a non optimizing growth framework and we derived results for the productive base sustainability of two large groups of countries, developed and developing. We applied the model in 23 developed and 21 developing countries by using three different scenaria of global CO_2 emissions' growth and we obtained results for the current productive base sustainability of each one of them.

The main empirical finding of the paper under two alternative utility function specifications is that when we follow the scenaria where global CO_2 emissions increase, then the productive base sustainability criterion is negative for almost all the countries under analysis. When global CO_2 emissions remain constant, the productive base sustainability criterion is positive both for the case of developed and for the case of developing countries. Our empirical findings confirm the perception that the intensification of the global warming phenomenon can erode the productive base sustainability of modern economies.

Appendix

The following calculations were performed using Mathematica.The first one refers to Canada (from the group of the developed countries) where we follow scenario 1, (x = grthgz =0.025; global CO_2 emissions increacement per 2.5%). The second example refers to Peru (from the group of the developing countries) where scenario 1 is used again. The results are shown in the next pages. The rest of the codes are available by the author at: http://www.soc.uoc.gr/vouvaki - Mathem. Code and at the CD which is included in the end of the thesis.

```
(*Acounnting prices, value function and derivative of value function CANADA*)

(*we define consumption hat*)

Clear[g, b, a1, a3, a4, η, ρ, γ, β, s, δ, σ, ν, Ψ, ϕ, ξ, m, x1, x2]
Clear[khat, k, zbar, z, zhat, alpha, p, n, gz, grthgz]

General::spell1 :
 Possible spelling error: new symbol name "zhat" is similar to existing symbol "khat". More…

x1 = 0; x2 = 0;

khat = k * Exp[-ξ * t]
```

$e^{-t\,\xi}\,k$

```
zhat = z * Exp[-ξ * t]
```

$e^{-t\,\xi}\,z$

```
chat[k_, z_, x1_, t_] =
  (1 - s) * Ψ * (((khat^(1 - ϕ) - s * Ψ * z^a4 / (η + δ))) * Exp[-(1 - ϕ) * (η + δ + ξ) * t] +
      s * Ψ * (zhat)^a4 / (η + δ))^(ϕ / (1 - ϕ)) * (zhat)^a4

General::spell :
 Possible spelling error: new symbol name "chat" is similar to existing symbols {khat, zhat}. More…
```

$$(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}$$

(*we define utility per capita as u= $\frac{c^{1-\sigma}}{1-\sigma}$ *)

```
u[k_, z_, gz_, grthgz_, t_, alpha_, p_] =
  (((chat[khat, z, x1, t] * alpha * Exp[g * t])^(1 - σ)) / (1 - σ)) -
   β ((p - gz / (m + grthgz)) * Exp[-m * t] + gz * Exp[grthgz * t] / (m + grthgz))^γ
```

$$-\left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{\gamma}\beta+\frac{\left(alpha\,e^{g\,t}\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{1-\sigma}}{1-\sigma}$$

```
(*value function*)
v1[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] =
 Exp[-(ρ - η) * t] * n * u[k, z, gz, grthgz, t, alpha, p]
```

$$e^{t\,(\eta-\rho)}\,n\left(-\left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{\gamma}\beta+\frac{\left(alpha\,e^{g\,t}\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{1-\sigma}}{1-\sigma}\right)$$

```
(*accounting price for k*)
```

pk[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_k v1[k, z, gz, grthgz, t, alpha, p, n]

$$\text{alpha}\, e^{g\,t-2\,t\,\xi+t\,(\eta-\rho)+t\,(\delta+\eta+\xi)\,(-1+\phi)}\,(e^{-2\,t\,\xi}\,k)^{-\phi}\,n\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\phi\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{-1+\frac{\phi}{1-\phi}}\left(\text{alpha}\,e^{g\,t}\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{-\sigma}$$

(*accounting price for n*)
pn[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_n v1[k, z, gz, grthgz, t, alpha, p, n]

$$e^{t\,(\eta-\rho)}\left(-\left(\frac{e^{\text{grthgz}\,t}\,gz}{\text{grthgz}+m}+e^{-m\,t}\left(-\frac{gz}{\text{grthgz}+m}+p\right)\right)^{\gamma}\beta+\frac{\left(\text{alpha}\,e^{g\,t}\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{1-\sigma}}{1-\sigma}\right)$$

(*accounting price for alpha*)
palpha[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] =
∂_{alpha} v1[k, z, gz, grthgz, t, alpha, p, n]

General::spell1 :
Possible spelling error: new symbol name "palpha" is similar to existing symbol "alpha". More…

$$e^{g\,t+t\,(\eta-\rho)}\,n\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\left(\text{alpha}\,e^{g\,t}\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{-\sigma}$$

(*accounting price for z*)
pz[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_z v1[k, z, gz, grthgz, t, alpha, p, n]

$$e^{t\,(\eta-\rho)}\,n\left(\text{alpha}\,e^{g\,t}\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{-\sigma}\left(a4\,\text{alpha}\,e^{g\,t-t\,\xi}\,(1-s)\,(e^{-t\,\xi}\,z)^{-1+a4}\,\Psi\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}+\frac{1}{1-\phi}\left(\text{alpha}\,e^{g\,t}\,(1-s)\,(e^{-t\,\xi}\,z)^{a4}\,\phi\,\Psi\left(-\frac{a4\,e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\,s\,z^{-1+a4}\,\Psi}{\delta+\eta}+\frac{a4\,e^{-t\,\xi}\,s\,(e^{-t\,\xi}\,z)^{-1+a4}\,\Psi}{\delta+\eta}\right)\left(\frac{s\,(e^{-t\,\xi}\,z)^{a4}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2\,t\,\xi}\,k)^{1-\phi}-\frac{s\,z^{a4}\,\Psi}{\delta+\eta}\right)\right)^{-1+\frac{\phi}{1-\phi}}\right)\right)$$

(*accounting price for gz*)

pgz[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_{gz} v1[k, z, gz, grthgz, t, alpha, p, n]

$$-e^{t(\eta-\rho)}\left(\frac{e^{grthgz\,t}}{grthgz+m}-\frac{e^{-m\,t}}{grthgz+m}\right) n \left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{-1+\gamma}\beta\gamma$$

(*accounting price for pollution*)
pp[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_{p} v1[k, z, gz, grthgz, t, alpha, p, n]

$$-e^{-m\,t+t(\eta-\rho)}\,n\left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{-1+\gamma}\beta\gamma$$

g = 0.014441 ; b = 0.026558 ; a1 = 0.325968 ; a3 = 0.59629 ; a4 = 0.077742 ;
η = 0.021663857 ; ρ = 0.03 ; γ = 1 ; β = 0.00000000589025 ; s = 0.192667465 ;
δ = 0.03 ; σ = 0.5 ; ν = 0.032928687 ; Ψ = 0.972305717 ; ϕ = 0.325968 ;
ξ = 0.015838539 ; m = 0.0083 ; λ = 0.010675682 ; x1 = 0 ; x2 = 0 ; grthgz = 0.025 ;

(*ACCOUNTING PRICES DEFINED BY THE INTEGRAL*)

k = 29053.44; z = 34.7; alpha = 0.972305717;
p = 785300000000; n = 23264538; gz = 6158700000;

(*value function*)
v1[k, z, gz, grthgz, t, alpha, p, n]

$$23264538\, e^{-0.00833614\,t}\Big(-5.89025\times10^{-9}\,(6.00354\times10^{11}\,e^{-0.0083\,t}+1.84946\times10^{11}\,e^{0.025\,t})+ 2.00555\,\Big(e^{0.014441\,t}\,(e^{-0.0158385\,t})^{0.077742}\,\big(4.77719\,(e^{-0.0158385\,t})^{0.077742}+ e^{-0.0454988\,t}\,(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032})\big)^{0.483609}\Big)^{0.5}\Big)$$

(*Integral of Value Function-Social Welfare*)

NIntegrate[v1[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

$-1.596760465039380\times10^{7249}$

(*Capital per worker*)

pk[k, z, gz, grthgz, t, alpha, p, n]

$$\left(266817.\,e^{-0.071071\,t}\,(e^{-0.0158385\,t})^{0.077742}\right)\Big/\Big((e^{-0.0316771\,t})^{0.325968}\,\Big(e^{0.014441\,t}\,(e^{-0.0158385\,t})^{0.077742}\,\big(4.77719\,(e^{-0.0158385\,t})^{0.077742}+ e^{-0.0454988\,t}\,(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032})\big)^{0.483609}\Big)^{0.5}\,\big(4.77719\,(e^{-0.0158385\,t})^{0.077742}+e^{-0.0454988\,t}\,(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032})\big)^{0.516391}\Big)$$

ack = NIntegrate[pk[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

NIntegrate::ncvb : NIntegrate failed to converge to prescribed accuracy after 7 recursive bisections in t near t = 91.24152131216795`. More…

60186.

(* n Population*)

pn[k, z, gz, grthgz, t, alpha, p, n]

$$e^{-0.00833614\,t}\left(-5.89025\times10^{-9}\,(6.00354\times10^{11}\,e^{-0.0083\,t}+1.84946\times10^{11}\,e^{0.025\,t})+2.00555\left(e^{0.014441\,t}\,(e^{-0.0158385\,t})^{0.077742}\left(4.77719\,(e^{-0.0158385\,t})^{0.077742}+e^{-0.0454988\,t}\left(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032}\right)\right)^{0.483609}\right)^{0.5}\right)$$

acn = NIntegrate[pn[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

$-6.863495269235005\times10^{7241}$

(*accounting price for alpha*)

palpha[k, z, gz, grthgz, t, alpha, p, n]

$$\left(2.39936\times10^{7}\,e^{0.00610486\,t}\,(e^{-0.0158385\,t})^{0.077742}\left(4.77719\,(e^{-0.0158385\,t})^{0.077742}+e^{-0.0454988\,t}\left(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032}\right)\right)^{0.483609}\right)\Big/\left(e^{0.014441\,t}\,(e^{-0.0158385\,t})^{0.077742}\left(4.77719\,(e^{-0.0158385\,t})^{0.077742}+e^{-0.0454988\,t}\left(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032}\right)\right)^{0.483609}\right)^{0.5}$$

acalpha = NIntegrate[palpha[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

2.03267×10^{10}

(*accounting price for z*)

pz[k, z, gz, grthgz, t, alpha, p, n]

$$\Bigg(2.32002\times10^{7}\,e^{-0.00833614\,t}\Bigg(\left(0.486296\,e^{0.014441\,t}\,(e^{-0.0158385\,t})^{0.077742}\left(-0.0107028\,e^{-0.0454988\,t}+0.0107028\,(e^{-0.0158385\,t})^{0.077742}\right)\right)\Big/\left(4.77719\,(e^{-0.0158385\,t})^{0.077742}+e^{-0.0454988\,t}\left(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032}\right)\right)^{0.516391}+\frac{1}{(e^{-0.0158385\,t})^{0.922258}}\left(0.00225285\,e^{-0.00139754\,t}\left(4.77719\,(e^{-0.0158385\,t})^{0.077742}+e^{-0.0454988\,t}\left(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032}\right)\right)^{0.483609}\right)\Bigg)\Bigg)\Big/\left(e^{0.014441\,t}\,(e^{-0.0158385\,t})^{0.077742}\left(4.77719\,(e^{-0.0158385\,t})^{0.077742}+e^{-0.0454988\,t}\left(-4.77719+1019.38\,(e^{-0.0316771\,t})^{0.674032}\right)\right)^{0.483609}\right)^{0.5}$$

acz = NIntegrate[pz[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

5.98802×10^{7}

(*accounting price for gz*)

pgz[k, z, gz, grthgz, t, alpha, p, n]

$$-0.137034\,e^{-0.00833614\,t}\,(-30.03\,e^{-0.0083\,t}+30.03\,e^{0.025\,t})$$

```
acpgz = NIntegrate[pgz[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]
```

$-2.592690770843490\times10^{7239}$

```
(* accounting price fpr pollution stock*)

pp[k, z, gz, grthgz, t, alpha, p, n]
```

$-0.137034\, e^{-0.0166361\, t}$

```
acp = NIntegrate[pp[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]
```

-8.23712

```
(*time derivative of the value function*)

ack
```

60186.

```
acn
```

$-6.863495269235005\times10^{7241}$

```
acalpha
```

2.03267×10^{10}

```
acz
```

5.98802×10^{7}

```
acpgz
```

$-2.592690770843490\times10^{7239}$

```
acp
```

-8.23712

```
growthalpha = 0.014441; growthn = 0.021663857;
growthp = 0.02198545696425092; growthz = -0.000268545; growthk = 0.032928687;
```

General::spell1 :
Possible spelling error: new symbol name "growthp" is similar to existing symbol "growthn". More…

General::spell : Possible spelling error: new symbol
name "growthz" is similar to existing symbols {growthn, growthp}. More…

General::spell : Possible spelling error: new symbol
name "growthk" is similar to existing symbols {growthn, growthp, growthz}. More…

```
vdot = (ack / n) * (growthk + growthn) + (acn * growthn) / k +
  acalpha * growthalpha * (alpha / n * k) + acz * growthz * (z / n * k) + acp * growthp * (p / n * k)
```

$-5.117802918789777\times10^{7235}$

```
(*Acounnting prices, value function and derivative of value function PERU*)

(*we define consumption hat*)

Clear[g, b, a1, a3, η, ρ, γ, β, s, δ, σ, ν, Ψ, ϕ, ξ, m, x1, x2]
Clear[khat, k, zbar, z, zhat, alpha, p, n, gz, grthgz]

General::spell1 :
 Possible spelling error: new symbol name "zhat" is similar to existing symbol "khat". More…

x1 = 0; x2 = 0;

khat = k * Exp[-ξ * t]
```

$e^{-t\xi}\,k$

```
zhat = z * Exp[-ξ * t]
```

$e^{-t\xi}\,z$

```
chat[k_, z_, x1_, t_] =
  (1 - s) * Ψ * (((khat^(1 - ϕ) - s * Ψ * z^a3 / (η + δ))) * Exp[-(1 - ϕ) * (η + δ + ξ) * t] +
      s * Ψ * (zhat)^a3 / (η + δ))^(ϕ / (1 - ϕ)) * (zhat)^a3

General::spell :
 Possible spelling error: new symbol name "chat" is similar to existing symbols {khat, zhat}. More…
```

$$(1-s)\,(e^{-t\xi}z)^{a3}\,\Psi\left(\frac{s\,(e^{-t\xi}z)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-t\xi}k)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}$$

```
(*we define utility per capita as u=c^(1-σ)/(1-σ)*)
u[k_, z_, gz_, grthgz_, t_, alpha_, p_] =
  (((chat[khat, z, x1, t] * alpha * Exp[g * t])^(1 - σ)) / (1 - σ)) -
   β ((p - gz / (m + grthgz)) * Exp[-m * t] + gz * Exp[grthgz * t] / (m + grthgz))^γ
```

$$-\left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{\gamma}\beta+\frac{\left(alpha\,e^{g\,t}\,(1-s)\,(e^{-t\xi}z)^{a3}\,\Psi\left(\frac{s\,(e^{-t\xi}z)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2t\xi}k)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{1-\sigma}}{1-\sigma}$$

```
(*value function*)
v1[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] =
 Exp[-(ρ - η) * t] * n * u[k, z, gz, grthgz, t, alpha, p]
```

$$e^{t\,(\eta-\rho)}\,n\left(-\left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{\gamma}\beta+\frac{\left(alpha\,e^{g\,t}\,(1-s)\,(e^{-t\xi}z)^{a3}\,\Psi\left(\frac{s\,(e^{-t\xi}z)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left((e^{-2t\xi}k)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{1-\sigma}}{1-\sigma}\right)$$

```
(*accounting price for k*)
```

pk[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_k v1[k, z, gz, grthgz, t, alpha, p, n]

$$\text{alpha}\, e^{g\,t-2\,t\,\xi+t\,(\eta-\rho)+t\,(\delta+\eta+\xi)\,(-1+\phi)}\,\left(e^{-2\,t\,\xi}\,k\right)^{-\phi}\,n\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\phi\,\Psi\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{-1+\frac{\phi}{1-\phi}}\left(\text{alpha}\,e^{g\,t}\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{-\sigma}$$

(*accounting price for n*)
pn[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_n v1[k, z, gz, grthgz, t, alpha, p, n]

$$e^{t\,(\eta-\rho)}\left(-\left(\frac{e^{\text{grthgz}\,t}\,\text{gz}}{\text{grthgz}+m}+e^{-m\,t}\left(-\frac{\text{gz}}{\text{grthgz}+m}+p\right)\right)^{\gamma}\beta+\frac{\left(\text{alpha}\,e^{g\,t}\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{1-\sigma}}{1-\sigma}\right)$$

(*accounting price for alpha*)
palpha[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] =
 ∂_{alpha} v1[k, z, gz, grthgz, t, alpha, p, n]

General::spell1 :
 Possible spelling error: new symbol name "palpha" is similar to existing symbol "alpha". More…

$$e^{g\,t+t\,(\eta-\rho)}\,n\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\left(\text{alpha}\,e^{g\,t}\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{-\sigma}$$

(*accounting price for z*)
pz[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_z v1[k, z, gz, grthgz, t, alpha, p, n]

$$e^{t\,(\eta-\rho)}\,n\left(\text{alpha}\,e^{g\,t}\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}\right)^{-\sigma}\left(a3\,\text{alpha}\,e^{g\,t-t\,\xi}\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{-1+a3}\,\Psi\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{\frac{\phi}{1-\phi}}+\frac{1}{1-\phi}\left(\text{alpha}\,e^{g\,t}\,(1-s)\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\phi\,\Psi\left(-\frac{a3\,e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\,s\,z^{-1+a3}\,\Psi}{\delta+\eta}+\frac{a3\,e^{-t\,\xi}\,s\,\left(e^{-t\,\xi}\,z\right)^{-1+a3}\,\Psi}{\delta+\eta}\right)\left(\frac{s\,\left(e^{-t\,\xi}\,z\right)^{a3}\,\Psi}{\delta+\eta}+e^{t\,(\delta+\eta+\xi)\,(-1+\phi)}\left(\left(e^{-2\,t\,\xi}\,k\right)^{1-\phi}-\frac{s\,z^{a3}\,\Psi}{\delta+\eta}\right)\right)^{-1+\frac{\phi}{1-\phi}}\right)\right)$$

(*accounting price for gz*)

pgz[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_{gz} v1[k, z, gz, grthgz, t, alpha, p, n]

$$-e^{t(\eta-\rho)}\left(\frac{e^{grthgz\,t}}{grthgz+m}-\frac{e^{-m\,t}}{grthgz+m}\right) n \left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{-1+\gamma}\beta\,\gamma$$

(*accounting price for pollution*)
pp[k_, z_, gz_, grthgz_, t_, alpha_, p_, n_] = ∂_p v1[k, z, gz, grthgz, t, alpha, p, n]

$$-e^{-m\,t+t(\eta-\rho)}\, n \left(\frac{e^{grthgz\,t}\,gz}{grthgz+m}+e^{-m\,t}\left(-\frac{gz}{grthgz+m}+p\right)\right)^{-1+\gamma}\beta\,\gamma$$

g = 0.00815; b = 0.00405; a1 = 0.095117; a3 = 0.330547; η = 0.026573374;
ρ = 0.03 ; γ = 1 ; β = 0.0000000907476 ; s = 0.1877 ; δ = 0.03 ; σ = 0.5 ;
ν = 0.012155219 ; Ψ = 1.67630338 ; ϕ = 0.425664 ; ξ = 0.010487368 ;
m = 0.0083 ; λ = 0.006023273 ; x1 = 0 ; x2 = 0 ; grthgz = 0.025 ;

(*ACCOUNTING PRICES DEFINED BY THE INTEGRAL*)

k = 8648.615385; z = 4.006080643; alpha = 1.67630338;
p = 785300000000; n = 16312.34615; gz = 6158700000;

(*value function*)
v1[k, z, gz, grthgz, t, alpha, p, n]

$$16312.3\, e^{-0.00342663\,t}\Big(-9.07476\times10^{-8}\,(6.00354\times10^{11}\,e^{-0.0083\,t}+1.84946\times10^{11}\,e^{0.025\,t})+ 3.80062\,\Big(e^{0.00815\,t}\,(e^{-0.0104874\,t})^{0.330547}\,\Big(8.79897\,(e^{-0.0104874\,t})^{0.330547}+ e^{-0.0385154\,t}\,\big(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\big)\Big)^{0.741141}\Big)^{0.5}\Big)$$

(*Integral of Value Function-Social Welfare*)

NIntegrate[v1[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

$-1.998768770281984\times10^{9379}$

(*Capital per worker*)

pk[k, z, gz, grthgz, t, alpha, p, n]

$$\left(278.35\,e^{-0.0547668\,t}\,(e^{-0.0104874\,t})^{0.330547}\right)\Big/ \Big((e^{-0.0209747\,t})^{0.425664}\,\Big(e^{0.00815\,t}\,(e^{-0.0104874\,t})^{0.330547}\,\Big(8.79897\,(e^{-0.0104874\,t})^{0.330547}+ e^{-0.0385154\,t}\,\big(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\big)\Big)^{0.741141}\Big)^{0.5}\,\Big(8.79897\, (e^{-0.0104874\,t})^{0.330547}+e^{-0.0385154\,t}\,\big(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\big)\Big)^{0.258859}\Big)$$

ack = NIntegrate[pk[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

399.146

(* n Population*)

pn[k, z, gz, grthgz, t, alpha, p, n]

$$e^{-0.00342663\,t}\left(-9.07476\times10^{-8}\,(6.00354\times10^{11}\,e^{-0.0083\,t}+1.84946\times10^{11}\,e^{0.025\,t})+3.80062\left(e^{0.00815\,t}\,(e^{-0.0104874\,t})^{0.330547}\left(8.79897\,(e^{-0.0104874\,t})^{0.330547}+e^{-0.0385154\,t}\left(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\right)\right)^{0.741141}\right)^{0.5}\right)$$

acn = NIntegrate[pn[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

$-1.225310419422398\times10^{9375}$

(*accounting price for alpha*)

palpha[k, z, gz, grthgz, t, alpha, p, n]

$$\left(18492.2\,e^{0.00472337\,t}\,(e^{-0.0104874\,t})^{0.330547}\left(8.79897\,(e^{-0.0104874\,t})^{0.330547}+e^{-0.0385154\,t}\left(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\right)\right)^{0.741141}\right)\Big/\left(e^{0.00815\,t}\,(e^{-0.0104874\,t})^{0.330547}\left(8.79897\,(e^{-0.0104874\,t})^{0.330547}+e^{-0.0385154\,t}\left(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\right)\right)^{0.741141}\right)^{0.5}$$

acalpha = NIntegrate[palpha[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

2.0088×10^{7}

(*accounting price for z*)

pz[k, z, gz, grthgz, t, alpha, p, n]

$$\left(8584.05\,e^{-0.00342663\,t}\left(\left(2.67639\,e^{0.00815\,t}\,(e^{-0.0104874\,t})^{0.330547}\left(-0.726015\,e^{-0.0385154\,t}+0.726015\,(e^{-0.0104874\,t})^{0.330547}\right)\right)\Big/\left(8.79897\,(e^{-0.0104874\,t})^{0.330547}+e^{-0.0385154\,t}\left(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\right)\right)^{0.258859}+\frac{1}{(e^{-0.0104874\,t})^{0.669453}}\left(0.297963\,e^{-0.00233737\,t}\left(8.79897\,(e^{-0.0104874\,t})^{0.330547}+e^{-0.0385154\,t}\left(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\right)\right)^{0.741141}\right)\right)\right)\Big/\left(e^{0.00815\,t}\,(e^{-0.0104874\,t})^{0.330547}\left(8.79897\,(e^{-0.0104874\,t})^{0.330547}+e^{-0.0385154\,t}\left(-8.79897+182.444\,(e^{-0.0209747\,t})^{0.574336}\right)\right)^{0.741141}\right)^{0.5}$$

acz = NIntegrate[pz[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]

4.34173×10^{6}

(*accounting price for gz*)

pgz[k, z, gz, grthgz, t, alpha, p, n]

$$-0.00148031\,e^{-0.00342663\,t}\,(-30.03\,e^{-0.0083\,t}+30.03\,e^{0.025\,t})$$

```
acpgz = NIntegrate[pgz[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]
```

$-3.245439411372504\times 10^{9369}$

```
(* accounting price for pollution stock*)

pp[k, z, gz, grthgz, t, alpha, p, n]
```

$-0.00148031\, e^{-0.0117266\, t}$

```
acp = NIntegrate[pp[k, z, gz, grthgz, t, alpha, p, n], {t, 0, 1000000}]
```

-0.126235

```
(*time derivative of the value function*)

ack
```

399.146

```
acn
```

$-1.225310419422398\times 10^{9375}$

```
acalpha
```

2.0088×10^{7}

```
acz
```

4.34173×10^{6}

```
acpgz
```

$-3.245439411372504\times 10^{9369}$

```
acp
```

-0.126235

```
growthalpha = 0.00815; growthn = 0.026573374; growthp = 0.02198545696425092;
growthz = -0.002464966; growthk = 0.012155219;
```

General::spell1 :
Possible spelling error: new symbol name "growthp" is similar to existing symbol "growthn". More…

General::spell : Possible spelling error: new symbol
name "growthz" is similar to existing symbols {growthn, growthp}. More…

General::spell : Possible spelling error: new symbol
name "growthk" is similar to existing symbols {growthn, growthp, growthz}. More…

```
vdot = (ack / n) * (growthk + growthn) + (acn * growthn) / k +
  acalpha * growthalpha * (alpha / n * k) + acz * growthz * (z / n * k) + acp * growthp * (p / n * k)
```

$-3.764837559764863\times 10^{9369}$

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PART II: Total Factor Productivity Growth and Environmental Externalities

5. Introduction

The sources of growth is an issue of particular importance in economics which has received considerable attention during the history of economic science. One of the most popular and successful ways of summarizing the contribution of each factor of production to output growth is the growth accounting framework introduced by Solow. Growth accounting leads to the well known concept of the Solow residual, which measures total factor productivity growth (TFPG), which is growth not attributed to the use of factors of production but in general to technical change that can include apart from labor augmenting technical change also emissions augmenting technical change, energy augmenting technical change etc.

A strong positive TFPG has been regarded as a desirable characteristic of the growth process. The traditional growth accounting framework, attributes growth to factors of production and TFPG is what remains from output growth after the contribution of the factors used to produce output is subtracted. This contribution is measured by the 'value' of the factor used which is reflected in the factor's share in output. To obtain this share, the cost of using the factor as it is determined in a market economy is used.

However, what if a factor is used in the production process but its cost is not accounted for in a market economy? That is, what if an unpaid factor is contributing to growth? This question is far from hypothetical since it has been understood in the recent decades that the growth process is using environment as a factor of production. In general, environment is used for depositing by-products of the production process, the most striking example being the emission of green house gasses which have been closely associated by scientific research with global warming and climate change phenomena[111]. The use of the environment is however equivalent with the use of an unpaid factor, in the absence of internalization of the use of the environment due to lack environmental policy. If however environment is an unpaid factor, which contributes to growth, then at least part of what we think is TFPG, is the unaccounted contribution of the environment. So positive TFPG estimates that would suggest a 'healthy' growth process might be the unaccounted contribution of the environment. When this contribution is accounted, TFPG might not be as strong and the growth process might not be as 'healthy' as we think, since the unpaid factor is excessive and inefficiently used. For example

[111] The IPCC Report, European Commission Report 2006, The Stern Report.

a negative TFPG after the contribution of the environment is accounted for, would imply in broad terms that the 'value' of the factors we use exceeds the 'value' of what we produce by these factors. Such a growth process is clearly not sustainable by any definition. Analyzing the contribution of unpaid factors in the growth process could have potentially significant policy implications. Given the fact that certain economies are characterized recently by large growth rates, one might want to examine whether unpaid factors are contributing to this growth, to what extend and what kind of policy is required in order to internalize the cost of these factors and thus use them efficiently. This might produce sustainable growth processes.

Thus, the second part of this dissertation analyzes extensively this matter that acquires particular importance today and examines whether the use of the environment, proxied by CO_2 emissions and by the use of energy as an input in the production process, can contribute to output growth in a group of developed and a group of developing countries.

More analytically, in chapter 6 entitled as: "Total Factor Productivity Growth and the Environment: A Case for Green Growth Accounting", we examine whether the use of the environment, proxied by CO_2 emissions, as a factor of production contributes, in addition to conventional factors of production to output growth, and thus it should be accounted for in total factor productivity growth (TFPG) measurement and deducted from the 'residual'. A theoretical framework of growth accounting methodology with environment as a factor of production which is unpaid in the absence of environmental policy is developed. Using data from a panel of 23 OECD countries, we show that emissions' growth have a statistically significant contribution to the growth of output, that emission augmenting technical change is present along with labor augmenting technical change and that part of output growth which is traditionally attributed to technical change should be attributed to the use of the environment as a not fully compensated factor of production. Our results point towards the need for developing a concept of "Green Growth Accounting".

In chapter 7 of the second part of this dissertation entitled: "Green" Total Factor Productivity Growth in Developing Countries, we further extend and analyze the idea of "Green Total Factor Productivity Growth" which consists of the decomposition of total output to the factors that constitute it with the inclusion of natural capital as an input in the production process in a context of a group of developing countries. We develop a theoretical framework of growth accounting methodology with environment as a factor of production which is unpaid in the absence of environmental policy and apply our model in a panel of 21 non-OECD countries. Our results show that emissions' growth have a statistically significant contribution to the growth of output per worker and emission augmenting technical change is present along with labor augmenting technical change.

In chapter 8 entitled: "Total Factor Productivity Growth with Externality Generating Inputs", we examine whether *energy*, as an input in the production process, contributes along with conventional inputs to output growth and changes Total Factor Productivity Growth (TFPG) measurements. After developing our theoretical framework by introducing the environment - in the form of energy - as an input in production, which is partially paid in the absence of environmental policy, we apply our model in a panel of 23 OECD countries and observe how TFPG measurements change when the unpaid part of energy, that is the CO_2 emission's part, becomes fully compensated by the introduction of an environmental tax on CO_2 emissions. Our results indicate that when the inputs used in production are "fully" paid, there is no technical change present to drive output growth.

6. Total Factor Productivity Growth and the Environment: A Case for Green Growth Accounting

6.1 Introduction

Growth Accounting is the empirical methodology that allows for the breakdown of output growth into its sources which are the factors of production and technological progress, and provides estimates of the contribution of each source in output growth. The concept of total factor productivity growth (TFPG) which is central in growth accounting, measures the part of output growth which is attributed to technological progress, and which corresponds to the part of output growth not 'accounted for' by factors of production such as capital or labour. Growth accounting still remains a central concept in growth theory, although there are still conceptual disputes about the subject, and Easterly and Levine (2001) state that "economists need to provide much more shape and substance to the amorphous term TFP". In this paper we try to provide some additional "shape" by considering the use of environment as a source of growth.

It was Solow in the late 1950's, (Solow, 1957) who provided an explicit integration of economic theory into the growth accounting calculations,[112] which imply decomposing total output growth and measuring the contribution to growth of specific factors, including that of technological progress. During the last decades many different approaches have been used to measure TFPG, which include dual approaches using mainly factor prices instead of factor quantities, and approaches which basically involve disaggregations and refinement of inputs in the production function.[113]

In the early 1970's, a new dimension was given to the theory of economic growth with the introduction into growth models of environmental damages created by emissions. This new dimension which has generated a large volume of literature on "Growth and the Environment"[114], implies a new way of looking at TFPG measurement. Brock (1973) stated that "received growth theory is biased because it neglects to take into account the pollution costs of economic growth". This is because in an unregulated market the cost of pollution is not internalized. Pollution in this case is an unpaid factor of production, with production becoming more costly if less pollution is allowed. In this context environment is used as *a factor of production* which is not fully compensated, and its use in the production process can be captured by introducing emissions as an input in an aggregate production function.[115]

Following this methodological approach, the idea developed in this part of the thesis is that when emissions are introduced as an input in the production process and are properly measured, the contribution from the use of environment in total output growth can also be measured. This contribution can be approximated even when emissions is an unpaid factor in the absence of environmental policy. In this sense, emissions can determine, along with other inputs and technological progress output growth in a growth account-

[112] See the historical note by Griliches (1996).

[113] See for example, Barro (1999), Barro and Sala-i-Martin (2005).

[114] See for example Aghion and Howitt (1998) or surveys such as: Brock and Taylor (2005), Xepapadeas (2005).

[115] In this context, the production function has been specified to include the flow of emissions as an input and some times, productivity enhancing environmental quality as a stock variable. This formulation has been used frequently in the theoretical analysis of growth and the environment. In addition to Brock (1973), see for example, Becker (1982), Tahvonen and Kuluvainen (1993), Bovenberg and Smulders (1995), Smulders and Gradus (1996), Mohtadi (1996), Xepapadeas (2005), Brock and Taylor (2005). See also Considine and Larson (2006) for the treatment of environment as a factor of production at the firm level.

ing framework. Therefore, the present paper can be regarded as an attempt to explore systematically whether the use of the environment as an input in production contributes to output growth, and how this contribution can be measured.[116],[117]

We develop a growth accounting framework for measuring TFP growth by approximating the use of the environment by carbon dioxide (CO_2) emissions. We argue that environment such as the atmosphere can be regarded as a component of social overhead capital (Uzawa, 2003), and that CO_2 emissions can be thought of as a reduction of this social capital - a form of disinvestment. Thus, we use CO_2 emissions as a proxy for the use of this component of social capital in the production process.[118]. Our purpose is to examine the contribution of CO_2 emissions' growth, as a proxy for the use of environment, on economic growth and to show that since external pollution costs which are created during the production process are not taken into account in the measurement of total factor productivity growth, the current measurements of TFP growth, or the Solow "residual", could provide biased results. Our basic hypothesis, which has been tested empirically, is that environment is basically an *unpaid* source of output growth. If this source is not taken into account into the growth accounting framework, then output growth which should be attributed to the use of the environment will be incorrectly attributed to TFPG. Furthermore, if emissions saving technical change is present this could be another source of growth in addition to the conventional labor augmented technical change. This hypothesis is tested empirically in this paper by using data from a panel of 23 OECD countries.[119]

[116]It is important to note that the approach we choose to follow is an aggregate macroeconomic approach that belongs to the Solow tradition of measuring TFP growth from a macroeconomic perspective. This is not the same as TFPG measurement at the micro-level where TFPG is usually measured with the use of distance functions and linear programming approaches. (See for instance, Pitman (1983), Fare, et all, (1989, 1993).

[117]In a recent paper Jeon and Sickles (2004) analyze productivity growth using the directional distance function method and treating CO_2 emissions as a undesirable output. Although they analyze a different time period, some of their results for OECD countries could be comparable to our own.

[118]Strictly speaking CO_2 emissions is not a pollutant but we treat them as such because of their close relation to climate change and the implied environmental damages. See for example the recent Stern Report (2006).

[119]The 23 countries used in our analysis are the following: Canada, U.S.A, Austria, Belgium, Denmark, Finland, France, Greece, Italy, Portugal, Spain, Sweden, Switzerland, U.K., Japan, Iceland, Ireland, Netherlands, Norway, Australia, Mexico, Turkey, Luxem-

Our theoretical and empirical analysis seems to suggest that the "unpaid"- due to absence of taxation - environmental factor, proxied by CO_2 emissions could be a source of growth, and an important component in the growth accounting methodology, supporting the case of a "Green Growth Accounting" approach. We feel that this type of analysis could be important, because if the use of the environment is a source of growth, as our results seem to suggest, but environment is used as an unpaid factor, environmental damages remain 'unpaid'. By being 'unpaid' or not 'fully paid' however, they are not kept at a 'socially optimal level' during the growth process and this fact might eventually erode the sustainability of the growth process itself.[120]

Emissions of CO_2 could be related to energy use and energy could have been regarded as an input in the production function with CO_2 emissions as a by product. In the absence of a carbon tax for a given period there still exist an unpaid factor since the full cost of energy - private and social (environmental) - is not fully paid by private markets, and this is a source of potential bias for TFPG measurement. In this paper we choose to use emissions as the 'environmental input' and not energy in order to provide a more direct link between and environment, since CO_2 emissions are related to climate change.[121]

The rest of the paper is structured as follows. Chapter 6.2 is a descriptive chapter that provides some stylized facts related to emissions growth and output growth in per worker terms. Chapter 6.3 develops the growth accounting framework and interprets emissions' share in output in the context of optimal growth and competitive market equilibrium. Since in general

bourg.

[120] In recent papers, Chimeli and Braden (2005) explore the relationship between total factor productivity (TFP) and the Environmental Kuznets Curve, while Kalaitzidakis et al (2006) try to determine an empirical relationship where measured TFP, when capital and labor are used as inputs in the production function, is the dependent variable, and CO_2 emissions are treated as an independent variable. Their results suggest the existence of such a relationship. Our approach differs basically because we provide a net TFPG estimate after all the factors used, including 'uncompensated' environment, have been accounted for. It also allows for the possibility of a 'negative residual' if the cost of using the environment is properly accounted and output growth is not sufficient to cover the true social cost of all inputs used, which will be a strong sign of unsustainable growth.

[121] The long term relationship between energy and CO_2 emissions in USA has been recently explored by Tol et al. (2006). If a stable relationship exits for a given period, then results based on CO_2 emissions can be expressed in terms of energy by appropriate conversion factors.

we don't have taxation for the emissions of CO_2 and therefore the 'environment's share' is not included in National Accounts, estimating TFPG, as it is the most common approach, using data on input shares might provide biased estimates. We try to solve this problem at the empirical level in chapters 6.4 and 6.5 by: (i) equating the emission's share in total output with the share of environmental damages in total output, using independent estimates for CO_2 damages, and (ii) by estimating directly the emission's share from an aggregate production function where CO_2 emissions is an input along with labor and capital. Estimation results suggest that the use of the environment seems to be a statistically significant factor in explaining output growth. This can be interpreted as an indication that the TFPG measurements that do not take the environmental factor into account might be biased in estimating the contribution of technological progress. Our results indicate furthermore, that labor augmenting technological progress, is not the only factor that constitutes the 'true residual' but 'emission augmenting technical change' might also be present. The last chapter concludes.

6.2 CO_2 Emissions and Growth: Some Descriptive Results

This chapter provides some stylized facts regarding possible links between the growth of CO_2 emissions and output growth for a group of 23 OECD economies[122].

Figure 1, shows gross domestic product (GDP) in per worker terms (GDP/W) for a group of 21 OECD countries[123], relative to the GDP/W in the USA.[124] The years we compare are 1965 and 1990 and it seems that the countries analyzed managed to reduce the growth "distance" from USA in GDP per worker terms and increased their GDP/W from 1965 to 1990, both in absolute terms and relative to the USA.

Figure 1

[122] Our data are taken from the Penn Tables v5.6. Real GDP measured in thousands of US$ is the variable (RGDPCH), multiplied by the variable POP in the Penn Tables. Capital stock and employment are retrieved from Real GDP and capital per worker (KAPW) and real GDP per worker (RGDPW). All values are measured in 1985 international prices. CO_2 data are taken from the World Bank and are measured in thousand tons of CO_2 emissions.

[123] Luxembourg, has been excluded for presentation purposes.

[124] USA is used as a benchmark country, so that USA=1.

Figure 2 that follows, makes the same comparisons using emissions of CO_2 per worker (CO_2/W) for the years 1965 and 1990 respectively. It can be noticed that for some countries (6 out of 21),[125] CO_2/W was reduced during these years, while for the rest (15 out of 21)[126], CO_2 emissions per worker increased.

Figure 2

Figure 3, shows CO_2 emissions per unit of GDP (CO_2/GDP) for the years 1965 and 1990. USA is taken as the benchmark country again and the comparisons show that for the majority of countries CO_2 (13 out of 21) [127] emissions per unit of GDP increased whereas in the rest (8 out of 21)[128] emissions per unit of GDP decreased.

Figure 3

In figure 4, the vertical axis measures the average annual growth of GDP per worker and the horizontal axis the corresponding growth of CO_2 per worker between 1965 and 1990. Each point of the scatter diagram represents one of the 23 countries we analyze. There is on the average a positive relationship between the two variables, suggesting that countries with high growth of CO_2 per worker can be associated with a high growth of GDP per worker. This can be regarded as an indication that the growth of CO_2 per worker contributes to the growth of GDP per worker.

figure 4

Figure 5, shows on the horizontal axis GDP per worker relative to the GDP per worker in USA at 1965, and on the vertical axis the average growth of CO_2 per worker for the examined period. Countries with GDP per worker close to the USA GDP per worker in 1965 (which is normalized to 1) had relatively low growth rates of CO_2 per worker. On the other hand, countries that were 'far' (below) in GDP per worker relative to the USA in 1965, show a relatively high rate of growth of CO_2 per worker. An attempt to explain this

[125] The countries are: Belgium, Denmark, France, Sweden, UK and Iceland.

[126] The countries are the following: Canada, Austria, Finland, Greece, Italy, Portugal, Spain, Switzerland, Japan, Ireland, Netherlands, Norway, Australia, Mexico, Turkey.

[127] The countries are: Austria, Finland, Greece, Italy, Portugal, Spain, Switzerland, Ireland, Netherlands, Norway, Australia, Mexico, Turkey.

[128] These countries are: Canada, Belgium, Denmark, France, Sweden, UK, Japan and Iceland.

would be to say that countries with low GDP per worker in 1965 relatively to the USA, were developing relatively fast and during their development processes emitted relatively more carbon dioxide per worker, probably due to the use of 'dirtier' technologies and not sufficiently strong emissions saving technical change.

$figure$ 5

These descriptive data seem to provide some indications that the growth of CO_2 emissions per worker is positively related to the growth of output per worker. This could imply that the use of the environment is a factor that influences the output growth of an economy, and as such it should be taken into account into growth accounting calculations. In the following we are trying to develop a theoretical and empirical framework for testing this hypothesis.

6.3 Primal Growth Accounting with Environmental Considerations

We state first the traditional Solow's residual under environmental considerations. Let,

$$Y = F(K, E) = F(K, AL) \tag{102}$$

where Y is aggregate output, K is physical capital, $E = AL$ is effective labour, with L being labour input and A reflecting labour augmenting (Harrod neutral) technical change. The 'Solow residual' is defined (e.g. Romer 1999, Barro and Sala-i-Martin 2004) as:

$$g_S = s_L \left(\frac{\dot{A}}{A} \right) = \frac{\dot{Y}}{Y} - s_K \left(\frac{\dot{K}}{K} \right) - s_L \left(\frac{\dot{L}}{L} \right) \tag{103}$$

where s_K and s_L are the shares of capital and labor in output, with two factors receiving their competitive rewards. Under constant returns of scale, $s_L + s_K = 1$, and we have:

$$g_S = s_L \left(\frac{\dot{A}}{A} \right) = \frac{\dot{y}}{y} - s_K \frac{\dot{k}}{k} \tag{104}$$

where $\dot{y}/y$ is the rate of growth of output per worker ($y = Y/L$) and $\dot{k}/k$ is the rate of growth of capital per worker ($k = K/L$) [129]. The rate of the exogenous

[129] As is the convention in this literature lower case letters denote per worker quantities.

labor augmenting technical change $x = \dot{A}/A$ can be directly determined by (104)

By following ideas appeared in Denison (1962), Dasgupta and Mäler (2000), Xepapadeas (2005) which relate environment to growth accounting, we define a standard neoclassical production function that includes human capital and emissions as an input of production and we use it to determine a growth accounting equation. Let

$$Y = F(K, H, E, X) \tag{105}$$

where in addition to K and E, H is human capital, $X = BZ$ is effective input of emissions, with Z being emissions in physical units and B reflecting emission saving technical change, or input augmenting technical change.

Differentiating (105) with respect to time, and denoting by $\epsilon_j, j = K, H, L, Z$ the elasticity of output with respect to inputs, the basic growth accounting equation is obtained as:

$$\frac{\dot{Y}}{Y} = \epsilon_K \left(\frac{\dot{K}}{K}\right) + \epsilon_H \left(\frac{\dot{H}}{H}\right) + \epsilon_L \left(\frac{\dot{A}}{A}\right) + \epsilon_L \left(\frac{\dot{L}}{L}\right) + \epsilon_Z \left(\frac{\dot{B}}{B}\right) + \epsilon_Z \left(\frac{\dot{Z}}{Z}\right) \tag{106}$$

Equation (106) says that the growth rate of GDP can be decomposed into the growth rate of manufactured capital, human capital, physical labor, emissions in physical units and technical change. To transform equation (106) into a growth accounting equation in factors shares, we use as before, profit maximization in a competitive market set up. We assume that physical and human capital receive there rental rates R_K and R_H, labor receives wage w and emission are taxed at a rate $\tau \geq 0$, since they create external damages. Thus, profits for the representative firm are defined as:

$$\Pi = F(K, H, E, X) - R_K K - R_H H - wL - \tau Z \tag{107}$$

with associated first-order conditions for profit maximization:

$$\frac{\partial F}{\partial K} = R_K \ , \ \frac{\partial F}{\partial H} = R_H \ , \ \frac{\partial F}{\partial E} A = \frac{\partial F}{\partial L} = w \tag{108}$$

$$\frac{\partial F}{\partial X} B = \frac{\partial F}{\partial Z} = \tau \tag{109}$$

Denoting by $s_j, j = K, H, L, Z$ the factors' shares in total output, then under profit maximization the basic growth accounting equation is obtained as:

$$\frac{\dot{Y}}{Y} = s_K \left(\frac{\dot{K}}{K}\right) + s_H \left(\frac{\dot{H}}{H}\right) + s_L \left(\frac{\dot{A}}{A}\right) + s_L \left(\frac{\dot{L}}{L}\right) + s_Z \left(\frac{\dot{B}}{B}\right) + s_Z \left(\frac{\dot{Z}}{Z}\right) \tag{110}$$

where: $s_K = \frac{R_K K}{Y}, s_H = \frac{R_H H}{Y}, s_L = \frac{wL}{Y}, s_Z = \frac{\tau Z}{Y}$.

If we assume that investment in physical and human capital is carried out up to the point where marginal products in each type of capital (physical and human capital) are equated in equilibrium,[130] (see for example Barro and Sala-i-Martin 2004), we have:

$$H = \frac{s_H}{s_K} K \tag{111}$$

Substituting (111) into (110) we obtain:

$$\frac{\dot{Y}}{Y} = s_{KH}\left(\frac{\dot{K}}{K}\right) + s_L\left(\frac{\dot{A}}{A}\right) + s_L\left(\frac{\dot{L}}{L}\right) + s_Z\left(\frac{\dot{B}}{B}\right) + s_Z\left(\frac{\dot{Z}}{Z}\right) \tag{112}$$

$$s_{KH} = s_K + s_H \tag{113}$$

Thus, the Solow residual augmented with human capital and emissions can be defined as:

$$\gamma = s_L\left(\frac{\dot{A}}{A}\right) + s_Z\left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_H\left(\frac{\dot{H}}{H}\right) - s_L\left(\frac{\dot{L}}{L}\right) - s_Z\left(\frac{\dot{Z}}{Z}\right) \tag{114}$$

or by using the assumption of equality of marginal products between physical and human capital as:

$$\gamma = s_L\left(\frac{\dot{A}}{A}\right) + s_Z\left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_{KH}\left(\frac{\dot{K}}{K}\right) - s_L\left(\frac{\dot{L}}{L}\right) - s_Z\left(\frac{\dot{Z}}{Z}\right) \tag{115}$$

Under constant returns to scale (114) and (115) become:

$$\gamma = \frac{\dot{y}}{y} - s_K\frac{\dot{k}}{k} - s_H\frac{\dot{h}}{h} - s_Z\frac{\dot{z}}{z} \tag{116}$$

$$\gamma = \frac{\dot{y}}{y} - s_{KH}\frac{\dot{k}}{k} - s_Z\frac{\dot{z}}{z} \tag{117}$$

By comparing the new definitions for TFPG, (114)-(115) or (116)-(117) with (103) or (104), it can be seen that the new definitions include the term

[130] This assumption has been used to justify relatively high estimates of capital's share in empirical growth equations.

$s_Z\left(\dot{Z}/Z\right)$. This indicates that there is one more source generating output growth in addition to capital and labour, namely emissions, along with the term $s_Z\left(\dot{B}/B\right)$ which reflect emission augmenting (input saving) technical change in addition to the standard labour augmenting technical change. In order to obtain a "net" estimate of TFPG the environment's contribution should be properly accounted. In the context of our analysis (115) - (117) can be regarded as the *Green Growth Accounting equations.* In order however to provide a meaningful definition of the TFPG when environment is an input, there is a need to clarify what is meant by the share of emissions in output, especially since when it comes to empirical estimations there might be data sets where $\tau = 0$, that is emissions are untaxed and we have one unpaid input in the production function.

6.4 Interpreting the Emissions' Share in Growth Accounting

The Social Planner

To interpret the emissions share even when no environmental taxation is present ($\tau = 0$), we consider the problem of a social planner seeking to optimize a felicity functional defined over consumption and environmental damages and to determine an optimal emission tax, optimal in the sense that if firms pay this tax on their emissions they will emit the socially desirable levels of emissions. An optimal tax would internalize the externalities that the emissions create during the production process.

We assume that emissions (flow variable), accumulate into the ambient environment and that the evolution of the emission stock S, is described by the first order differential equation:

$$\dot{S}(t) = Z(t) - mS(t)\ ,\ S(0) = S_0, m > 0 \tag{118}$$

where m reflects the environment's self cleaning capacity[131]. The stock of emissions generate damages according to a strictly increasing and convex damage function $D(S)$, $D' > 0, D'' \geq 0$.

Assume that utility for the "average person" is defined by $U(c(t), S(t))$ where $c(t)$ is consumption per capita, $c(t) = C(t)/N(t)$, with $N(t)$ being

[131] We use a very simple pollution accumulation process which has been often used to model global warming. The inclusion of environmental feedbacks and nonlinearities which represent more realistic situations will not change the basic results.

population. We assume as usual that $U_c(c,S) > 0$, $U_S(c,S) < 0$ $U_{cS}(c,S) \leq 0$, that U is concave in c for fixed S, and finally that U is homogeneous in (c,S). Then social utility at time t is defined as $N(t)\,U(c(t),S(t)) = N_0 e^{nt} U(c(t),S(t))$ where n is the exogenous population growth rate and N_0 can be normalized to one. The objective for the social planner is to choose consumption and emission paths to maximize:

$$\max_{\{c(t),Z(t)\}} \int_0^\infty e^{-(\rho-n)t} U(c,S)\,dt \tag{119}$$

where, $\rho > 0$ is the utility discount rate, subject to the dynamics of the capital stock and the pollution stock (118). The capital stock dynamics can be described in the following way. Assume a constant returns to scale Cobb-Douglas specification for the production function (105):

$$Y = K^{a_1} H^{a_2} (AL)^{a_3} (BZ)^{a_4} \tag{120}$$

Expressing output in per worker terms we obtain:

$$\begin{aligned} \frac{Y}{L} &= \left(\frac{K}{L}\right)^{a_1}\left(\frac{H}{L}\right)^{a_2}\left(\frac{AL}{L}\right)^{a_3}\left(\frac{BZ}{L}\right)^{a_4}, \text{ or} \\ y &= e^{\zeta t} k^{a_1} h^{a_2} Z^{a_4},\ \zeta = x a_3 + a_4(b-n) \end{aligned}$$

where labor augmenting technical change grows at the constant rate x, input (emission) augmenting technical change grows at a constant rate b, labor grows at the population rate n, and $h = \frac{H}{L}$. Assuming equality of depreciation rates and equality of marginal products between manufactured and human capital in equilibrium, the social planner's problem can be written as:[132]

$$\max_{\{\hat{c}(t),Z(t)\}} \int_0^\infty e^{-\omega t} U(\hat{c},S)\,dt\ , \tag{121}$$

$$\omega = \rho - n - (1-\theta)\,\xi\ ,\ \xi = \frac{\zeta}{1-a_1-a_2}$$

subject to:

$$\dot{\hat{k}} = f\left(\hat{k},Z\right) - \hat{c} - (\eta+\delta+\xi)\,\hat{k}, \quad f\left(\hat{k},Z\right) = s\tilde{A}\hat{k}^{\beta} Z^{a_4} \tag{122}$$

$$\dot{S} = Z - mS \tag{123}$$

[132] For the derivation see Appendix.

where ˆ indicate variables in efficiency units (see Appendix). The current value Hamiltonian for this problem is:

$$\mathcal{H} = U(\hat{c}, S) + p\left[f\left(\hat{k}, Z\right) - \hat{c} - (\eta + \delta + \xi)\hat{k}\right] + \lambda(Z - mS) \tag{124}$$

and the optimality conditions implied by the maximum principle are:

$$U_{\hat{c}}(\hat{c}, S) = p\ ,\ U_{\hat{c}\hat{c}}(\hat{c}, S)\dot{\hat{c}} + U_{\hat{c}S}(\hat{c}, S)\dot{S} = \dot{p} \tag{125}$$

$$pf_Z\left(\hat{k}, Z\right) = -\lambda \ or\ Z = g\left(\hat{k}, \lambda, p\right) \tag{126}$$

$$\dot{p} = \left(\rho + \delta + \theta\xi - f_{\hat{k}}\left(\hat{k}, Z\right)\right)p \text{ or} \tag{127}$$

$$\frac{\dot{\hat{c}}}{\hat{c}} = \frac{1}{\theta}\left[f_{\hat{k}}\left(\hat{k}, g\left(\hat{k}, \lambda, U_{\hat{c}}(\hat{c}, S)\right)\right) - \rho - \delta - \xi\theta\right] - \frac{U_{\hat{c}S}}{U_{\hat{c}\hat{c}}}\dot{S} \tag{128}$$

$$\dot{\lambda} = (\omega + m)\lambda - U_S(\hat{c}, S) \tag{129}$$

The system of (128), (129) along with (122) and (123), form a dynamic system, which along with the appropriate transversality conditions at infinity (Arrow and Kurz 1970) characterizes the socially optimal paths of $\left(\hat{c}, \hat{k}, \lambda, S, Z\right)$.

Let the value function of the problem be defined as:

$$J(K_0, S_0) = \max \int_0^{\infty} e^{-\omega t} U(\hat{c}, S)\, dt \tag{130}$$

then it holds that (Arrow and Kurz 1970):

$$\frac{\partial J}{\partial S(t)} = \lambda(t) < 0 \tag{131}$$

Thus the costate variable λ can be interpreted as the shadow cost of the pollution stock. By comparing (126) with (109) and noting (131) it is clear that if a time dependent tax $\tau(t) = -\lambda(t)/p(t)$ is chosen, then firms will choose the socially optimal amount of emissions as input.

Then the emission's share can be written as:

$$s_Z = \frac{\tau Z}{Y} = \frac{\left(-\hat{\lambda}\right)Z}{Y},\ \hat{\lambda} = \frac{-\lambda}{p} = \frac{-\lambda}{U_{\hat{c}}} \tag{132}$$

where from (132) $\hat{\lambda}$ can be interpreted as the shadow cost of the pollution stock in terms of marginal utility. Thus the share of emissions in output coincides, under optimal environmental taxation, with the share of environmental damages in total output. It can be further shown that under the emission tax $\tau(t) = \hat{\lambda}(t)$ competitive equilibrium will coincide with the social planners solution.

Competitive Equilibrium

The representative consumer considers the stock of pollution as exogenous and chooses consumption to maximize lifetime utility, or:

$$\max_{c(t)} \int_0^\infty e^{-(\rho-n)t} U(c, S)\, dt \tag{133}$$

subject to the budget flow constraint:

$$\dot{a} = w + ra - c - na + \tau z \tag{134}$$

where a is per capita assets, w, r the competitive wage rate and interest rate respectively and τz are per capita transfers due to environmental taxation, $z = Z/L$.

The representative firm maximizes profits given by (107), where by assuming that physical capital, human capital and loans are perfect substitutes as stores of value we have $r = R_K - \delta = R_H - \delta$.

In equilibrium $a = k + h$. Then the following proposition can be stated:

Proposition 2 *Under optimal environmental taxation, that is* $\tau(t) = \frac{-\lambda(t)}{p(t)}$, *the paths* $\left(\hat{c}(t), \hat{k}(t), S(t), Z(t)\right)$ *of a decentralized competitive equilibrium coincide with the socially-optimal paths.*[133]

For proof see Appendix.

6.5 TFPG Measurement Issues

As shown above, under optimal taxation the time paths for consumption, capital and pollution at the social optimum coincide with the corresponding optimal paths in a decentralized competitive equilibrium. Our basic problem

[133] It can be shown that a similar result holds if we define the model in terms of energy, and there is a simple proportional relationship between energy and emissions.

in measurement is that usually in practice we don't have taxation (optimal or not) for CO_2 emissions, so we need an estimate of damages as a proxy for taxation. The only clear case where CO_2 emissions have a cost for those emitting can be found in the recently created European emission trading scheme. This however is a very recent development and our data set corresponds to the "no regulation" case. Furthermore, since we don't have taxation on emissions and therefore the share of emission taxes are not included in National Accounts, estimating TFPG using data from National Accounts, might provide biased estimates since the share of emissions damages is ignored.

TFP growth estimation involves, most of the times, a direct implementation of growth accounting equations such as (103) using data for Y, K, L, s_K, s_L. There is a difficulty however, as indicated above, if we want to include emissions in the equation. Theory suggests that s_Z is emission damages as a share of GDP. If optimal taxation is applied then s_Z is can be measured as a share of GDP. If however emissions are not taxed, that is environment as an unpaid factor of production, then we need an independent estimate of marginal emission damages. In the absence of such estimate, the implementation of growth accounting equation like (114) or (115) using data on Y, K, L, Z, s_K, s_L, s_z is not possible. Thus, the presence of the environment as an input in the production function and the absence of emission taxation make the non econometric estimations which is usually followed, problematic. In this case, direct adjustments using independent estimates of emission damages, or econometric estimation could be used.

6.6 Direct Adjustment using Marginal Damage Cost Estimates of Carbon Dioxide Emissions

In the absence of environmental policy, but if independent marginal damage cost estimates of CO_2 (MDCCO_2) emissions exist, then adjusted TFPG estimates can be obtained using:

$$\hat{g}_S^i = g_S^i - s_Z^i \left(\frac{\dot{Z}}{Z}\right)_i \tag{135}$$

which can be derived directly from (116) or (117), where g_S^i is the estimate of the traditional Solow residual in country i, $\left(\frac{\dot{Z}}{Z}\right)_i$ the growth of CO_2 emissions, and s^i_Z is the share of CO_2 emissions in GDP defined as

$$s^i_{zt} = \frac{p_z Z_{it}}{GDP_{it}} \tag{136}$$

Since, in the absence of optimal taxation, the share of emissions cannot be obtained from tax data, we use our theoretical result that under optimal taxation the emissions' share in GDP should be equal to the share of damages from carbon dioxide in GDP. Thus, with p_z a proxy for MDCCO_2, (136) can be obtained by using existing MDCCO_2 estimates (e.g. Tol 2005).

6.7 Econometric Estimation

In this case the measurement of TFP growth is based on an aggregate production function which includes CO_2 emissions as an input. This can be regarded as a more appropriate way to estimate input shares and the share of CO_2 emissions which is an unpaid factor in the production process, since it's share in GDP cannot be measured by existing data in the absence of CO_2 emission taxes. An additional advantage of econometric estimation is that of direct testing the statistical significance of emissions growth as a determinant of output growth.

Using the Cobb-Douglas specification (120), we obtain under constant returns the loglinear specification:[134]

$$\ln y = \alpha_0 + (xa_3 + ba_4)\, t + a_1 \ln k + a_2 \ln h + a_4 \ln z \ , \ \sum_{i=1}^{4} a_i = 1 \tag{137}$$

Equation (137) provides estimates of input elasticities. To have a meaningful interpretation of these elasticities as factors' shares in the absence of optimal environmental policy, we need to consider the choice of emissions in the context of the constraint optimization problem:

$$\begin{aligned} \max \Pi \ &= \ F(K, H, AL, BZ) - R_K K - R_H H - wL \\ &\quad \text{subject to} \quad Z \leq \bar{Z} \end{aligned} \tag{138}$$

[134] In the empirical analysis we use as proxy for H, an index constructed as $H_{it} = \exp(\phi(\epsilon_{jt}))$. Where ϵ_{jt} is average years in education in country i at year t, and ϕ is a piece-wise linear function with zero intercept and slope 0.134 for $\epsilon_{jt} \leq 4$, 0.101 for $4 < \epsilon_{jt} \leq 8$, and 0.068 for $\epsilon_{jt} > 8$.(see Hall and Jones (1999); Henderson and Russel (2005)). Data on education were obtained from the World Bank, World Development Indicators (2002).

The upper bound on emissions could reflect technical constraints associated with production technologies or emissions. For example, even without CO_2 taxation, general environmental policies on air pollutants (SO_2, NO_x) might introduce technological responses or capacity constraints which eventually generate upper bounds for CO_2 emissions. Associating the Lagrangian multiplier μ with the constraint $Z \leq \bar{Z}$ the first order condition for the optimal input choices, including emission choice, which correspond to (138) are:

$$\frac{\partial F}{\partial K} = R_K,\ \frac{\partial F}{\partial H} = R_H,\ \frac{\partial F}{\partial L} = w,\ \frac{\partial F}{\partial Z} = \mu$$

by the envelope theorem μ is the shadow cost of emissions Z, and measures the response of maximum profits to changes in the upper bound $\bar{Z}$. This shadow cost should be distinguished from the shadow cost of the pollution stock, defined in (131), that measures the response of maximum welfare to a change in the stock of pollutants, the stock of CO_2 in our case.

Thus in the absence of environmental policy the share of the unpaid factor in equilibrium is defined as;

$$s_Z = \frac{F_Z Z}{Y} = \frac{\mu Z}{Y} \tag{139}$$

In general this share will be *different* from the correct share $\left(-\hat{\lambda}Z\right)/Y$, unless $\bar{Z}$ is set at the level corresponding to the social welfare maximization path for the emissions' flow, in which case $\mu = \hat{\lambda}$. This however, is not the case for the period under investigation.

Therefore the elasticities obtained from the production function can be interpreted as shares associated with the constraint optimization problem (138) but not with the social welfare optimization problem (121). This has certain implications for the interpretation of any estimation results.

Given an estimate of $\hat{s}_Z$, the shadow value of emissions can be obtained as $\hat{\mu} = \hat{s}_Z\,(Y/Z)$ where Y/Z is the observed ouput-emissions ratio. This not however the 'social shadow cost' of pollution since this 'social shadow cost' is λ, which is based on a social welfare function that incorporates environmental damages.[135]

[135] There is a subtle point here associated with the shadow cost of pollutants obtained by productivity studies using mainly micro-data, where emissions or undesirable outputs are included and distance functions or linear programming methodologies are used for esti-

In the growth accounting exercise the contribution of CO_2 emissions on output growth using elasticities estimated from an aggregate production function, in the absence of CO_2 related environmental policy, can be interpreted in terms of emissions contributions under the existing technological constraints, and not as the 'true' contribution, when environment is properly valued by the welfare cost of using it. On the other hand this is a useful measure since it provides an indication of the impact on aggregate output, from introducing an environmental policy that restricts emissions.

Actually, since in the absence of a CO_2 policy it is expected that emissions constrained only by technological restrictions would be high[136], relative to the case where the socially optimal regulation is followed, the estimate of μ is expected to be low relative to λ.

In this context elasticities can be interpreted as shares, and we can set:

$$a_1 = s_K, a_2 = s_H, a_4 = s_Z \tag{140}$$

By comparing (137) with (114), TFPG can be obtained by estimating $xa_3 + a_4 b$. In this case TFPG is approximated by the contribution of labor augmented technical change and emissions augmented technical change.

There are several ways to further specify the production function.

- With $a_4 \neq 0$, by imposing in (137) $a_2 = 0$, we obtain a production function with emissions but without human capital, or

$$\ln y = (xa_3 + a_4 b)\, t + a_1 \ln k + a_4 \ln z \tag{141}$$

- With $a_4 \neq 0$, $a_2 = 0$ and by using, instead of the labour (L) in physical units, the quality adjusted labor input defined as $L_h = LH$ we have:

$$\ln y_h = (xa_3 + a_4 b)\, t + a_1 \ln k_h + a_4 \ln z_h \tag{142}$$

  where all variables are measures in per 'quality adjusted' worker terms.

mation purposes. The shadow cost estimates reflect the impact on the objective function associated with emissions, but they do not reflect damages due to emissions. So although these estimates are appropriate for studying the impact of sectoral environmental policies on firms profits or costs, they do not reflect the welfare cost of using the environment, especially if environmental policy is not well defined, or is not present during the sample period.

[136]We have unregulated profit maximization in this case.

- Imposing $a_2 \neq 0$ and the assumption of equality of marginal products between human and physical capital, we obtain:

$$\ln y = (xa_3 + a_4 b)\, t + (a_1 + a_2) \ln k + a_4 \ln z \tag{143}$$

  It is clear that for $a_4 = 0$ we have the traditional aggregate production function without emissions as an input.

Each of the production function specifications (141), (142),(143) with the elasticities interpreted as shares by (140), can be associated with a growth accounting equation. Specification (137), which is the most general has as a counterpart the growth accounting equation:

$$\frac{\dot{y}}{y} = \gamma + s_K \frac{\dot{k}}{k} + s_H \frac{\dot{h}}{h} + s_Z \frac{\dot{z}}{z} \tag{144}$$

$$\gamma = xa_3 + a_4 b \tag{145}$$

The counterparts of (141), (142) can be easily obtained by imposing appropriate restrictions on elasticities.

Using (137) or (144), TFPG can be estimated econometrically, either from the trend term $xa_3 + a_4 b$ of (137) or the constant term γ of (144). Alternatively, using the estimated shares $\hat{s}_K, \hat{s}_H, \hat{s}_Z$ from (137) and average growth rates of output and inputs per worker, TFPG can be calculated from (144) as:

$$\hat{\gamma} = \overline{\left(\frac{\dot{y}}{y}\right)} - \hat{s}_K \overline{\left(\frac{\dot{k}}{k}\right)} - \hat{s}_Z \overline{\left(\frac{\dot{z}}{z}\right)} \tag{146}$$

The corresponding measures for the other specifications follow directly.

6.8 Green TFPG Estimates

In this chapter we provide TFP growth estimates within the framework developed in the previous section by using: (i) independent estimates of MDCCO_2, and (ii) estimates obtained from econometric estimation.

6.9 Direct Adjustment of TFPG Estimates

We adjust previous estimates of TFPG using estimates of MDCCO_2 and growth of CO_2 emissions. Tol (2005) reports 103 such estimates gathered by

28 published studies. In order to cover the range of MDCCO_2 estimates, we calculate the emission's share (136) using three point estimates for MDCCO_2, $p_Z = (\$20/tC, \$93/tC, \$350/tC)$. The results are shown in table 1.

Table 1

In table 1, the second column presents traditional TFPG (TTFPG) estimates for 1960–1995 reported in Barro and Sala-i-Martin (2004), the third column shows the corresponding average annual growth of CO_2 emissions, and columns 4-12 show the emission's share in GDP, the 'green' TFPG estimates (GTFPG) and the proportional deviation between the TTFPG and the GTFPG estimates, for the three point estimates of MDCCO_2. It can be noticed that for countries like Canada, USA, Italy and Japan, for which CO_2 emissions grow during the relevant period, total factor productivity growth is overestimated by TTFP relative to GTFPG. The average overestimation ranges from around 4.5% when MDCCO_2 is \$20$/tC$, to 80% when MDCCO_2 is \$350$/tC$.[137] This means that when the cost of using the environment is taken into account a certain proportion of what was thought as the contribution of technical change to output growth, is actually the contribution of environment, which was the uncompensated factor because of suboptimal environmental policy. In France where the growth of CO_2 emissions is very small the effect from accounting for the the use of the environment is also very small. For the UK where CO_2 emissions declined during the period under investigation, TTFPG estimates underestimated total factor productivity growth. This is because the recorded output growth corresponds to a decline in the use of the uncompensated factor, therefore there is a larger contribution of technical change to output growth relative to what is captured by TTFPG estimates. So our results suggest that when emissions grow during a given period and policy is not optimal a part of what is interpreted as growth due to technical progress should be attributed to the use of the environment as a factor of production. Negative TFPG estimates in this context could be interpreted as implying that the 'unpaid factor' environment, outweights, as a source of growth, technical change.

6.10 Econometric Estimation of TFPG

[137] The closest observable proxy for CO_2 'price' is the recent carbon dioxide allowance price in the European Union. For the period March 2005-May 2006, this average price was \$26.22 per metric ton, with a maximum of \$37 and a minimum of \$11.5.

Following the analysis in chapter 6.7 we estimate the following models:
Production Function Equations

$$\begin{array}{ll} PF1 & \ln y = (xa_3 + ba_4)\, t + a_1 \ln k + a_2 \ln h + a_4 \ln z \\ PF2 & \ln y = (xa_3 + a_4 b)\, t + a_1 \ln k + a_4 \ln z \\ PF3 & \ln y_h = (xa_3 + a_4 b)\, t + a_1 \ln k_h + a_4 \ln z_h \end{array} \tag{147}$$

Growth Accounting Equations

$$\begin{array}{ll} GA1 & \frac{\dot{y}}{y} = \gamma + a_1 \frac{\dot{k}}{k} + a_2 \frac{\dot{h}}{h} + a_4 \frac{\dot{z}}{z} \\ GA2 & \frac{\dot{y}}{y} = \gamma + a_1 \frac{\dot{k}}{k} + a_4 \frac{\dot{z}}{z} \\ GA3 & \frac{\dot{y}_h}{y_h} = \gamma + a_1 \frac{\dot{k}_h}{k_h} + a_4 \frac{\dot{z}_h}{z_h} \end{array} \tag{148}$$

There is a clear correspondence between $PF1 - PF3$ and $GA1 - GA3$. Regarding the estimation of the production function and the growth accounting equations the following observations are in order:

- Estimation of the growth accounting (GA) equations represent estimations of the corresponding production functions in first differences, since we use the approximation $\dot{x}/x = \ln x_t - \ln x_{t-1}$. Thus the GA estimation could address problems associated with the stationarity of the variables in levels.

- The estimation of the production function (PF) models represents estimation of a primal model, that might suffer from endogeneity associated with inputs, implying inconsistency of direct estimators of the production function. However as it has been shown by Mundlak (1996, proposition 3), under constant returns to scale, OLS estimates of a k-input Cobb-Douglas production function, in average productivity form, with regressors in inputs-labour ratio, are consistent. This type of production function is exactly what we have in $PF1$-$PF3$.

- To estimate the PF or the GA models we adopt a panel estimation approach with 'fixed effects' to allow for unobservable 'country effects' (e.g. Islam (1995). As shown by Mundlak (1996) this estimator applied to the primal problem is superior to the dual estimator which is applied to the dual functions. Furthermore the 'fixed effects' estimator addresses the problem of correlation between the constant term γ, which is the TFPG estimator in the GA models, with the regressors.[138]

[138] This correlation has been regarded as one of the disadvantages of the regression approach in TFPG measurement (Barro 1999, Barro and Sala-i-Martin 2004).

- GA models can provide individual country TFPG estimates through the 'fixed effects' estimator. They are not however capable of identifying separately the contributions of labour augmenting and input augmenting technical change. Separate identification of the effect of the two possible sources of technical change is possible in the PF context. It should be noticed first that if both sources of technical change are modeled with the traditional way via a simple time trend, it is impossible to separate these two distinct effects using a single-stage estimation procedure. From $PF1$-$PF3$, it is evident that the parameters a_3 and α_4 cannot all be identified using a single-stage estimation procedure due to the linear dependency among some of the right-hand side variables and the resulting singularity of the variance-covariance matrix. At most either a_3 or a_4 can be identified implying respectively no technical change in conventional or damage abatement inputs (Kumbhakar, Heshmati and Hjalmarsson, 1997)[139].

  An alternative model capable to overcome the aforementioned identification problem can be applied by altering the specification of technical change in the production function. More specifically, it is possible to separate these effects by employing Baltagi and Griffin (1988) general index to model technical change in conventional inputs and traditional simple time-trend to account for changes in the productivity of damage abatement input (Karagiannis et al., 2002). In particular relation $PF1$ may take the form[140]:

$$\begin{aligned} \ln y_{it} &= \zeta t + A(t) + a_1 \ln k_{it} + a_2 \ln h_{it} + a_4 \ln z_{it} \\ A(t) &= \sum_{t=1}^{T} (ba_4)_t \, D_t \\ \zeta &= x a_3 \end{aligned}$$

[139] Hypothetically the Cobb-Douglas production function in relations (148) can be estimated including only the technical change in conventional inputs under a fixed or a random effects formulation and then in a second-stage individual country effects can be regressed separately against time to identify the technical change in damage abatement inputs. However, this consists only an artificial way to separate these two effects and in general is unsatisfactory solution to aforementioned identification problem. Moreover, in econometric grounds, arguments related to the efficiency of the estimated parameters surely apply compared to a single-stage estimation procedure.

[140] Relations ($PF2$) and ($PF3$) can be adjusted accordingly.

v and D_t is a time dummy for year t. All the relevant parameters in the above relation can be identified by imposing the restriction that as initially was suggested by Baltagi and Griffin (1988). The above specification, apart of enabling the identification of the two technical change effects is flexible as $A(t)$ is not constrained to obey any functional form, it is capable of describing complex and sometime erratic patterns of technical change consisting of rapid bursts of rapid changes and periods of stagnation, which might be relevant when we study the emission, that is, the input augmenting technical change.

- All different specifications PF and GA were estimated using weighted least squares (WLS) in order to take into account both cross-section heteroscedasticity and contemporaneous correlation among countries in the sample. The estimation is carried out in two steps. In the first step the model is estimated via simple OLS. Using the obtained residuals the conditional country specific variance is calculated and it is used to transform both the dependent and independent variables of the second-stage regression. Specifically for each country, y_i and each element of x_i (independent variables) are divided by the estimate of the conditional standard deviation obtained from the first-stage. Then a simple OLS is performed to the transformed observations expressed as deviations of their means. This results in a feasible generalized least square estimator described by Wooldridge (2000, Ch. 8) and Greene (2003, Ch. 11)

Tables 2a, 2b show estimates of the shares s_k, s_h, s_z for models $PF1-PF3$ and $GA1 - GA3$ respectively[141].

Table 2a

Table 2b

The estimates of the input shares from the PF estimation, suggest a value for capital's share between 32% and 49.6%, a share for CO_2 emissions between 7.8% and 3.3% and a share for education in the only equation which is used

[141] PF models were also estimated by using as regressors the original regressors lagged, one period, and by instrumental variables estimation using as instruments the original regressors lagged one period. There was no substantial change in the results.

as a proxy for human capital, of 4.3%.[142] When we use the GA equations, the share of capital goes down by approximately 10% while the share of emissions goes up to around 15%. The higher value of the capital share both in PF and GA estimations occur in the equation where labor input is adjusted for education with the use of the variable $L_h = LH$. In all estimations where labour is measured in physical units, the sum of capital's share and emissions' share is between 35% and 39%., an estimate within the expected range. The estimates for the CO_2 share in all estimated regressions, with the interpretation given in (139), are highly significant and in a sense this suggests a significant contribution of CO_2 emissions in output. This result seems to justify empirically the introduction of emissions as an input in the production function. Furthermore, by using (139), we can obtain the shadow cost of emissions as, $\mu = \hat{s}_z (Y/Z)$. Using the average values for GDP and CO_2 for the 23 OECD countries, the average shadow value of emissions μ for the sample period is between 32$ and 76$ per ton of CO_2. This value, which reflects the private costs in terms of profits related to CO_2 emissions, should be contrasted with the value of λ that reflects the social cost of the accumulated CO_2.

Table 3a, provides overall average estimates of labor augmenting technical change x, emission augmenting technical change b, and estimates of average TFPG obtained as $xa_3 + ba_4$. For the models that includes human capital (approximated by years of education) or does not include human capital at all, average TFPG is around 1%. When we use quality adjusted labor as input, the TFPG estimate drops to 0.4%. It should be noticed here, that our methodology allows to distinguish between two different types of technical change and identifies positive emissions augmenting technology. This

[142] Capital's share increases and emissions' share decreases as we move from a model where labour is measured in physical units, to a model where labour is measured in 'quality adjusted terms' as $L_h = LH$. This can be explained in the context of an argument put forward by Griliches (1957) for a Cobb-Douglas production function. Consider the two production functions, disregarding technical change to simplify notation, $Y = K^{b_1} L^{b_2} Z^{b_3}$ and $Y = K^{a_1} (HL)^{a_2} Z^{a_3}$ and the 'auxiliary' equation $H = K^{p_1} L^{p_2} Z^{p_3}$. If the true production function is the one where labour is measured in 'quality adjusted terms', then input elasticities will be $\epsilon_1 = a_1 + p_1 a_2$, $\epsilon_2 = a_2 + p_2 a_2$, $\epsilon_3 = a_3 + p_3 a_2$. If there is a positive relationship between labour quality and capital, since higher quality of labor increases the marginal productivity of capital, and a negative relationship between labour quality and emissions (because higher quality of labor could imply high-tech and relatively clean production process), then $p_1 > 0$ and $p_3 < 0$, and capital's elasticity increases, while emissions elasticity decreases when we use quality adjusted labour input.

result can be also regarded as an empirical verification for introducing input augmenting technical change in the production function, through the term $X = BZ$.

Table 3a

Table 3b provides individual country TFPG estimates from the GA models. The estimates are obtained by adding to the overall constant of each regression the estimate of individual country fixed effect.

Table 3b

As shown in table 3b the average TFPG estimates are very close to the estimates obtained from the production function in table 3a.

Table 4 uses the growth accounting equations (146) and the estimated shares from the production function to obtain TFPG estimates for individual countries.

Table 4

It should be noticed that the average estimates of TFPG in table 4,, are very close to those obtained directly from the regressions using $xa_3 + ba_4$, and the GA estimates This can be regarded as providing a confirmation of the robustness of our estimations. Negative estimates of TFPG correspond to the case where we use quality adjusted labor as input. These numbers seem to suggest that for these specific countries, the contribution of physical capital, capital quality adjusted labor and emissions to output per worker growth, exceeds the growth of output per worker.

6.11 Concluding Remarks

This part of the thesis aimed at formulating a new approach to Total Factor Productivity Growth measurement methodology, at a macroeconomic level, which would take into account the use of environment in the traditional TFPG measurement. We approximate the use of environment by CO_2 emissions. Our contribution at the theoretical level lies in deriving growth accounting equations with the input space of the aggregate production function augmented to include emissions and emission augmenting technical change, and interpreting the emissions share in output, in the context of a complete equilibrium under optimal taxation, as well as in the contrasting case where emissions is an unpaid factor, that is when emissions are not taxed. At the empirical level we provide (i) adjustments of existing TFPG estimates when CO_2 damages are taken into account, (ii) direct estimates of TFPG from an aggregate production function, and (iii) decomposition of technical change to labour augmenting and emissions augmenting technical change. Our approach can be regarded as a Green TFPG measurement methodology.

Our results suggest that when emissions grow, that is environment is used in production, traditional estimates overestimate TFPG relative to our estimates, by attributing part of environment's contribution to output growth, to technical change. The opposite happens when emissions decline, that is, when there are savings of environment as a factor of production, then traditional estimates underestimate TFPG. The size of deviation depends on size of damage estimates of CO_2 emissions. Direct econometric estimation of TFPG, suggests an average TFPG which for the period 1965-1990 and for the countries under examination is around 1%, or less. It also suggests that emissions in the form of CO_2 is a statistically significant input in the aggregate production function and that emission augmenting technical change coexist with labour augmenting technical change. This implies that the use of the environment approximated by CO_2 emissions, which is an unpaid factor, contributes to the growth of output along with physical capital, human capital, and labour, and its contribution should be accounted for in TFPG measurements. It should be also noted that the environment's contribution we estimated through the production function analysis might underestimate or overestimate the "socially optimal contribution", which is associated with an optimal tax determined by marginal environmental damages along the optimal path. If marginal damages are relatively high the socially optimal use of the environment in the growth process, should be relatively small, while the opposite holds for low marginal damages. If, in the absence of optimal environmental policy, this contribution is sizable, and our results suggest that the CO_2 emissions contribution is statistically significant with a share in output which could be as high as 14%, then excess use of the environment as an input might question the eventual sustainability of the current growth process. For example if, after solving the social planner's problem, we have an estimate of λ, the true shadow value of the CO_2, and calculate emissions' share, s_Z as $\left(-\hat{\lambda}Z\right)/Y$, then the growth accounting equation (**??**) might produce a negative result. This result can be interpreted as an indication that total use of resources, including the "unpaid" environment properly valued, exceeds the output growth generated by these resources. In this case development that uses "unpaid" factors may be considered as not sustainable.[143] This observation provides a link between direct adjustments and econometric estimations, which approach the problem from different directions. The two approaches will coincide only along a socially optimal path.

Areas of future research include TFPG estimates by approximating environment's use not just by CO_2 emissions, but by a more general index that will include additional environmental variables; introduction of stock variables into the aggregate production function; use of our production function estimates along with damage functions for CO_2 to solve the social planners problem and define the structure and the parameters of the corresponding value functions; reformulating, at a more general level, some of the recent empirical approaches to growth to take into account possible unpaid and damage generating factors of production. We hope that this approach will enhance growth empirics by incorporating the environmental dimension in a meaningful way.

[143] Along the socially-optimal path the use of the "unpaid" factor the environment, will be determined by its true social shadow cost.

Appendix

Derivation of the Social Planner's Problem

Capital accumulation in per worker terms, assuming that the two capital goods depreciate at the same constant rate (Barro and Sala-i-Martin, 2004), is given by:

$$\dot{k} + \dot{h} = y - c - (\eta + \delta)(k + h) \tag{149}$$

Define in efficiency units $k = \hat{k}e^{\xi t}$,and $h = \hat{h}e^{\xi t}$, $c = \hat{c}e^{\xi t}$ so that $\dot{k} = \dot{\hat{k}}e^{\xi t} + \xi\hat{k}e^{\xi t}$ and $\dot{h} = \dot{\hat{h}}e^{\xi t} + \xi\hat{h}e^{\xi t}$. Substituting $\dot{k}$ and $\dot{h}$ in (149) we obtain:

$$\dot{\hat{k}}e^{\xi t} + \xi\hat{k}e^{\xi t} + \dot{\hat{h}}e^{\xi t} + \xi\hat{h}e^{\xi t} = e^{\zeta t}(\hat{k}e^{\xi t})^{a_1}(\hat{h}e^{\xi t})^{a_2}Z^{a_4} - \hat{c}e^{\xi t} - (\eta + \delta)(\hat{k}e^{\xi t} + \hat{h}e^{\xi t})$$

dividing by $e^{\xi t}$:

$$\begin{aligned} \dot{\hat{k}} + \dot{\hat{h}} &= e^{-\xi t}\left(e^{\zeta t}\hat{k}^{a_1}e^{\xi t a_1}\hat{h}^{a_2}e^{a_2\xi t}Z^{a_4}\right) - \hat{c} - (\eta + \delta + \xi)(\hat{k} + \hat{h}), \text{ or} \\ \dot{\hat{k}} + \dot{\hat{h}} &= e^{(\zeta - \xi + a_1\xi + a_2\xi)t}\hat{k}^{a_1}\hat{h}^{a_2}Z^{a_4} - \hat{c} - (\eta + \delta + \xi)(\hat{k} + \hat{h}) \end{aligned}$$

to make the above equation time independent we choose ξ such that $\zeta - \xi + a_1\xi + a_2\xi = 0$ or $\xi = \frac{\zeta}{1-a_1-a_2} = \frac{xa_3+a_4(b-n)}{1-a_1-a_2}$

$$\dot{\hat{k}} + \dot{\hat{h}} = \hat{k}^{a_1}\hat{h}^{a_2}Z^{a_4} - \hat{c} - (\eta + \delta + \xi)(\hat{k} + \hat{h}) \tag{150}$$

Assuming as above that the allocation between physical and human capital is such that the marginal products for each type of capital are equated in equilibrium if we use both forms of investment, we have that[144]:

$$a_1\frac{\hat{y}_t}{\hat{k}_t} - \delta = a_2\frac{\hat{y}_t}{\hat{h}_t} - \delta \tag{151}$$

The equality between marginal products implies a one to one relationship between physical and human capital, or:

$$\hat{h} = \frac{a_2}{a_1}\hat{k},\ \dot{\hat{h}} = \frac{a_2}{a_1}\dot{\hat{k}} \tag{152}$$

[144] This substitution is convenient since by adopting it we do not need a seperate state equation for human capital. It does not however affect the basic results of this section regarding the interpretation of the emissions share in output.

Using (152) in (150) we obtain:

$$\dot{\hat{k}} + \frac{a_2}{a_1}\dot{\hat{k}} = \hat{k}^{a_1}\left(\frac{a_2}{a_1}\hat{k}\right)^{a_2} Z^{a_4} - \hat{c} - (\eta+\delta+\xi)\left(\hat{k} + \frac{a_2}{a_1}\hat{k}\right)$$

$$\begin{aligned} \dot{\hat{k}} &= \tilde{A}\hat{k}^{\beta} Z^{a_4} - \hat{c} - (\eta+\delta+\xi)\,\hat{k}, \qquad (153) \\ \tilde{A} &= \left(\frac{a_2^{a_2} a_1}{a_1^{a_2}(a_1+a_2)}\right),\ \beta = a_1 + a_2 \end{aligned}$$

Considering a utility function $U(c,S) = \frac{1}{1-\theta}c^{1-\theta}S^{-\gamma} \quad \theta, \gamma > 0$ we obtain using the substitution $c = \hat{c}e^{\xi t}$.

$$\begin{aligned} U(c,S) &= \frac{1}{1-\theta}c^{1-\theta}S^{-\gamma} = \frac{1}{1-\theta}\left(\hat{c}e^{\xi t}\right)^{1-\theta} S^{-\gamma} = \qquad (154) \\ &= e^{(1-\theta)\xi t}\frac{1}{1-\theta}\hat{c}^{1-\theta}S^{-\gamma} = e^{(1-\theta)\xi t}U(\hat{c},S) \end{aligned}$$

Using (119), (154), (118), and (153) the social planners problem can be written as (121) ■

Proof of Proposition 1:. *Consumers:* Defining the current value Hamiltonian for the representative consumer as:

$$H = U(c,S) + \pi(w + ra - c + na + \tau z) \qquad (155)$$

standard optimality conditions imply:

$$\begin{aligned} U_c(c,S) &= \pi\ ,\ U_{cc}(c,S)\,\dot{c} + U_{cS} = \dot{\pi} \qquad (156) \\ \dot{\pi} &= (\rho - r)\,\pi \text{ or} \qquad (157) \\ \frac{\dot{c}}{c} &= \frac{1}{\theta}(r-\rho) - \frac{U_{cS}}{U_{cc}}\dot{S} \qquad (158) \end{aligned}$$

Firms: The profit function for the firm can be written in per worker terms, using the Cobb-Douglas specification and setting $k = \hat{k}e^{\xi t}$, $h = \hat{h}e^{\xi t}$, and $\zeta - \xi + a_1\xi + a_2\xi = 0$, $\xi = \zeta - a_1\xi - a_2\xi$ as:

$$\Pi = F(K,H,E,X) - R_K K - R_H H - wL - \tau Z \qquad (159)$$

or

$$\begin{aligned} \frac{\Pi}{L} &= e^{\zeta t}k^{a_1}h^{a_2}Z^{a_4} - R_K k - R_H h - w - \tau z \\ \frac{\Pi}{L} &= e^{\xi t}\hat{k}^{a_1}\hat{h}^{a_2}Z^{a_4} - R_K\hat{k} - R_H\hat{h} - w - \tau z \end{aligned}$$

$$\tilde{\pi} \equiv \frac{\Pi}{L} = e^{\xi t}\left[f\left(\hat{k},\hat{h},Z\right) - R_K\hat{k} - R_H\hat{h} - we^{-\xi t} - \tau z e^{-\xi t}\right],\ z = \frac{Z}{L} \quad (160)$$

In equilibrium firms take R_K, R_H, w, and τ as given and maximize for any given level $\hat{l} = Le^{\xi t}$ by setting:

$$f_{\hat{k}} = R_K = r + \delta \quad (161)$$

$$f_{\hat{h}} = R_H = r + \delta \quad (162)$$

$$f_Z = \frac{\tau}{\hat{l}} \Rightarrow f_Z\hat{l} = \tau, \quad (163)$$

$$f_Z \;=\; \tau\frac{1}{L}e^{-\xi t},\ z = \frac{Z}{L},\ \hat{l} = Le^{\xi t},\ L = \hat{l}e^{-\xi t},\ f_Z = \frac{\tau}{\hat{l}}. \quad (164)$$

$$e^{\xi t}\left[f\left(\hat{k},\hat{h},Z\right) - f_{\hat{k}}\hat{k} - f_{\hat{h}}\hat{h} - \left(f_Z\hat{l}\right)ze^{-\xi t}\right] = w \quad (165)$$

The wage w equals the marginal value of labor and ensures that profits are zero in equilibrium, since by substituting (161)-(165) into (160) we obtain:

$$\begin{aligned} f\left(\hat{k},\hat{h},Z\right) - R_K\hat{k} - R_H\hat{h} - e^{\xi t}\left[f\left(\hat{k},\hat{h},Z\right) - f_{\hat{k}}\hat{k} - f_{\hat{h}}\hat{h} - \tau z e^{-\xi t}\right]e^{-\xi t} - \tau z e^{-\xi t} &= \\ f\left(\hat{k},\hat{h},Z\right) - f_{\hat{k}}\hat{k} - f_{\hat{h}}\hat{h} - f\left(\hat{k},\hat{h},Z\right) + f_{\hat{k}}\hat{k} + f_{\hat{h}}\hat{h} + \left(f_Z\hat{l}\right)ze^{-\xi t} - \left(f_Z\hat{l}\right)ze^{-\xi t} &= 0 \end{aligned}$$

Equilibrium: In equilibrium $a = k + h$ so $\hat{a} = \hat{k} + \hat{h}$, then the flow budget constraint :

$$\dot{a} = w + ra - c - na + \tau z \quad (166)$$

can be written as:

$$\dot{k} + \dot{h} = w + r\left(k + h\right) - c - n\left(k + h\right) + \tau z \quad (167)$$

Setting as before $k = \hat{k}e^{\xi t}$ and $h = \hat{h}e^{\xi t}$, $c = \hat{c}e^{\xi t}$, and taking the time derivatives of k and h we obtain:

$$\begin{aligned} &\dot{\hat{k}}e^{\xi t} + \xi\hat{k}e^{\xi t} + \dot{\hat{h}}e^{\xi t} + \xi\hat{h}e^{\xi t} = \\ &w + r\left(\hat{k}e^{\xi t} + \hat{h}e^{\xi t}\right) - \hat{c}e^{\xi t} - n\left(\hat{k}e^{\xi t} + \hat{h}e^{\xi t}\right) + \tau z \end{aligned} \quad (168)$$

substituting (161)-(165) into (167), and using in equilibrium $r = f_{\hat{k}} - \delta = f_{\hat{h}} - \delta$, $f_Z\hat{l} = \tau$, $\hat{l} = Le^{\xi t}$ we obtain:

$$\begin{aligned} &\dot{\hat{k}}e^{\xi t} + \xi\hat{k}e^{\xi t} + \dot{\hat{h}}e^{\xi t} + \xi\hat{h}e^{\xi t} = \\ &e^{\xi t}\left[f\left(\hat{k},\hat{h},Z\right) - f_{\hat{k}}\hat{k} - f_{\hat{h}}\hat{h} - \left(f_Z\hat{l}\right)ze^{-\xi t}\right] + \left(f_{\hat{k}} - \delta\right)\hat{k}e^{\xi t} + \\ &\left(f_{\hat{h}} - \delta\right)\hat{h}e^{\xi t} - \hat{c}e^{\xi t} - n\left(\hat{k}e^{\xi t} + \hat{h}e^{\xi t}\right) + \left(f_Z\hat{l}\right)z \end{aligned} \quad (169)$$

Dividing by $e^{\xi t}$ we obtain under the Cobb-Douglas assumption:

$$\dot{\hat{k}} + \dot{\hat{h}} = \hat{k}^{a_1}\hat{h}^{a_2}Z^{a_4} - \hat{c} - (\eta + \delta + \xi)(\hat{k} + \hat{h}) \tag{170}$$

Using as above the assumption that in equilibrium the allocation between physical and human capital is such that the marginal products for each type of capital are equated if we use both forms of investment, we have as before $a_1 \frac{\hat{y}_t}{\hat{k}_t} - \delta = a_2 \frac{\hat{y}_t}{\hat{h}_t} - \delta$ and $\hat{h} = \frac{a_2}{a_1}\hat{k}$, $\dot{\hat{h}} = \frac{a_2}{a_1}\dot{\hat{k}}$. Then (170) becomes

$$\dot{\hat{k}} = f\left(\hat{k}, Z\right) - \hat{c} - (\eta + \delta + \xi)\,\hat{k} \ \ , \ \ f\left(\hat{k}, Z\right) = s\tilde{A}\hat{k}^{\beta}Z^{a_4} \tag{171}$$

which is the social planners transition equation.

Setting $c = \hat{c}e^{\xi t}$ and $\dot{c} = \xi\hat{c}e^{\xi t} + \dot{\hat{c}}e^{\xi t}$ into (158) and using (161) we obtain

$$\frac{\dot{\hat{c}}}{\hat{c}} = \frac{1}{\theta}\left[f_{\hat{k}}\left(\hat{k}, Z\right) - \rho - \delta - \xi\theta\right] - \frac{U_{\hat{c}S}}{U_{\hat{c}\hat{c}}}\dot{S} \tag{172}$$

Under optimal taxation we have from the social planner's problem that $f_Z\left(\hat{k}, Z\right) = -\lambda/p = \tau$, with $p = U_{\hat{c}}\left(\hat{c}, S\right)$, then $Z = g\left(\hat{k}, \lambda, p\right)$. Substituting Z into the equation above and into (118) we obtain

$$\frac{\dot{\hat{c}}}{\hat{c}} = \frac{1}{\theta}\left[f_{\hat{k}}\left(\hat{k}, g\left(\hat{k}, \lambda, p\right)\right) - \rho - \delta - \xi\theta\right] - \frac{U_{\hat{c}S}}{U_{\hat{c}\hat{c}}}\dot{S}, \tag{173}$$

$$\dot{S} = g\left(\hat{k}, \lambda\right) - mS \tag{174}$$

The dynamic system (171), (173) and (174) determines the evolution of $\left(\hat{c}, \hat{k}, S\right)$ in a decentralized competitive equilibrium under optimal emission taxation. By comparing them with (122), (128), (129) it is clear that the path of the decentralized competitive equilibrium under optimal emission taxation coincides with the socially optimal path. ■

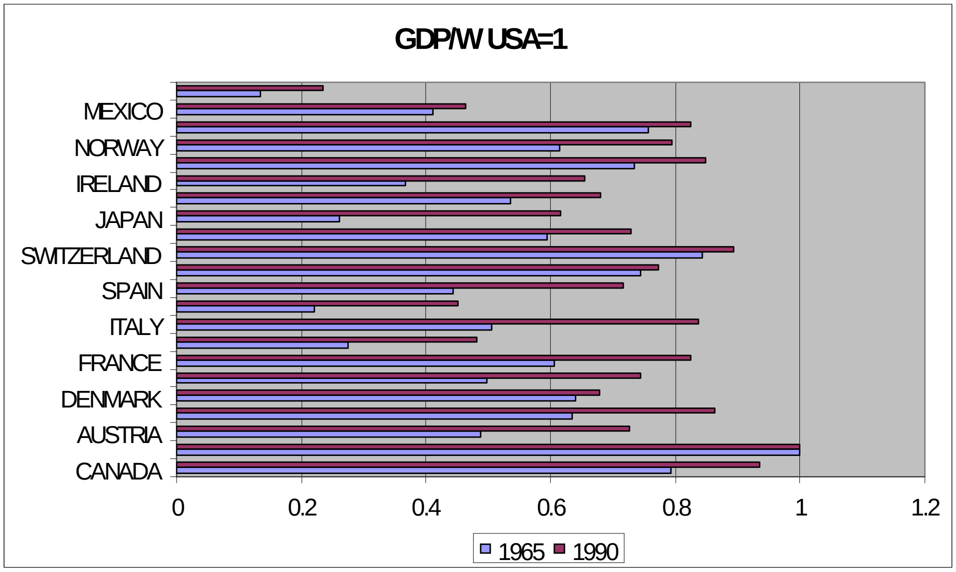

Figure 1: GDP per worker in 1965 and 1990 (USA=1)

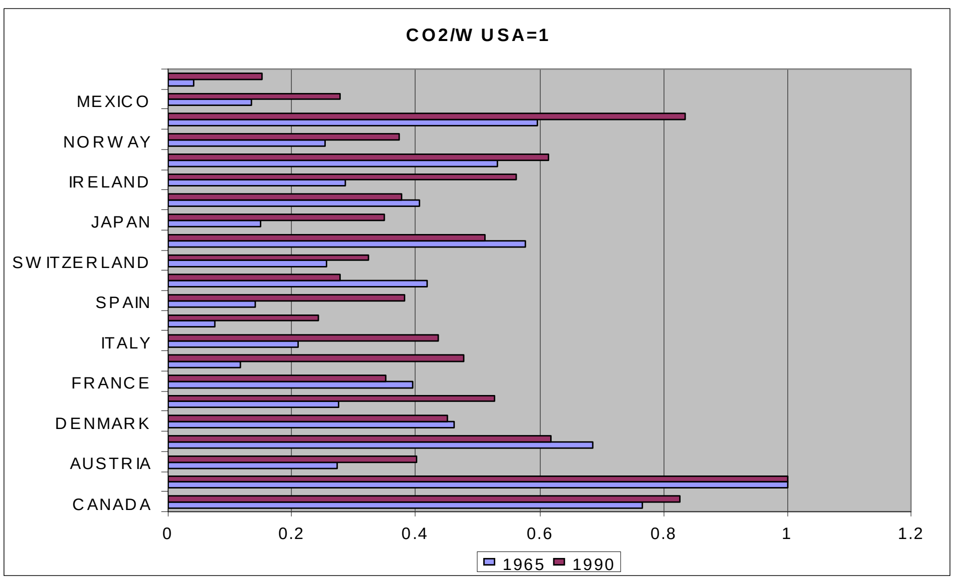

Figure 2: CO_2 per worker in 1965 and 1990 (USA=1)

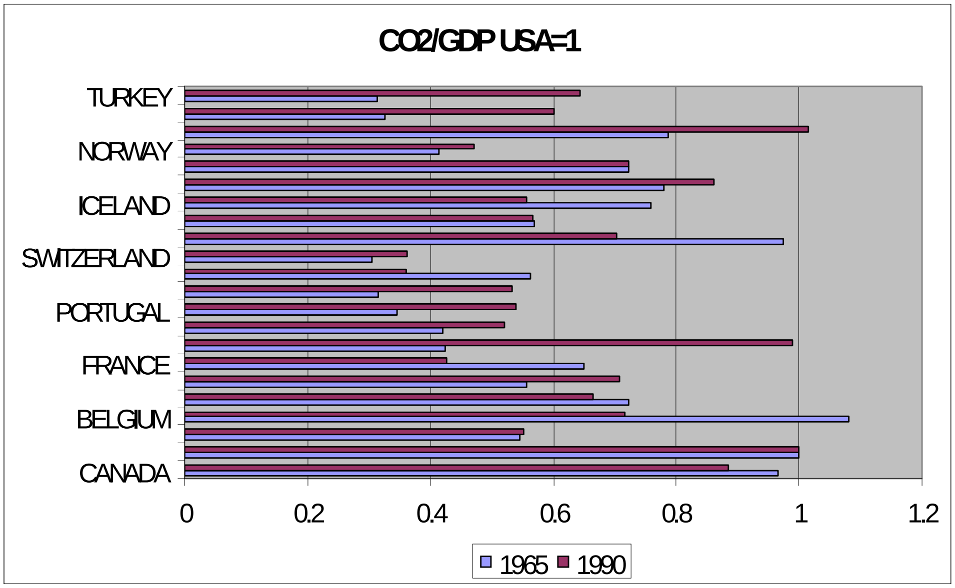

Figure 3: CO_2/GDP in 1965 and 1990 (USA=1)

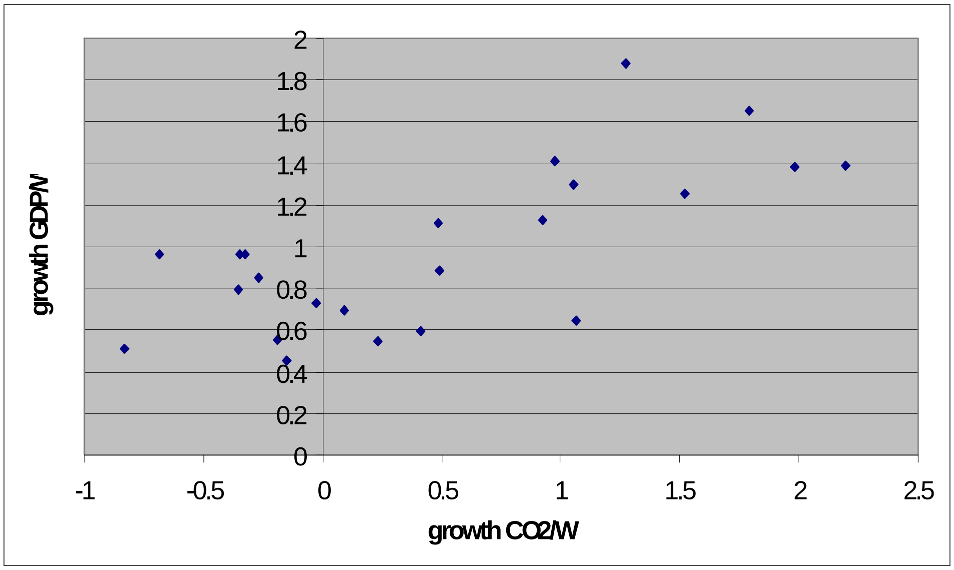

Figure 4: Growth of GDP per worker vs growth of CO_2 per worker.

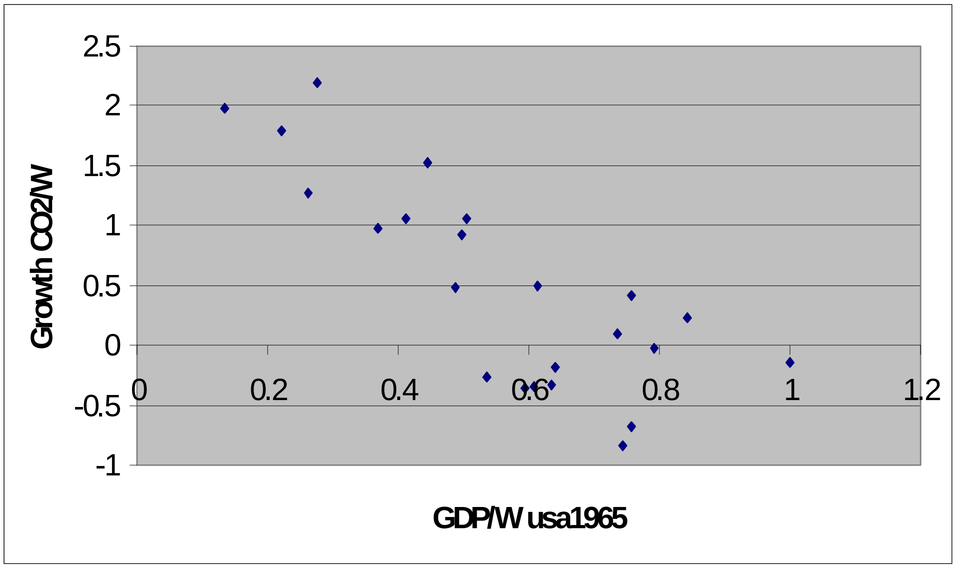

Figure 5: Growth CO_2/W vs GDP/W (GDP/W for USA=1 at 1965)

Table1– *Direct adjustments of traditional TFPG estimates*

Countries	*Trad.TFPG* (%)	*Growth*CO_2 (%)	$MDCCO_2$ \$20/tC			$MDCCO_2$ \$93/tC			$MDCCO_2$ \$350/tC		
(1)	(2)	(3)	s_{iz} (4)	*GTFPG* (%) (5)	% *Dev.* (6)	s_{iz} (7)	*GTFPG* (%) (6)	% *Dev.* (9)	s_{iz} (10)	*GTFPG* (%) (11)	% *Dev.* (12)
CANADA	0.57	2.12	0.0241	0.52	–9.01	0.1123	0.33	–41.9	0.4226	–0.33	–157
U.S.A.	0.76	1.32	0.0266	0.72	–4.62	0.1237	0.60	–21.5	0.4657	0.14	–80.9
FRANCE	1.3	0.04	0.0146	1.30	–0.05	0.0679	1.30	–0.22	0.2556	1.29	–0.84
ITALY	1.53	2.97	0.0128	1.49	–2.50	0.0597	1.35	–11.6	0.2248	0.86	–43.7
U.K.	0.8	–0.35	0.0213	0.81	0.94	0.0991	0.83	4.39	0.3729	0.93	16.5
JAPAN	2.65	4.07	0.0156	2.59	–2.39	0.0724	2.35	–11.1	0.2724	1.54	–41.9

Column (2): Traditional TFPG estimates. Source: Barro and Sala-i-Martin (2004)
Column (3): Average annual growth of CO_2 emissions
Columns (4,7,10): Emissions share in GDP using the corresponding MDCCO_2 estimate.
Columns (5,8,11): Green TFPG estimates
Columns (6,9,12): Proportional deviation between traditional TFPG and GTFPG estimates.

Table2a– *Production Function Estimation for the three PF models*

	$PF1$	$PF2$	$PF3$
c	-0.25711	-0.20460	-0.08791
$a_1 = s_k$	0.32199	0.32597	0.49580
$a_4 = s_z$	0.07603	0.07774	0.03294
$a_2 = s_h$	0.04256	–	–
ba_4	0.002059	0.002064	0.0028012
xa_3	0.009169	0.008611	0.000593
R^2	0.99	0.99	0.99
DW	2.00875	2.02950	2.00932

All coefficients are significant at 1% level

Table2b– *Growth Accounting Estimation for the three GA models**

	$GA1$	$GA2$	$GA3$
$a_1 = s_k$	0.21494	0.21485	0.44633
$a_4 = s_z$	0.14407	0.14448	0.15488
$a_2 = s_h$	0.02405	–	–
R^2	0.89	0.89	0.97
DW	2.05828	2.05849	2.06371

All coefficients are significant at 1% level

(*) We do not report the constant term since the overall constant plus the fixed effect estimator for each county defines the TFPG for this country. These estimates are reported in table 3b.

Table 3a:− *TFPG and technical change estimates using the production function*

	xa_3	ba_4	x	b	*TFPG*
$PF1$	0.00917	0.00206	0.01639	0.02708	0.01122
$PF2$	0.00861	0.00206	0.01444	0.02656	0.01067
$PF3$	0.00059	0.00280	0.00126	0.08504	0.00339

Table 3b: *TFPG estimates using the growth accounting equations*

Countries	$GA1$	$GA2$	$GA3$
CANADA	0.009825	0.009452	−0.00057
U.S.A.	0.005149	0.004922	−0.003864
AUSTRIA	0.011807	0.011726	−0.00208
BELGIUM	0.017204	0.01691	0.01179
DENMARK	0.007932	0.007759	−0.000514
FINLAND	0.017121	0.016993	0.007033
FRANCE	0.014472	0.014404	0.002705
GREECE	0.014883	0.015025	−0.001442
ITALY	0.018542	0.018566	0.007159
LUXEMBOURG	0.021252	0.021199	0.013261
PORTUGAL	0.023597	0.023525	0.009182
SPAIN	0.010792	0.010754	−0.00578
SWEDEN	0.009019	0.00885	0.000109
SWITZERLAND	0.005414	0.005204	−0.002261
U.K	0.01332	0.013055	0.007811
JAPAN	0.023158	0.022758	0.007299
ICELAND	0.011533	0.010966	0.002536
IRELAND	0.022938	0.022673	0.013404
NETHERLANDS	0.010253	0.00991	0.003105
NORWAY	0.018458	0.018253	0.01395
AUSTRALIA	0.007183	0.006713	0.000304
MEXICO	0.005397	0.004921	−0.006345
TURKEY	0.014218	0.013845	0.000786
AVERAGES	0.013629	0.013408	0.003373

Table 4: *TFPG calculations using factor shares estimates from the production function*

Countries	$PF1$	$PF2$	$PF3$
CANADA	0.00657	0.005774	−0.002668
U.S.A.	0.00221	0.001713	−0.006308
AUSTRIA	0.00659	0.006204	−0.003676
BELGIUM	0.01329	0.012640	0.009634
DENMARK	0.00399	0.003563	−0.003396
FINLAND	0.01424	0.013842	0.0070440
FRANCE	0.00959	0.009315	−0.000681
GREECE	0.01306	0.013059	0.001541
ITALY	0.01589	0.015753	0.007459
LUXEMBOURG	0.01761	0.017429	0.009761
PORTUGAL	0.02146	0.021091	0.011636
SPAIN	0.00682	0.006479	−0.004975
SWEDEN	0.00356	0.003142	−0.004999
SWITZERLAND	0.00230	0.001786	−0.003274
U.K	0.00931	0.008716	0.005570
JAPAN	0.01724	0.016188	0.007519
ICELAND	0.00705	0.005885	−0.000350
IRELAND	0.01981	0.019137	0.013902
NETHERLANDS	0.00739	0.006656	0.001841
NORWAY	0.01816	0.017760	0.013792
AUSTRALIA	0.00578	0.004844	0.000414
MEXICO	0.00441	0.003427	−0.00555
TURKEY	0.01253	0.011634	0.00356
Averages	0.010385	0.0098277	0.002513

7. Green Growth Accounting in Developing Countries

7.1 Introduction

One of the basic issues of economic growth is to discover the factors which are the drivers of output growth and provide useful insights for the characteristics of a sustainable growth process. In this framework, developing countries are the countries that have the most urgent need of adopting policies that will provide them the basic directions towards a long run economic growth in the 21st century where environmental consciousness is among the main points of global interest. The need for a sustainable development process, is the goal to be attained not only by the developed but also by the developing countries. United Nations World Conservation Strategy, the Report of the World Commission on Environment and Development also known as the Brundtland Report[145], Agenda 21, the Kyoto Protocol, the Stern Report, are some of the well documented reports which suggest that environmental degradation on the name of development cannot be a solution anymore. When these concepts and arguments are applied to growth accounting they could suggest that the traditional growth accounting measurements might be a misleading indicator of growth especially for developing countries. That is because one of the production factors that create growth, the environment, is not properly accounted in growth accounting measurements and this might lead to incorrect TFPG results for these countries. Based on this idea, the analysis of chapter 7 has two basic aims. The first, is to provide a well defined theoretical framework for measuring TFPG by including the use of the environment as an input in the production process for a group of 21 developing countries.[146] The second is to provide measurement results of the "Green" TFPG (GTFPG) for those countries and comparisons with prior estimates of other studies.

We follow the theoretical model of chapter 6 where the structure of the TFPG model is augmented with the input "environment". By considering

[145] United Nations (1987)

[146] The 21 Developing countries used in our analysis are the following: Peru, Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Jamaica, Bolivia, Colombia, Ecuador, Iran, Srilanka, Syria, Yugoslavia, India, Kenya, Madagascar, Malawi, Sierra Leone, Zimbabwe.

Carbon Dioxide (CO_2) emissions as a proxy for the use of this unpaid environmental factor, the environment (a place where the negative externalities of the production process are deposited) is introduced in our model as an input in the production function and is considered as a source of growth. In other words, we treat the environment as a sort of social-natural capital which is an unpaid source of growth[147] that has been omitted from the current traditional growth accounting measurements.

This idea is then tested empirically for a group of 21 developing countries and our results suggests that the environment can be considered as an extra unpaid (due to the lack of environmental policy) source of growth for developing countries. In our model, emission's augmented technical change is also present along with labor augmented technical change. This way we assume the existence of some kind of "abatement" in the production process along with labor productivity. We believe that this kind of analysis addresses the problem of environmental degradation in an effective way because it highlights the contribution of the environment in total output growth and reflects the use of CO_2 emissions as an environmental proxy in the aggregate output production. If the environment as a factor of production, had a price[148], then it would be less exploited due to the positive cost of its use and this would lead to a much more efficient use of this factor and would change the growth accounting measurement results.

Based on this idea, we graphically describe the relationship between emissions growth and output growth in per worker terms for the group of the 21 developing countries in the next chapter 7.2. In chapter 7.3 we develop the "Green" TFPG model and provide the measurements of Green TFPG using two approaches. Independent estimates for CO_2 damages and also econometric estimation of a growth accounting equation and a production function equation (chapters 7.4.1, 7.4.2). The results encourage our belief of an extra factor of production, the environment. The last chapter concludes.

7.2 Emissions-Output Growth in Developing Countries

This chapter attempts to illustrate graphically the link between the growth of CO_2 emissions and the growth of the final output in a data set of the 21

[147] Unpaid in the sense that there is no optimal environmental policy for emissions.

[148] The price of the factor of production *environment* could be a tax on the emissions released in the ambient environment

developing countries[149], [150]. The figures that follow reveal a relationship between the environment proxied by CO_2 emissions and the growth of the final output in these countries. The years compared are 1965 and 1990. Figure 1, shows the level of gross domestic product in per worker terms (GDP/W) for the group of the 21 developing countries. We observe an increase in gross domestic product per worker from year 1965 compared to the year 1990 for 16 of the countries[151] and a reduction in GDP/W for only 5 developing countries.

$Figure$ 1

Figure 2 that follows shows emissions of CO_2 per worker (CO_2/W) for the years 1965 and 1990 respectively for the same group of countries. It can be noticed that in some cases (5 out of 21),[152] CO_2/W was decreased during these years, while for the rest (16 out of 21)[153], CO_2 emissions per worker increased. Almost the same result is also confirmed in Figure 3 that follows, which represents CO_2 emissions per unit of GDP (CO_2/GDP) for the years 1965 and 1990. As figure 2 shows, for the majority of the developing countries (16 out of 21)[154], CO_2 emissions per unit of GDP increased by comparing year 1965 to 1990, whereas in the rest countries, emissions per unit of GDP decreased[155].

$Figure$ 2

$Figure$ 3

[149] Peru, Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Jamaica, Bolivia, Colombia, Ecuador, Iran, Srilanka, Syria, Yugoslavia, India, Kenya, Madagascar, Malawi, Sierra Leone, Zimbabwe.

[150] Our data are taken from the Penn Tables v5.6. Real GDP measured in thousands of US$ is the variable (RGDPCH), multiplied by the variable POP in the Penn Tables. Capital stock and employment are retrieved from Real GDP and capital per worker (KAPW) and real GDP per worker (RGDPW). All values are measured in 1985 international prices. CO_2 data are taken from the World Bank and are measured in thousand tons of CO_2 emissions.

[151] The 16 developing countries whose GDP/W in 1990 had increased compared to 1965 are: Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Bolivia, Colombia, Ecuador, Srilanka, Syria, Yugoslavia, India, Kenya, Malawi, Zimbabwe.

[152] Peru, Srilanka, Kenya, Malawi, Sierra Leone.

[153] Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Jamaica, Bolivia, Colombia, Ecuador, Iran, Syria, Yugoslavia, India, Madagascar, Zimbabwe

[154] Peru, Thailand, Paraguay, Morocco, Dominican Republic, Guatemala, Honduras, Jamaica, Bolivia, Ecuador, Iran, Syria, Yugoslavia, India,Madagascar, Zimbabwe

[155] These countries are: Colombia, Srilanka, Kenya, Malawi, Sierra Leone.

Figure 4, represents on the vertical axis the average growth of GDP per worker (GDP/W) and in the horizontal axis the growth of CO_2 per worker (CO_2/W) for the years 1965 and 1990. Each point of the scatter diagram represents one of the 21 countries. There is on the average a positive relationship between the two variables, suggesting that countries with high growth of CO_2 per worker can be associated with a high growth of GDP per worker. This can be regarded as an indication that the growth of CO_2 per worker contributes to the growth of GDP per worker.

figure 4

The last six figures (5, 6, 7, 8, 9, 10) depict the evolution of GDP/W and CO_2/W for the years 1965-1990 for Peru, Iran, Syria, India, Yugoslavia and Zimbabwe respectively. These figures represent peculiar patterns. GDP per worker and emissions per worker is upward sloping only for Syria, India and Yugoslavia. (*figures* 7, 8, 9). Peru, Iran and Zimbabwe follow on the average, an inverted U shape both for $GDP/W$and CO_2/W (*figures* 5, 6, 10).

figures 5, 6, 7, 8, 9, 10

The descriptive data, provide us with some indications that the growth of CO_2 emissions per worker seem to be positively related to the growth of output per worker. This could imply that the use of the environment is a factor that influences the output growth of an economy, and as such it should be taken into account into growth accounting measurements. We next develop a theoretical and empirical framework for testing this hypothesis which, provides a "green" perspective to TFPG measurement.

7.3 "Green" TFPG - The Model

Following the analysis of chapter 6.3, we use a standard neoclassical production function that includes emissions as an input of production[156] but not human capital[157]:

[156] We follow the idea appeared in Denison (1962), Dasgupta and Mäler (2000), Xepapadeas (2005) which relate environment to growth accounting. Our model does not include human capital due to the lack of data for the countries analyzed.

[157] We do not include human capital because of lack of appropriate data for the developing countries during the examined period.

$$Y = F(K, E, X) \tag{175}$$

where K is physical capital, $E = AL$ is effective labour, with L being labour in physical units and A reflecting labor augmenting technical change and $X = BZ$ is effective input of emissions, with Z being emissions in physical units and B reflecting emission saving technical change, or input augmenting technical change.

Defining the factor shares in a competitive equilibrium market set up, the "green" residual is defined as follows:

$$\gamma = s_L \left(\frac{\dot{A}}{A}\right) + s_Z \left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K \left(\frac{\dot{K}}{K}\right) - s_L \left(\frac{\dot{L}}{L}\right) - s_Z \left(\frac{\dot{Z}}{Z}\right) \tag{176}$$

The term $s_Z \left(\dot{B}/B\right)$ in (176) reflects emission augmenting technical change in addition to the standard labour augmenting technical change $s_L(\dot{A}/A)$, while the term $s_Z \left(\dot{Z}/Z\right)$ indicates that there is an extra source generating output growth apart from capital and labour, namely emissions. More specifically, $s_Z \left(\dot{Z}/Z\right)$ reflects the contribution of the environment to output growth that we believe it should be properly accounted and could be regarded a "Green" contribution to total output growth.[158].

Under constant returns to scale (176) becomes:

$$\frac{\dot{y}}{y} = \gamma + s_K \frac{\dot{k}}{k} + s_Z \frac{\dot{z}}{z}$$

We next try to clarify the interpretation of the share of emissions in output, since emissions is an unpaid factor in production because there is no environmental policy. In order to effectively interpret the emissions' share in "Green" TFPG even when no environmental taxation is present ($\tau = 0$), we consider the problem of a social planner who optimizes a felicity functional defined over consumption and environmental damages and we determine an optimal emission tax[159] $\tau > 0$, that would internalize the externalities that

[158] In the conventional formulation for the estimation of TFP growth the definition of the production function does not include emissions so that $s_Z \equiv 0$.

[159] Optimal in the sense that if firms pay this tax on their emissions they will emit the socially desirable levels of emissions.

the production process creates. Then, the share of emissions can written as:

$$s_Z = \frac{\tau Z}{Y} = \frac{\left(-\hat{\lambda}\right) Z}{Y},\ \hat{\lambda} = \frac{-\lambda}{p} = \frac{-\lambda}{U_{\hat{c}}} \tag{177}$$

where $\hat{\lambda}$ can be interpreted as the shadow cost of the pollution stock in terms of marginal utility $U_{\hat{c}}$. Thus the share of emissions in output coincides, under optimal environmental taxation, with the share of environmental damages in total output. It can be further shown that under the emission tax $\tau(t) = \hat{\lambda}(t)$ competitive equilibrium will coincide with the social planners solution[160].

7.4 "Green" TFPG Measurements

The environmental factor which is used as an input in the production function in our model is in practice an unpaid production factor since there is no taxation for CO_2 emissions for the period analyzed. When we start considering the environment as a source of growth we need to determine a cost for it's use. A proxy for the cost of the use of the environment is the marginal CO_2 emission damages. We choose to measure our "green" TFPG using: 1) Two direct adjustments based on: i) Independent estimates of the emission damages on share of GDP taken from the World Bank[161], ii) Measurements of the marginal damage cost estimates of CO_2 (MDCCO_2) by using existing MDCCO_2 estimates from Tol (2005). 2) Estimates of the share of CO_2 emissions by using econometric methods, a methodology which has the advantage of testing the statistical significance of emissions growth as a determinant of output growth.

7.4.1) Direct Adjustments: Theoretical Formulation and Empirical Results

i) Estimates of the emission shares using World Bank estimates

The "Green" residual, in the absence of environmental policy can be measured by using independent estimates of CO_2 damages. We use the estimates of carbon dioxide damages as proportion of GDP provided by the World Bank[162] and adjust previous estimates of TFPG using data on CO_2

[160] For the solution see Tzouvelekas, Vouvaki and Xepapadeas, (2006).

[161] World Bank (2001)

[162] *Toward a measure of genuine savings*, World Development Indicators, World Bank, 2001

damages from the World Bank and growth of CO_2 emissions using (135). The results we obtain are illustrated in *Table 1.*

Table 1

Table 1 presents the traditional TFP growth rates from 1940–1990 reported in Barro and Sala-i-Martin (2004). The 1st column reports the countries we test [163]. The 2nd column contains the CO_2 growth rates of those countries and the 3rd column the share of CO_2 emission damages in GDP, (s_Z) taken directly from the World Bank estimates. In the 4th column the traditional TFP growth rates are reported, while the 5th column presents our "Green" TFP growth for the same time period. What we observe from this first adjustment is that after the introduction of the environmental factor, TFP growth rates reduce marginally and the reduction is based on the contribution of the environmental damage of CO_2 emissions which were excluded from previous TFPG measurements. This is a first indication that the introduction of the environment affects TFPG measurement and that the environment could be an element in growth accounting, in the sense that part of the growth of total output per worker can be explained by the growth of CO_2 per worker.

ii) Estimates of the emission share using marginal damage cost of CO_2 *emissions*

A second approach to adjust TFPG measurements is by estimating s_z, the share of CO_2 emissions in GDP, using an approximate measure of p_z, the cost or damage per units of CO_2 emissions. We use (135) and (136) and approximate s_Z^i. Then $\hat{g}_S^i$ is our adjusted "Green residual". Z_{it} is CO_2 emissions for country i in year t and GDP_{it} being Gross Domestic Product produced in country i in year t. We then perform sensitivity analysis by choosing three different values for p_z. The first value is 20$ per ton of CO_2, a value that is proposed by the World Bank to represent the cost or damage per tons of CO_2 emissions[164]. The price of p_z taken by the World Bank can be regarded as a proxy for the price that is assigned to the cost or damage per ton of emissions created by CO_2, in the European permits market [165].

[163] These countries were chosen because there were estimates avaliable for the Traditional TFPG measurement from Barro and Sala-i-Martin (2004) and a comparison between the traditional and the Green residual could be made.

[164] Towards a measure of Genuine Savings, World Development Indicators, 2001

[165] Current prices (2006), have been reported in the range of 20euros per ton of CO_2.

This price should be the cost of taxation on CO_2 emissions, if an optimal tax was set on emissions in a competitive framework where the basic equivalence between emission taxes and emission permits holds. This equilibrium price should be equal to the marginal damages of CO_2 emissions. Although, these conditions do not hold in the actual permits market for CO_2, we believe that an approximation on these grounds could provide useful indications. The second value of p_z,we use is 93$ per ton of CO_2[166], and the third value of p_z we use equals 350$ per ton of CO_2[167].Using (135), (136) and the proxy of p_z = 20$, 93$ and 350$, we obtain the "Green" TFPG presented in *table 2*.

Table 2

The results of *table 2* indicate that "Green" TFPG reduces and some times can even take negative prices as p_z - the cost or damage per units of CO_2- increases. (Columns 5, 8, 11 - *table 2*). Columns (4, 7, 10 - *table 2*) show the share of the environmental factor in GDP and we observe an increase in this contribution as the cost per unit of CO_2 increases. Columns (6, 9, 12 - *table 2*), show the percentage deviations between the traditional and the "green" TFPG. The percentage deviations increase, as the cost of per unit CO_2 increases from 20$, to 93$ to 350$.

7.4 2) Econometric Estimation: Theoretical Formulation and Empirical Results

We next use econometric estimations to measure the share of emissions in total output, a methodology which has the advantage of testing the statistical significance of emissions growth as a determinant of output growth and thus can provide more appropriate measurements. We use an aggregate production function which includes CO_2 emissions as an input, but in contrast with chapter 6, we leave out of the production function human capital due to the lack of data for the case of developing countries. The econometric estimation is considered as a more appropriate way to estimate input shares and the share of CO_2 emissions which is an unpaid factor in the production

[166]The price for the cost or damage per ton of CO_2 emissions is proposed by Tol (2005) and represents the mean of the 28 published studies that he combined in his analysis.

[167]This value is also taken from the study of Tol (2005) and represents the higher value p_z can obtain.

process since it's share in GDP cannot be measured by existing data in the absence of CO_2 emission taxes.

Following the analysis of chapter 6.7, we use a Cobb-Douglas specification that includes emissions:

$$Y = A_0 K^{a_1} (AL)^{a_2} (BZ)^{a_3} \tag{178}$$

and we simplify the notation in (178) by setting $A_0 = 1$. Under constant returns to scale (178) in per worker terms becomes:

$$y = e^{(xa_2 + a_3 b)t} k^{a_1} z^{a_3} \tag{179}$$

where $y = \frac{Y}{L}, k = \frac{K}{L}$. Taking logs, we have the log linear form:

$$\ln y = (xa_2 + ba_3)\, t + a_1 \ln k + a_3 \ln z, \tag{180}$$

$$a_2 = 1 - a_1 - a_3 \tag{181}$$

Equation (180) provides estimates of input elasticities. To have a meaningful interpretation of these elasticities as factors' shares in the absence of optimal environmental policy, we need to consider the choice of emissions in the context of the constraint optimization problem:

$$\max \Pi = F(K, AL, BZ) - R_K K - wL \quad \text{subject to } Z \leq \bar{Z} \tag{182}$$

where the upper bound for emissions reflect technical constraints associated with production technologies and emissions. Associating the Lagrangian multiplier μ with the constraint $Z \leq \bar{Z}$ the first order condition for the optimal input choices, including emission choice, which correspond to (182) are:

$$L = F(K, AL, BZ) - R_K K - wL + \mu \left(\bar{Z} - Z\right) \tag{183}$$

and

$$\frac{\partial F}{\partial K} = R_K, \; \frac{\partial F}{\partial L} = w, \; \frac{\partial F}{\partial Z} = \mu$$

by the envelope theorem μ is the shadow cost of emissions Z, and measures the response of maximized profits to changes in the upper bound $\bar{Z}$. This shadow cost should be distinguished from the shadow cost of the pollution stock, defined in (131), that measures the response of maximum welfare to a change in the stock of pollutants, the stock of CO_2 in our case. Thus in the absence of environmental policy the share of the unpaid factor in equilibrium is defined as:

$$s_Z = \frac{F_Z Z}{Y} = \frac{\mu Z}{Y} \tag{184}$$

In general this will be different from the correct share $\left(-\hat{\lambda} Z\right)/Y$, unless $\bar{Z}$ is set at the level corresponding to the social welfare maximization path for the emissions' flow, which clearly is not the case for the period under investigation.

Therefore the elasticities obtained from the production function can be interpreted as shares associated with the constraint optimization problem (234) but not with the social welfare optimization problem[168]. This has certain implications for the interpretation of any estimation results. Given an estimate of $\hat{s}_Z$ the shadow value of emissions can be obtained as $\hat{\mu} = \hat{s}_Z \left(Y/Z\right)$ where Y/Z is the observed ouput-emissions ratio. This is not however a 'true shadow cost' of pollution in developing countries since the 'true shadow cost' λ, is based on a social welfare function that incorporates environmental damages and preferences in developing countries.

In the growth accounting exercise the contribution of CO_2 emissions on output growth using elasticities estimated from an aggregate production function, in the absence of CO_2 related environmental policy, can be interpreted in terms of emissions contributions under the existing technological constraints, and not as the 'true' contribution, when environment is properly valued by the welfare cost of using it. On the other hand this is a useful measure since it provides an indication of the impact from introducing an environmental policy that restricts emissions on aggregate output.

Actually since in the absence of a CO_2 policy it is expected that emissions constrained by technological restrictions, would be high[169], relative to the case where the socially optimal regulation is followed, the estimate of μ is expected to be low relative to λ.

In this context elasticities can be interpreted as shares, and we can set:

$$a_1 = s_K, \;\; a_3 = s_Z \tag{185}$$

By comparing (180) with (176), TFPG can be obtained by estimating

[168] For the solution of the social planner see Tzouvelekas, Vouvaki and Xepapadeas, (2006).

[169] We have unregulated profit maximization in this case.

$xa_2 + a_3 b$. In this case TFPG is approximated by the contribution of labor augmented technical change and emissions augmented technical change. For $a_3 = 0$ we have the traditional aggregate production function without emissions as an input. The equation that follows is the most general growth accounting equation with the introduction of the environment:

$$\begin{aligned} \frac{\dot{y}}{y} &= \gamma + s_K \frac{\dot{k}}{k} + s_Z \frac{\dot{z}}{z} && (186) \\ \gamma &= xa_2 + a_3 b && (187) \end{aligned}$$

Using (180) or (186), TFPG can be estimated econometrically, either from the trend term $xa_2 + a_3 b$ of (180) or the constant term γ of (186). Alternatively, using the estimated shares $\hat{s}_K, \hat{s}_Z$ from (180) or (186) and average growth rates of output and inputs per worker, TFPG can be calculated from (186) as:

$$\hat{\gamma} = \overline{\left(\frac{\dot{y}}{y}\right)} - \hat{s}_K \overline{\left(\frac{\dot{k}}{k}\right)} - \hat{s}_Z \overline{\left(\frac{\dot{z}}{z}\right)} \tag{188}$$

We can use the following two formulations in order to econometrically estimate TFPG, either by using a production function or a growth accounting equation that follow:

$$\text{Production Function} \quad \ln y = (xa_2 + a_3 b)\, t + a_1 \ln k + a_3 \ln z \tag{189}$$

$$\text{Growth Accounting} \quad \frac{\dot{y}}{y} = \gamma + a_1 \frac{\dot{k}}{k} + a_3 \frac{\dot{z}}{z} \tag{190}$$

The estimation of the growth accounting (GA) equation (190) represent estimation of the corresponding production function (PF) (189) in first differences, since we use the approximation $\dot{x}/x = \ln x_t - \ln x_{t-1}$. Thus the GA estimation could address problems associated with the stationarity of the variables in levels.

Following the econometric analysis of chapter 6.7, we use the following model to estimate "Green" TFPG:

$$\begin{aligned} \ln y_{it} &= \zeta t + A(t) + a_1 \ln k_{it} + a_3 \ln z_{it} \\ A(t) &= \sum_{t=1}^{T} (ba_3)_t \, D_t \\ \zeta &= xa_2 \end{aligned}$$

and D_t is a time dummy for year t. All the relevant parameters in the above relation can be identified by imposing the restriction that as initially was suggested by Baltagi and Griffin (1988). The above specification, apart of enabling the identification of the two technical change effects is flexible as $A(t)$ is not constrained to obey any functional form, it is capable of describing complex and sometime erratic patterns of technical change consisting of rapid bursts of rapid changes and periods of stagnation, which might be relevant when we study the emission, that is, the input augmenting technical change. We estimate PF and GA using weighted least squares and our results are summarized in tables 3-5.

Tables 3a, 3b show estimates of the shares s_k, s_z for the production function model PF and the growth accounting model GA respectively[170].

Table 3*a*

Table 3*b*

The estimates of the input shares from the PF estimation, suggest a value for capital's share 9.5% and a share for CO_2 emissions of 33%. When we use the GA equation, the share of capital goes up by approximately $25,6\%$ while the share of emissions goes down to around 8%.

The estimates for the CO_2 share with the interpretation given in (184) in all estimated regressions, are highly significant and in a sense that suggests a significant contribution of CO_2 emissions in output. This result seems to justify empirically the introduction of emissions as an input in the production function of the developing countries. Furthermore, by using (184), we can obtain the shadow cost of emissions as, $\mu = \hat{s}_z \left(Y/Z\right)$. Using the average values for GDP and CO_2 for the 21 countries of our analysis, the shadow value of emissions μ is between 136$ and 565$ per ton of CO_2.

Table 4a, provides estimates of labor augmented technical change x, CO_2 emission augmented technical change b, and estimates of average TFPG obtained as $(xa_2 + ba_3)$. Our methodology allows to distinguish between two different types of technical change and identifies positive emissions augmenting technology. This result can be also regarded as an empirical verification for introducing input augmenting technical change in the production func-

[170] The PF model was also estimated by using as regressor the original regressor lagged, one period, and by instrumental variables estimation using as instruments the original regressors lagged one period. There was no substantial change in the results.

tion, that is the specification BZ.

$Table\ 4a$

Table 4b provides individual country TFPG estimates from the GA model. The estimates are obtained by adding to the overall constant of each regression the estimate of individual country fixed effect.

$Table\ 4b$

As shown in *table 4b* the average TFPG estimates are very close to the estimates obtained from the production function in *table 4a*.

Table 5 uses the growth accounting equation (188) and the estimated shares from the production function to obtain TFPG estimates for individual countries.

$Table\ 5$

It should be noticed that the average estimates of TFPG in *table 5* are very close to those obtained directly from the regressions using $xa_2 + ba_3$, and the GA estimates This can be regarded as providing a confirmation of the robustness of our estimations. Negative estimates of TFPG correspond to the case where we use quality adjusted labor as input. These numbers seem to suggest that for these specific countries, the contribution of physical capital, capital quality adjusted labor and emissions to output per worker growth, exceeds the growth of output per worker.

7.5 Concluding Remarks

The aim of this chapter is to provide a new perspective in Total Factor Productivity Growth measurement for developing countries by taking into account the contribution of the environment in total output growth. We chose to approximate the use of the environment by CO_2 emissions and we developed a theoretical and an empirical analysis in order to include this new factor of production in TFPG measurements and measure its actual contribution in the growth of the final output. We included in our model emission augmenting technical change and interpreted the emissions share in GDP, in a context of a completive equilibrium under optimal taxation, and in a context where emissions is an unpaid factor, that is untaxed. Our results provide adjustments of existing TFPG estimates when CO_2 emissions are taken into account and direct estimates of TFPG from an aggregate production function. Our approach can be regarded as a "Green" TFPG Measurement Methodology.

Our results suggest an average TFPG for the period 1965-1990 for the developing countries under examination of the order of less than 1%. They also suggest that emissions in the form of CO_2 is a statistically significant input in the aggregate production function and that emission augmenting technical change coexist with labour augmenting technical change. This implies that the use of the environment approximated by CO_2 emissions, which is an unpaid factor, contributes to the growth of output of developing countries along with physical capital, human capital, and labour, and its contribution should be accounted in the context of a "green TFPG" or a "green residual estimation".

When environment's contribution in TFPG is accounted, it seems that TFPG in developing countries is low and in some cases as indicated in *tables 4b* and *5* even negative. This result questions tha sustainability of the development process in these countries. It should be also noted that the environment's contribution we estimated through the production function analysis might underestimate or overestimate the "socially optimal contribution", which is associated with an optimal tax determined by marginal environmental damages along the optimal path. If marginal damages are high the socially optimal use of the environment in the growth process, should be small, while the opposite holds for low marginal damages. If in the absence of optimal environmental policy this contribution is sizable, and our results suggest that the CO_2 emissions contribution is statistically significant with a share in output which could be as high as 33%, then excess use of the environment as an input might question the eventual sustainability of the current growth process. For example if, after solving the social planner's problem, we have an estimate of λ, the true shadow value of the CO_2, and calculate emissions' share, s_Z as $\left(-\hat{\lambda}Z\right)/Y$, then the growth accounting equation (**??**) might produce a negative result. This result can be interpreted as an indication that total use of resources, including the "unpaid" one properly valued, exceeds the output growth generated by these resources. In this case development that uses "unpaid" factors is not sustainable.[171]

Our future research includes TFPG estimates, within this new framework, for developing countries, introduction of stock variables into the aggregate

[171] Along the socially-optimal path this will not happen since the use of the "unpaid" factor - the environment - will be determined by its true shadow cost.

production function, use of our production function estimates along with damage functions for CO_2 to actually solve the social planners problem, and define the structure and the parameters of value functions, and at a more general level reformulating some of the recent empirical approaches to growth to take into account possible unpaid, and damage generating, factors of production. We hope that this approach will enhance growth empirics by incorporating the environmental dimension in growth accounting in a meaningful way.

Figures and Tables

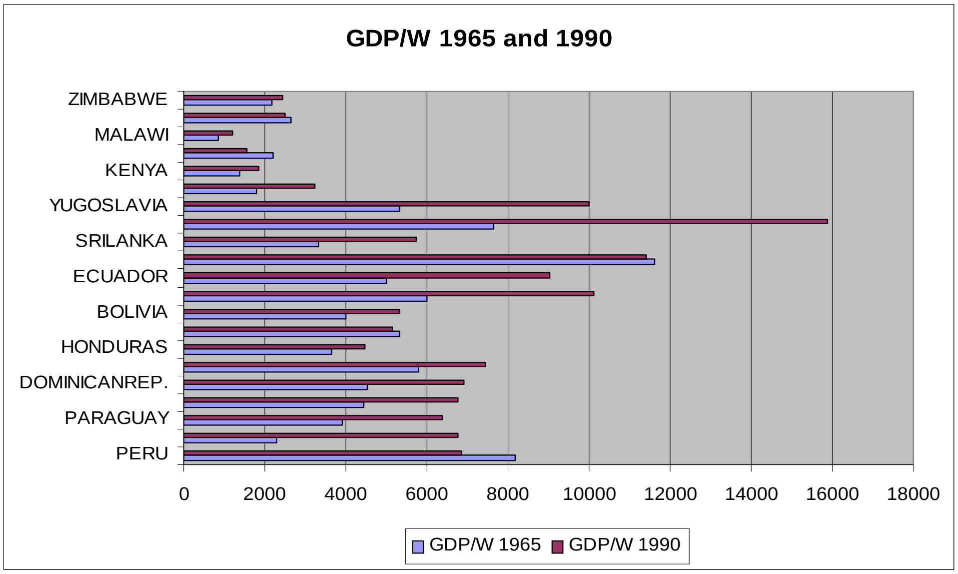

Figure 1: GDP per worker in developing countries 1965 and 1990.

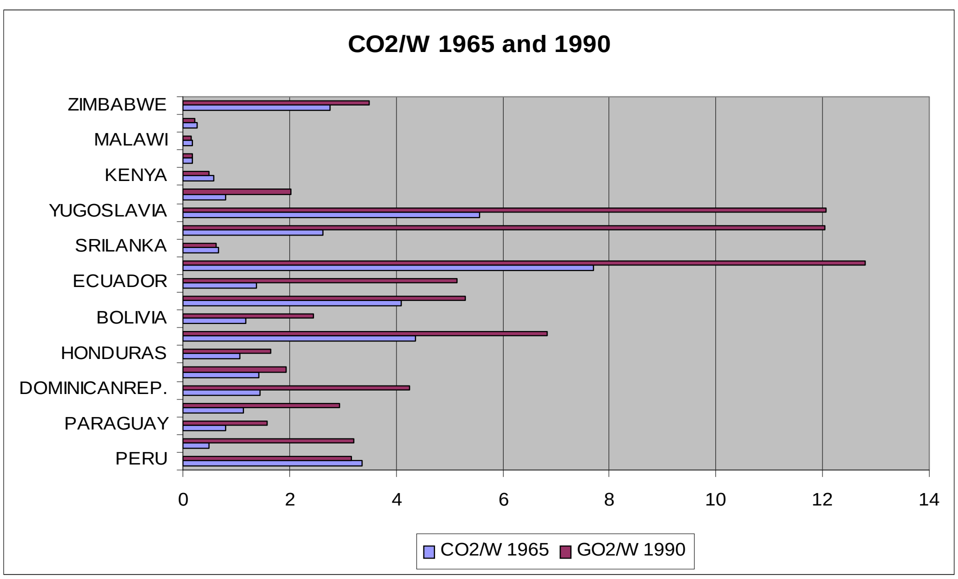

Figure 2: CO_2 per worker in 1965 and 1990

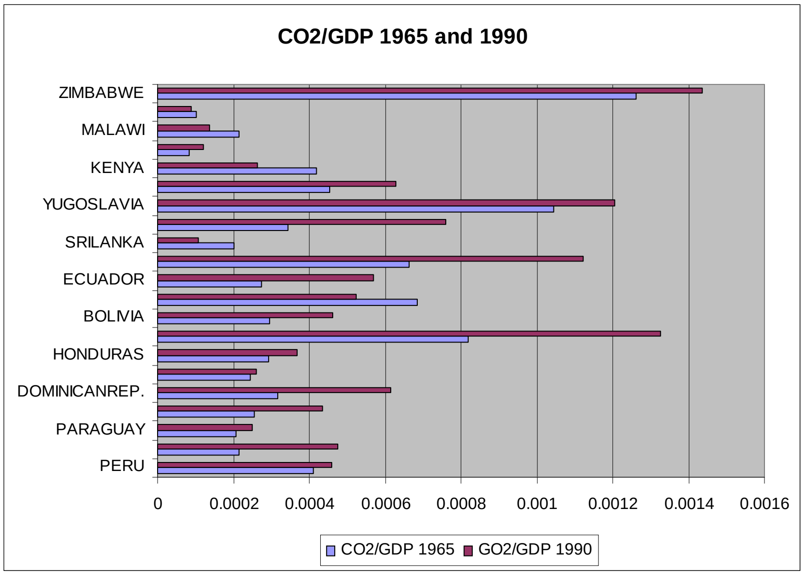

Figure 3: CO_2/GDP in 1965 and 1990

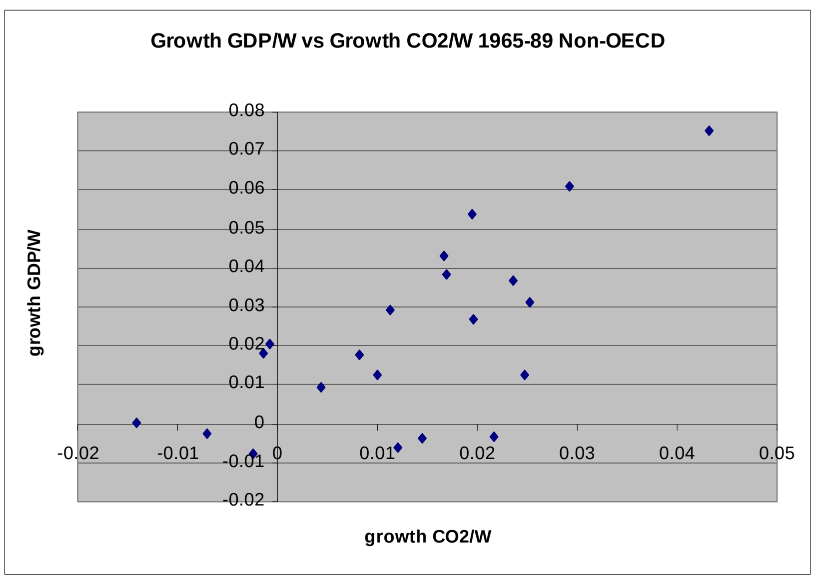

Figure 4: Growth of GDP per worker vs growth of CO_2 per worker.

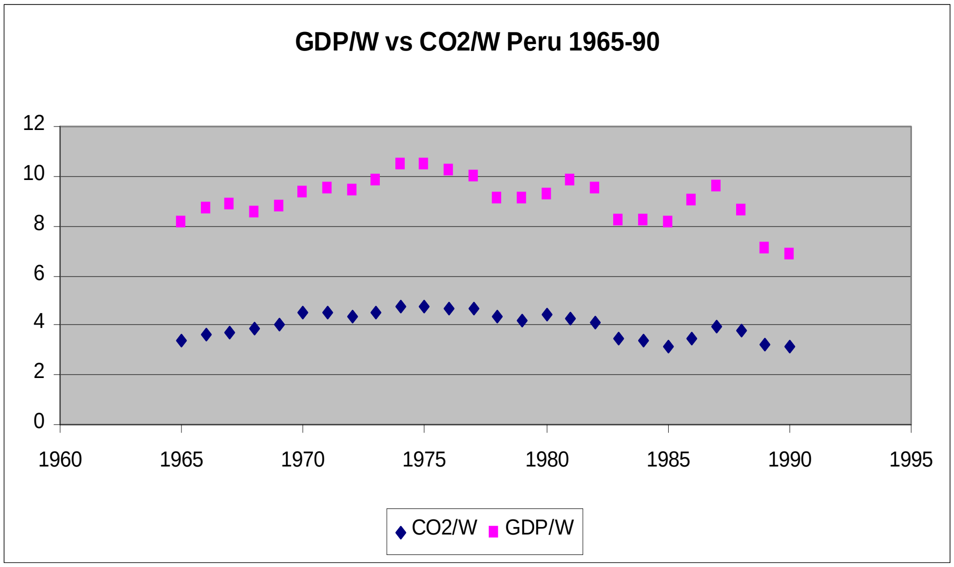

Figure 5: GDP/W vs CO2/W Peru 1965-90

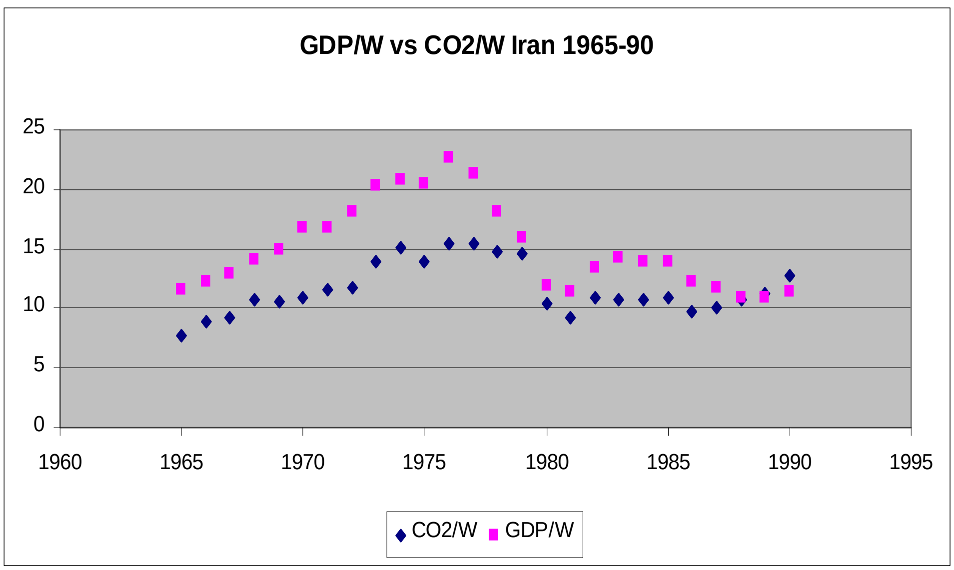

Figure 6: GDP/W vs CO2/W Iran 1965-90

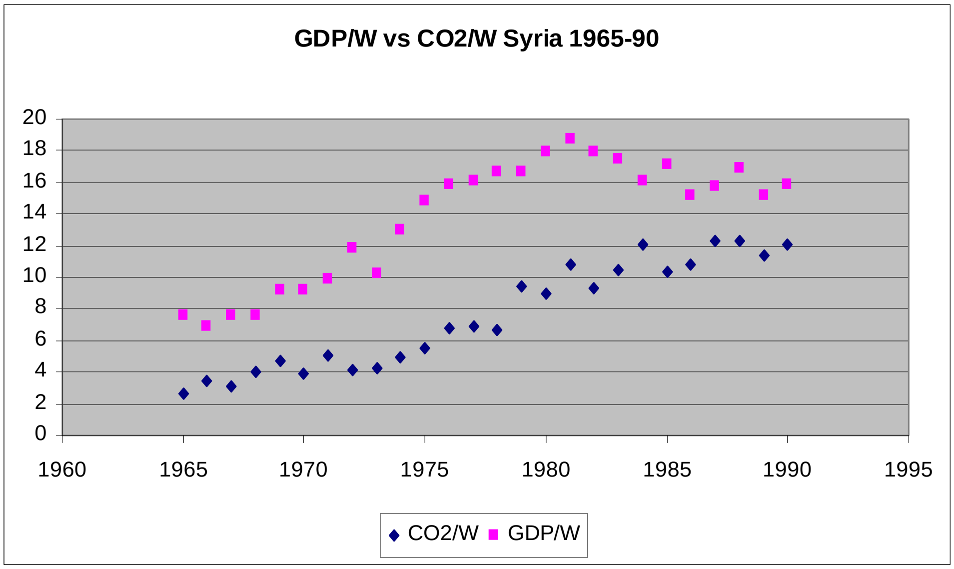

Figure 7: GDP/W vs CO2/W Syria 1965-90

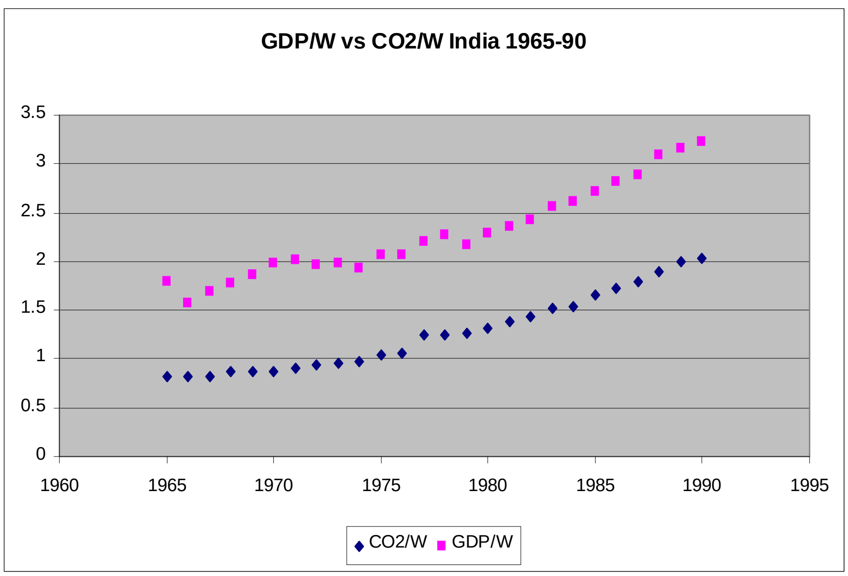

Figure 8: GDP/W vs CO2/W India 1965-90

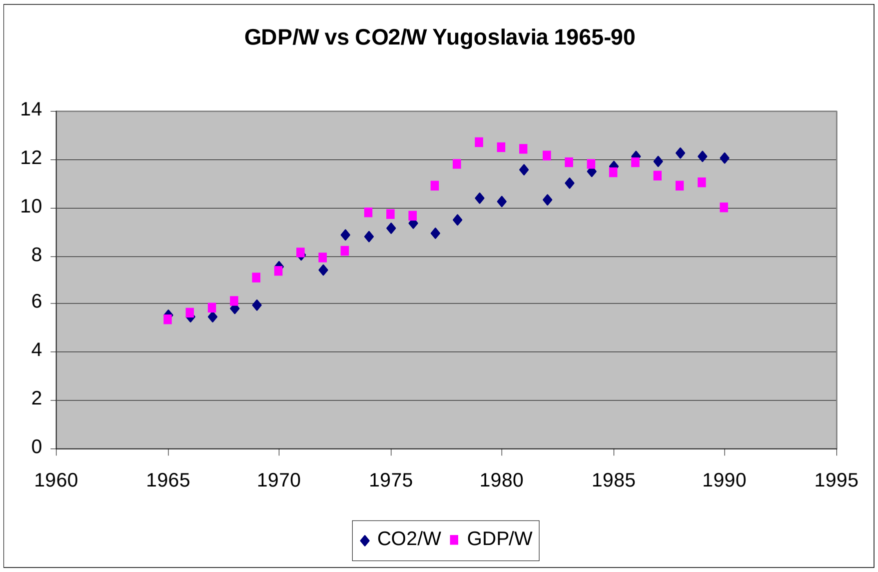

Figure 9: GDP/W vs CO2/W Yugoslavia 1965-90

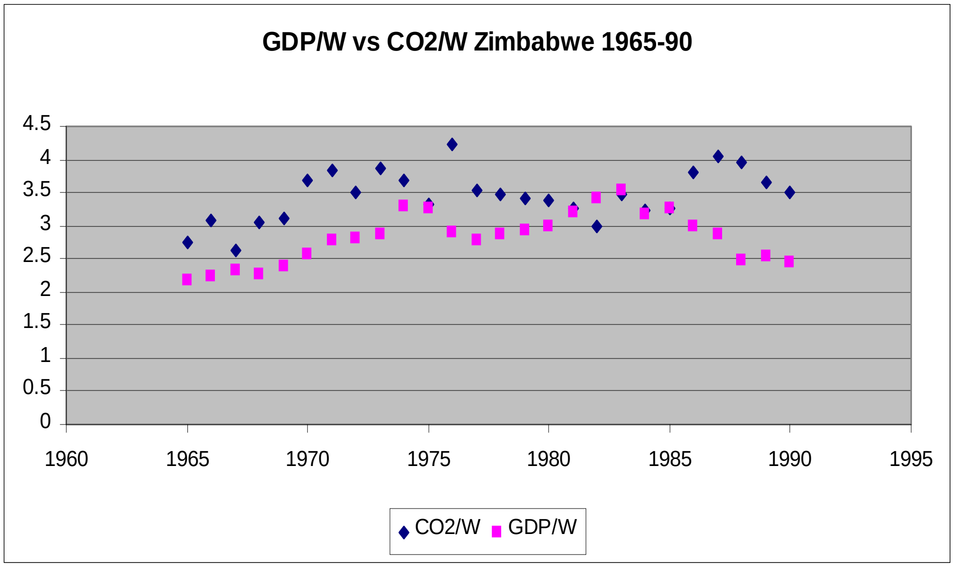

Figure 10: GDP/W vs CO2/W Zimbabwe 1965-90

Table 1: Traditional and Adjusted *TFP* growth rates from 1940–1990 using s_z from the World Bank

Countries (1)	*Growth* CO_2 (2)	s_{iz} (3)	*Trad.TFPG* (4)	*GTFPG* (5)
Peru	3.21	0.003	−0.62	−0.62
Colombia	3.88	0.004	0.84	0.82
HongKong	6.43	0.001	2.3	2.29
Mexico	4.51	0.005	1.13	1.11
Argentina	2.73	0.003	0.54	0.53
Chile	3.28	0.004	1.38	1.36

Column (1): Countries

Column (2): CO_2 growth *100

Column (3): s_z – share of CO_2 emissions. Source: The World Bank

Column (4): Traditional TFPG estimates. Source: Barro and Sala-i-Martin (2004)

Column (5): "Green" TFPG

Table 2: Traditional and Adjusted *TFP* growth rates from 1940–1990 using s_z from the World Bank

Countries	*T.TFPG* (%)	*Gr.CO*$_2$ (%)	MDCCO_2 \$20/tC			MDCCO_2 \$93/tC			MDCCO_2 \$350/tC		
(1)	(2)	(3)	s_{iz} (4)	*GTFPG* (%) (5)	% *Dev.* (6)	s_{iz} (7)	*GTFPG* (%) (8)	% *Dev.* (9)	s_{iz} (10)	*GTFPG* (%) (11)	% *Dev.* (12)
Peru	–0.62	2.41	0.0088	–0.64	3.22	0.0411	–0.72	16.13	0.1545	–0.99	59.68
Colombia	0.84	2.53	0.0113	0.81	–3.57	0.0526	0.71	–15.48	0.1979	0.34	–59.52
HongKong	2.29	6.79	0.0079	2.25	–1.75	0.0367	2.05	–10.48	0.1381	1.36	–40.61
Mexico	1.13	5.60	0.0122	1.06	–6.19	0.0565	0.81	–28.32	0.2128	–0.06	–105.31
Argentina	0.54	2.47	0.0122	0.51	–5.55	0.0569	0.40	–25.92	0.2141	0.01	–98.15
Chile	1.38	2.75	0.0126	1.34	–2.90	0.0585	1.22	–11.59	0.2202	0.77	–44.20

*Column (2): Traditional TFPG estimates. Source: Barro and Sala-i-Martin (2004)
Column (3): Average annual growth of CO_2 emissions
Columns (4,7,10): Emissions share in GDP using the corresponding MDCCO_2 estimate.
Columns (5,8,11): "Green" TFPG estimates
Columns (6,9,12): Proportional deviation between traditional TFPG and GTFPG estimates.

Table3a– *Production Function Estimation for the PF model*

	PF
c	0.2484
$a_1 = s_k$	0.0951
$a_3 = s_z$	0.3305
ba_3	0.0013
xa_2	0.0047
R^2	0.9997
DW	1.8519

All coefficients are significant at 1% level

Table3b– *Growth Accounting Estimation for the GA model**

	GA
$a_1 = s_k$	0.2562
$a_3 = s_z$	0.0801
R^2	0.8567
DW	2.0696

All coefficients are significant at 1% level

(*) We do not report the constant term since the overall constant plus with the fixed effect estimator for each county define the TFPG for this country.

Table 4a:–*TFPG estimates using the production function*

	xa_2	ba_3	x	b	*TFPG*
PF	0.0047	0.0013	0.0081	0.0040	0.0060

Table 4b: *TFPG estimates using the growth accounting equation*

Countries	*GA*
PERU	−0.0099
THAILAND	0.0207
PARAGUAY	0.0021
MOROCCO	0.0109
DOMINICANREP	−0.0001
GUATEMALA	0.0035
HONDURAS	0.0025
JAMAICA	−0.0027
BOLIVIA	0.0012
COLOMBIA	0.0138
ECUADOR	0.0093
IRAN	−0.0202
SRILANKA	0.0142
SYRIA	0.0199
YUGOSLAVIA	0.0099
INDIA	0.0114
KENYA	0.0144
MADAGASCAR	−0.0159
MALAWI	0.0002
SIERRALEONE	−0.0141
ZIMBABWE	0.0074
Average	0.0037

Table 5: *TFPG calculations using factor shares estimates from the production function*

Countries	*PF*
PERU	−0.0074
THAILAND	0.0122
PARAGUAY	0.0050
MOROCCO	0.0032
DOMINICANREP	−0.0025
GUATEMALA	0.0039
HONDURAS	0.0008
JAMAICA	−0.0073
BOLIVIA	−0.0013
COLOMBIA	0.0152
ECUADOR	0.0024
IRAN	−0.0141
SRILANKA	0.0199
SYRIA	0.0074
YUGOSLAVIA	0.0103
INDIA	0.0080
KENYA	0.01482
MADAGASCAR	−0.0149
MALAWI	0.0104
SIERRALEONE	−0.0044
ZIMBABWE	0.0026
Average	0.0031

8. Total Factor Productivity Growth with Externality Generating Inputs

8.1 Introduction

In the context of a Green Growth Accounting framework, the present paper is an attempt to further extend the traditional total factor productivity growth (TFPG) measurements or the Solow residual that was first introduced in 1957 (Solow 1957), by including the use of the environment, proxied by energy use, as an extra input in the production process. In this context energy is an input that generates an environmental externality and furthermore it is a partially unpaid factor of production in the absence of environmental taxes which would internalize the environmental externality associated with its use. If we start by accepting that the environment is contributing to output growth but since, in the absence of internalization, its contribution is not accounted for in the traditional TFPG measurements, then what is interpreted as TFPG might be the unaccounted contribution of the environment and thus traditional TFPG measurements might be biased upwards[172]. It is obvious that there exists a direct functional relationship between energy and emissions. This relationship can be also deducted at the data level since emissions data are constructed from energy data. Nevertheless, although energy is paid as an input in production, there is also an unpaid part of energy which is the CO_2 emission's[173] created from the use of energy. This part is considered unpaid since no carbon policy was in general applied in the OECD or the non-OECD countries until the recent Kyoto protocol and more specifically no carbon tax policy was in use for the period analyzed in the present paper[174]. The functional relationship

[172] In Tzouvelekas, Vouvaki, and Xepapadeas (2007) CO_2 emissions were introduced as an extra input in the production function and contributed to total output growth. In the present paper we seek to measure the Solow residual by using *energy* instead of emissions as a proxy for the use of the environment.

[173] There are also other 'greenhouse' gases created by the use of energy but carbon dioxide (CO_2) emissions are considered to be one of the most important of them all as has been indicated by various reports.

[174] The period we analyze in this paper is 1965-1990. In 1991 Sweden reformed the energy taxation system and a carbon tax was introduced. See: Bengt Johansson, Economic Instruments in Practice 1: Carbon Tax in Sweden, Swedish Environmental Protection Agency. Nevertheless, for the period of our analysis in this paper carbon taxes were not in use.

between energy and emissions shows that for the 23 OECD countries[175] we analyze, there is a strong proportional relationship between energy and CO_2 emissions. Based on this fact, we seek to estimate the contribution of the uninternalized or the unpaid part of emissions, which is embodied into energy, in TFPG measurements. First, we set up a model that examines the equivalence of the 'emission based model' and the 'energy based model'[176] under optimal emission taxation and exogenous energy prices. We use this model to derive an externality adjusted TFPG measure and then apply it to a panel of OECD countries. The results show that TFPG measurements are significantly affected when we assign a certain price to the emission's part which is the unpaid part of energy input. Our results can be interpreted as externality adjusted TFPG measurements.

The rest of the paper is structured as follows. In chapter 8.2, we develop a model based on neoclassical growth theory that includes energy as an input in production and we further develop a growth accounting framework that allows us to measure TFPG when energy is a partially paid factor of production. Chapter 8.3 tries to interpret the energy's share in output in a context of an optimal growth model and competitive market equilibrium. The problem that needs to be addressed is that for the period we analyze there is no taxation or other environmental policy for the emission's part of energy and therefore estimating TFPG in the traditional way, that is through econometric estimation based on production function or using data on input shares in GDP, might provide biased estimates. chapter 8.4 attempts to solve this problem by using two different approaches for the measurement of the externality adjusted TFPG. First, we estimate the input shares by using an aggregate production function which includes energy as an input in the production process. From this aggregate production function we can estimate either an overall average traditional TFPG[177] for all the countries of the sample, as the coefficient of the time trend of the aggregate production

[175]The 23 countries used in our analysis are the following: Canada, U.S.A, Austria, Belgium, Denmark, Finland, France, Greece, Italy, Portugal, Spain, Sweden, Switzerland, U.K., Japan, Iceland, Ireland, Netherlands, Norway, Australia, Mexico, Turkey, Luxembourg.

[176]In an "emission based model", emissions are regarded as an input in the aggregate production function while in an "energy based model" energy is regarded as an input in the aggregate production function. Both models can be regarded as alternative approaches of introducing environment as a factor of production.

[177]We use the term "traditional TFPG" to indicate TFPG measurements which are not adjusted for non internalized externalities.

function, or individual countries TFPGs by using the estimated input shares from the production function and the average growth rates of output and inputs per worker for each one of the countries we analyze. Second, we convert these traditional TFPG estimates to an externality adjusted TFPG concept by a specific adjustment. This adjustment is carried out by subtracting from output growth the growth associated with the value of the unpaid part of energy. This unpaid part relates to emissions which are created during the production process and which are not accounted for in the traditional measurements due to the lack of an environmental tax. To value the unpaid part we use current estimates of the marginal damages from CO_2 emissions. Our results are summarized in chapter 8.5. These results suggest that when the emission's part of energy, valued by marginal damages from CO_2 emissions, is accounted for in the measurements, the Solow residual can even take negative values. This indicates that when we account for the environmental cost of the emissions created from the use of energy, in other words when this unpaid part of energy becomes internalized, TFPG could become negative. A negative residual could imply that when each input used in the production process is fully paid for its contribution in total output growth then no TFP that can drive growth is present. Clearly this growth process is not sustainable, by any definition of sustainability, since the value of output is less than the value of inputs used to produce this output. The last section concludes.

8.2 The Model

We use the neoclassical production function:

$$Y = F\left(K, H, W, X\right) \tag{191}$$

where K is physical capital, H is human capital, $W = AL$ is effective labour, with L being labour in physical units and A reflecting labor augmenting technical change and $X = BE$ is effective input of energy, with E being energy in physical units and B reflecting energy saving technical change, or input augmenting technical change. Differentiating (191) with respect to time, and denoting by $\epsilon_j, j = K, H, L, E$ the elasticity of output with respect to inputs, the basic growth accounting equation is obtained as:

$$\frac{\dot{Y}}{Y} = \epsilon_K \left(\frac{\dot{K}}{K}\right) + \epsilon_H \left(\frac{\dot{H}}{H}\right) + \epsilon_L \left(\frac{\dot{A}}{A}\right) + \epsilon_L \left(\frac{\dot{L}}{L}\right) + \epsilon_E \left(\frac{\dot{B}}{B}\right) + \epsilon_E \left(\frac{\dot{E}}{E}\right) \tag{192}$$

We assume that energy is related to emissions by the following function:

$$E(t) = \phi(Z(t), t) \tag{193}$$

where $Z(t)$ is emissions created by the use of energy E at time t and the introduction of t as a separate argument into (193) indicates that there could be technical change in the energy-emission relationship with the result of producing for example more energy with less emissions. We assume that $\phi_Z > 0$, $\phi_{ZZ} \geq 0$ and that the inverse function exist, so we can alternatively express emissions as a function of energy use[178]:

$$Z(t) = \phi^{-1}(E(t), t) = \psi(E(t), t) \tag{194}$$

differentiating (193) with respect to time we have:

$$dE = \frac{\partial \phi(Z(t), t)}{\partial Z} dZ + \frac{\partial \phi(Z(t), t)}{\partial t} dt$$

$$\frac{dE}{dt} = \frac{\partial \phi(Z(t), t)}{\partial Z} \frac{dZ}{dt} + \frac{\partial \phi(Z(t), t)}{\partial t}$$

dividing by E we have:

$$\frac{\dot{E}}{E} = \frac{\partial \phi(Z(t), t)}{\partial Z} \frac{\dot{Z}}{E} + \frac{\partial \phi(Z(t), t)}{\partial t} \frac{1}{E}$$

and multiplying by $\frac{Z}{Z}$ we have:

$$\frac{\dot{E}}{E} = \frac{\partial E}{\partial Z} \frac{Z}{E} \frac{\dot{Z}}{Z} + \frac{\partial E}{\partial t} \frac{Z}{E} \frac{1}{Z}$$

if we set the second part of the equation, $\frac{\partial E}{\partial t} \frac{Z}{E} \frac{1}{Z} = \nu$ then:

$$\frac{\dot{E}}{E} = \epsilon_{E_Z} \left(\frac{\dot{Z}}{Z} \right) + \nu \tag{195}$$

[178] As we show in the section of the paper where competitive equilibruim is analyzed, existence of a competitive equilibruim when the emissions incorporated into a given amount of energy are taxed, requires a simple proportional relationship between energy and emissions.

where ϵ_{E_Z} is the elasticity of energy with respect to emissions from (193). Then (192) becomes:

$$\frac{\dot{Y}}{Y} = \epsilon_K \left(\frac{\dot{K}}{K}\right) + \epsilon_H \left(\frac{\dot{H}}{H}\right) + \epsilon_L \left(\frac{\dot{A}}{A}\right) + \epsilon_L \left(\frac{\dot{L}}{L}\right) + \epsilon_E \left(\frac{\dot{B}}{B}\right) + \epsilon_E \left(\epsilon_{E_Z} \frac{\dot{Z}}{Z} + \nu\right)$$

$$\frac{\dot{Y}}{Y} = \epsilon_K \left(\frac{\dot{K}}{K}\right) + \epsilon_H \left(\frac{\dot{H}}{H}\right) + \epsilon_L \left(\frac{\dot{A}}{A}\right) + \epsilon_L \left(\frac{\dot{L}}{L}\right) + \epsilon_E \left(\frac{\dot{B}}{B}\right) + \epsilon_E \epsilon_{Ez} \left(\frac{\dot{Z}}{Z}\right) + \epsilon_E \nu \tag{196}$$

Therefore the growth accounting equation can be expressed either in terms of energy by (192) or in terms of emissions by (196). To transform (196) into a growth accounting equation in factor shares we use profit maximization in a competitive market set up. Profits for the representative firm are defined as:

$$\Pi = F(K, H, W, X) - R_K K - R_H H - wL - p_E E - \tau\psi(E) \tag{197}$$

where p_E is the competitive price for energy, τ is the emission tax, and we assume no technical change in the energy-emission relationship to simplify things. The associated first-order conditions for profit maximization are:

$$\frac{\partial F}{\partial K} = R_K \ , \ \frac{\partial F}{\partial H} = R_H \tag{198}$$

$$\frac{\partial Y}{\partial L} = \frac{\partial F}{\partial W}\frac{\partial W}{\partial L} = \frac{\partial F}{\partial W}\frac{\partial AL}{\partial L} = \frac{\partial F}{\partial W}A => \frac{\partial F}{\partial W} = \frac{\partial Y}{\partial L}\frac{1}{A} \tag{199}$$

$$\frac{\partial F}{\partial L} = \frac{\partial F}{\partial W}A = w \tag{200}$$

$$\frac{\partial Y}{\partial E} = \frac{\partial F}{\partial X}\frac{\partial X}{\partial E} = \frac{\partial F}{\partial X}\frac{\partial BE}{\partial E} = \frac{\partial F}{\partial X}B => \frac{\partial F}{\partial X} = \frac{\partial Y}{\partial E}\frac{1}{B} \tag{201}$$

$$\frac{\partial F}{\partial E} = \frac{\partial F}{\partial X}B = p_E + \tau\psi_E(E) \tag{202}$$

Then input shares are defined as[179]:

$$s_K = \frac{R_K K}{Y}, s_H = \frac{R_H H}{Y}, s_L = \frac{wL}{Y}, \ s_E = \frac{p_E E + \tau\psi_E(E)E}{Y} \tag{203}$$

[179] The share of energy (s_E) consists of two parts. The paid part for energy and the share corresponding to the emissions generated by energy. If $\tau = 0$ then the part which reflects the use of the environment is unpaid.

Thus the Solow residual augmented with energy is defined as:

$$\gamma = s_L \left(\frac{\dot{A}}{A}\right) + s_E \left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K \left(\frac{\dot{K}}{K}\right) - s_H \left(\frac{\dot{H}}{H}\right) - s_L \left(\frac{\dot{L}}{L}\right) - s_E \left(\frac{\dot{E}}{E}\right) \tag{204}$$

or by replacing (195) into (204) we have the following expression:

$$\gamma = s_L \left(\frac{\dot{A}}{A}\right) + s_E \left(\frac{\dot{B}}{B}\right) = \frac{\dot{Y}}{Y} - s_K \left(\frac{\dot{K}}{K}\right) - s_H \left(\frac{\dot{H}}{H}\right) - s_L \left(\frac{\dot{L}}{L}\right) - s_E \left(\epsilon_{E_Z} \left(\frac{\dot{Z}}{Z}\right) + \nu\right)$$

Under constant returns to scale (204) becomes:

$$\gamma = \frac{\dot{y}}{y} - s_K \frac{\dot{k}}{k} - s_H \frac{\dot{h}}{h} - s_E \frac{\dot{e}}{e} \tag{205}$$

where lower case letters indicate per worker (or per capita) quantities. It can be seen from (205) that the contribution of the environment in TFPG is reflected in the term $s_E \frac{\dot{e}}{e}$. This indicates that there is one more source generating output growth, the environment used as an input in production, in addition to capital and labour. Thus, in order to obtain a "net" estimate of TFPG the environment's contribution should be properly accounted. Relationships (204) and (205) can be considered as externality adjusted growth accounting equations and γ is the "externality adjusted Solow residual". In order to provide a meaningful definition of the TFPG when environment is an input, we need to clarify what is meant by the share of energy in output. This is because the total cost of energy includes apart from the price of energy that is accounted for in the measurements, since energy has a market price, the untaxed (or unpaid) value of emissions that energy creates.

8.3 Interpreting the Shares of Inputs in the Externality Adjusted TFPG Measurements

The Social Planner

To interpret the share of energy, when energy use releases emissions which are an environmental externality, we consider the problem of a social planner who optimizes a felicity functional defined over consumption and environmental damages. We determine an optimal tax τ, that if paid, it would internalize the externalities that the emission's part of energy creates during the production process. We assume that emissions (flow variable), accumulate into the ambient environment and that the evolution of the emission stock S, is described by the first order differential equation[180]:

$$\dot{S}(t) = Z(t) - mS(t)\ ,\ S(0) = S_0, m > 0 \tag{206}$$

$$\psi(E) = Z = \phi^{-1}(E) \tag{207}$$

$$\dot{S}(t) = \psi(E) - mS(t) \tag{208}$$

where m reflects the environment's self cleaning capacity[181]. The stock of emissions generate damages according to a strictly increasing and convex damage function $D(S)\,,\ D' > 0, D'' \geq 0$.

Assume that utility for the "average person" is defined by a function $U(c(t), S(t))$ where $c(t)$ is consumption per capita, $c(t) = C(t)/N(t)$, with $N(t)$ being population and $S(t)$ being the stock of pollution. We assume that $U_c(c,S) > 0$, $U_S(c,S) < 0$ $U_{cS}(c,S) \leq 0$, that U is concave in c for fixed S, and finally that U is homogeneous in (c,S). Then social utility at time t is defined as $N(t)U(c(t), S(t)) = N_0 e^{nt} U(c(t), S(t))$ where n is the exogenous population growth rate and N_0 can be normalized to one. The objective for the social planner is to choose consumption and energy paths to maximize:

$$\max_{\{c(t),E(t)\}} \int_0^\infty e^{-(\rho-n)t} U(c,S)\, dt \tag{209}$$

where, $\rho > 0$ is the rate of time preference, subject to the dynamics of the capital stock and the pollution stock (208). The capital stock dynamics can be described in the following way. Assume a constant returns to scale Cobb-Douglas specification for the production function (191):

$$Y = K^{a_1} H^{a_2} (AL)^{a_3} (BE)^{a_4} \tag{210}$$

where: $a_1 + a_2 + a_3 + a_4 = 1$ and $E(t) = \phi(Z(t))$ as defined above. Expressing

[180] Emissions here are defined in terms of energy use.

[181] We use a very simple emission accumulation process which has been often used to model global warming. The inclusion of environmental feedbacks and nonlinearities which represent more realistic situations are of further research but we expect that it will not change the basic results.

output in per worker terms we obtain:

$$\begin{aligned} \frac{Y}{L} &= \left(\frac{K}{L}\right)^{a_1}\left(\frac{H}{L}\right)^{a_2}\left(\frac{AL}{L}\right)^{a_3}\left(\frac{BE}{L}\right)^{a_4} \\ \frac{Y}{L} &= y = k^{a_1}h^{a_2}(e^{xt})^{a_3}(e^{(b-n)t}E)^{a_4}, \text{ or} \\ y &= e^{\zeta t}k^{a_1}h^{a_2}E^{a_4}, \ \zeta = xa_3 + a_4(b-n) \end{aligned} \tag{211}$$

Labor augmenting technical change grows at the constant rate x, input (energy) augmenting technical change grows at a constant rate b, labor grows at the population rate n,and as usual $y = \frac{Y}{L}$, $k = \frac{K}{L}$, $c = \frac{C}{L}$ and $h = \frac{H}{L}$ and $e_L = \frac{E}{L}$ are expressed in per capita (or per unit of worker) terms. Assuming equality of depreciation rates and equality of marginal products between manufactured and human capital in equilibrium the social planner's problem can be written as:[182]

$$\max_{\{\hat{c}(t),E(t)\}} \int_0^\infty e^{-\omega t}U(\hat{c},S)\,dt\ ,\omega = \rho - n - (1-\theta)\xi \tag{212}$$

subject to:

$$\dot{\hat{k}} = f\left(\hat{k},E\right) - \hat{c} - p_E\hat{e}_L - (\eta+\delta+\xi)\hat{k}, \quad f\left(\hat{k},E\right) = s\tilde{A}\hat{k}^{\beta}E^{a_4} \tag{213}$$

$$\dot{S} = \psi(E) - mS,\ Z = \psi(E) \tag{214}$$

with $k = \hat{k}e^{\xi t}$, $h = \hat{h}e^{\xi t}$, $c = \hat{c}e^{\xi t}$ and $e_L = \hat{e}_Le^{\xi t}$, where ^denotes per effective worker magnitudes and $\xi = \frac{\zeta}{1-a_1-a_2}$. The current value Hamiltonian for this problem is:

$$\mathcal{H} = U(\hat{c},S) + p\left[f\left(\hat{k},E\right) - \hat{c} - p_E\hat{e}_L - (\eta+\delta+\xi)\hat{k}\right] + \lambda(\psi(E,t) - mS) \tag{215}$$

the optimality conditions implied by the maximum principle are:

[182] For the derivation see Appendix 1.

$$U_{\hat{c}}(\hat{c},S)=p\ ,\ U_{\hat{c}\hat{c}}(\hat{c},S)\dot{\hat{c}}+U_{\hat{c}S}(\hat{c},S)\dot{S}=\dot{p} \tag{216}$$

$$p\left[f_E\left(\hat{k},E\right)-p_E\frac{e^{-\xi t}}{L}\right]=-\lambda\psi_E(E,t) \tag{217}$$

$$p\left[f_E\left(\hat{k},E\right)-\frac{p_E}{\hat{l}}\right]=-\lambda\psi_E(E,t) \tag{218}$$

$$pf_E\left(\hat{k},E\right)-p\frac{p_E}{\hat{l}}=-\lambda\psi_E(E,t) \tag{219}$$

$$pf_E\left(\hat{k},E\right)\hat{l}-pp_E=-\lambda\psi_E(E,t)\hat{l},\ \text{dividing with } p \text{ we have:} \tag{220}$$

$$f_E\hat{l}=p_E-\frac{\lambda\psi_E(E,t)\hat{l}}{p},\quad =where\ E=g\left(\hat{k},\lambda,p,\hat{l}\right) \tag{221}$$

$$\dot{p}=\left(\rho+\delta+\theta\xi-f_{\hat{k}}\left(\hat{k},E\right)\right)p\ \text{or} \tag{222}$$

$$\frac{\dot{\hat{c}}}{\hat{c}}=\frac{1}{\theta}\left[f_{\hat{k}}\left(\hat{k},g\left(\hat{k},\lambda,U_{\hat{c}}(\hat{c},S),\hat{l}\right)\right)-\rho-\delta-\theta\xi\right]-\frac{U_{\hat{c}S}(\hat{c},S)}{U_{\hat{c}\hat{c}}(\hat{c},S)}\dot{S} \tag{223}$$

$$\dot{\lambda}=(\omega+m)\lambda-U_S(\hat{c},S) \tag{224}$$

The system of (223), (224) along with the two differential equation below:

$$\dot{\hat{k}} = f\left(\hat{k},g\left(\hat{k},\lambda,U_{\hat{c}}(\hat{c},S),\hat{l}\right)\right)-\hat{c}-p_E\hat{e}_L-(\eta+\delta+\xi)\hat{k} \tag{225}$$

$$\dot{S} = \psi\left[g\left(\hat{k},\lambda,U_{\hat{c}}(\hat{c},S),\hat{l}\right),t\right]-mS \tag{226}$$

form a dynamic system, which along with the appropriate transversality conditions at infinity (Arrow and Kurz 1970) characterizes the socially optimal paths of $\left(\hat{c},\hat{k},\lambda,S,E\right)$.

Let the value function of the problem be defined as:

$$J(K_0,S_0)=\max\int_0^\infty e^{-\omega t}U(\hat{c},S)\,dt \tag{227}$$

then it holds that (Arrow and Kurz 1970)

$$\frac{\partial J}{\partial S(t)}=\lambda(t)<0 \tag{228}$$

Thus the costate variable λ can be interpreted as the shadow cost of the emission stock. By comparing (202) with (221) and noting (228) it is clear that if a time dependent tax $\tau(t) = -\frac{-\lambda\hat{l}}{p}$ is chosen, then firms will choose the socially optimal amount of energy as input by fully internalizing the externality.

Then the energy share can be written as:

$$s_E = \frac{[p_E + \tau\psi_E(E)]\,E}{Y}, \text{ with } \tau = \frac{-\lambda\hat{l}}{p} = \frac{-\lambda\hat{l}}{U_c} \tag{229}$$

The share of energy in output consists of two parts. The first one is associated with the market price of the energy used in production and the second part is associated with the tax imposed on the emissions created by the use of the production factor energy. This second part reflects the cost of externality associated with the use of energy in production. Under the optimal emission tax it can be shown that the solution of the competitive equilibrium will coincide with the social planners solution.

Competitive equilibrium

The representative consumer considers the stock of pollution as exogenous and chooses consumption to maximize lifetime utility, or:

$$\max_{c(t)} \int_0^\infty e^{-(\rho-n)t} U(c, S)\, dt \tag{230}$$

subject to the budget flow constraint:

$$\dot{a} = w + ra - c - na + \tau z \tag{231}$$

where a is per capita assets, c, w, r the competitive wage rate and interest rate respectively and τz are per capita lump sum transfers due to environmental taxation, $z = Z/L$. The representative firm maximizes profits and in equilibrium $a = k + h$. Then we have the following proposition.

Proposition 3 *Under optimal taxation, $\tau = \frac{-\lambda\hat{l}}{p}$ of the emission content of energy used, the paths $\left(\hat{c}(t), \hat{k}(t), S(t), Z(t)\right)$ of a decentralized competitive equilibrium coincide with the socially-optimal paths*[183].

[183] See proof in Appendix 2.

8.4 Externality Adjusted TFPG Measurement

To obtain the externality adjusted TFPG we proceed in the following way. From the aggregate production function we can estimate: i) an overall average traditional TFPG for all the countries of the sample as the coefficient of the time trend of the aggregate production function or ii) individual countries TFPG's by using the estimated input shares from the production function and the average growth rates of output and inputs per worker for each one of the countries we analyze.

There is however the part of energy that is unpaid. This is the emissions created by the use of energy that do not have a "price"[184]. Thus in our measurements we might "loose" the part of the energy input which is associated with the generation of the environmental externality and which remains unpaid if the price of energy does not include an environmental tax (optimal or not) or other policy instrument. Thus, traditional TFPG measurements can be biased. If emissions were taxed at a rate $\tau > 0$, environment could be considered a paid factor of production and the externalities created by the use of energy would be internalized. If however emissions are not subject to any regulatory policy, (which is the realistic case at least for the sample period), environment is an unpaid factor of production and we need independent estimates of marginal CO_2 emission damages to adjust TFPG measurements.

The Cobb-Douglas production function (210), under constant returns to scale takes the log linear specification:

$$\ln y = a_0 + (xa_3 + ba_4)t + a_1 \ln k + a_2 \ln h + a_4 \ln e_Z, \ \sum_{i=1}^{4} a_i = 1 \qquad (232)$$

where:

$$xa_3 + ba_4 = \gamma_{total} = TFPG \qquad (233)$$

In *(233)*, γ_{total} is γ in (204) that includes labor augmenting (xa_3) and energy augmenting (ba_4) technical change.

Equation (232) provides estimates of input elasticities. To have a meaningful interpretation of these elasticities as factors' shares in the absence of

[184]A "price" in this case could be an environmental tax for the period we analyze, a traditional permit system with a well defined emission permit price or a binding emission limit.

optimal environmental policy, we need to consider the choice of energy in the context of the constraint optimization problem:

$$\begin{aligned} \max \Pi &= F(K, H, AL, BE) - R_K K - R_H H - wL - p_E E \\ &\quad \text{subject to} \quad \psi(E) = Z \leq \bar{Z} \end{aligned} \tag{234}$$

The upper bound on emissions created by the use of energy, could reflect emission limits associated with environmental policy. The Lagrangian for the problem is:

$$L = F(K, H, AL, BE) - R_K K - R_H H - wL - p_E E + \lambda_1 \left[\bar{Z} - \psi(E)\right]$$

Associating the Lagrangian multiplier λ_1 with the constraint $Z \leq \bar{Z}$ the first order conditions for the optimal input choices which correspond to (234) are:

$$\frac{\partial F}{\partial K} = R_K, \ \frac{\partial F}{\partial H} = R_H, \ \frac{\partial F}{\partial L} = w, \ \frac{\partial F}{\partial E} = p_E + \lambda_1 \frac{\partial \psi(E)}{\partial E} = p_E + \lambda_1 \frac{\partial Z}{\partial E} \tag{235}$$

by the envelope theorem λ_1 is the shadow cost of Z and measures the response of maximum profits to changes in the upper bound of emissions. This shadow cost should be distinguished from the shadow cost of the cost of CO_2 stock, defined in (228), that measures the response of maximum welfare to a change in the stock of CO_2.

When environmental policy, which is applied by using emission limits, is chosen optimally in the sense of maximizing social welfare, then it is a standard result that $\lambda_1 = \tau$, where τ is the optimal emission tax defined as: $\tau = \frac{-\lambda \hat{l}}{p} = \frac{-\lambda \hat{l}}{U_c}$. Therefore under optimal emission limits the emissions share is defined as:

$$s_E = \frac{(p_E + \tau \psi_E) E}{Y} \tag{236}$$

When there is no environmental policy, then there is no emission constraint or equivalently $\tau = 0$, and the emissions' share is simply:

$$\tilde{s}_E = \frac{p_E E}{Y} \tag{237}$$

Thus the elasticities obtained from the production function can be interpreted as shares associated with the constraint optimization problem (234) where the constraint can be binding or not. However, the elasticities cannot be associated with the social welfare optimization problem (212) in the absence of optimal environmental policy. We interpret elasticities as shares and we set:

$$a_1 = s_K,\ a_2 = s_H,\ a_4 = s_E \tag{238}$$

Specifying the production function (232), with the elasticities interpreted as shares by (238), the TFPG can be estimated econometrically by the constant term γ_{total} of (233).

We can also measure TFPG by using the estimated shares $\hat{s}_K, \hat{s}_H, \hat{s}_E$ from (232) and the average growth rates of output and inputs per worker for each one of the countries we analyze and estimate $\hat{\gamma}_i$ for each country using the following equation:

$$\hat{\gamma}_i = \overline{\left(\frac{\dot{y}}{y}\right)} - \hat{s}_K \overline{\left(\frac{\dot{k}}{k}\right)} - \hat{s}_H \overline{\left(\frac{\dot{h}}{h}\right)} - \hat{s}_E \overline{\left(\frac{\dot{e}}{e}\right)} \tag{239}$$

Since our data correspond to a period of time where environmental policy regarding CO_2 emissions was not present[185], what we actually estimate by (232) when we set $a_4 = s_E$, is not s_E but $\tilde{s}_E$, so to obtain externality adjusted TFPG estimates that include the share which corresponds to the damages of the emission generated by the use of energy, we need to subtract the term $\frac{\tau\psi_E E}{Y}$ from (233) to obtain :

$$\gamma_{adj\ total} = \gamma_{total} - \frac{\tau\psi_E E_{total}}{Y_{total}} \tag{240}$$

where E_{total} and Y_{total} in (240) are the overall averages of energy and output accordingly for the group of the 23 OECD countries we analyze.

By substracting the term $\frac{\tau\psi_E E}{Y}$ from the individual country estimates (239), we obtain:

$$\gamma_{adji} = \hat{\gamma}_i - \frac{\tau\psi_E E_i}{Y_i} \tag{241}$$

where E and Y are the averages of energy and output for each country over the sample period. The numerical results are summarized in chapter 8.5 that follows.

8.5 Externality Adjusted TFPG Results

[185] Our data correspond to the 1965-1990 period of time.

Based on the analysis of chapter 8.4, the results of the estimated production function (232) are summarized in *table 1* that follows[186].

Table 1: Estimated shares and TFPG results using the production function estimation from (232).

	$\Pr oduction\ Function$
$a_1 = s_k$	0.298
$a_2 = s_h$	0.027
$a_4 = s_e$	0.16
$TFPG = \gamma_{total}\ \%$	1.21
R^2	0.99
DW	2.08

Table 1 shows the shares of the three inputs, capital s_k, human capital s_h and energy s_e we use. The results suggest a value for capital's share around 29.8%, which can be considered as a plausible estimate, a share for energy as an input at 16% and a share for education which is used as a proxy for human capital of 2.7%. Therefore overall total factor productivity growth (γ_{total}) is estimated at 1.21%.

All estimators are highly significant. The estimation of (232) represents estimation of a primal model, that might suffer from endogeneity associated with inputs, implying inconsistency of direct estimators of the production function. However as it has been shown by Mundlak (1996, proposition 3), under constant returns to scale, OLS estimates of a k-input Cobb-Douglas production function, in average productivity form, with regressors in inputs-labour ratio, are consistent. This is exactly the type of production function we have in our model.

To estimate (232) we adopt a panel estimation approach with 'fixed effects' to allow for unobservable 'country effects' (e.g. Islam (1995). As shown by Mundlak (1996) this estimator applied to the primal problem is superior to the dual estimator which is applied to the dual functions. Furthermore the 'fixed effects' estimator addresses the problem of correlation between the

[186] Our data are taken from the Penn Tables v5.6. Real GDP measured in thousands of US$ is the variable (RGDPCH), multiplied by the variable POP in the Penn Tables. Capital stock and employment are retrieved from Real GDP and capital per worker (KAPW) and real GDP per worker (RGDPW). All values are measured in 1985 international prices. Energy data are taken from the International energy agency, Eurostatand, OECD, refer to the total primary energy supply and are measured in million tons of energy.

constant term γ_{total}, which is the TFPG estimator with the regressors[187].

The estimation was performed using weighted least squares (WLS) in order to take into account both cross-section heteroscedasticity and contemporaneous correlation among countries in the sample. The estimation is carried out in two steps. In the first step the model is estimated via simple OLS. Using the obtained residuals the conditional country specific variance is calculated and it is used to transform both the dependent and independent variables of the second-stage regression. Specifically for each country, y_i and each element of x_i (independent variables) are divided by the estimate of the conditional standard deviation obtained from the first-stage. Then a simple OLS is performed to the transformed observations expressed as deviations of their means. This results in a feasible generalized least square estimator described by Wooldridge (2000, Ch. 8) and Greene (2003, Ch. 11).

The results of the externality adjusted TFPG by using the estimated shares of the production function and the average values of each type of capital for each one of the countries under analysis, are summarized in *table 2* that follows. *Column 1* shows the countries we analyze, *column 2* shows the results obtained by the estimation of (239) and *column 3* shows the results of the externality adjusted TFPG obtained by (241). In order to perform the adjustment indicated by (241) we need the parameters ψ_E and τ. We obtain ψ_E as the coefficient of the relationship $Z = \sigma E$, where $\sigma = \psi_E$. This parameter was obtained by the regression of energy measured in million tons on CO_2 emissions measured in million tons. The value of the coefficient is 2.43 and this value is highly significant with $R^2 = 99\%$[188]. As τ, which should be interpreted as a tax imposed on the emissions created by the use of energy we used a value of $20\$/tCO_2$. This value is taken from Tol (2005) and represents the marginal damage cost of CO_2 emissions. Thus, to obtain the externality adjusted TFPG, we approximate the environmental policy parameter τ, by the marginal damage of CO_2 emissions.

Table 2: TFPG results using (239) and (241).

[187] This correlation has been regarded as one of the disadvantages of the regression approach in TFPG measurement (Barro 1999, Barro and Sala-i-Martin 2004).

[188] Correction for first order autoregressive at the residual was also performed. The first order autoregressive coefficient was significant.

Countries (1)	$TFPG = \hat{\gamma}_i$ % (2)	$\gamma_{adji\ (\tau=20\$/t)}$ % (3)
CANADA	0.670	−1.979
U.S.A.	0.275	−2.206
AUSTRIA	0.635	−0.779
BELGIUM	1.079	−1.039
DENMARK	0.321	−1.289
FINLAND	1.144	−1.107
FRANCE	0.705	−0.778
GREECE	0.831	−0.479
ITALY	1.537	0.387
LUXEMBOURG	1.699	−2.580
PORTUGAL	1.690	0.649
SPAIN	0.415	−0.695
SWEDEN	−0.040	−2.028
SWITZERLAND	−0.059	−1.122
U.K	0.859	−0.896
JAPAN	1.646	0.235
ICELAND	0.473	−2.533
IRELAND	1.638	−0.172
NETHERLANDS	0.489	−1.414
NORWAY	1.564	−0.247
AUSTRALIA	0.567	−1.226
MEXICO	0.330	−0.814
TURKEY	1.420	0.214
Averages	0.865	−0.952

In *column 2* the value of $\hat{\gamma}_i$ in % is between 0.2% and 1.7% with the exception of two countries that give negative TFPG results. The average traditional TFPG for the 23 countries is 0.865%. In *column 3* where γ_{adji} in % after the adjustment for the externality is presented there are only four positive values of TFPG. The average value for all the countries is negative and close to 0.95%. We also performed sensitivity analysis using two more arbitrary values for τ .The value of $10\$/tCO_2$ and $5\$/tCO_2$. The results we obtained indicated that when $5\$/tCO_2 < \tau < 10\$/tCO_2$, the externality adjusted TFPG takes positive values (when $\tau = 5\$/tCO_2$) and negative values (when $\tau = 10\$/tCO_2$).Thus we can consider a value between $5\$/tCO_2$ and $10\$/tCO_2$ as a turning point for the sign of the externality adjusted

TFPG.

The overall average TFPG from (240) using the overall averages of the input energy (E_{total}) and output (Y_{total}) of the 23 countries we analyze and $\tau = 20\$/tCO_2$, are summarized in *table 3* that follows:

Table 3: TFPG results using (240).

γ_{total}	0.012
$\frac{\tau\psi_E E_{total}}{Y_{total}}{}_{(\tau=20\$/t)}$	0.019
$\gamma_{adj\ total}$	-0.007

From the results, $\gamma_{adj\ total}$ is negative. This shows that if the externality is internalized, with a tax of $20\$/t$, value imposed on the emissions part of the input energy, then all the inputs can be regarded as receiving their marginal products. In this case, there seems to be no contribution from TFPG to output growth, what is regarded as productivity growth in the non internalized part of the externality associated with the use of energy.

8.6 Concluding Remarks

This part of the thesis tries to extend the traditional measurement of Total Factor Productivity Growth by taking into account the use of the environment proxied by the use of energy as an input in the production process. We use an aggregate production function model. The basic problem that comes up in the estimation of TFPG through this model, is that the share of energy can be considered as containing a part associated with an uninternalized externality. This means that even though energy is paid as an input in production, there is also an unpaid part of energy, which is the CO_2 emission's created from the use of this factor, which is unpaid since there is no carbon policy for the countries and the years we investigated in this study. We attempt to solve this problem by adjusting traditional TFPG estimates by the marginal environmental damages of CO_2 emission's which are associated with energy use. We use a production function to estimate the shares of inputs and an overall average traditional TFPG, directly from a panel set of 23 OECD countries as the coefficient of the time trend of the aggregate production function. We also estimate individual traditional TFPG results by using the shares obtained from the production function estimation combined with the average per country values of the inputs and output in production. We obtain the externality adjusted TFPG estimates, by subtracting from output growth the value of the unpaid part of energy which is associated with embodied emissions which are not accounted for in the traditional measurements due to the lack of an environmental policy. We use current estimates of the marginal damages from CO_2 emissions to approximate the value of the unpaid energy part. Our results indicate that our externality adjusted residual measurements are significantly affected relative to the non-adjusted TFPG estimates. The externality adjusted TFPG estimates could take negative values depending on the value of the marginal CO_2 emission damages. If this value is close to $20\$/tCO_2$ then the residual takes negative values, that is: when each input used in the production process is fully paid for its contribution in total output growth and no TFPG can be detected. When the value of marginal CO_2 emission damages is close to $5\$/tCO_2$, then the externality adjusted residual is positive and TFPG is present.

Our results seems to support the idea that part of what has been regarded as TFPG is actually the "unpaid" part of the environment use in production. The extend to which this part is sufficiently large, so that TFPG is non existent at all for a certain time period, is an issue that largely depends on the estimates of environmental damages. Nevertheless, there seems to be strong, empirical support that at least part of what has been thought as TFPG is the unaccounted use of the environment in the growth process.

Appendix 1

Derivation of the Social Planner's Problem

Net investment is total output minus consumption energy cost and minus the depreciation of human and man made capital. Capital accumulation in per worker terms, assuming that the two capital goods depreciate at the same constant rate (Barro and Sala-i-Martin, 2004), is given by:

$$\dot{k} + \dot{h} = y - c - p_E e_L - (\eta + \delta)(k + h) \tag{242}$$

where p_E is the price of energy in terms of consumption. Set $k = \hat{k}e^{\xi t}$ and $h = \hat{h}e^{\xi t}$, $c = \hat{c}e^{\xi t}$ and $e_L = \hat{e}_L e^{\xi t}$ so that $\dot{k} = \dot{\hat{k}}e^{\xi t} + \xi\hat{k}e^{\xi t}$ and $\dot{h} = \dot{\hat{h}}e^{\xi t} + \xi\hat{h}e^{\xi t}$. Substituting $\dot{k}$ and $\dot{h}$ in (242) we obtain:

$$\dot{\hat{k}}e^{\xi t} + \xi\hat{k}e^{\xi t} + \dot{\hat{h}}e^{\xi t} + \xi\hat{h}e^{\xi t} = e^{\zeta t}(\hat{k}e^{\xi t})^{a_1}(\hat{h}e^{\xi t})^{a_2}E^{a_4} - \hat{c}e^{\xi t} - p_E\hat{e}_L e^{\xi t} - (\eta + \delta)(\hat{k}e^{\xi t} + \hat{h}e^{\xi t})$$

dividing by $e^{\xi t}$:

$$\begin{aligned}\dot{\hat{k}}+\dot{\hat{h}} &= e^{-\xi t}\left(e^{\zeta t}\hat{k}^{a_1}e^{\xi t a_1}\hat{h}^{a_2}e^{a_2\xi t}E^{a_4}\right)-\hat{c}-p_E\hat{e}_L-(\eta+\delta+\xi)(\hat{k}+\hat{h}),\ \text{or}\\ \dot{\hat{k}}+\dot{\hat{h}} &= e^{(\zeta-\xi+a_1\xi+a_2\xi)t}\hat{k}^{a_1}\hat{h}^{a_2}E^{a_4}-\hat{c}-p_E\hat{e}_L-(\eta+\delta+\xi)(\hat{k}+\hat{h})\end{aligned}$$

to make the above equation time independent we choose ξ such that $\zeta-\xi+a_1\xi+a_2\xi=0$ or $\xi=\frac{\zeta}{1-a_1-a_2}=\frac{xa_3+a_4(b-n)}{1-a_1-a_2}$

$$\dot{\hat{k}}+\dot{\hat{h}}=\hat{k}^{a_1}\hat{h}^{a_2}E^{a_4}-\hat{c}-p_E\hat{e}_L-(\eta+\delta+\xi)(\hat{k}+\hat{h}) \tag{243}$$

Assuming as above that the allocation between physical and human capital is such that the marginal products for each type of capital are equated in equilibrium if we use both forms of investment, we have that[189]:

$$a_1\frac{\hat{y}_t}{\hat{k}_t}-\delta=a_2\frac{\hat{y}_t}{\hat{h}_t}-\delta \tag{244}$$

The equality between marginal products implies a one to one relationship between physical and human capital, or:

$$\hat{h}=\frac{a_2}{a_1}\hat{k},\ \dot{\hat{h}}=\frac{a_2}{a_1}\dot{\hat{k}} \tag{245}$$

Using (245) in (243) we obtain:

$$\begin{aligned}\dot{\hat{k}}+\frac{a_2}{a_1}\dot{\hat{k}} &= \hat{k}^{a_1}\left(\frac{a_2}{a_1}\hat{k}\right)^{a_2}E^{a_4}-\hat{c}-p_E\hat{e}_L-(\eta+\delta+\xi)\left(\hat{k}+\frac{a_2}{a_1}\hat{k}\right)\\ \left(\frac{a_1+a_2}{a_1}\right)\dot{\hat{k}} &= \hat{k}^{a_1}\left(\frac{a_2}{a_1}\right)^{a_2}\hat{k}^{a_2}E^{a_4}-\hat{c}-p_E\hat{e}_L-(\eta+\delta+\xi)\left(\frac{a_1+a_2}{a_1}\right)\hat{k}\end{aligned}$$

dividing with $\left(\frac{a_1+a_2}{a_1}\right)$ we have:

$$\begin{aligned}\dot{\hat{k}} &= \tilde{A}\hat{k}^{\beta}E^{a_4}-\alpha\hat{c}-p_E\alpha\hat{e}_L-(\eta+\delta+\xi)\,\hat{k}, \\ \tilde{A} &= \left(\frac{a_2^{a_2}a_1}{a_1^{a_2}\left(a_1+a_2\right)}\right),\ \beta=a_1+a_2,\ \alpha=\left(\frac{a_1}{a_1+a_2}\right)\end{aligned} \tag{246}$$

[189]This substitution is convenient since by adopting it we do not need a seperate state equation for human capital. It does not however affect the basic results of this section regarding the interpretation of the unpaid part of energy associated with emissions generated by a given quantity of energy which is unpaid due to the abscence of carbon taxes.

By abusing notation and in order to simplify relationships we will keep writing $\hat{c}$ and $\hat{e}_L$, instead of $\alpha\hat{c}$ and $\alpha\hat{e}_L$in the capital accumulation equation (246) since the results are not affected.

Considering a utility function $U(c,S) = \frac{1}{1-\theta}c^{1-\theta}S^{-\gamma} \quad \theta, \gamma > 0$ we obtain using the substitution $c = \hat{c}e^{\xi t}$.

$$\begin{aligned} U(c,S) &= \frac{1}{1-\theta}c^{1-\theta}S^{-\gamma} = \frac{1}{1-\theta}\left(\hat{c}e^{\xi t}\right)^{1-\theta}S^{-\gamma} = \\ &= e^{(1-\theta)\xi t}\frac{1}{1-\theta}\hat{c}^{1-\theta}S^{-\gamma} = e^{(1-\theta)\xi t}U(\hat{c},S) \end{aligned} \tag{247}$$

Using (209), (247), (214), and (246) the social planners problem can be written as (212)

Appendix 2

Consumers

Defining the current value Hamiltonian for the problem as:

$$H = U(c,S) + \pi(w + ra - c + na + \tau z) \tag{248}$$

standard optimality conditions imply:

$$U_c(c,S) = \pi\ ,\ U_{cc}(c,S)\dot{c} = \dot{\pi} \tag{249}$$

$$\dot{\pi} = (\rho - r)\pi \text{ or} \tag{250}$$

$$\frac{\dot{c}}{c} = \frac{1}{\theta}(r - \rho) \tag{251}$$

Firms

The representative firm maximizes profits (197) assuming that physical capital, human capital and loans are perfect substitutes as stores of value we have $r = R_K - \delta = R_H - \delta$.The profit function for the firm can be written in per worker terms, using the Cobb-Douglas specification and setting $k = \hat{k}e^{\xi t}$, $h = \hat{h}e^{\xi t}$, and $\zeta - \xi + a_1\xi + a_2\xi = 0$, $\xi = \zeta - a_1\xi - a_2\xi$ as:

$$\Pi = F(K,H,W,X) - R_K K - R_H H - wL - p_E E - \tau\psi(E) \tag{252}$$

or:

$$\frac{\Pi}{L} = e^{\zeta t} k^{a_1} h^{a_2} E^{a_4} - R_K k - R_H h - w - p_E e_L - \tau \frac{\psi(E)}{L}, \tag{253}$$

where $k = \hat{k} e^{\xi t},\ h = \hat{h} e^{\xi t},\ e_L = \hat{e}_L e^{\xi t}$

$$\frac{\Pi}{L} = e^{\zeta t} (\hat{k} e^{\xi t})^{a_1} (\hat{h} e^{\xi t})^{a_2} E^{a_4} - R_K \hat{k} e^{\xi t} - R_H \hat{h} e^{\xi t} - w - p_E \hat{e}_L e^{\xi t} - \tau \frac{\psi(E)}{L}$$

$$\frac{\Pi}{L} = e^{(\zeta + a_1 \xi + a_2 \xi) t} \hat{k}^{a_1} \hat{h}^{a_2} E^{a_4} - R_K \hat{k} e^{\xi t} - R_H \hat{h} e^{\xi t} - w - p_E \hat{e}_L e^{\xi t} - \tau \frac{\psi(E)}{L}$$

where $\zeta = \xi - a_1 \xi - a_2 \xi$ we obtain:

$$\tilde{\pi} \equiv \frac{\Pi}{L} = e^{\xi t} \left[f\left(\hat{k}, \hat{h}, E\right) - R_K \hat{k} - R_H \hat{h} - w e^{-\xi t} - p_E \hat{e}_L - \tau \frac{\psi(E)}{L} e^{-\xi t} \right] \tag{254}$$

In equilibrium firms take R_K, R_H, w, and p_E and τ as given and maximize for any given level $\hat{l} = L e^{\xi t}$ by setting:

$$f_{\hat{k}} = R_K = r + \delta \tag{255}$$

$$f_{\hat{h}} = R_H = r + \delta \tag{256}$$

$$f_E = \frac{p_E + \tau \psi_E(E)}{\hat{l}} \Rightarrow f_E \hat{l} = p_E + \tau \psi_E(E)^{190} \tag{257}$$

$$e^{\xi t} \left[f\left(\hat{k}, \hat{h}, E\right) - f_{\hat{k}} \hat{k} - f_{\hat{h}} \hat{h} - \left(p_E + \tau \psi_E(E)\right) e_L e^{-\xi t} \right] = w, \tag{258}$$

$$\hat{e}_L = e_L e^{-\xi t} = \frac{E}{L} e^{-\xi t} \tag{259}$$

$$e^{\xi t} \left[f\left(\hat{k}, \hat{h}, E\right) - f_{\hat{k}} \hat{k} - f_{\hat{h}} \hat{h} - \left(f_E \hat{l}\right) e_L e^{-\xi t} \right] = w \tag{260}$$

Competitive equilibrium implies that profits are zero. The zero profit condition implies:

$$f\left(\hat{k}, \hat{h}, E\right) - R_K \hat{k} - R_H \hat{h} - e^{\xi t} \left[f\left(\hat{k}, \hat{h}, E\right) - f_{\hat{k}} \hat{k} - f_{\hat{h}} \hat{h} - \left(p_E + \tau \psi_E(E)\right) e_L e^{-\xi t} \right] e^{-\xi t} - \tag{261}$$

$$p_E e_L e^{-\xi t} - \tau \frac{\psi(E)}{L} e^{-\xi t} = 0$$

For the zero profit condition to hold it is necessary that:

$$\tau\psi_E(E)\frac{E}{L}e^{-\xi t}=\tau\frac{\psi(E)}{L}e^{-\xi t}$$

which implies that

$$\begin{aligned}\psi_E(E)\,E &= \psi(E) \text{ or} \\ \frac{d\psi(E)}{dE}\frac{E}{\psi(E)} &= 1\end{aligned} \tag{262}$$

Therefore, existence of competitive equilibrium when the emissions embodied to energy are taxed, requires that the emission function has unit elasticity with respect to energy or that it can be written as $Z=\sigma E$.

Equilibrium

In equilibrium $a=k+h$ so $\hat{a}=\hat{k}+\hat{h}$. Then the flow budget constraint:

$$\dot{a}=w+ra-c-na+\tau z \tag{263}$$

can be written as:

$$\dot{k}+\dot{h}=w+r(k+h)-c-n(k+h)+\tau z \tag{264}$$

Setting as before $k=\hat{k}e^{\xi t}$ and $h=\hat{h}e^{\xi t}$, $c=\hat{c}e^{\xi t}$, and taking the time derivatives of k and h we obtain:

$$\begin{aligned}&\dot{\hat{k}}e^{\xi t}+\xi\hat{k}e^{\xi t}+\dot{\hat{h}}e^{\xi t}+\xi\hat{h}e^{\xi t}= \\ &w+r\left(\hat{k}e^{\xi t}+\hat{h}e^{\xi t}\right)-\hat{c}e^{\xi t}-n\left(\hat{k}e^{\xi t}+\hat{h}e^{\xi t}\right)+\tau z\end{aligned} \tag{265}$$

substituting (255)-(258) into (265), and using in equilibrium $r=f_{\hat{k}}-\delta=f_{\hat{h}}-\delta$, $f_E\hat{l}=p_E+\tau\psi_E(E)$, $\hat{l}=Le^{\xi t}$ we obtain:

$$\dot{\hat{k}}e^{\xi t}+\xi\hat{k}e^{\xi t}+\dot{\hat{h}}e^{\xi t}+\xi\hat{h}e^{\xi t}=$$
$$e^{\xi t}\left[f\left(\hat{k},\hat{h},E\right)-f_{\hat{k}}\hat{k}-f_{\hat{h}}\hat{h}-\left(p_E+\tau\psi_E\left(E\right)\right)e_Le^{-\xi t}\right]+$$
$$\left(f_{\hat{k}}-\delta\right)\hat{k}e^{\xi t}+\left(f_{\hat{h}}-\delta\right)\hat{h}e^{\xi t}-\hat{c}e^{\xi t}-n\left(\hat{k}e^{\xi t}+\hat{h}e^{\xi t}\right)+\tau z, \tag{266}$$

where , $z=\dfrac{\psi\left(E\right)}{L}$. Dividing with $e^{\xi t}$ we have:

$$\dot{\hat{k}}+\xi\hat{k}+\dot{\hat{h}}+\xi\hat{h}=\left[f\left(\hat{k},\hat{h},E\right)-f_{\hat{k}}\hat{k}-f_{\hat{h}}\hat{h}-\left(p_E+\tau\psi_E\left(E\right)\right)e_Le^{-\xi t}\right]$$
$$+\left(f_{\hat{k}}-\delta\right)\hat{k}+\left(f_{\hat{h}}-\delta\right)\hat{h}-\hat{c}-n\left(\hat{k}+\hat{h}\right)+\tau\frac{\psi\left(E\right)}{L}e^{-\xi t} \tag{267}$$
$$\dot{\hat{k}}+\dot{\hat{h}}=\left[f\left(\hat{k},\hat{h},E\right)-\left(r+\delta\right)\left(\hat{k}+\hat{h}\right)-\left(p_E+\tau\psi_E\left(E\right)\right)e_Le^{-\xi t}\right]$$
$$+r\hat{k}+r\hat{h}-\hat{c}-n\left(\hat{k}+\hat{h}\right)+\tau\frac{\psi\left(E\right)}{L}e^{-\xi t}-\xi(\hat{k}+\hat{h}) \tag{268}$$

$$\begin{aligned}\dot{\hat{k}}+\dot{\hat{h}}&=f\left(\hat{k},\hat{h},E\right)-\left(n+\delta+\xi\right)\left(\hat{k}+\hat{h}\right)-\left(p_E+\tau\psi_E\left(E\right)\right)e_Le^{-\xi t}-\hat{c}+\tau\frac{\psi\left(E\right)}{L}e^{-\xi t}\\ \dot{\hat{k}}+\dot{\hat{h}}&=f\left(\hat{k},\hat{h},E\right)-\left(n+\delta+\xi\right)\left(\hat{k}+\hat{h}\right)-\hat{c}-p_E\hat{e}_L-\tau\psi_E\left(E\right)\frac{E}{L}e^{-\xi t}+\tau\frac{\psi\left(E\right)}{L}e^{-\xi t}\end{aligned}$$

using (262) we have:

$$\dot{\hat{k}}+\dot{\hat{h}}=\hat{k}^{a_1}\hat{h}^{a_2}E^{a_4}-\hat{c}-p_E\hat{e}_L-(\eta+\delta+\xi)(\hat{k}+\hat{h}) \tag{269}$$

Using as above the assumption that in equilibrium the allocation between physical and human capital is such that the marginal products for each type of capital are equated if we use both forms of investment, we have as before $a_1\frac{\hat{y}_t}{\hat{k}_t}-\delta=a_2\frac{\hat{y}_t}{\hat{h}_t}-\delta$ and $\hat{h}=\frac{a_2}{a_1}\hat{k}$, $\dot{\hat{h}}=\frac{a_2}{a_1}\dot{\hat{k}}$. Then (269) becomes

$$\dot{\hat{k}}=f\left(\hat{k},E\right)-\alpha\hat{c}-\alpha p_E\hat{e}_L-\left(\eta+\delta+\xi\right)\hat{k}\ \ ,\ \ f\left(\hat{k},E\right)=s\tilde{A}\hat{k}^{\beta}E^{a_4} \tag{270}$$

which is the social planners transition equation (213).

Setting $c=\hat{c}e^{\xi t}$ and $\dot{c}=\xi\hat{c}e^{\xi t}+\dot{\hat{c}}e^{\xi t}$ into (251) we obtain

$$\frac{\dot{\hat{c}}}{\hat{c}}=\frac{1}{\theta}\left[f_{\hat{k}}\left(\hat{k},E\right)-\rho-\delta-\xi\theta\right]-\frac{U_{\hat{c}S}\left(\hat{c},S\right)}{U_{\hat{c}\hat{c}}\left(\hat{c},S\right)}\dot{S} \tag{271}$$

Under optimal taxation $\tau = -\lambda\hat{l}/p$. We have therefore, from the social planner's problem that $f_E\left(\hat{k}, E\right)\hat{l} = p_E - \left(\lambda\psi_E(E,t)\hat{l}\right)/p$ with $p = U_{\hat{c}}(\hat{c}, S)$, $E = g\left(\hat{k}, \lambda, p, \hat{l}\right)$ while from the firms problem, (257), we have $f_E\left(\hat{k}, E\right)\hat{l} = p_E + \tau\psi_E(E)$. The optimality conditions for the choice of energy coincide. It should be noticed that $\tau/\hat{l} = -\lambda/p$, that is the tax per effective worker is equal to the shadow cost of emissions expressed in utility terms.

Substituting E into the equation above and into (214) we obtain

$$\frac{\dot{\hat{c}}}{\hat{c}} = \frac{1}{\theta}\left[f_{\hat{k}}\left(\hat{k}, g\left(\hat{k}, \lambda, U_{\hat{c}}(\hat{c}, S), \hat{l}\right)\right) - \rho - \delta - \theta\xi\right] - \frac{U_{\hat{c}S}(\hat{c}, S)}{U_{\hat{c}\hat{c}}(\hat{c}, S)}\dot{S} \quad (272)$$

$$\dot{S} = \psi\left[g\left(\hat{k}, \lambda, U_{\hat{c}}(\hat{c}, S), \hat{l}\right), t\right] - mS \quad (273)$$

The dynamic system (270), (271) and (273) determines the evolution of $\left(\hat{c}, \hat{k}, S\right)$ in a decentralized competitive equilibrium under optimal emission taxation. By comparing them with (223), (225) and (226) it is clear that the path of the decentralized competitive equilibrium under optimal emission taxation coincides with the socially optimal path.

9. Conclusions and Areas for Further Research

Based on part I of this thesis where we define the concept of sustainability and measure sustainability conditions for developed and developing countries and part II, where we extend the subject of total factor productivity growth measurements by introducing the environment as an input in production, this last chapter is an attempt to summarize the novel theoretical and empirical results and findings and indicate areas for further research.

To do that, we begin with the basic results of the first part of this dissertation. The aim of chapter 3 is to develop a model capable of approaching sustainability by measuring the change in current social welfare (CCSW) conditions of economies. Based on a non-optimizing framework, we develop a model that allows us to choose policies with respect to their impact on current social welfare (CSW) conditions. We consider two different approaches for choosing policy instruments, a feedback and an arbitrary rule and determine two corresponding criteria for measuring the change in CSW conditions. Our theoretical framework is designed to provide applied results for actual economies. Positive changes in social welfare imply positive genuine investment and current productive-base sustainability. Negative changes in social welfare (thus negative genuine investment) are regarded as an indicator of currently unsustainable policies. When policy rules are chosen in an arbitrary way, then genuine investment should be adjusted accordingly and this remark might have important implications. Thus, by considering a "Solow" economy, where domestic population growth, migration, labor augmenting technical change, and environmental damages associated with pollutant flows generated by economic activities are present, we determine CSW conditions, value functions and accounting prices. The application of our theoretical model to the case of the Greek economy provides us with findings that show that migration inflows, exogenous technical change, growth of capital per worker, and SO_2 emissions damages, are important factors for characterizing the current changes in social welfare conditions of the Greek economy. Our main finding is that the Greek economy seems to be currently 'productive-base sustainable', given the current estimates of SO_2 emission damages, which is the only pollutant considered in our analysis. Taking into account environmental damages of SO_2 emissions has an undoubtelly negative effect on the current social welfare conditions and affects social welfare conditions in a negative way. Our approach provides empirical confirmation of this result and can also be used to quantify environmental impacts on social welfare.

We then extend our model to the case of two large groups of countries, developed and developing (chapter 4) and attempt to determine the sustainability conditions for those two large groups of countries in terms of current change on social welfare (CCSW). We observe that one of the basic variables that affects CCSW conditions is CO_2 along with other GHG's emissions which are considered to be the basic contributors to the global warming phenomenon. Thus, we formulate a model able to provide empirical results for the productive base sustainability of those economies which are negatively affected by CO_2 and GHG's emissions. We determine the criterion that measures current change of the productive base by taking into account the environmental damage created from the global warming. We derive results for the productive base sustainability criterion in a context of a non optimizing growth framework for the two large groups of countries, 23 developed and 21 developing using three different scenaria of global CO_2 emissions' growth. Our main empirical finding is that when global CO_2 emissions increase, the productive base sustainability criterion is negative for almost all the countries under analysis and when global CO_2 emissions remain constant, the productive base sustainability criterion is positive both for the case of developed and for the case of developing countries.

In the second part of the dissertation, we analyze the concept of Total Factor Productivity Growth (TFPG). Our aim was to formulate a new approach to TFPG measurement which would take into account the use of the environment in the form of CO_2 emissions and energy, in a group of developed and developing economies.

We begin by approximating the use of the environment with CO_2 emissions as an input in the production process and formulate a theoretical model that includes emissions and emission augmenting technical change (chapter 6). We interpret the emission's share in output in a context of a completive equilibrium under optimal taxation since emissions is an unpaid factor of production, that is when emissions are not taxed. We next apply our model to a group of 23 OECD countries and provide direct adjustments of existing TFPG estimates when CO_2 damages are taken into account in the aggregate production function. We also decompose technical change to labour augmenting and emissions augmenting technical change. Our results show that when emissions grow, the traditional estimates overestimate TFPG relative to our estimates, by attributing part of environment's contribution to output growth, to technical change. The opposite happens when emissions decline, that is, when there are savings of environment as a factor of production, then traditional estimates underestimate TFPG. The size of deviation depends on size of damage estimates of CO_2 emissions. Thus, our approach can be considered as a Green TFPG measurement methodology that introduces the environment as an extra input in the production function that if accounted, changes current TFPG results. The direct econometric estimation suggests an average TFPG which for the period 1965-1990 we analyze, around 1%, or less. It also suggests that emissions in the form of CO_2 is a statistically significant input in the aggregate production function and that emission augmenting technical change coexists with labour augmenting technical change. This implies that the use of the environment approximated by CO_2 emissions, which is an unpaid factor in production, contributes to the growth of output along with physical capital, human capital, and labour and its contribution should be properly accounted in TFPG measurements. In the case where an optimal tax, determined by marginal environmental damages along the optimal path, is imposed on emissions, this would internalize the externalities created by the use of the "unpaid" environmental factor and this factor would obtain a price. Nevertheless, there is always the possibility to overestimate or underestimate the "socially optimal" use of the environmental factor. Our results show that if marginal damages are relatively high, the socially optimal use of the environment in the growth process should be relatively small, while the opposite would hold for low marginal damages. If, in the absence of optimal environmental policy, this contribution is sizable, and our results suggest that the contribution of CO_2 emissions is statistically significant with a share in output as high as 14%, then excess use of the environment as an input might question the eventual sustainability of the current growth process. For example if, after solving the social planner's problem, we have an estimate of λ, the true shadow value of the CO_2, and calculate emissions' share, s_Z as $\left(-\hat{\lambda}Z\right)/Y$, then the growth accounting equation (114) might produce a negative result. This result can be interpreted as an indication that total use of resources, including the "unpaid" one properly valued, exceeds the output growth generated by these resources. In this case development that uses "unpaid" factors cannot be considered sustainable.

The results we obtained for TFPG measurements for the case of the 23 OECD countries are then extended to the case of 21 developing countries (chapter 7). Our aim is to measure again the contribution of the environmental factor, approximated by CO_2 emissions in a group of developing countries and form a theoretical and an empirical analysis able to provide measurable results for the contribution of the environment in the growth of the final output. To do that, we follow the same theoretical and empirical methodology as before and interpret the emissions share in output, in a context of a completive equilibrium under optimal taxation, where emissions is an unpaid factor, that is they are not taxed. We also provide adjustments of existing TFPG estimates and our results suggest an average TFPG for the period 1965-1990 for the countries under examination of the order of 1%. This implies that the use of the environment, approximated by CO_2 emissions, which is an unpaid factor, contributes to the growth of output along with physical capital, human capital, and labour, and its contribution should be accounted in the context of a "green TFPG" or a "green residual estimation". As before, the "socially optimal contribution of the environment, might be under or overestimated. This is closely associated with the "optimal" tax determined by marginal environmental damages along an optimal path. If there is no optimal environmental policy, our results suggest that the CO_2 emissions contribution is statistically significant with a share in output as high as 33% and the excess use of the environment as an input in production might question the eventual sustainability of the current growth process.

Chapter 8 is a last extension of the traditional measurements of Total Factor Productivity Growth. Our aim is to take into account the use of the environment proxied by the use of energy as an input in the production process. Using an aggregate production augmented with energy, we define the shares of the inputs used in production in a context of a competitive equilibrium model. In this set up, energy is a partially paid input in the production process. More analytically, the share of energy is considered as containing a part associated with an uninternalized externality. This means that eventhough energy is paid as an input in production, there was also an unpaid part of energy, which is the CO_2 emission's created from the use of this factor, which is unpaid since there is no carbon policy for the countries and the years we investigate. We attempt to solve this problem by adjusting traditional TFPG estimates by the marginal environmental damages of CO_2 emission's which are associated with energy use. We use a production function to estimate the shares of inputs and an overall average traditional TFPG, directly from a panel set of 23 OECD countries as the coefficient of the time trend of the aggregate production function. We also estimate individual traditional TFPG results by using the shares obtained from the production function estimation combined with the average per country values of the inputs and output in production. We obtain the externality adjusted TFPG estimates, by subtracting from output growth the value of the unpaid part of energy which is associated with embodied emissions that are not accounted for in the traditional measurements due to the lack of an environmental policy. We use current estimates of the marginal damages from CO_2 emissions to approximate the value of the unpaid energy part. Our results indicate that our externality adjusted residual measurements are significantly affected relative to the non-adjusted TFPG estimates. The externality adjusted TFPG estimates can take negative values depending on the value of the marginal CO_2 emission damages. If this value is close to $20\$/tCO_2$ then the residual takes negative values, that is: when each input used in the production process is fully paid for its contribution in total output growth and no TFPG can be detected. When the value of marginal CO_2 emission damages is close to $5\$/tCO_2$, then the externality adjusted residual is positive and TFPG is present. Our results seem to support the idea that part of what is regarded as TFPG is actually the "unpaid" part of the environment use in production. The extend to which this part is sufficiently large, so that TFPG is non existent at all for a certain time period, is an issue that largely depends on the estimates of environmental damages. Nevertheless, there seems to be strong, empirical support that at least part of what has been thought as TFPG is the unaccounted use of the environment in the growth process.

In this thesis, productive base sustainability conditions were analyzed, flows and stock of carbon dioxide were used as factors that determine growth and have an effect on productive base sustainability conditions. It was shown that the global warming phenomenon has a significant negative effect on sustainability conditions of current economies and that traditional total factor productivity growth measurements are biased at the introduction of the environment as a driver of growth. The unpaid part of emissions and energy used as environmental inputs in production, showed that there exists a deviation between the traditional Solow residual and our green TFPG or the externality adjusted TFPG. All these results, summarize the contribution of the present thesis. Therefore, starting from the concept of sustainable development that constitutes one of the most important and significant international environmental goals of today, our attempt to transform this definition into something measurable and tangible and to explore the impact of the widely used concept such as TFPG or sustainability conditions lead to the development of this thesis that we believe provides a contribution to the quest for theoretical and empirical foundations and the insight which will allow us to characterize whether our future is on a sustainable path or not and which might provide indications about sustainabilty promoting policies.

The research developed in the present thesis could be extended along various lines. In chapter 3, the model developed could be extended and made more realistic by including transition equations for stocks of pollutants, natural resources (depletable or renewable), human capital, or by introducing uncertainty in the evolution of the economy. These extensions would provide better insights regarding the changes in social welfare conditions of economies and would enhance our ability to provide meaningful estimates of such changes.

In chapters 6 and 7 and 8, areas of future research could include TFPG estimates by approximating environment's use not just by CO_2 emissions, but by a more general index that will include additional environmental variables; introduction of stock variables into the aggregate production function; use of our production function estimates along with damage functions for CO_2 to solve the social planners problem and define the structure and the parameters of the corresponding value functions; reformulating, at a more general level, some of the recent empirical approaches to growth to take into account possible unpaid and damage generating factors of production.

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