Thema

Reappraising the Role of Energy in the Economy

Dissertation

zur Erlangung des akademischen Grades
doctor rerum politicarum
(Dr. rer. pol.)

vorgelegt dem
Rat der Wirtschaftswissenschaftlichen Fakultät
der Friedrich-Schiller-Universität Jena

am 11. Juli 2012

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Datum der Verteidigung: 29. Januar 2013

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Deutschsprachige Zusammenfassung

Die Bedeutung des Energiekonsums für das Wirtschaftswachstum ist zurück auf der Agenda. Erstmalig ist dessen Bedeutung nach der Ölpreiskrise in den 1970er Jahren in das Zentrum der Betrachtung gerückt. Zwei neue Entwicklungen haben das Interesse an der Thematik wieder aufleben lassen. Zum einen lässt sich seit der Jahrtausendwende ein kontinuierlicher Anstieg der Energiepreise feststellen. Die wachsende Energienachfrage der gegenwärtig industrialisierenden Länder überkompensiert die Effizienzgewinne des Energiekonsums, der erzielt werden konnte. Gleichzeitig gibt es Berechnungen wonach die Ölgewinnung den Höhepunkt erreicht hat, was die Befürchtungen über eine Verknappung der weltweiten Ölreserven noch verstärkt (Hubbert, 1949; Campbell und Laherrère, 1998; Campbell und Heapes, 2008). Zum anderen gibt es ein stärkeres Bewusstsein für die Schädigungen der Umwelt aufgrund des zunehmenden Verbrauchs fossiler Energieressourcen sowie der damit verbundene Erhöhung der CO_2-Konzentration in der Atmosphäre (Stern, 2008).

Wie haben wir bislang auf diese Entwicklung reagiert? Es gibt sehr optimistische Szenarien, wonach das Wirtschaftswachstum weitestgehend vom Energiekonsum entkoppelt werden kann. Gleichzeitig gibt es Einschätzungen wonach die CO_2 Emissionen vom Energiekonsum entkoppelt werden können. Eine oft diskutierte Möglichkeit der Entkopplung des Wirtschaftswachstums vom Energiekonsum ist die Entwicklung industrialisierter Länder hin zur Dienstleitungsgesellschaft. Dies ist mit der Erwartung verbunden, dass die Energienachfrage nach der Übergangsphase geringer ist, da der Energiekonsum pro Einheit Output im Dienstleistungsbereich im Durchschnitt geringer ist als in der Industrie. Heute lässt sich feststellen, dass die erwartete Reduktion nur bedingt erreicht werden konnte (Baksi und Green, 2007). Gilt vielmehr auch heute noch, dass Energie und Wachstum gekoppelt sind? Dies legen zumindest die theoretischen Ausführungen führender Wissenschaftler nahe, die Energie und Wachstum aufgrund biophysikalischer Gesetze eng miteinander verbunden sehen (Cleveland et al., 1984; Ayres and Warr, 2009). Von empirischer Seite gibt es wenig eindeutige Belege für die Kopplung von Energie und Wachstum – nach mehr als dreißigjähriger Forschung auf diesem Gebiet (Ozturk, 2010; Payne, 2010).

Das verbindende Element der empirischen Untersuchungen, die dieser Dissertation zugrunde liegen, ist sowohl eine kritische Auseinandersetzung mit den Möglichkeiten die beschriebene Entkopplung zu erreichen als auch eine empirische Analyse des tatsächlichen Potenzials für eine Entkopplung. Um diese Frage umfassend beantworten zu können, gehen wir zunächst einen Schritt zurück und widmen uns der grundlegenden Frage, ob es Belege für eine Abhängigkeit zwischen Energiekonsum und Wirtschaftswachstum gibt. Wenn es eine systematische Evidenz für diesen Zusammenhang gibt, ergibt sich daraus zwangsläufig, dass die Möglichkeiten beschränkt aus dieser engen Beziehung auszubrechen. Die Folge wäre, dass der Energiekonsum nicht beliebig reduziert werden kann, ohne dass das Wirtschaftswachstum gefährdet wird. In diesem Fall wäre ein Verlass auf die Reduktion des Energiekonsums als Mittel zur Vermeidung des Klimawandels unzureichend. Stattdessen verbliebe lediglich die Reduktion der CO2-Emissionen als Instrument für ein nachhaltiges Wirtschaftswachstum.

Ein systematischer Weg der Aufarbeitung und Analyse empirischer Funde über den Zusammenhang zwischen Energiekonsum und Wirtschaftswachstum ist der einer Meta-Analyse der relevanten Literatur. In Kapitel 2 der Dissertation analysieren wir die relevante Literatur mithilfe von Meta-Regressions-Methoden. In einer kürzlich veröffentlichten explanatorischen Meta-Analyse widmen sich Chen et al. (2012) lediglich der Frage mit welcher Wahrscheinlichkeit und unter welchen Umständen eine bestimmte Kausalitätsrichtung (Energie verursacht kausal Wirtschaftswachstum oder umgekehrt) auf Grundlage einer kleinen Anzahl an Beobachtungen auftritt. Sie können jedoch nicht die Frage beantworten, ob diese Kausalrichtung tatsächlich einen wahren Effekt darstellt. Die drängendere Frage hingegen ist, ob es in der gesamten empirischen Literatur zu diesem Thema Evidenz für einen wahren Effekt gibt, nämlich in Bezug auf das Verhältnis zwischen Energiekonsum und Wirtschaftswachstum. Um das Vorhandensein dieses wahren Effektes zu untersuchen, benutzen wir Meta-Signifikanz-Tests nach Stanley (2005; 2008). Da die zugrundeliegenden Studien auf einer Vielzahl unterschiedlicher Spezifikationen beruhen, analysieren wir zudem den Einfluss der wichtigsten Faktoren auf das Auffinden eines wahren Effekts, die in der Literatur diskutiert worden sind. Dabei handelt es sich um den Einfluss der sektoralen Aggregation des Outputs, die Wahl der Energievariable, der Entwicklungsstand einzelner Länder, die Wahl der Kontrollvariablen, sowie die Wahl der ökonometrischen Methode (Payne, 2010). Unsere Studie basiert auf 1020 Kausalitätstests zwischen Energiekonsum und Wirtschaftswachstum auf der Grundlage von insgesamt 75 Studien für 108 Länder.

Unsere Ergebnisse bestätigen den Einfluss der sektoralen Aggregation des Outputs, der Wahl der Kontrollvariablen, sowie des Entwicklungsstandes. Was die sektorale Aggregation des Wachtumsvariable betrifft, bestätigen unsere Ergebnisse, dass Kausalitätstests verzerrte Ergebnisse liefern können wenn der Aggregationslevel nicht nicht dem der Energievariable entspricht. Dies ist der Fall wenn die erklärenden Variablen einen unterschiedlichen Bezugspunkt in Hinblick auf die ökonomische Aktivität haben (Zachariadis, 2007; Gross, 2012). Hinzukommt, dass die Einbeziehung von Kontrollvariablen die Identifikation eines Kausalzusammenhangs zwischen Energie und Wirtschaftswachstum signifikant beeinflussen kann wenn eine der Variablen (oder beide) stark mit der Kontrollvariable korrelieren. Der Entwicklungsstand der Volkswirtschaften hat insofern einen Einfluss als die Evidenz für Kausalität bei Ländern mit einem hohen Einkommen stärker gestört zu sein scheint als bei Ländern mit einem niedrigen Einkommen. Entgegen oft geäußerter Auffassungen, dass die Wahl der ökonometrischen Methode selbst einen Einfluss ausübt, finden wir, dass die Gründe für die Identifikation eines Kausalzusammenhangs vielmehr inhaltlich begründet werden kann. Darüber hinaus finden wir, dass die Wahl der Energievariable in Ländern mit hohem Einkommen keinen Einfluss auf das Ergebnis hat. Dies kann problematische Politikimplikationen in solchen Fällen herbeiführen, in denen das Finden von Kausalität auf eine einzelne Energieressource zurückgeführt wird, diese aber tatsächlich auch mit allen anderen Energieressourcen hochkorreliert ist.

Ein weiterer wichtiger Einflussfaktor, der bislang nur unzureichend in der Literatur behandelt wurde, ist die Zeit. Genau genommen sind es tiefgreifende Wandel, die zunehmend eine Störung des Verhältnisses von Energiekonsum zu Wirtschaftswachstum herbeigeführt haben. Im Kontext der zugrundeliegenden Literatur wurden strukturelle Wandel wie sektorale Verschiebungen sowie eine Auslagerung industrieller Produktion in Entwicklungs- oder Schwellenländer diskutiert (Gross, 2012). Wir folgern daraus, dass in der Analyse des Zusammenhangs zwischen Energiekonsum und Wirtschaftswachstum ein neuer Weg beschritten werden sollte. Anstelle einer reinen Beschreibung des sich nicht-monoton entwickelnden Verhältnisses von Energie zu Wachstum mithilfe neuer ökonometrischer Verfahren sollte vielmehr eine detaillierte Auseinandersetzung mit den zugrundeliegenden Dynamiken erfolgen. Nur so kann das Verhältnis adäquat erfasst werden.

Im dritten Kapitel der Dissertation gehen wir einen Schritt weiter und befassen uns mit den wichtigsten Determinanten des Energie-Wachstums-Verhältnisses. Wir argumentieren, dass die sektorale Aggregation den größten Einfluss auf die Identifikation eines Kausalzusammenhangs zwischen Energie und Wirtschaftswachstum ausübt. Kürzlich veröffentlichte Studien (Zachariadis, 2007; Bowden und Payne, 2009) analysieren den Kausalzusammenhang zwischen Energiekonsum und Wirtschaftswachstum sowohl auf der makroökonomischen als auch auf der sektoralen Ebene. Während das Verhältnis zwischen Energie und Wachstum auf Makro-Ebene neutral zu sein scheint, finden beide Studien in Einzelfällen Evidenz für (Granger) Kausalität auf einer niedrigeren Aggregationsebene. Im Rahmen statistischer Analysen ist es nicht ungewöhnlich, dass Evidenz für einen statistischen Effekt auf einer geringeren Ebene gefunden wird, obwohl die Ergebnisse für die gesamte Population das Gegenteil andeuten. Dieses Phänomen wird auch „Simpson's Paradox“ genannt, nach E. Simpson (1951). Es gilt jedoch zu berücksichtigen, dass – wenn die Ergebnisse von der Aggregationsebene abhängen – die empirische Untersuchung zwingend auf der „richtigen“ Aggregationsebene stattfinden muss. Ansonsten können die Ergebnisse verfälscht sein, was wiederum falsche Politikimplikationen zur Folge haben kann. Die verzerrende Wirkung aufgrund des Paradoxons wird noch verstärkt wenn die Variablenpaare, die für den Kausalitätstest herangezogen werden, nicht dieselbe Aggregationsebene abdecken. Aus diesem Grund führen wir die Diskussion „angemessener“ Variablenpaare fort, die Zachariadis (2007) begonnen hat.

Die Tatsache, dass Sektoren sich in Hinblick auf das Verhältnis zwischen Energiekonsum und Wirtschaftswachstum unterscheiden, ist aus der „Environmental Kuznets Curve“ (EKC) Literatur bekannt. Demnach führen Verschiebungen in der sektoralen Struktur zu Änderungen in der Energienachfrage über die Zeit. Im Zuge der Industrialisierung erhöht sich die Nachfrage und nimmt in der Phase der Tertiärisierung wieder ab (Kahn, 1979; Panayotou, 1993; Panayotou et al., 2000; Smil, 2000; Schaefer, 2005). Die daraus resultierende Divergenz von Energiekonsum und Wirtschaftswachstum stellt auch empirische Untersuchungen vor eine Herausforderung. Um das zunehmende Auseinanderdriften von Energie und Wachstum zu berücksichtigen, sollten die wichtigsten Erkenntnisse aus der EKC Literatur in die Literatur über die Kausalität von Energie und Wachstum überführt werden, wie zum Beispiel die steigende (technische) Energieeffizienz der Produktion, sowie die Auslagerung energieintensiver Produktion.

Unsere Analyse beruht auf dem Autoregressive Distributed Lag (ARDL) Bounds Test von Pesaran und Shin (1999) und Pesaran et al. (2001). Wir analysieren Granger Kausalität zwischen Energiekonsum und Wirtschaftswachstum für die USA von 1970 bis 2007 sowohl auf der Makro-Ebene als auch für die Sektoren Industrie, Dienstleistungen und Transport. In Übereinstimmung mit dem Großteil der Studien, die für die USA veröffentlicht wurden, finden wir Neutralität zwischen Energie und Wachstum auf der Makro-Ebene. Zudem finden wir Kausalität von Wachstum zu Energie im Dienstleistungssektor. Im Transportsektor finden wir Evidenz für bidirektionale Kausalität. Zudem können wir den Kausalzusammenhang im Industriesektor rekonstruieren wenn wir für die Auslagerung energieintensiver Produktion kontrollieren.

Vergleicht man die Evidenz für Neutralität auf der Makro-Ebene mit dem Finden von Kausalität auf sektoraler Ebene, wird ersichtlich, dass die Kausalität zwischen Energie und Wachstum nur auf sektoraler Ebene adäquat untersucht werden kann. Die Ergebnisse für die gesamte Volkswirtschaft spiegeln den tatsächlich existierenden Kausalzusammenhang hingegen nicht wider.

Im vierten Kapitel der Dissertation beschäftigen wir uns mit dem Phänomen, das wir das „Energie Paradoxon des Sektorwandels" nennen. Vor dem Hintergrund der Ergebnisse aus dem dritten Kapitel, nämlich dass man Evidenz für die Bedeutung von Energie fürs das Wirtschaftswachstum eher in energieintensiven Sektoren (Industrie, Transport) findet, stellt sich die Frage, ob Energie in der heutigen Dienstleistungsgesellschaft nur noch eine untergeordnete Rolle spielt. Die Beantwortung dieser Frage ist auch besonders vor dem Hintergrund wichtig, dass der Dienstleistungssektor derjenige Sektor mit den höchsten Wachstumsraten in den letzten Jahrzehnten war. Wenn im Dienstleistungssektore – entgegen der allgemeinen Auffassung – ein Zusammenhang zwischen Energie und Wachstum besteht, schließt sich die Frage an wie dieser Wachstumsmotor auf zukünftig steigende Energiepreise reagiert.

Sowohl in der existierenden Literatur als auch in den vorangegangen Kapiteln dieser Dissertation wurde die Bedeutung des Energiekonsums für das aggregierte Wirtschaftswachstum umfassend besprochen (Kilian, 2008; Ozturk, 2010). Im Gegenzug wurde der Auswirkung des Energiekonsums auf die Struktur einer Volkswirtschaft weniger Aufmerksamkeit zuteil. Es lässt sich beobachten, dass in allen OECD Ländern ein kontinuierlicher Wandel von der Industriegesellschaft hin zur Dienstleistungsgesellschaft stattgefunden hat, sowohl was die Wertschöpfungs- als auch die Beschäftigungsanteile anbelangt. In dieser Übergangsphase hat der Industriesektor mit seinen hohen Zugewinnen an Arbeitsproduktivität kontinuierlich an Beschäftigten verloren, die im Zuge der Expansion des Dienstleistungssektors mit seinen geringeren Zugewinnen in der Arbeitsproduktivität absorbiert worden sind. Vor diesem Hintergrund sehen sowohl Politiker als auch die Öffentlichkeit in der Dienstleistungsgesellschaft die Möglichkeit auch zukünftig hohe Wachstumsraten der Wirtschaft sowie hohe Beschäftigungszahlen zu garantieren. Wenn jedoch die Energiekosten weiterhin stark ansteigen, ist nicht gesichert, dass der Strukturwandel unverändert fortschreiten wird.

Seit Baumols (1967) zukunftsweisender Arbeit über das „Cost Disease" im Dienstleistungsgewerbe hat sich eine umfangreiche Literatur mit den Produktivitätsdifferenzialen zwischen den Sektoren als Grund für den sektoralen Wandel befasst. In diesen Veröffentlichungen wird allerdings nie ein kausaler Einfluss der Energie auf den sektoralen Wandel in Betracht gezogen (im Gegensatz zu der umgekehrten Kausalrichtung, siehe Schaefer, 2005, Huntington, 2010). In Abgrenzung zu der existierenden Literatur schreiben wir in diesem Kapitel der Energie eine zentrale Rolle in Bezug auf die Erklärung der beobachteten Produktivitätsdifferenziale zu. Damit verbunden sind ebenso Verschiebungen in der sektoralen Wertschöpfung sowie bei den Anteilen der Beschäftigten. Insbesondere heben wir die Rolle der technologischen Bedingungen der Energienutzung hervor, welche sich zwischen den Sektoren unterscheiden.

In der zweiten Hälfte des zwanzigsten Jahrhunderts ist der Energiepreis – im Vergleich zur immer teurer werdenden Arbeit – weitestgehend stagniert oder sogar gefallen. Dies hatte in allen Sektoren gleichermaßen den Anreiz zurfolge Energie für Arbeit zu substituieren. Abhängig von der jeweiligen Produktionstechnologie der Sektoren ergaben sich daraus unterschiedliche Größenordnungen der Substitution zwischen den Sektoren, und somit auch der möglichen Kostenreduktionen. Die Produktionstechnologie des Industriesektors ermöglicht eine weitreichende Substitution von Energie (zusammen mit Kapital) für Arbeit. Dies ist im Dienstleistungssektor, ausgenommen im Transportsektor, nicht der Fall. Für die Erbringung einer Dienstleistung ist deutlich weniger Energienutzung erforderlich. Demnach ist das Potenzial einer Substitution von Energie für Arbeit durch die Produktionstechnologie im Dienstleistungssektor sehr gering.

Basierend auf diesen Beobachtungen argumentieren wir, dass zwischen den Sektoren Unterschiede in der Technologie bestehen. Diese bestimmen wie — und in welchem Umfang — Energie (und Kapital) für Arbeit substituiert werden können. Diese Unterschiede sind maßgeblich dafür verantwortlich warum Sektoren mit einer hohen Energieintensität einen höheren Produktivitätsanstieg aufweisen als Sektoren mit einer geringen Energieintensität. Die Untersuchung dieser Hypothese beruht auf Daten für die USA für die Jahre 1970 bis 2005. Basierend auf dem ARDL Bounds Test von Pesaran und Shin (1999) und Pesaran et al. (2001) testen wie die beschriebene Beziehung für die drei Sektoren Industrie, Transport und Dienstleistungen, sowie für die Makro-Ebene. Die empirischen Belege zeigen, dass die stark ansteigende Nutzung günstiger Energie im „progressiven" Industriesektor indirekt zu einem Großteil des inflationären Wachstums des „stagnierenden" Dienstleistungssektors beigetragen hat, wo Energie nur eine untergeordnete Rolle spielt. Wir nennen dieses Phänomen das „Energie Paradoxon des sektoralen Wandels". Im Umkehrschluss lässt sich daraus ableiten, dass die Dienstleistungsgesellschaft, die fundamentaler Bestandteil heutiger Wachstumsstrategien ist, in Probleme geraten könnte, wenn Energiepreise weiterhin ansteigen.

Im fünften Kapitel widmen wir uns schließlich der Frage welche Auswirkungen die Abhängigkeit des Wirtschaftswachstums vom Energiekonsum für die Klimapolitik hat. Seit dem „First Assessment Report on Climate Change" des Intergovernmental Panel on Climate Change (IPCC) im Jahre 1990 gibt es einen anhaltende Debatte über die Quantifizierung zukünftiger Treibhausgase (Hoffert et al., 1998; Canadell et al., 2007; LeQuéré et al., 2009). Im wirtschaftswissenschaftlichen Umfeld wird oft die

CO_2-Intensität (das Verhältnis von CO_2-Emissionen zum Bruttonationaleinkommen) herangezogen, um den Status einer Volkswirtschaft im Prozess der Vermeidung des Klimawandels abzubilden. Eine Volkswirtschaft wird dann als entkoppelt bezeichnet, wenn sie ohne negative Auswirkungen auf die Umwelt wächst. Wie und in welchem Umfang dies möglich ist, wird kontrovers diskutiert.

Um die Determinanten der CO_2-Intensität zu erfassen, bedienen sich Analysten oft der Kaya-Identität, benannt nach dem japanischen Energieökonomen Yoichi Kaya (Raupach et al., 2007; Galiana und Green, 2009). Die Kaya-Identität setzt die CO_2-Identität in ein Verhältnis mit ihren Haupteinflussfaktoren, nämlich der Energieintensität der Produktion (Energie geteilt durch BNE) sowie die CO_2-Intensität des Energiekonsums (CO_2 geteilt durch Energie). Die Kaya-Identität diente auch als Grundlage des Special Report on Emission Scenarios (SRES) des IPCC (Nakicenovic et al., 2000).

Es wird jedoch die Befürchtung geäußert, dass der Umfang, in dem die Energieintensität zurückgegangen ist, nicht in gleichem Maße fortschreiten wird. Dies ist besonders vor dem Hintergrund kritisch, dass — global betrachtet — die CO_2-Intensität in den vergangenen vierzig Jahren allein aufgrund der Energieintensität zurückgegangen ist und — gleichzeitig — die meisten Szenarien des SRES von einen starken und fortschreitenden Rückgang der Energieintensität (>1% pro Jahr) ausgehen. Abgesehen von Energieeinsparungen aufgrund des technologischen Fortschritts wird ein erheblicher Teil des Rückgangs der Energieintensität sowohl dem sektoralen Wandel zugeschrieben als auch der Auslagerung energieintensiver Produktion in Entwicklungs- und Schwellenländer zugeschrieben. Der sektorale Wandel hat jedoch eine doppelte Wirkung: Abgesehen von einem Beitrag zu geringerer Energieintensität führt dieser auch zu einer Verzerrung nationaler Statistiken (Kander, 2005; Henriques und Kander, 2010; Gross, 2012). Alle beschriebenen Effekte führen gemeinsam dazu, dass das „wahre" enge Verhältnis zwischen Energie und Wirtschaftswachstum (Cleveland et al., 1984; Ayres und Warr, 2009) nicht aus den Daten ersichtlich ist.

Wenn Energie und Wachstum tatsächlich eng miteinander verbunden sind, kann die Energieintensität nicht beliebig zurückgefahren werden. Basierend auf einem Datensatz aus 44 Studien und 534 Kausalitätstests über das Verhältnis von Energie und BNE zeigen unsere Meta-Signifikanztests (Stanley, 2005; 2008), dass Energie und BNE tatsächlich stark voneinander abhängig sind. Zudem finden wir, dass die beschriebenen strukturellen Wandel eine maßgebliche Rolle bei der Verschleierung des „wahren" Effekts zwischen Energie und BNE spielen.

Dieses Ergebnis erlaubt es uns einige Implikationen für Emissionsszenarien basierend auf der Kaya-Identität abzuleiten, welche nicht geeignet ist, wenn es mögliche Interaktionen zwischen den (erklärenden) Variablen gibt. Wenn sich die beschriebenen strukturellen Wandel zukünftig wieder abschwächen, wird die Energieintensität voraussichtlich nicht weiterhin in demselben Maße zurückgehen wie oft angenommen wird. Es ist wahrscheinlicher, dass sie zu einem (hohen) Niveau konvergiert — wodurch auch die CO_2-Intensität in der kurzen Frist konstant konvergiert. Wenn die enge Bindung zwischen Energie und BNE fortbesteht, muss der Energieverbrauch zwangsläufig wieder steigen, um zukünftiges Wirtschaftswachstum zu ermöglichen. Daraus folgt auch, dass die CO_2-Emissionen mit ansteigen werden, bis zu dem Punkt an dem die CO_2-Intensität des Energieverbrauchs hinreichend gesenkt worden ist. Folglich verbleibt als einzige Strategie für die Vermeidung des Klimawandels eine umfangreiche Investition in die Reduktion der CO_2-Intensität des Energieverbrauchs, und zwar weitestgehend unabhängig von der weiteren Entwicklung der Energieintensität.

Contents

Acknowledgements

This dissertation is dedicated to those who accompanied me over the last years. I am indebted to my supervisor Ulrich Witt who promoted my research project throughout the time when I had the privilege of being part of the Evolutionary Economics Group at the Max Planck Institute of Economics. I share the credit of my work with my co-authors Stephan B. Bruns and David I. Stern. Without their passionate dedication this work would not have been possible. I very much enjoyed both the mental and professional support of my colleagues. These include Chad Baum, Christina Günther, Wolfhard Kaus, Leonhard K. Lades, and Benjamin Volland. Special thanks go to Alessio Moneta who contributed to my work with his exceptional methodological expertise. I owe my deepest gratitude to Inken Poßner, Karin Serfling, and Ramona Taubert who always cared for making my work easier. I also want to thank Ariane Bretschneider, Maria Hennicke, Clemens Klix, Susanne Kochs, Natalija Kovalenko, Katja Mehlis, Stefanie Picard, Annemarie Strehl, and Silvia Volkmann for their research assistance for Chapters 2 and 5. I am grateful to the Max Planck Society for financing my studies. Finally, I thank my family, my friend, and my friends for giving me their love and the strength to come through this journey.

1

Introduction

The role that energy plays in economic growth is back on the agenda. After the oil price shock of the 1970s, the topic had already attracted much attention. Two new developments have revived this interest. First, since the turn of the millennium, energy prices have begun a secular rise again. A growing energy demand of the newly industrializing countries over-compensates for ongoing energy efficiency gains in the industrialized world. At the same time, it is generally assumed that oil extraction has reached its maximum, nourishing concerns about the depletion of world oil resources (Hubbert, 1949; Campbell and Laherrère, 1998; Campbell and Heapes, 2008). Second, there is a growing awareness of the environmental threats implied by increasing fossil energy consumption and its effect on the CO_2 concentration in the atmosphere (Stern, 2008).

How do economists respond to this development? There are rather optimistic assessments of the future challenges arguing that economic activity can be decoupled from energy input on the one hand and from the output of carbon emissions on the other. This, at least, is an implication which can be drawn from the majority of economic growth models which consider the role of resources (for a recent overview see Stern, 2011). To give an example, Solow (1974) shows that sustainability is achievable in a model with a nonrenewable natural resource with no extraction costs and nondepreciating capital when the elasticity of substitution between the two inputs is unity, and when certain other technical conditions are met. More recent models (Dasgupta and Heal, 1979; Hartwick, 1977; Dixit et al., 1980), too, have in common that depleted resources can be replaced by more abundant substitutes, or by forms of human-made capital. A central problem of these models, however, is the underlying a priori assumption that the substitution is technologically feasible (Stern, 2011). However, the development of the technology, on which the substitutability assumption relies, is not described in the growth model.

Beginning with Stiglitz (1974), another body of literature analyzes the role of nonrenewable resources, together with capital, in an endogenous growth framework (see also Aghion and Howitt, 1998; Barbier, 1999; Scholz and Ziemes, 1999; Groth and Schou, 2002; Di Maria and Valente, 2008 for recent contributions). This literature investigates whether, and under what circumstances, technical progress is effective in ensuring sustained consumption (Bretschger, 2005). A general finding is that the rate of resource augmenting progress must be strictly positive and at least equal to the discount rate to obtain nondeclining consumption in the long run. Due to externalities in knowledge production, there may be too little innovation in an endogenous growth world (Stern, 2011). It must, however, be noted that models which incorporate the role of resources, including energy, in the growth process remain isolated in the resource economics field. The vast majority of economic growth models have tended to downplay the importance of energy in economic growth. The principal models used to explain the growth process (e.g., Aghion and Howitt, 2009) do not include energy as a factor of production. This omission is probably because energy has been abundant in recent decades and its cost share is low, so that the constraints imposed by energy availability on economic growth are weaker than they were in the past and it can implicitly be assumed that energy supply increases in the long-run as needed (Buenstorf, 2004; Kander and Stern, 2012).

Unlike the neoclassical approach to economics, many energy and ecological economists (e.g., Cleveland et al., 1984; Ayres and Warr, 2005, 2009; Hall et al., 2003) argue that a growing supply of energy plays a crucial role in economic growth. Ecological economists derive their view of the role of energy in economic growth from the biophysical foundations of the economy. In this context, the term "biophysical" mainly refers to the laws of thermodynamics, which is applied to economic production. The mass-balance principle means that, in order to obtain a given material output, greater or equal quantities of matter must be used as inputs with the residual a pollutant or waste product (Ayres and Kneese, 1969). Therefore, there are minimal material input requirements for any production process producing material outputs. The second law of thermodynamics (the efficiency law) implies that a minimum quantity of energy is required to carry out the transformation or movement of matter or, more generally, perform physical work. Carrying out transformations in finite time requires more energy than these minima (Baumgärtner, 2004). Since all production involves work, all economic activities must require energy. Accordingly, there must be limits to the substitution of other factors of production for energy so that energy is always an essential factor of production. As a consequence, substitution between capital and resources and technological progress can only play limited roles in mitigating the scarcity of resources (Stern, 1997). In other words, the biophysical approach to economic growth theory, in contrast to the neoclassical approach, is based on the assumption that the supply or consumption of energy is strongly coupled with economic growth. The amount of energy cannot arbitrarily be reduced in the production of a given amount of output, because the decline in energy intensity is limited by the laws of thermodynamics.

In one of the most comprehensive theoretical works on the role of energy in the economy, Ayres and Warr (2009) argue that cheaper resource inputs, due to discoveries, economies of scale and experience (or learning-by-doing) enable tangible goods and intangible services to be produced and delivered at ever lower cost. This is another way of saying that resource flows are productive. Both lower costs and competitive markets lead to lower prices for all products and services. If the price elasticity is non-zero, lower prices encourage higher demand. Since demand for final goods and services necessarily corresponds to the sum of factor payments, most of which go back to labor as wages and salaries, it follows that wages of labor tend to increase as output rises. This, in turn, stimulates the further substitution of natural resources, especially fossil fuels, and mechanical power produced from resource inputs, for human (and animal) labor. This continuing substitution drives further increases in scale, experience, learning and still lower costs. Hence, a growing economy will also use ever more energy over time. Kander and Stern (2012) find that the expansion of energy services is a major factor in explaining the industrial evolution and economic growth in Sweden, especially before the second half of the 20th century. At the same time, their finding calls into question whether the importance of energy for economic growth can only be observed in energy intensive production processes.

Today we know that the potential to reduce energy intensity is below expectations (Baksi and Green, 2007). It is often argued that, for example, a good part of the decoupling has been achieved through the transition of developed economies toward the "service economy". It is based on the assumption that, after the transition, the demand for energy is lower because the consumption of energy per unit of output is, on average, comparatively lower in the services than in the industry sector (e.g. Kahn, 1979; Panayotou, 1993; Panayotou et al., 2000; Smil, 2000; Schäfer, 2005). In this context the question should be addressed whether the transition to the service economy can be considered a way to persistently escape from the coupling between energy and gross domestic product (GDP). Further reductions in energy intensity, apart from real reductions due to energy-saving technological progress, can be attributed to the increasing offshoring of industrial production. However, these reductions are only of a statistical nature since the energy intensity of end-use products has remained almost unchanged.

The common thread of this dissertation is both to critically reflect upon existing considerations how the decoupling can be achieved, as well as to empirically analyze the true potential to do so. In order to be able answer this question, however, we have to take a step back and analyze whether there is evidence for interdependence between energy consumption and GDP. If there is systematic evidence for such a coupling, the possibility to break up the coupling would considerably be limited. If, as a consequence, energy cannot arbitrarily be saved without harming economic growth, the decarbonization of energy use becomes the only instrument to mitigate climate change.

The most systematic way of collecting and analyzing the scientific knowledge about the relationship between energy and GDP is to conduct a meta-regression analysis of the relevant literature. This analysis is done in Chapter 2 by using meta-regression techniques. In an explanatory meta-regression analysis of a small sample of studies, Chen et al. (2012) relate only the likelihood of finding a certain causality outcome to a number of study-specific characteristics. However, the more urgent question is to what extent the entire literature provides evidence for a true empirical effect, namely that energy and GDP are closely related. To test for the existence of a true effect, we use meta-significance testing (MST) as proposed by Stanley (2005; 2008). Since the underlying studies test for causality under various circumstances, we analyze the impact of the main driving factors of the ambiguous results, as discussed in the literature, on the finding of the true effect. Specifically, we assess the impact of the (sectoral) level of aggregation of output, the choice of the energy variable, the development stage of the countries, the choice of control variables as well as the choice of the econometric methodology (Payne, 2010). Our study is based on 1020 causality tests between energy consumption and GDP from a total of 75 studies and 108 countries.

Our results confirm the impact of the level of (sectoral) aggregation of output, the choice of control variables as well as the development stage. With regard to the level of sectoral aggregation, we confirm that results from causality tests may be spurious if the level of aggregation is not appropriate, in the sense that the scope of economic activity differs among the explaining variables (Zachariadis, 2007; Gross, 2012). In addition, the inclusion of control variables may affect the causality between energy and GDP if they are highly correlated with (one of) the explaining variables. The development stage of the economy has an effect insofar as in High income countries the evidence for causality has been significantly more confounded compared to Low income countries. Contrary to frequent conjectures expressed in the literature, the choice of the methodology alone does not affect the finding of causality. We argue that the reasons for this can rather be found in contextual aspects of the studies. Moreover, we find that the differentiation between total energy and single energy sources does not have an effect in High income countries. This, in our view, may lead to problematic policy implications if the relationship between energy and GDP is traced back to a single energy source, although it is highly correlated with total energy consumption.

Apart from this, an even more important influencing factor, which has not been sufficiently discussed in the literature yet, is the effect of time. To be precise, it is the effect of associated radical changes which have increasingly confounded the relationship between energy and GDP. In the context of the underlying literature, structural changes such as sectoral shifts as well as an offshoring of industrial production, in addition to higher technical energy efficiency due to technological change, are assumed to distort the finding of causality (Gross, 2012). Hence, we suggest that a new path needs to be taken in analyzing the relationship between energy and GDP. Instead of mainly describing the nonmonotonic relationship between energy and GDP by means of new econometric techniques, the relationship can be adequately assessed only by disentangling the dynamics underlying the relationship between energy and GDP.

In Chapter 3 we further discuss the major determinants of the relationship between energy and GDP. We argue that the identification of a causal relationship is mainly driven by the level of aggregation. Recent studies (e.g. Zachariadis, 2007; Bowden and Payne, 2009) investigate the causality between energy consumption and economic growth both on the macro as well as on the sector level. While the relationship between energy and growth seems to be neutral on the macro level, both studies find evidence for Granger causality for a lower level of aggregation in some cases. In statistical analyses it is not uncommon that evidence can be found for a lower level aggregation, although the results for the total population suggests the opposite. This phenomenon has been named 'Simpson's Paradox' after E. Simpson (1951).[1] However, if the results for Granger causality tests are found to be dependent on the level of aggregation and not on the variables, it is necessary to analyze the causal relationship at the correct level of aggregation. Otherwise, the results are spurious and policy advice should be given with caution. The paradox becomes even more

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[1] "[...] situations in which statistical dependencies that are consistent in subpopulations disappear or are reversed in whole populations [...]" (see Hoover, 2008, p. 19).

severe if the pairs of variables for Granger causality analyses are not matching. For this reason, we will extend Zachariadis' notion of appropriate pairs for causality analyses.

The fact that sectors differ with respect to their relationship between energy and growth, is well known in the Environmental Kuznets Curve (EKC) literature: changes of the industry composition have a changing impact on the energy demands of the economy over time. In the early phases of modern economic growth, when a country industrializes, structural change is believed to increase these demands. Later on when the country enters the post-industrial phase, or the service economy, the energy demands are believed to decline (e.g. Kahn, 1979; Panayotou, 1993; Panayotou et al., 2000; Smil, 2000; Schäfer, 2005).[2] The resulting divergence between energy and economic growth is also a challenge for Granger causality analyses. In order to account for the decreasing energy intensity in a Granger causality framework, we suggest to include major findings from the EKC literature: one major finding is the role of the increasing energy productivity of production, which leads to the divergence between energy and growth. Another main finding is the role of trade, especially for goods producing industries, where energy intensive production is being offshored according to the Pollution Haven Hypothesis (PHH).

For our analysis we use the recently developed autoregressive distributed lag (ARDL) bounds testing approach as proposed by Pesaran and Shin (1999) and Pesaran et al. (2001). We analyze the evidence for long-run as well as short-run Granger causality between final energy consumption and GDP for the U.S. from 1970 to 2007 at the macro level as well as for the industry sector, the commercial sector, and the transport sector. After identifying appropriate pairs of variables for the Granger causality test, we test bivariate as well as multivariate specifications of the model in order to avoid omitted variable bias. The choice of additional control variables is based on major findings of the EKC literature as well as its limitations discussed in the literature.

In line with the majority of studies for the U.S., we find neutrality between energy and growth at the macro level. In addition, we find evidence for unidirectional long-run Granger causality in the commercial sector from growth to energy. We also find evidence for bi-directional Granger causality in the transport sector. Adding or removing additional control variables is found to create or break long-run causality.

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[2] Henriques and Kander (2010) emphasize the need to account for sector specific price deflators. Otherwise, the impact of the energy efficient commercial sector on overall energy intensity would be overestimated according to 'Baumol's cost disease' (Baumol, 1967).

This finding is important especially in the transport sector, where controlling for the increasing energy productivity of production neutralizes the long-run relationship when growth is the dependent variable. For the industry sector we find that controlling for trade is important for identifying short-run Granger causality when growth is the dependent variable. We conclude that some of the divergence across sectors can be explained by the fundamental differences between goods and service producing industries. In various specifications energy productivity is found to Granger cause growth as well as energy. The latter is interpreted as evidence for 'Jevon's Paradox'.[3] We find only weak evidence for the impact of energy prices on energy consumption for the transport sector. Given the evidence of long-run Granger causality on the sector level, compared to a neutral relationship on the macro level, we conclude that the Granger causality between energy and growth should only be analyzed on the sector level. Otherwise, results for the total economy are spurious.

In Chapter 4 we focus on what we dub the "energy paradox of sectoral change". In the light of the evidence we show in the previous chapter, namely that energy plays a core role for the growth of energy intensive sectors, the question arises whether energy is less important in the service sector, the major growth engine of the last decades. If there is a connection between energy and GDP, how will the economy adjust to less cheap energy in the near future? With respect to aggregate economic growth, the importance of energy use has been extensively discussed, yielding rather controversial results (for recent summaries see, e.g., Kilian, 2008; Payne, 2010). However, these studies neglect the structural effects through which changing energy use affects aggregate economic performance (Gross, 2012). In the past decades, economic growth in all OECD economies has been accompanied by an expansion of value added and employment in the service sector relative to the industrial sector (Schettkat, 2007) — a phenomenon often being dubbed the rise of a "service economy". In this process, the service sector has absorbed labor that was laid off in the industrial sector with its much higher labor productivity growth rates. Policy makers and the public therefore often trust that the "service economy" has the potential to align economic growth with high employment rates also in the future. It is not clear, though, whether the patterns of structural change will be the same in the future if energy costs continue to strongly increase and, accordingly, what the future growth prospects of the "service economy" will be.

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[3] Jevons (1864) maintained that technological efficiency gains — specifically the more "economical" use of coal in engines doing mechanical work — actually increased the overall consumption of coal, iron, and other resources, rather than "saving" them, as many claimed. Twentieth-century economic growth theory also sees technological change as the main cause of increased production and consumption ('rebound effect'; see also Alcott, 2005).

Since Baumol's (1967) seminal paper on "cost disease" in the service sector, a huge body of literature has focused on the role that productivity differentials between sectors play for economic growth (see Nordhaus, 2008 for a recent summary). However, these studies have hardly ever considered the influence of changing energy costs on the productivity differentials (for an exception see Kander, 2005). In the present paper we will therefore explore the role of energy for explaining the shifts between the value added and employment shares of the respective sectors. More specifically, we want to highlight the role of the technological conditions of energy use that differ between the sectors. As will be shown, these differences prove to be crucial to understanding how a changing gross energy price (including tax) affects sectoral productivity growth and drives the ascendancy of the "service economy".

Over much of the second half of the 20th century, the price of energy stagnated, or even fell, relative to the ever increasing price of labor. The falling relative price of energy created incentives to substitute energy for labor in all sectors. Yet, for reasons of their specific technologies, the sectors differ with respect to the extent of substitution and, hence, possible cost savings. In the industrial sector, the production technology allows for a large-scale substitution of both energy and capital for labor. This is not the case in the service sector, with the exception of transport. (When the service sector is divided up into "transport services" and "commercial services" as the remainder, the technology of the transport sector turns out to be characterized by an energy-labor ratio that is even higher than that of the industry sector.) In order to provide commercial services, little energy is needed. Hence, the potential range for substituting energy for labor is severely technologically constrained in that sector.

Based on these observations, we argue that there are technological differences between the sectors in how, and to what extent, energy (plus capital) can be substituted for labor. These differences are a major reason for why productivity increases are significantly higher, in real terms, in sectors with a high energy intensity of production than in those with a low energy intensity. To evaluate this hypothesis empirically, we use U.S. data for the period from 1970 to 2005. By means of the ARDL bounds test developed by Pesaran and Shin (1999) and Pesaran et al. (2001), we test the relationship for the three sectors industry, transport, and commerce, as well as for the macro level. The evidence we find suggests that the soaring use of cheap energy in the "progressive" industry sector has indirectly fueled much of the inflationary development of the "stagnant" commercial service sector in which energy is of only minor quantitative importance. We dub this phenomenon the "energy paradox of sectoral change". By reverse inference, the energy paradox seems to suggest that the "service economy" may not fulfill existing political expectations regarding the attainment of both high economic growth and employment rates, if gross energy prices continue to rise substantially in the future.

Given that energy and GDP are strongly interdependent, what are the implications for climate policy? We address this question in Chapter 5. Ever since the First Assessment Report on Climate Change by the Intergovernmental Panel on Climate Change (IPCC) in 1990, there has been an ongoing debate on the quantification of future greenhouse gas emission (e.g. Hoffert et al., 1998; Canadell et al., 2007; Le Quéré et al., 2009). In the economic field, the carbon intensity, i.e. the ratio between carbon emissions and economic production (GDP), is often used to assess the state of an economy in climate change mitigation. An economy that is able to sustain GDP growth without having a negative impact on environmental conditions, is said to be decoupled. Exactly how, if, or to what extent this can be achieved is a subject of much debate.

To assess the determinants of carbon intensity analysts often use the Kaya identity, which was proposed by the Japanese energy economist Yoichi Kaya (see e.g. Raupach et al., 2007; Galiana and Green, 2009). The Kaya identity relates the carbon intensity to its main driving factors: the energy intensity of production (Energy/GDP), as well as the carbon intensity of energy (CO_2/Energy). It plays a core role e.g. in the IPCC Special Report on Emissions Scenarios (SRES, see Nakicenovic et al., 2000).

In achieving today's lower carbon intensity, however, some argue that the extent to which its main driver, the energy intensity, has declined will not proceed. Still, most SRES scenarios rely on a rapid and ongoing decline in energy intensity (exceeding 1.0% per year). Apart from energy savings due to technological progress, a significant part of the decline can be attributed to structural changes such as sectoral shifts, as well as offshoring of industrial production. However, the effect of the described structural changes on the relation between energy and GDP is twofold. Apart from contributing to lower energy intensity, these factors have also biased national statistics (Kander, 2005; Henriques and Kander, 2010; Gross, 2012). All of these effects tend to hide the true relationship, namely that energy and GDP are closely related (Cleveland et al., 1984).

If, in fact, energy and GDP go hand in hand, the energy intensity cannot be arbitrarily reduced. Using meta-significance testing (Stanley, 2005; 2008) for a sample of 44 studies and 534 causality tests, which deal with the causality between energy and GDP, we find that energy and GDP are strongly coupled. In addition, we find support for our reasoning that the described structural changes play a major role in hiding the true relationship.

This finding has some strong implications for emission scenarios based on the Kaya identity, since it does not account for possible interactions among the (explaining) variables. When the described structural changes come to a halt, the decline in energy intensity cannot pass on unchanged. It is more likely that it will converge to a (high) level, as will the carbon intensity in the short term. If the coupling between energy to growth persists, the consumption of energy must further increase to enable economic growth in the future. As a consequence, carbon emissions will catch up unless the carbon intensity of energy has been reduced sufficiently. Similarly, the only strategy to reach our climate targets in the long run is to invest in the decarbonization of energy use today, widely irrespective of the development of energy intensity.

In Chapter 6 we summarize the main conclusions which can be derived from this dissertation. At the basis of all findings, we infer that energy, indeed, plays a significant role in the economy. Calculations of future energy demands need to take into account that the potential to decouple economic growth from the consumption of energy is limited. Since there are many indications that energy and GDP are causally interlinked, an underprovision of energy supply would entail the risk of lower economic growth. Since we show that even the growth of the less energy consuming service sector indirectly depends on energy via an energy-related "cost disease", strategies which were intended to reduce the consumption of energy widely failed to break the relationship between energy and GDP. In this respect, rising energy costs may also cause serious problems for the service economy, still the major driver of economy-wide growth.

Hence, we should take into account that economic growth rates may be considerably lower in the near future if the rise in energy prices persists. In such a case, we might soon be confronted with the choice of two fundamentally different strategies. First, it has been suggested to return to cheap but high-emitting fossil fuels. This would keep the average price of energy low and enable persistent economic growth in a low energy price regime. However, if new technologies which aim at neutralizing the resulting emissions — such as Carbon Dioxide Capture and Storage — do not become operational, the carbon intensity of energy would again strongly increase. Our finding that the decline in carbon intensity has been driven almost exclusively by the decline in energy intensity reiterates the danger of a return to high-emitting fossil fuels. In this respect, a weakness of those economic growth models becomes apparent, which sensitively rely on high levels of (unexplained) technological progress or widely ignore the importance of energy for economic growth or the environmental impact related to the emission of greenhouse gases.

Since leading climate researchers argue that an increase of the average world temperature of more than two degrees may entail unforeseeable climatic disasters, the focus of any energy policy needs to be concentrated on an alternative strategy, namely the decarbonization of energy use. In this respect, a milestone will be the development of an economic growth theory which resolves the apparent conflict of objectives between high rates of economic growth on the one hand and increasing pollution on the other.

2

Reconsidering the Relationship Between Energy and GDP: Meta-Regression Results

2.1 Introduction

Although renowned theorists such as Cleveland et al. (1984) and Ayres and Warr (2009) argue that energy consumption and GDP are closely related, there is no overwhelming support from the empirical side — even after more than thirty years of research (Ozturk, 2010; Payne, 2010). Motivated by the oil crisis in the late 1970s, Kraft and Kraft (1978) analyze the causality between energy consumption and GDP using the concept of Granger causality. Ever since, the focus on the empirical side has rather been on adapting more advanced econometric techniques than on investigating the dynamics underlying the relationship between energy and GDP (Karanfil, 2009).

In order to shed light on the ambiguous findings, we analyze the relevant literature by means of meta-regression techniques. In an explanatory meta-regression analysis of a small sample of studies, Chen et al. (2012) relate only the likelihood of finding a certain causality outcome to a number of study-specific characteristics. However, the more urgent question is to what extent the entire literature provides evidence for a true empirical effect, namely that energy and GDP are closely related. To test for the existence of a true effect, we use meta-significance testing (MST) as proposed by Stanley (2005; 2008). Since the underlying studies test for causality under various circumstances, we analyze the impact of the main driving factors of the ambiguous results, as discussed in the literature, on the finding of the true effect. Specifically, we assess the impact of the (sectoral) level of aggregation of output, the choice of the energy variable, the development stage of the countries, the choice of control variables as well as the choice of the econometric methodology (Payne, 2010). Our study is based on 1020 causality tests between energy consumption and GDP from a total of 75 studies and 108 countries.

Our results confirm the impact of the level of (sectoral) aggregation of output, the choice of control variables as well as the development stage. With regard to the level of sectoral aggregation, we confirm that results from causality tests may be spurious if the level of aggregation is not appropriate, in the sense that the scope of economic activity differs among the explaining variables (Zachariadis, 2007; Gross, 2012). In addition, the inclusion of control variables may affect the causality between energy and GDP if they are highly correlated with (one of) the explaining variables. The development stage of the economy has an effect insofar as in High income countries the evidence for causality has been significantly more confounded compared to Low income countries. Contrary to frequent conjectures expressed in the literature, the choice of the methodology alone does not affect the finding of causality. We argue that the reasons for this can rather be found in contextual aspects of the studies. Moreover, we find that the differentiation between total energy and single energy sources does not have an effect in High income countries. This, in our view, may lead to problematic policy implications if the relationship between energy and GDP is traced back to a single energy source, although it is highly correlated with total energy consumption.

Apart from this, an even more important influencing factor, which has not been sufficiently discussed in the literature yet, is the effect of time. To be precise, it is the effect of associated radical changes which have increasingly confounded the relationship between energy and GDP. In the context of the underlying literature, structural changes such as sectoral shifts as well as an offshoring of industrial production, in addition to higher technical energy efficiency due to technological change, are assumed to distort the finding of causality (Gross, 2012). Hence, we suggest that a new path needs to be taken in analyzing the relationship between energy and GDP. Instead of mainly describing the nonmonotonic relationship between energy and GDP by means of new econometric techniques, the relationship can be adequately assessed only by disentangling the dynamics underlying the relationship between energy and GDP.

In Section 2.2 we reconsider the relationship between energy and GDP from an empirical perspective. Section 2.3 discusses the choice of studies as well as the estimation strategy. The results are presented and discussed in Section 2.4. Section 2.5 concludes.

2.2 The Relationship between Energy and GDP from an Empirical Perspective

Out of all causality tests running from energy to GDP, 36% of the tests included in our data set show evidence for causality (at the 10% level of significance), whereas 39% of the tests running from GDP to energy show evidence in the other direction. All remaining causality tests indicate that there is no relationship in the respective direction of causality. Reasons for the inconclusive evidence have recently been discussed (e.g., Ozturk, 2010; Payne, 2010). In this study, we test the validity of the main driving factors of the results, which have been discussed in the underlying literature, namely the (sectoral) level of aggregation of output, the choice of the energy variable, the development stage of the countries, the choice of control variables as well as the choice of the econometric methodology.

Deviating from the greater part of studies, some do not analyze the relationship between energy and GDP at the macro level. However, instead of appropriately analyzing the relationship between sectoral energy and sectoral GDP, the sectoral classification of the energy variable does not match the sectoral classification of the output variable in some cases. As a consequence, the results may be spurious when the main variables do not cover the same scope of economic activity (Zachariadis, 2007; Gross, 2012).

With regard to the choice of the energy variable, the results are potentially distorted whenever an energy variable other than total energy consumption is used for the causality test. Examples of this are: coal, electricity, natural gas, non-renewable energy, nuclear energy, oil, petrol, petroleum products as well as renewable energy sources. Similar to a corresponding sectoral level of energy and GDP, an energy variable other than total energy consumption may not cover the same scope of economic activity as GDP (Gross, 2012). Hence, the results may be spurious, too.

With regard to the development stage of the economy, it is important to note that causality tests between energy and GDP have been conducted for almost all countries in the world. Ozturk (2010), among others, argues that the ambiguous findings emerge from country-specific characteristics. To give an example, De Janosi and Grayson (1992) argue that energy consumption in developing countries is more responsive to economic growth than in developed countries.

Apart from bivariate analyses, a group of studies investigates the relationship between energy and GDP in a multivariate framework. Frequently used control variables are: employment, real fixed capital, gross fixed capital formation, energy price as well as carbon emissions. From an empirical point of view, the major difference between the variables is the extent to which the control variables correlate with the explaining variable. If, namely, a control variable is highly collinear with the explaining variable, the inclusion of a control variable may absord the significance of the explanatory variable.

With regard to the econometric methodology, a distinction should be made between standard causality tests according to Granger (1969) and those tests which account for cointegration among the variables. The concept of Granger causality allows an analysis of whether or not lagged values of the independent variable predict current values of the dependent variable. Another variant also includes future values in the estimation (Sims, 1972). For the standard Granger test all variables included in the test regression are assumed to have the same lag length. However, a problem arises if the outcome of the causality test is sensitive with respect to the lag length. This is considered by another variant of the basic Granger test (Hsiao, 1979). A further development of the basic Granger test is independent of the order of integration (Toda and Yamamoto, 1995).

The basic Granger test should be distinguished from the concept of cointegration. It allows the determination of a long-run relationship between the variables in an error correction model (ECM). Hereby, an error correction term (ECT) measures the deviation from the long-run relationship of the previous period. If the ECT is found to be significant, the dependent variable adjusts to shocks of other variables from the previous period. Accordingly, the explaining variables are interpreted as causing the dependent variable. Within the ECM, the lagged values of the independent variables can be used to test for causality according to the Granger test. In addition, the effect of both the lagged values of the independent variable and the ECT can be tested simultaneously. The, so-called, joint causality test allows combining the interpretation of long-run causality related to the ECT as well as the interpretation of short-run causality related to the standard Granger test. Frequently used models to test for cointegration are the tests developed by Engle and Granger (1987), Johansen (1988; 1991), and Pesaran et al. (2001).

Another point raised in the literature is the dependence of the relationship on the time period chosen for the causality test (e.g., Karanfil, 2009). A prominent example is the study by Akarca and Long (1980). By extending the time period of the original study by Kraft and Kraft (1978) by two years, they show that the former results are no longer valid. Other studies vary the time period within the same study and find that, in some cases, the results differ (e.g., Abosedra and Baghestani, 1991).

2.3 Empirical Analysis

2.3.1 Choice of Studies

For the analysis of meta-significance between energy and GDP we consider those studies which investigate the causality between an energy variable and an output variable (Table 2.1). Possible specifications of the energy variable are: total energy consumption, coal, electricity, natural gas, non-renewable energy, nuclear energy, oil, petrol, petroleum products as well as renewable energy sources. Possible specifications of the energy variable are GDP, GNP as well as value added from the different sectors of the economy. The variables are either related to the macroeconomic level or to single sectors of the economy such as commercial, services, transportation, industry, residential and agriculture.

Most of the studies are recorded in two recently published surveys (Ozturk, 2010; Payne, 2010). Nevertheless, we searched Scopus, EconLit, and Google Scholar for combinations of the keywords "Energy," "Electricity," "Coal," "Gas," "Oil," "Nuclear," "GDP," "Growth," "Income," "Output," "Economy," "Causality," "Cointegration," and "Relation" in order to avoid the problem of selection bias. We also include unpublished studies in order to increase the robustness of the analysis. However, we do not expect publication selection bias to be present in the underlying literature. Since no evidence for causality between energy and GDP ist also considered a relevant finding ('neutrality'), those studies with insignificant results have not systematically been excluded from publication, even in refereed journals such as Energy Economics, Energy Policy, and Applied Energy.

With regard to the estimation techniques used in the relevant literature, we include the methods developed by Granger (1969), Sims (1972), Hsiao (1979), Engle and Granger (1987), Johansen (1988; 1991), and Toda and Yamamoto (1995), which are applied to time series data. Other methods such as 'instantaneous' Granger causality and the Autoregressive distributed lags (ARDL) bounds test developed by Pesaran and Shin (1999) and Pesaran et al. (2001) deviate from the these methods by allowing also for a contemporaneous relationship among the variables. Therefore, these methodologies should be regarded separately from the standard approaches where only lagged values of the explanatory variables are considered. Moreover, we exclude studies with unique methodologies such as nonparametric approaches (e.g., Azomahou et al., 2006) and threshold cointegration (e.g., Esso, 2010). The majority of studies use annual data. Hence, we exclude studies with quarterly as well as monthly data. Both nonstandard methodologies as well as in-year data are excluded

Table 2.1 — Studies included in the meta-analysis

Paper	Country	Energy variable		Income	Control	Method
		Level	Aggregation	aggregation	variables	
Abosedra and Baghestani (1991)	USA	M	TOT	M	—	G
Acaravici (2010)	TUR	M	EL	M	—	J
Adom (2011)	GHA	M	EL	M	—	TY
Akinlo (2008)	11 Sub-Sahara African countries	M	TOT	M	Energy pr.; government exp.	G
Akinlo (2009)	NGA	M	EL	M	—	J
Alam et al. (2011)	IND	M	TOT	M	Empl.; capital; energy pr.; CO2	TY
Altinay and Karagol (2005)	TUR	M	EL	M	—	G
Ang (2008)	MYS	M	TOT	M	CO2	J
Belloumi (2009)	TUN	M	TOT	M	—	J
Boehm (2008)	15 EU countries	M	EL	M	—	G; J
Bowden and Payne (2009)	USA	M; C; I; R; T	TOT	M	Empl.; capital	TY
Chang and Soruco Carballo (2011)	BRA; JAM; PER; URY	M	TOT	M	—	G
Chebbi (2009)	TUN	M	TOT	M	CO2	J
Chiou-Wei et al. (2008)	8 Asian countries; USA	M	TOT	M	—	J
Chontanawat et al. (2008)	>100 countries	M	TOT	M	—	H
Ciarreta et al. (2009)	PRT	M	EL	M	Energy pr.	TY
Erol and Yu (1987)	CAN; FRA; ITA; JPN; GBR; DEU	M	TOT	M	—	G
Esso (2010)	CMR; COG; CIV; GHA; KEN; ZAF	M	TOT	M	—	TY
Fallahi (2011)	USA	M	TOT	M	—	G
Ghosh (2002)	IND	M	EL	M	—	G
Glasure and Lee (1997)	SGP; KOR	M	TOT	M	—	G; EG
Glasure (2002)	KOR	M	TOT	M	Energy pr.; gov. exp.; money	J
Golam Ahamad and Nazrul Islam (2011)	BGD	M	EL	M	—	J
Hondroyiannis et al. (2002)	GRC	M; I; R	TOT	M	Energy pr.	J
Jamil and Ahmad (2010)	PAK	M; A; I; R; S	EL	M; A; I; R; S	Energy pr.	J
Jamil and Ahmad (2011)	POK	M; R	EL	M; R	Capital; Energy pr.; degree days	J

Note: M: Macro; C: Commercial sector; T: Transport sector; I: Industry sector; R: Residential sector; S: Service sector; A: Agricultural sector
TOT: Total energy; EL: Electricity; CO: Coal; O: Oil; NG: Natural Gas; F: Fuels; P: Petrol; RE: Renewables; N: Nuclear
G: Granger; S: Sims; EG: Engle-Granger; TY: Toda-Yamamoto; J: Johansen-Juselius; H: Hsiao

[1] quality adjusted energy

Table 2.1 — Studies included in the meta-analysis (continued)

Paper	Country	Energy variable		Income	Control	Method
		Level	Aggregation	aggregation	variables	
Jobert and Karanfil (2007)	TUR	M	TOT	M	—	G
Jumbe (2004)	MWI	M	EL	M	—	EG; G
Kaplan et al. (2011)	TUR	M	TOT	M	Empl.; capital; energy pr.	J
Karanfil (2008)	TUR	M	TOT	M	—	J
Lee (2006)	G-11 countries	M	TOT	M	—	
Lorde et al. (2010)	BRB	M; Non-R	EL	R	Empl.; capital; technology	J
Lotfalipour et al. (2010)	IRN	M	TOT; O; NG	M	CO2	TY
Masih and Masih (1996)	IND; PAK; MYS; SGP; PHL	M	TOT	M	—	J
Masih and Masih (1998)	THA; LKA	M	TOT	M	Energy pr.	J
Mehrara (2007)	IRN; KWT; SAU	M	TOT	M	—	TY
Menyah and Wolde-Rufael (2010a)	USA	M	N; RE	M	CO2	TY
Menyah and Wolde-Rufael (2010b)	ZAF	M	TOT	M	Capital; CO2	TY
Mozumder and Marathe (2007)	BGD	M	EL	M	—	J
Oh and Lee (2004)	KOR	M	TOT^1	M	Empl.; capital	J
Pao and Tsai (2011)	RUS	M	TOT	M	CO2	J
Paul and Bhattacharya (2004)	IND	M	TOT	M	Capital; empl.	EG; H; J
Paul and Uddin (2010)	BGD	M	TOT	M	—	G
Payne (2009)	USA	M	RE; Non-RE	M	Empl.; capital	TY
Payne (2010)	USA	M	N	M	Empl.; capital	TY
Pradhan (2010)	BGD; IND; NPL; PAK; LKA	M	EL; O	M	—	J
Rafiq and Salim (2011)	IND; MYS; THA; CHN	M	TOT	M	Energy pr.	J
Sa'ad (2010)	NGA	M	TOT	M	—	J
Salim et al. (2008)	IND; CHN	M	TOT	M	Energy pr.	J
Sari and Soytas (2009)	DZA; IND; NGA; SAU; VEN	M	TOT	M	Employm.; CO2	TY
Shiu and Lam (2004)	CHN	M	EL	M	—	J
Soytas et al. (2001)	TUR	M	TOT	M	—	
Soytas et al. (2007)	USA	M	TOT	M	Empl.; capital; CO2	TY
Soytas and Sari (2009)	TUR	M	TOT	M	Empl.; capital; CO2	TY

Note: M: Macro; C: Commercial sector; T: Transport sector; I: Industry sector; R: Residential sector; S: Service sector; A: Agricultural sector
TOT: Total energy; EL: Electricity; CO: Coal; O: Oil; NG: Natural Gas; F: Fuels; P: Petrol; RE: Renewables; N: Nuclear
G: Granger; S: Sims; EG: Engle-Granger; TY: Toda-Yamamoto; J: Johansen-Juselius; H: Hsiao
[1] quality adjusted energy

Table 2.1 — Studies included in the meta-analysis (continued)

Paper	Country	Energy variable		Income aggregation	Control variables	Method
		Level	Aggregation			
Türkekul and Unakltan (2011)	TUR	A	EL	A	Energy pr.	TY
Vaona (2011)	ITA	M	RE; Non-RE	M	—	TY
Vecchione (2011)	ITA	M	EL	M	Degree days	J
Vlahinic-Dizdarevic and Zikovic (2010)	HRV	M; I; R	TOT	M	—	J
Wolde-Rufael (2009)	17 African countries	M	TOT	M	Employm.; capital	TY
Wolde-Rufael (2010a)	IND	M	N	M	Employm.; capital	TY
Wolde-Rufael (2010b)	CHN; IND; JPN; KOR; ZAF; USA	M	CO	M	Employm.; capital	TY
Wolde-Rufael and Menyah (2010)	9 developed countries	M	N	M	Employm.; capital	TY
Yoo (2006)	IND; MYS; SGP; THA	M	EL	M	—	H
Yoo and Ku (2009)	ARG; FRA; DEU; CHE	M	N	M	—	H
Yoo and Kwak (2010)	ARG; BRA; CHL; ECU; PER	M	EL	M	—	H
Yu and Hwang (1984)	USA	M	TOT	M	—	S
Yu and Choi (1985)	PHL; POL; KOR; GBR; USA	M	TOT; NG	M	—	G
Yuan et al. (2007)	CHN	M	EL	M	—	J
Yusof and Latif (2011)	MYS	M	EL	M	—	G
Zachariadis (2007)	G7 countries	M; R; I; T; S	TOT	M; R; I; T; S	—	J; TY
Zachariadis and Pashourtidou (2007)	CYP	R; S	EL	R; S	Energy pr.; degree days	
Zamani (2007)	IRN	M; A; I	TOT; EL.; NG; P	M; A; I	—	J
Zarnikau (1997)	USA	M	TOT[1]	M	—	G
Zhang and Cheng (2009)	CHN	M	TOT	M	Capital; CO2; popul.	TY
Zhao and Yuan (2008)	CHN	M	TOT	M	CO2	J
Ziramba (2009)	ZAF	M	CO; EL.; O	I	Employm.	TY
Zou and Chau (2006)	CHN	M	O	M	—	G; EG

Note: M: Macro; C: Commercial sector; T: Transport sector; I: Industry sector; R: Residential sector; S: Service sector; A: Agricultural sector
TOT: Total energy; EL: Electricity; CO: Coal; O: Oil; NG: Natural Gas; F: Fuels; P: Petrol; RE: Renewables; N: Nuclear
G: Granger; S: Sims; EG: Engle-Granger; TY: Toda-Yamamoto; J: Johansen-Juselius; H: Hsiao

[1] quality adjusted energy

for reasons of comparability.

We exclude panel studies due to the underlying assumption of structural equality across the countries within the panel. Since we aim at disentangling both the country as well as the study specific effects on the evidence for a true empirical effect, panel studies are not useful for our analysis. Similarly, we exclude studies for the sub-country level, e.g., cities, regions, and provinces, for reasons of comparability. It is reasonable to assume that economic dynamics differ between the country and the sub-country level.

We can only include those studies, which contain all relevant information needed for the empirical tests, particularly information on the lag structure of each variable. This information is needed for the calculation of the explanatory variable of MST, namely the degrees of freedom. The dependent variable of MST is the size of the test statistic. This makes it necessary to take the test statistic from each causality analysis. If the required information is not provided in the paper, we contacted the corresponding authors. We exclude potentially relevant studies only if we did not receive any reply or if the answer was incomplete after all. Moreover, we exclude studies if the estimation strategy is incorrect (e.g., an inconsistent lag order used for the Johansen-Juselius cointegration test and the VECM estimation building on that) or if the presentation of results is unclear (e.g., negative F-statistics). We documented the reasons for exclusion for all studies. In sum, our dataset covers 1020 causality tests from 75 studies and 108 countries.

2.3.2 Meta-Significance Testing

We use MST to investigate the presence of a true empirical effect (Stanley, 2005, 2008). Given the presence of a true effect, the test statistic of a regression coefficient increases with the square root of the degrees of freedom. If there is no effect, the test statistic is independent of the degrees of freedom and varies randomly around zero. This relationship is represented by the test regression

$$\ln |t_i| = \beta_0 + \beta_1 \ln (df_i) + \varepsilon_i, \tag{2.1}$$

where t is the value of the test statistic and df the degrees of freedom. If $\beta_1 > 0$, there is evidence for a true effect. Alternatively, if $\beta_1 = 0$, there is no evidence for an effect. If $\beta_1 < 0$, and if the degrees of freedom coincide with time, the test regression indicates that there used to be a relationship between energy and GDP at the beginning, but this relationship has disappeared over time. Possible reasons for the disappearance are publication bias or structural changes in the relationship between energy and GDP. As argued before, the literature is not likely to be subject to publication bias. Hence, if β_1 is found to be negative, we interpret this as evidence for structural changes in the relationship between energy and GDP (Card and Krueger, 1995).

Given the wide range of methodologies to test the relationship, the application of MST requires the test statistics to be standardized. Hence, we obtain a common measure of causality by transforming χ^2 and F distributed values into t distributed values. This transformation is done by choosing those t values which generate the same p value. We assess the influence of this transformation on β_1 by the use of an analysis of variance (ANOVA). We do not find significantly different β_1 coefficients for the different distributions.

In order to investigate the evidence for a true empirical relationship between energy and GDP, as well as to analyze the influence of its determinants discussed in the literature, we subdivide our sample into subsamples according to these determinants. Then, we run a MST regression in each subsample[1]. If the resulting MST regressions provide significantly different β_1 coefficients across the subsamples, the estimations indicate that the determinants have an influence on β_1. We drop outliers which lie outside a distance of two standard deviations from the mean in both dimensions, namely the test statistic as well as the degrees of freedom[2]. Moreover, we bootstrap the distribution of β_1 to release the inference from distributional assumptions.

The impact of the determinants is assessed as follows: first, the studies are divided into those studies which use output measures at the macro level and those which use output measures at the sectoral level. Second, the resulting subsamples are subdivided with respect to the aggregation of the energy variable. Here, we differentiate between those studies which use total energy consumption and those which take only a part of total energy consumption, e.g., electricity consumption. Third, these subsamples are further broken up with respect to the development stage of each country. We use the earliest available World Bank country classification (in the year 1987) to assess the initial development stage of each country. The corresponding data are taken from the World Bank Indicators (2012f). We summarize Low and Lower middle income countries as 'Low' and Upper Middle and High income countries as 'High'. Fourth, we further subdivide the sample with regard to the choice of control variables. We extract those control variables which are highly correlated with one of

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[1] We considered to evaluate the influence of the factors on the β_1 coefficient within a single model (ANOVA). However, the model is subject to multicollinearity due to the high amount of interaction effects.

[2] As a consequence, the sample size of subsamples may not add up to the sample size of the respective original sample.

the explanatory variables, as this correlation affects the size of the test statistic. In this regard, we consider carbon emissions as well as the real fixed capital stock to be highly correlated with GDP and energy in particular[3]. For example, energy and capital are often found to be complements (e.g., Berndt and Wood, 1975) and energy is strongly coupled with carbon emissions (e.g., Nakicenovic, 1996). Finally, we assess the influence of different causality methods on β_1. We only detect a systematic difference between those studies which find cointegration and those which use standard methods. We could not find a systematic difference within both categories of estimation techniques. Hence, we subdivide the subsamples into those studies which find cointegration on the one hand and those which do not on the other.

2.4 Results and Discussion

2.4.1 Results

For the full sample, the coefficients are found to be significantly negative for both directions of causality[4]. Since the degrees of freedom coincide with the underlying time series, this can be interpreted as evidence for bidirectional causality, which first existed but then has declined over time.

Consecutively, we split up the full sample into subsamples according to the determinants, which are assumed to drive the results as discussed before. For those studies which are conducted at the macro level only, the coefficient is still significantly negative (Table 2.2), whereas the entire subsample of non-macro studies does not indicate any relationship (Table A.1). Overall, the results for the various combinations of subaggregates tend to show no effect. Hence, we concentrate on the results for the macro studies in the following.

With regard to the role of the aggregation of energy, the slope we find for the macro studies remains negative in those cases where the causality between total energy and total GDP is analyzed. In those cases where only single energy variables are chosen, we do not find evidence for meta-significance. This can be explained by the fact that these variables cover only a part of the scope of economic activity of total GDP. However, this is the case only for Low income countries. For High income countries, the choice of energy aggregation does not alter the significantly

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[3] A group of studies incorrectly takes gross capital formation. In general terms, it refers to the growth rate of the real fixed capital stock.

[4] Since in our data a small sample size coincides with a low variation in the degrees of freedom, we restrict the discussion of results to sample sizes larger than 10 observations. Otherwise, the estimation coefficients cannot be reasonably interpreted.

negative slope. This may be due to the fact that the energy mix in high income countries remains more stable over time, which is associated with a higher correlation between a single energy variable and total energy consumption. Hence, from an empirical perspective, single energy variables show a similar correlation with GDP as total energy consumption. For total energy consumption, on the contrary, additional information on the development stage do not seem to matter. A comparison of the significance levels of both High and Low income countries reveals, however, that the significance for Low income countries is systematically weaker. This indicates that the negative effect is less clear cut due to a higher variance of the test statistic.

With regard to the control variables, we find that those variables, which are highly correlated with the explaining variables, absorb a large part of the significance of each individual test. With regard to cointegration, we cannot find evidence for an effect for studies with cointegration. Studies without cointegration show a negative beta coefficient throughout.

Overall, there is no evidence for a true effect between energy and GDP. Evidence for positive beta coefficients, on the contrary, can only be found in incorrectly specified models.

2.4.2 Discussion

First of all, our results confirm the relevance of the potential driving factors according to the underlying literature. We find a clear pattern only for those studies which investigate the relationship at the macro level, both for energy as well as GDP. On the contrary, the results for analyses based on inappropriate combinations of sectoral aggregations are found to be spurious. This is because they do not cover the same scope of economic activity (Zachariadis, 2007; Gross, 2012). Since the significance of the negative estimation coefficient is considerably higher for High income countries compared to Low income countries, the relationship between energy and GDP seems to be weaker. We find that control variables which are highly collinear with the explaining variables, energy in particular, absorb the significance. Since these control variables do not have additional explanatory power with regard to the relationship between energy and GDP, the choice of control variables should be motivated by economic theory instead. Whether or not there is evidence for cointegration among the variables does not seem to be driven by the estimation strategy chosen for the causality analysis. Instead, the finding of cointegration is associated with the influence of other determinants shown in the table.

In the course of major structural changes most High income countries have gone through, e.g., the development to the less energy consuming "service economy",

Table 2.2 — Estimations for Beta 1 Coefficients: Macro Energy and Macro GDP

Direction of causality			Energy aggregation			Development stage			Control variables			Cointegrated		
Energy causes growth	−0.53***	[380]	Total	−0.56***	[279]	Low	−0.40*	[148]	Yes	4.06	[15]	Yes	4.81	[10]
												No	−0.54	[6]
									No	−0.40*	[134]	Yes	−0.72	[40]
												No	−0.62***	[86]
						High	−0.65**	[131]	Yes	−0.29	[11]	Yes	−0.21	[6]
												No	0.15	[5]
									No	−0.72***	[120]	Yes	0.12	[9]
												No	−0.78***	[112]
			Disaggr.	−0.31	[97]	Low	−0.06	[47]	Yes		[0]	Yes		[0]
												No		[0]
									No	−0.06	[47]	Yes	−0.17	[31]
												No	−0.45	[16]
						High	0.79**	[49]	Yes	5.83	[4]	Yes		[0]
												No	5.83	[4]
									No	−0.87**	[46]	Yes	−3.34	[13]
												No	−1.32***	[32]
Growth causes energy	−0.26**	[383]	Total	−0.29***	[280]	Low	−0.49*	[153]	Yes	1.71	[14]	Yes	−0.61	[9]
												No	−0.58	[6]
									No	−0.56**	[137]	Yes	1.96	[42]
												No	−0.59*	[84]
						High	−0.27**	[132]	Yes	−0.03	[10]	Yes	0.02	[6]
												No	0.47	[5]
									No	−0.27**	[122]	Yes	1.52**	[10]
												No	−0.34***	[112]
			Disaggr.	−0.14	[102]	Low	0.31	[54]	Yes		[0]	Yes		[0]
												No		[0]
									No	0.31	[54]	Yes	0.56*	[36]
												No	−0.16	[17]
						High	−0.78**	[49]	Yes	−3.10	[4]	Yes		[0]
												No		[0]
									No	−0.83**	[45]	Yes	−1.18	[13]
												No	−1.41***	[32]

Note: ***,**,* denotes significance at the 1%, 5%, 10%; number of observations in squared brackets; inferences based on bootstrapping.

the relationship between energy and GDP is not left unaffected. As a consequence, the relationship between energy and GDP has become uneven, which makes it less likely to find a cointegration relationship in High income countries, compared to Low income countries. About one third of the tests for Low income countries show evidence for cointegration. For High income countries the share of studies which find cointegration is considerably lower. The weaker negative slope for Low income countries in the column headed "Development stage" can be explained by the higher dispersion of results for Low income countries on the right-hand side of the table. This may be due to the fact that development paths differ more across Low income countries than across High income countries.

Whereas we find that the differentiation between total energy consumption and the consumption of single energy sources plays a role in Low income countries, the kind of aggregation does not matter in High income countries. This finding is highly critical for those studies which analyze, for example, the effect of single energy sources on GDP. Suppose such a link exists, this could, in fact, also be driven by any other energy variable. In order to avoid false policy implications for single energy sources, the impact of all energy sources together on GDP should be considered in a multivariate framework instead.

Another, even more important, influencing factor which has not been sufficiently discussed in the literature is the effect of time. To be precise, it is the effect of associated radical changes which have increasingly confounded the relationship between energy and GDP. Since the length of the underlying time series approximately coincides with the degrees of freedom, the evidence for a negative coefficient in most cases indicates the presence of structural changes, which affect the statistical relationship (Card and Krueger, 1995). By bringing insights from the environmental Kuznets curve literature to the causality approach, Gross (2012) argues that, apart from higher technical energy efficiency due to technological change, structural changes such as sectoral shifts as well as an offshoring of industrial production have to be taken into account. Otherwise, today's relationship between energy and GDP can hardly be reconstructed. Our findings tentatively confirm this argument as the slope for (post-industrial) High income countries is more negative compared to Low income countries. This indicates that the statistical relationship between energy and GDP in High income countries has been more subject to structural changes than in Low income countries.

The question arises: how did we loose track of the relationship between energy and GDP from an empirical perspective, while theory stresses that energy and GDP are closely related (Cleveland et al., 1984; Ayres and Warr, 2009)? Ever since the seminal paper by Kraft and Kraft (1978), the number of studies on the relationship between energy and GDP has strongly increased. Apparently, the usual approach to analyze the relationship, e.g., in bivariate regressions at the macro level, or with inappropriate control variables, is insufficient to reconstruct how both parameters interact. However, instead of only describing the nonmonotonic relationship between energy and GDP by means of new econometric techniques, we suggest that a new path needs to be taken. Without disentangling the underlying dynamics, which determine the relationship between energy and GDP today, the relationship cannot be adequately assessed.

2.5 Conclusions

In our view, it is time to reconsider the relationship between energy and GDP from an empirical point of view, because the empirical evidence has systematically moved away from what can be considered a true effect from a theoretical point of view, namely that energy and GDP are closely related (Cleveland et al., 1984; Ayres and Warr, 2009). The systematic decline in empirical evidence is reflected by an overall negative estimation coefficient between the test statistic and the degrees of freedom derived from our meta-significance analysis based on Stanley (2005; 2008). The analysis covers 1020 causality tests between energy consumption and GDP from a total of 75 studies and 108 countries.

Moreover, we find that both the impact of the level of (sectoral) aggregation of output as well as the choice of control variables as well as the development stage significantly affects the results. With regard to the level of sectoral aggregation, we confirm that results from causality tests may be spurious if the level of aggregation is not appropriate, in the sense that the scope of economic activity differs among the explaining variables (Zachariadis, 2007; Gross, 2012). In addition, the inclusion of control variables may affect the causality between energy and GDP, if they are highly correlated with (one of) the explaining variables. The development stage of the economy has an effect insofar as in High income countries the evidence for causality has been significantly more confounded compared to Low income countries. Contrary to frequent conjectures expressed in the literature, the choice of the methodology alone does not affect the finding of causality. We argue that reasons for this can rather be found in contextual aspects of each underlying study. Finally, we find that the differentiation between total energy and single energy sources does not have an effect in High income countries. This, in our view, may lead to problematic policy implications if the relationship between energy and GDP is traced back to a single energy source, although it is highly correlated with total energy consumption.

To conclude, we emphasize the need to develop a better theoretical foundation for empirical analyses of the relationship between energy and GDP. By bringing insights from the environmental Kuznets curve literature to the causality approach, the study by Gross (2012) takes a new path to account for the nonmonotonic relationship between energy and GDP. We should further disentangle the underlying dynamics so that the relationship between energy and GDP can be adequately assessed.

3

Explaining the (Non-) Causality Between Energy and Economic Growth in the U.S.[1]

3.1 Introduction

What is the causality between energy consumption and economic growth? It is the key question of the empirical energy growth literature initiated by Kraft and Kraft (1978), which has been left unanswered univocally — after more than three decades of empirical research. It has been discussed that conflicting results may arise due to different time periods of the studies, countries' characteristics, variables used, and different econometric methodologies see Ozturk (2010) and Payne (2010) for an overview.

In this paper we will argue that another, even more important, reason for the weak evidence is the level of aggregation. Recent studies (e.g. Zachariadis, 2007; Bowden and Payne, 2009) investigate the causality between energy consumption and economic growth both on the macro as well as on the sector level. While the relationship between energy and growth seems to be neutral on the macro level, both studies find evidence for Granger causality for a lower level of aggregation in some cases. In statistical analyses it is not uncommon that evidence can be found for a lower level aggregation, although the results for the total population suggests the

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[1] This chapter is based on Gross, C., 2012, Explaining the (Non-) Causality Between Energy and Economic Growth in the U.S. – A Multivariate Sectoral Analysis, Energy Economics 34 (2), 489-499.

opposite. This phenomenon has been named 'Simpson's Paradox' after E. Simpson (1951).[2] However, if the results for Granger causality tests are found to be dependent on the level of aggregation and not on the variables, it is necessary to analyze the causal relationship at the correct level of aggregation. Otherwise, the results are spurious and policy advice should be given with caution. The paradox becomes even more severe if the pairs of variables for Granger causality analyses are not matching. For this reason, we will extend Zachariadis' notion of appropriate pairs for causality analyses.

The fact that sectors differ with respect to their relationship between energy and growth, is well known in the Environmental Kuznets Curve (EKC) literature: changes of the industry composition have a changing impact on the energy demands of the economy over time. In the early phases of modern economic growth, when a country industrializes, structural change is believed to increase these demands. Later on when the country enters the post-industrial phase, or the service economy, the energy demands are believed to decline (e.g. Kahn, 1979; Panayotou, 1993; Panayotou et al., 2000; Smil, 2000; Schäfer, 2005).[3] The resulting divergence between energy and economic growth is also a challenge for Granger causality analyses. In order to account for the decreasing energy intensity in a Granger causality framework, we suggest to include major findings from the EKC literature: one major finding is the role of the increasing energy productivity of production, which leads to the divergence between energy and growth. Another main finding is the role of trade, especially for goods producing industries, where energy intensive production is being offshored according to the Pollution Haven Hypothesis (PHH).

For our analysis we use the recently developed autoregressive distributed lag (ARDL) bounds testing approach as proposed by Pesaran and Shin (1999) and Pesaran et al. (2001). We analyze the evidence for long-run as well as short-run Granger causality between final energy consumption and GDP for the U.S. from 1970 to 2007 at the macro level as well as for the industry sector, the commercial sector, and the transport sector. After identifying appropriate pairs of variables for the Granger causality test, we test bivariate as well as multivariate specifications of the model in order to avoid omitted variable bias. The choice of additional control variables is based on major findings of the EKC literature as well as its limitations discussed in

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[2] "[...] situations in which statistical dependencies that are consistent in subpopulations disappear or are reversed in whole populations [...]" (see Hoover, 2008, p. 19).

[3] Henriques and Kander (2010) emphasize the need to account for sector specific price deflators. Otherwise, the impact of the energy efficient commercial sector on overall energy intensity would be overestimated according to 'Baumol's cost disease' (Baumol, 1967).

the literature.

In line with the majority of studies for the U.S., we find neutrality between energy and growth at the macro level. In addition, we find evidence for unidirectional long-run Granger causality in the commercial sector from growth to energy. We also find evidence for bi-directional Granger causality in the transport sector. Adding or removing additional control variables is found to create or break long-run causality. This finding is important especially in the transport sector, where controlling for the increasing energy productivity of production neutralizes the long-run relationship when growth is the dependent variable. For the industry sector we find that controlling for trade is important for identifying short-run Granger causality when growth is the dependent variable. We conclude that some of the divergence across sectors can be explained by the fundamental differences between goods and service producing industries. In various specifications energy productivity is found to Granger cause growth as well as energy. The latter is interpreted as evidence for 'Jevon's Paradox'.[4] We find only weak evidence for the impact of energy prices on energy consumption for the transport sector. Given the evidence of long-run Granger causality on the sector level, compared to a neutral relationship on the macro level, we conclude that the Granger causality between energy and growth should only be analyzed on the sector level. Otherwise, results for the total economy are spurious.

The paper is organized as follows: first, we discuss reasons for the inconclusive evidence for Granger causality in the existing empirical literature. We further elaborate Zachariadis' identification of appropriate pairs for causality analyses and use those pairs we consider appropriate for our analysis. We also discuss our extensions of the basic bivariate models mostly used in the empirical literature. Section 3.3 describes the econometric methodology. We investigate the causal relationship between energy consumption and economic growth in the U.S. for the period 1970-2007 and three economic sectors as well as for the macro level. Cointegration tests are based on the ARDL bounds testing procedure as proposed by Pesaran and Shin (1999) and Pesaran et al. (2001). Afterward, we analyze the existence of long-run and short-run Granger causality. In Section 3.4 we discuss our findings and the final section concludes.

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[4] Jevons (1864) maintained that technological efficiency gains — specifically the more "economical" use of coal in engines doing mechanical work — actually increased the overall consumption of coal, iron, and other resources, rather than "saving" them, as many claimed. Twentieth-century economic growth theory also sees technological change as the main cause of increased production and consumption ('rebound effect'; see also Alcott, 2005).

3.2 Reasons for the Inconclusive Evidence for Causality between Energy and GDP

3.2.1 Simpsons' Paradox: The 'Correct' Level of Aggregation

Theoretical approaches to the relationship between energy and growth are manifold (see Stern, 2004 for a summary). Ecological economists, in particular, emphasize the dependence of economic production on natural resource flows (e.g. Schurr et al., 1960; Cleveland et al., 1984; Ayres and Warr, 2009; Stern, 2011). Nevertheless, the empirical evidence from the energy-growth literature is rather mixed and weak.

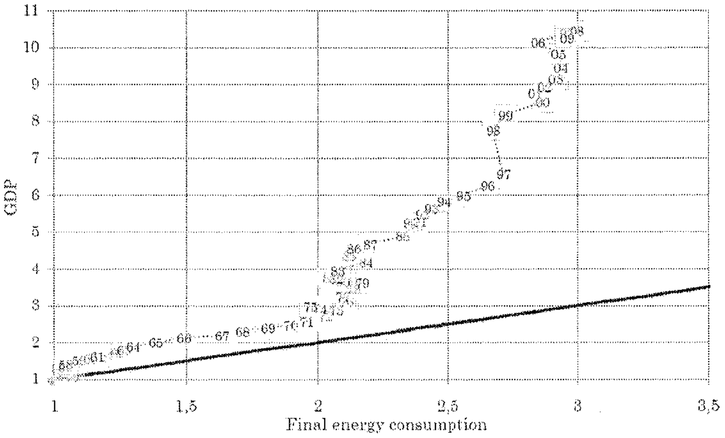

Fig. 3.1: Development of GDP and energy consumption in the U.S., 1949-2009 (1949=1); solid line represents constant energy intensity.

Fig. 3.1 shows the development of GDP in constant prices as a function of final energy consumption in British thermal units (Btu) in the U.S. from 1949 to 2009.[5] Until the late 1970s the relationship is almost linear. After the oil crisis in the late 1970s energy consumption drops back, while GDP remains almost constant. At the beginning of the 1980s, the slope is continuously increasing with another drop-back in

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[5] The majority of studies has been published for the U.S. For reasons of compatibility and data availability, we also limit our analysis to the U.S.

the late 1990s. The figure indicates that studies covering the years until the oil crisis should be more likely to find evidence for a relationship between energy consumption and growth, while later studies have to deal with the decreasing energy intensity. In the EKC literature, the decreasing energy intensity at the macro level is also known as the de-coupling between energy and growth. As the theory of the EKC assumes that the development of energy-related parameters is invertedly U-shaped with respect to increasing growth per capita, it describes a non-linear relationship between growth and energy-related parameters.

A shortcoming of the empirical energy growth literature is the underlying assumption of the same relationship between energy and growth over time. Causality is either running from energy to growth ('growth'), from growth to energy ('conservation'), is bi-directional ('feedback') or absent ('neutrality'). An obvious solution to account for the, in fact, nonmonotonic development of the relationship between energy and growth is to control for structural breaks. However, recent studies, which investigate the causality between energy consumption and economic growth both at the macro as well as at the sector level, show that the reason for the divergence is more fundamental and should be elaborated in more detail.

While Zachariadis (2007) and Bowden and Payne (2009) do not find evidence for Granger causality between energy and growth for the macro level, both studies find evidence for Granger causality for a lower level of aggregation in some cases. Without explicitly referring to Simpsons' Paradox, both studies show that the causality between energy and growth is hidden when only the macro level is taken into consideration. Figs. B.1-B.3 indicate why the results differ across the three sectors industry, commercial, and transport and why the results for the macro level are poorly related to the evidence at the sectoral level. The figures show the same plot as in Fig. 3.1, but with the development of sectoral value added relative to the development of sectoral final energy consumption. We find an decreasing energy intensity in all sectors. However, the scales differ so that the decrease in energy intensity is not equal across sectors. We will later argue that the increasing energy productivity of the capital stock explains large parts of the divergence. In the industry sector, in addition, we find an almost arbitrary development of energy and value added, which makes an in-depth investigation necessary. We assume that the separability of the value added chain of goods producing industries explains parts of the divergence.

However, before the discussion of additional control variables, which account for the sector-specific developments, we analyze the choice of appropriate pairs of variables for the causality test.

3.2.2 (In-) Appropriate Pairs of Variables

The Reference Model: Total Final Energy Consumption and Total GDP

In the empirical literature on the causality between energy and growth we find a consensus rather with respect to econometric techniques than the choice of variables. Zachariadis (2007) suggests "to select appropriate pairs of energy and economic variables (and the corresponding additional variables in multivariate models) in order to ensure that causality test results will be meaningful. In this respect one can observe in several causality studies that the pairs of variables are not matching. [...] Since the energy and economy variables in such cases do not cover the same area of economic activity or are sometimes expressed in different units [...], it is questionable whether profound policy implications can be deduced from their results" (Zachariadis, 2007, p. 1238). Accordingly, the results from different studies are ambiguous only at first sight given that they are based on various combinations of different variables. Disaggregating the studies with respect to the parameters used for causality tests clarifies that results inevitably differ among the studies. In the light of the numerous combinations of pairs of variables, we select the most common pair as a reference model, namely total (final) energy consumption (measured in thermal equivalents) and total GDP in constant prices.[6] This pair has been adapted in the studies by Kraft and Kraft (1978), Akarca and Long (1980), Abosedra and Baghestani (1991), Yu and Hwang (1984), Yu and Choi (1985), Cheng (1995), Zarnikau (1997), Soytas and Sari (2003), Soytas et al. (2007), and Chiou-Wei et al. (2008) see also Table B.1 in the Appendix. None of these studies finds evidence for long-run Granger causality in either direction.[7]

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[6] Until 1991 income statistics (GNP) accounted also for production outside the U.S., while energy statistics have always accounted only for the amount of energy consumption within the U.S. (see also OTA, 1990). It potentially distorts the statistical relationship between energy and growth in those studies using GNP instead of GDP.

[7] Kraft and Kraft (1978), Akarca and Long (1980), and Abosedra and Baghestani (1991) use GNP instead of GDP. Moreover, Akarca and Long show that the results found by Kraft and Kraft sensitively depend on the time period. Zarnikau (1997) analyzes 'instantaneous Granger causality' (see Section 3.3.5). Finally, Stern (1993) chooses primary (which excludes electricity) instead of final energy consumption.

Total Energy Consumption or Consumption of Single Resources?

Instead of total (final) energy consumption, another branch of studies selects single (groups of) energy sources together with total GDP as a pair for the causality test. Sari et al. (2008) use single energy sources, Murry and Nan (1996) as well as Narayan and Prasad (2008) use electricity, Thoma (2004) uses (sectoral) electricity consumption together with an industry production index, Bowden and Payne (2009) use (sectoral) primary energy consumption, and Payne (2009) as well as Payne and Taylor (2010) use (non-) renewable energy. If different energy aggregates are used across studies, the results naturally differ by comparison. Instead of analyzing the results in detail, we briefly discuss how the development of single energy sources matches with the development of total GDP.

Fig. B.4 and Fig. B.5 show the development of energy consumption of different energy sources as well as the development of market shares of different energy sources. From 1949 to 2009 total GDP multiplied by a factor of 7 (Fig. B.6). While natural gas, renewables, as well as petroleum products grow moderately by a factor of 4, electricity grew by a factor of 12. The consumption of coal dropped almost to zero. At first sight, the high increase of electricity consumption suggests that electricity is an important partner variable for a causality analysis with total GDP. However, is the consumption of electricity also a relevant factor with respect to its market share?

Fig. B.5 shows the share of each energy source in total energy consumption. It is evident that energy consumption is dominated by the consumption of petroleum products as well as natural gas. The market share of coal went down from about 37% and is almost negligible today. Although Fig. B.4 suggests that the consumption of electricity as well as the consumption of renewable energy carriers is continuously growing, both variables are almost negligible with respect to their market shares. In such cases, one should be aware that a causality analysis between electricity consumption and growth is based on an energy variable which accounts only for 10% of total energy consumption. Such an analysis potentially suffers from omitted variable bias. Moreover, Marchetti (1977) shows that energy sources are subject to substitution over time. In a causality analysis framework the selection of single energy sources then inevitably leads to a distortion of the results: the increase or decrease of a single resource is not necessarily related to economic growth, especially if an emerging gap in energy supply is filled by another resource.

Bowden and Payne (2009) use primary energy consumption instead of final energy consumption, which excludes the consumption of (secondary) electricity. As the consumption of electricity, however, is one of the main drivers of the increase in total (final) energy consumption, the use of primary energy potentially underrates its growth rate. Another reason for the inappropriateness of primary energy consumption is that the demand for energy is a derived demand. What is really demanded by both consumers and firms are energy services (e.g. heat, lighting, mobility), which relate to useful energy. As useful energy is not directly measured, the most appropriate approach is to use statistics of final energy use, which is the last stage before transforming energy to useful energy (and thus to energy services).[8]

GDP or Other Growth Indices?

Several empirical studies use GDP per capita (Soytas and Sari, 2006; Chontanawat et al., 2006, 2008) or an industry production index (Yu and Jin, 1992; Thoma, 2004; Sari et al., 2008) instead of total GDP as a growth variable. Fig. B.6 shows the development of GDP, GDP per capita, industry production, and final energy consumption. It shows an increasing gap between GDP and final energy consumption, while the development of the industry production index and GDP per capita is much closer to total final energy consumption. However, GDP per capita as well as the industry production index do not cover the same scope of economic activity as final energy consumption. While total final energy consumption covers, in sum, four sectors (residential, industry, transport, commerce), the industry production index of output accounts only for about 30% of economic activity. Per capita GDP, compared to the absolute value of GDP, is rather a measure of prosperity and is not necessarily related to the market value of all final goods and services produced within a country. Accordingly, the results found for the industry production index as well as per capita GDP should be regarded separately from the results found for total GDP.

Thermal Equivalents or Energy Quality Indices?

The simplest form of aggregation is to add up the individual energy sources according to their thermal equivalents. The thermal equivalent approach is advantageous because it uses a simple and well-defined accounting system based on the conservation of energy and the fact that thermal equivalents are easily and uncontroversially measured. Most methods of energy aggregation in economics and ecology are based on this approach (see Cleveland et al., 2000).

In deviation from the thermal equivalents approach, Schurr et al. (1960) emphasize the economic importance of energy quality. They argue that weighting energy use for changes in the composition of energy input is important because a large part of

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[8] I thank an anonymous referee for raising this point.

the growth effects of energy are due to substitution of higher quality energy sources such as electricity for lower quality energy sources such as coal. For this purpose, the quality of these fuels is supposed to be reflected by the typical prices per unit of energy. For the causality tests the quality of energy sources is calculated by a Divisia index, as suggested by Berndt (1978).

The problem is that the weight of each energy source critically depends on the 'correct' price, which may not correctly reflect the marginal product of each energy source (Kaufmann, 1994). Hong (1983) and Zarnikau (1997; 1999) demonstrated that the application of the Divisia index and thermal equivalents leads to different conclusions regarding trends in energy-output ratios for the U.S. economy. Divisia energy indices for U.S. industrial and residential energy consumption have grown much faster than heating value energy aggregates. This divergence is the result of an increasing electrification and price-related factors.

Instead of thermal equivalents, a number of studies (Stern, 1993; Zarnikau, 1997; Stern, 2000) use a discrete approximation of the Divisia index as suggested by Berndt (1978). Warr and Ayres (2010) use exergy instead of energy, which has been proposed by Ayres and Martinas (1995) and Ayres et al. (1996). The results from the exergy approach used in the empirical study by Warr and Ayres (2010) lack in compatibility. So far, this approach has not been applied in other studies, particularly due to the high complexity of calculation. In this study we use the aggregation of energy sources according to their thermal equivalents.

Sectoral Energy Consumption Paired with Sectoral GDP or Other Combinations of Aggregates?

As discussed above, the most common pair of variables used in the literature is total GDP and total final energy consumption on the macro level. On the sector level value added is an appropriate measure of economic activity. It is consistent with the use of GDP for the macro level since adding up the value added of individual sectors leads to the construction of the GDP variable.

Instead, Zachariadis (2007) uses total GDP and final energy consumption of the transport sector as a pair of variables for the transport sector. Indeed, as energy statistics such as those provided by the U.S. Energy Information Administration (EIA, 2011e) also account for transport fuels from non-commercial vehicles, it could be justified to consider a broader basis of output relating to the overall input of transport fuels. However, the choice of transport energy and total GDP is subject to several distortions: the share of transportation services in total GDP is almost negligible. Thus, the pontential linkages between the input of transport fuels and the related output would be distorted by all other economic activities. As an example, total GDP is dominated by the commercial sector, which does not make extensive use of transport services compared to e.g. the industry sector. Taking GDP as the growth variable would then mainly account for production processes where transport services are not required. Moreover, a more technical reason for the mismatch of both variables is the fact that the price index of total GDP does not correspond to the price index of transport services.

An alternative would be to use the value added of the transport sector as a partner variable for transport energy. Fig. B.7 shows that from 1970 to 2007 the main driver of total inland transport kilometers (the sum of total inland passenger transport passenger-km and total inland freight transport ton-km) is commercial transport (here defined as total inland transport km minus total inland passenger-km of private cars), while passenger-km of private cars remain almost constant. The figure is based on data provided by OECD.Stat (2010a; 2010b). Given an even development of energy efficiency of both commercial and private transport, the increase in total energy consumption is mainly caused by the increase of commercial transport, which is accounted for in transport value added statistics. Accordingly, we assume that, in the case of the U.S., transport value added is less subject to distortions than total GDP and should be preferred as a variable for the causality test.

Bowden and Payne (2009) take the sectoral (primary) energy consumption and total GDP as a pair of variables for all sectors. Similar to the case of Zachariadis' analysis, there is a potential mismatch between the level of economic activity when total GDP is paired with the sectoral level of energy consumption.

To sum up, we consider final energy consumption (measured in thermal equivalents) and economic growth on the sector level an appropriate pair of variables for our causality analysis. Moreover, we assume that a multivariate causality analysis should be preferred to a bivariate approach in order to avoid omitted variable bias. Our choice of additional variables is based on major findings from the EKC literature as well as its limitations discussed in the literature. It will be discussed in the following.

3.2.3 Omitted Variable Bias

Increasing Energy Productivity of the Capital Stock

Fig. 3.1 indicated an increasing divergence between energy consumption and economic growth. Despite the different scales in each sector, this finding is evident both for the macro level as well as for the three sectors. One major determinant for the declining energy intensity is the role of technological progress. Technological advances are typically incorporated to the economy through investment (Baily et al., 1981). When old capital goods get less and less (energy) efficient over time, firms are likely to replace them. Since new vintages are less energy consuming, firms may decide to replace the oldest and less efficient machinery. Since different vintages of capital goods coexist, there should be a smooth increase of the capital to energy ratio over time (see also Fig. B.8). Evidence for correlation between the energy efficiency of production and the capital to energy ratio was found by Wang (2007) and Wang (2011). The assumption of complementarity between capital goods and energy consumption is consistent with the empirical evidence put forward by Hudson and Jorgenson (1974), or Berndt and Wood (1975).

Including the capital to energy ratio in the analysis provides a direct measure of advances in energy productivity embodied in the newly produced capital goods. In our view, any neglect of the role of energy productivity would inevitably lead to an undervaluation of the role of energy consumption for economic growth, *vice versa*: an increase of the capital to energy ratio in previous periods could, for example, explain why output grows — although the amount of energy consumption remains constant (or even decreases). Also implications from Granger causality tests are eventually misleading if the increasing energy productivity of the capital stock is not considered: if the amount of energy consumption stays constant, while output grows, energy is still equally important in absolute terms, but a Granger causality analysis between energy and growth alone would eventually discard the Granger causal relationship. In order to account for price induced replacements of the capital stock, we also suggest to control for the average energy price paid for in each sector.

Offshoring of the Role of Imported Intermediate Goods

While accounting for the capital to energy ratio enables us to control for the increasing energy productivity, Fig. B.1, in addition, reveals a seemingly arbitrary development starting in the mid 1970s, by which only the industry sector is affected. A fundamental difference among the three sectors is the degree to which the production chain can be separated. The production process of services is inseparable and must inevitably, apart from a few exceptions, be provided in the home country. In the case of the goods producing industry sector the production process can be separated and parts of the value added chain can be offshored to foreign countries. In the home country, the separability of the production of goods affects the relationship between energy and growth in two ways: (1) the import of intermediate goods distorts the price level of goods in national statistics via an imprecise calculation of the Producer's Price Index (PPI). This leads to an overvaluation of value added in the industry sector. (2) The indirect amount of energy consumption associated with non-energy (intermediate) imports is not accounted for in national statistics e.g. from the U.S. Bureau of Economic Analysis (BEA). This leads to an underestimation of the energy associated with the production of final goods within the borders of the U.S.

Regarding the biased intermediate input price index, Yeats (2001) found that 30% of world trade in manufacturing are intermediate inputs. Houseman et al. (2010) argue that the dramatic acceleration of imports from developing countries is imparting a significant bias to official statistics. This can lead to problems related to price declines, which are associated with the shift to lowcost foreign suppliers. To maintain the consistency, the deflation of current value added would also necessitates an adjustment for the value of imported intermediate inputs. However, these price changes are not accurately reflected in deflators based on domestic products, such as the PPI (see also OTA, 1990). If growth in the input price index is overstated, productivity and real value added will also be overstated.

Regarding the neglect of indirect energy consumption, the Office of Technology Assessment (OTA, 1990) estimates that to assemble all of the motor vehicles made in 1985 requires more than five times higher indirect energy consumption than direct energy consumption. The "division between direct and indirect energy use is especially appropriate when the energy associated with international trade is considered. [...] Nevertheless, as production networks continue to extend beyond a country's borders, the inclusion of the indirect energy embodied in the trade of non-energy products is increasingly important in calculating a country's total energy use" (OTA, 1990,

p. 3). In the context of the EKC, Suri and Chapman (1998) show that industrialized countries have been able to reduce their energy requirements by importing (intermediate) manufactured goods. Once openness, measured as the trade to GDP ratio, is controlled for, Suri and Chapman can explain large parts of the downward slope of the EKC.

Incentives for offshoring of energy intensive production have also been investigated in the EKC literature: the PHH states that differences in environmental regulations between developed and developing countries may be compounding a general shift away from industry production in the developed world and causing developing countries to specialize in the most pollution intensive industry sectors. Since the costs of meeting environmental regulations are lower in most developing countries than in developed countries, it is possible that developing countries may possess a comparative advantage in pollution-intensive production (see Cole, 2004 for an overview). As a consequence, trade liberalization or openness (Harrison, 1996) will lead to more rapid growth of pollution intensive industries in less developed economies (Tobey, 1990; Rock, 1996). Several studies could not find empirical evidence for offshoring of pollution (see Aguayo and Gallagher, 2005; Kander and Lindmark, 2006; Levinson, 2010). Accordingly, we restrict our interpretation of the implications from the PHH only to the offshoring of energy consumption, not necessarily pollution.

In order to control for the biased input price index as well as the neglect of indirect energy consumption, we suggest to account for trade in our causality analysis. It allows us to control for the total energy consumption (here defined as the sum of direct and indirect final energy consumption) needed for the production of final goods within the borders of the U.S. Although the growth of the U.S. industry sector is not directly affected by (shortages in) the amount of energy consumption of exporting nations, the production chain in the U.S. sensitively depends on the availability of intermediate manufactured goods from exporting nations. Accordingly, the internalization of the indirect energy consumption related to the production of final goods in the U.S. is, in our view, necessary to be included in the following empirical analysis.

3.3 Data and Econometric Methodology

3.3.1 Data Description

Data on GDP as well as sectoral value added are provided by the U.S. Bureau of Economic Analysis (BEA, 2010) for the U.S. and cover the period from 1970 to 2007.[9] In order to transform the output measures into constant U.S. Dollars, we used sector specific deflators for sectoral value added as well as a GDP deflator for total GDP. The deflators are provided by the same source. The NAICS-based data on value added are available for three sectors — industry (including agriculture, mining, manufacturing), commerce (wholesale trade, retail trade, information, finance, insurance, real estate, rental and leasing, professional and business services, educational services, health care and social assistance, arts, entertainment, recreation, accommodation and food services, and government), as well as transport (transportation and warehousing). We excluded the residential sector from the analysis because the focus of this paper is on the production side of the economy. Moreover, we assume that the linkage between energy consumption and income in the residential sector is rather indirect, as households use energy mainly to run the appliances which have been produced in the industry sector.

Energy data are provided by the U.S. Energy Information Administration (EIA, 2011a; 2011c; 2011d; 2011e) and cover the same sectors as the output data. The energy input is measured as final energy consumption in Billion Btu. Consumer price estimates for energy by end-use sector (in current U.S. Dollars per Million Btu) are provided by the same source (EIA, 2011b). The end-use prices by sector have been transformed into constant prices using a consumer price index for energy derived from OECD.Stat (2010c).

Trade is approximated by the import penetration rate in constant prices. It measures the ratio between imports and domestic demand and shows to what degree domestic demand is satisfied by imports. The data provided by OECD.Stat (2008) allow to differentiate between the import penetration of goods and the import penetration of services. We chose import penetration of goods as a proxy for trade in the industry sector and import penetration of services for the commercial sector[10]. As

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[9] As other datasets used in this study are only available from 1970 to 2007, we had to shorten the time period of the dataset provided by the BEA. To test the results of the bivariate cases for robustness, we conducted the tests also for the full period (not reported). We found that the results for the full period did not significantly deviate from the results for the period from 1970 to 2007.

[10] We also took alternative measures for trade into consideration e.g. the trade to GDP ratio (see Suri and Chapman, 1998). However, we found that import penetration is the most adequate proxy for our analysis.

transportation services cannot be separated or offshored, we assume that trade does not have to be controlled for in the transport sector.

Capital data used for the calculation of the capital to energy ratio are taken from the EU-KLEMS Growth and Productivity Accounts (2009b). The real fixed capital stock is calculated in constant U.S. Dollars and includes all assets, except for software. We did this recalculation in order to circumvent valuation problems related to intangible assets. The data are also NAICS-based and are selected for the same sectors as described above. The capital to energy ratio is calculated as the real fixed capital stock divided by the sector specific amount of energy consumption as defined above. We prefer the real fixed capital stock for the capital variable to e.g. the gross capital formation, because it measures the stock of capital in each period, whereas gross capital formation measures its flow. The choice of a capital variable in levels is necessary, because the energy variable is also presented in levels.

Let Y, EC, EP, CAP and $TRADE$ represent output (GDP on the macro level and value added in the case of the sectors), final energy consumption, energy price, the capital to energy ratio and trade. All variables have been transformed to logs.

3.3.2 Estimation Strategy

For the analysis of cointegration between energy consumption and economic growth, we use the ARDL bounds testing procedure recently developed by Pesaran and Shin (1999) and Pesaran et al. (2001). There are several advantages of the ARDL approach over alternatives such as those suggested by Engle and Granger (1987) and Johansen and Juselius (1990). (1) Here, it is not a prerequisite to examine the non-stationarity property and order of integration of the variables; (2) bounds tests produce robust results also for small sample sizes like the present one (Pesaran and Shin, 1999) and (3) empirical studies have established that energy market-related variables are either integrated of order 1 [$I\,(1)$] or $I(0)$ in nature and one can rarely be confronted with $I(2)$ series (Narayan and Smyth, 2007, 2008), justifying the application of ARDL for our analysis (see also Ghosh, 2009). Narayan (2005) added tables with critical F values for sample size ranging from 30 to 80 in the tables provided by Pesaran and Shin. As our sample size is within this range, we will use the critical values provided by Narayan.

The ARDL bounds testing procedure involves three steps: (1) we conduct a Phillips-Perron test to ensure that the variables are not $I\,(2)$, (2) we apply an unrestricted error correction model (ECM) to test for cointegration among the variables. If evidence for a long-run relationship can be found, we calculate an error correction term (ECT), which contains information about the long-run relationship. Otherwise, those

Table 3.1 — Results of the Phillips–Perron test

Sector	Variable	Level	First difference
Total	Y	–.056	–4.912***
	EC	–1.187	–4.675***
Industry	Y	.399	–5.147***
	EC	–2.146	–5.633***
	EP	–3.119	–3.773***
	CAP	–1.575	–4.653***
	$TRADE$	.297	–5.128***
Commercial	Y	.010	–4.863***
	EC	–.818	–6.055***
	EP	–2.668*	–4.589***
	CAP	–.395	–6.231***
	$TRADE$	.009	–5.565***
Transport	Y	1.255	–5.729***
	EC	–1.174	–3.819***
	EP	–1.549	–5.396***
	CAP	.064	–3.253**

Notes. ***, **, * denotes 1%, 5%, 10% level of significance

information would be lost in a first-differenced restricted ECM. (3) We examine the existence of long-run ('strong') and short-run ('weak') Granger causality in an restricted ECM. This test provides further details on the long-run relationship as well as on short-run dynamics.

3.3.3 Stationarity

Although the ARDL modelling approach does not require unit root tests to test whether all variables are $I(0)$ or $I(1)$, it is important to conduct the unit root test in order to ensure that no variable is $I(2)$ or higher. If a variable is found to be $I(2)$, then the critical F-statistics, as computed by Pesaran et al. (2001) and Narayan (2005), are no longer valid. For stationarity tests we use the semi-parametric Philips-Perron test, as proposed by Phillips and Perron (1988). The results of the stationarity tests (see Table 3.1) show that most of the variables are non-stationary at level. After differencing the variables once, all variables are confirmed to be stationary. As none of the variables is integrated of order two, the ARDL bounds procedure can be used to examine the existence of a long-run relationship in the following step.

3.3.4 Cointegration

The notation of a multivariate unrestricted ECM in first log-differences for the ARDL $(p, q_1 \ldots, q_n)$ bounds approach with two regressors is:

$$\begin{aligned}\Delta Y_{it} &= \mu + \alpha Y_{it-1} + \theta EC_{it-1} + \lambda C_{it-1} \\ &+ \sum_{j=1}^{p-1} \gamma_j \Delta Y_{it-j} + \sum_{j=0}^{q_1-1} \psi_j \Delta EC_{it-j} + \sum_{j=0}^{q_2-1} \omega_j \Delta C_{it-j} + u_{it}.\end{aligned} \tag{3.1}$$

The residual term, u, is assumed to be a white noise error process. The model is tested for $i =$ Macro, Industry, Commercial, and Transport. C is a place holder for control variables. Depending on the model specification (see Table 3.2) we use one explanatory variable and up to three control variables. In the bivariate case, the individual lag length of ΔY_{it} and ΔEC_{it} is denoted by p and q_1, respectively. The lag length of ΔC_{it} is denoted by q_2 in the multivariate case. The optimal lag order is selected following the minimum values of the Bayesian information criterion (BIC). According to Pesaran et al. (2001), the BIC is generally used in preference to other criteria because it tends to define more parsimonious specifications. Using μ as an intercept term in first differences allows the estimation of a deterministic trend in the levels of the variables. In the bivariate case, the null hypothesis of 'no long-run relationship' is tested with the aid of an F-test of the joint significance of the lagged level coefficients: H_0: $\alpha = \theta = 0$ against H_1: $\alpha \neq \theta \neq 0$. In the multivariate case, the null hypothesis of 'no long-run relationship' is: H_0: $\alpha = \theta = \lambda = 0$ against H_1: $\alpha \neq \theta \neq \lambda \neq 0$. As long as it can be assumed that the error term u_t is a white noise process, or is stationary and independent of EC_{it}, EC_{it-1}, and Y_{it}, Y_{it-1} (and C_{it}, C_{it-1} in the multivariate case), the ARDL models can be estimated consistently by ordinary least squares. The null hypothesis of no cointegration will be rejected provided the upper critical bound is less than the computed F-statistic. In order to test the reversed cointegration relationship between EC and Y, the unrestricted ECM model is tested with ΔEC_{it} as the dependent variable and ΔY_{it} as the forcing variable in the bivariate case. In the multivariate case, the cointegrating relationship between EC, Y and C if Y and C are the forcing variables is tested with ΔEC_t as the dependent variable.

In case we reject the null hypothesis of no cointegration in Eq. (3.1), we calculate an ECT by $\widehat{\xi_{it}} = Y_{it} - \widehat{\beta} EC_{it}$, where $\widehat{\beta} = -\frac{\widehat{\theta}}{\widehat{\alpha}}$ and $\widehat{\alpha}$ and $\widehat{\theta}$ are the OLS estimators in the bivariate case. In the multivariate case, we calculate an error correction term

Table 3.2 — Model Specifications

Model	Depend. variable	Explan. variable	Control variables *EP*	*CAP*	*TRADE*
A	x	y	—	—	—
B_1	x	y	✓	—	—
B_2	x	y	—	✓	—
B_3	x	y	—	—	✓
C_1	x	y	✓	✓	—
C_2	x	y	✓	—	✓
C_3	x	y	—	✓	✓
D	x	y	✓	✓	✓

Notes. $x = Y$, $y = EC$ for causality running from EC to Y and $x = EC$, $y = Y$ vice versa.

by $\widehat{\xi_{it}} = Y_{it} - \widehat{\beta} EC_{it} - \widehat{\delta} C_{it}$, where $\widehat{\beta} = -\frac{\widehat{\theta}}{\widehat{\alpha}}$, $\widehat{\delta} = -\frac{\widehat{\lambda}}{\widehat{\alpha}}$ and $\widehat{\alpha}$, $\widehat{\theta}$ and $\widehat{\lambda}$ are the OLS estimators obtained from the ARDL model. To be theoretically meaningful the coefficient of the ECT should be negative and range between zero and one in absolute term. This ensures the ECT maintains the equilibrium relationship between the cointegrated variables over time.

We estimate the unrestricted ECM for various combinations of forcing variables, as summerized in Table 3.2. The bivariate Model A is the reference model with only Y and EC as a pair of variables. Models B_1, B_2, and B_3 are augmented with EP, CAP, and $TRADE$, respectively. Models C_1, C_2, and C_3 contain sets of two control variables. Model D is the full model including all variables. Given the large number of model specifications we will, in an intermediate step, select those models for which we find evidence for cointegration and which minimize the BIC. We will also include the basic Model A as a reference model.

3.3.5 Long-run and Short-run Granger Causality

Having found that there exists a long-run relationship between the variables, the next step is to analyze the evidence for Granger causality between the variables. A time series (X) is said to Granger-cause another time series (Y) if the prediction error of current Y declines by using past values of X in addition to past values of Y. This concept of causality is generally accepted in the energy growth literature. However, we are aware of Zellner's (1979) objection to the concept of Granger causality[11]. Concerning Zellner's objection to the atheoretical concept of Granger causality, we suggest to include findings derived from the EKC literature.

In order to test for Granger long-run and Granger short-run causality in the bivariate case, we run an restricted ECM of ΔY on $\eta\widehat{\xi}$, ΔEC, $(p-1)$-lagged ΔY's and (q_1-1)-lagged ΔEC's. In the multivariate case, we run additional tests on the (q_2-1)-lagged ΔC's according to

$$\Delta Y_{it} = \mu + \eta\widehat{\xi_{it-1}} + \sum_{j=1}^{p-1} \gamma_j \Delta Y_{it-j} + \sum_{j=0}^{q_1-1} \psi_j \Delta EC_{it-j} + \sum_{j=0}^{q_2-1} \omega_j \Delta C_{it-j} + u_{it}. \qquad (3.2)$$

The coefficient of the ECT η is a measure of long-run Granger causality between Y and EC (and C). The null hypothesis of no long-run Granger causality is: $H_0 : \eta = 0$ against $H_1 : \eta \neq 0$. If no long-run relationship between Y and EC (and C) has been found in Eq. (3.1), we test the same model with $\eta\widehat{\xi_{it-1}} = 0$(see Ghosh, 2009) and re-estimate the optimal lag order. An F-test on the (q_1-1)-lagged ΔEC indicates the significance of short-run Granger causality between Y and EC. Analogously, an F-test on the (q_2-1)-lagged ΔC's indicates the significance of Granger short-run causality between Y and C. Hence, the null hypothesis that EC does not Granger-cause Y in the short run is $H_0 : \psi_j = 0$ against $H_1 : \psi_j \neq 0$. The null hypothesis that C does not Granger-cause Y in the short run is $H_0 : \omega_j = 0$ against $H_1 : \omega_j \neq 0$.

In contrast to long-run Granger causality, short-run Granger causality is a measure for weak Granger causality. As it tests the joint significance of the $(q-1)$-lagged differences of the explanatory variables, it does not contain information on the long-run relationship. In addition, Eq. (3.2) also contains a contemporaneous term of the explanatory variable(s). When the contemporaneous term is included, one also seeks to determine whether one variable 'instantaneously' Granger-causes another variable i.e. at a higher frequency than reported in the dataset[12].

In order to test long-run as well as short-run Granger causality from growth to

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[11] Zellner (1979) criticizes that "it is not satisfactory to identify cause with temporal ordering, as temporal ordering is not the ordinary, scientific or philosophical foundation of the causal relationship. Second, Granger's approach is atheoretical. In order to implement it practically, an investigator must impose restrictions [and] limit the information set to a manageable number of variables [...]" (see also Hoover, 2008).

[12] Whereas "strict Granger causality relates to the past of one time series influencing the present and future of another time series [...], instantaneous causality relates to the present of one time series influencing the present of another time series" (Hiemstra and Jones, 1994, p. 1644). For the U.S., Zarnikau (1997) analyzes instantaneous Granger causality. He finds evidence for bi-directional instantaneous Granger causality.

energy, the restricted model is tested with ΔEC_{it} as the dependent variable.

3.4 Empirical Results and Discussion

3.4.1 Results of the Cointegration Tests and Model Selection

Macro Level

The results for the bounds cointegration test are reported in Table 3.3. The corresponding lag lengths are shown in Table B.2. We tested the model for a maximum lag order of three. We cannot find evidence for cointegration on the macro level. This is because the corresponding F-Tests on the lagged levels of the explanatory variables are lower than the upper bound critical values reported by Narayan (2005), see Table B.4. Accordingly, there is no long-run relationship between energy consumption and growth at the macro level. In order to investigate the short-run dynamics, we will run an restricted ECM on Model A in the next step.

Industry Sector

There is no evidence for cointegration between energy and growth in the industry sector. Model B_3 minimizes the BIC when output is the dependent variable and Model B_2 minimizes the BIC when energy is the dependent variable. These models will be tested for the existence of short-run dynamics in addition to the basic Model A. This result indicates that it is important to allow for different sets of explanatory variables, because output seems to be better explained by trade (in addition to energy), while energy seems to be better explained if the capital to energy ratio is added to the basic model.

Commercial Sector

We find evidence for cointegration in the commercial sector (Model B_2, C_3) when energy is the dependent variable. We find no evidence for cointegration when growth is the dependent variable. Accordingly, the long-run relationship in the commercial sector is forced rather by economic growth than by additional consumption of energy. This result reflects the fact that the growth of the commercial sector has rather been driven by its expansion of employment than of other factors of production. As Model B_2 minimizes the BIC when energy is the dependent variable, we will also run an restricted ECM on this specification.

Table 3.3 — Results of Unrestricted ECM

		Dependent variable			
		ΔY		ΔEC	
Sector	Model	F-statistics	BIC	F-statistics	BIC
Macro	A	2.24	-205.91	4.28	-198.06
Industry	A	.23	-127.77	1.96	-143.00
	B_1	.17	-122.91	2.10	-139.41
	B_2	.79	-125.82	1.82	-258.19^{-}
	B_3	1.92	-145.42^{-}	1.13	-144.99
	C_1	1.18	-121.65	1.92	-254.77
	C_2	2.42	-139.72	1.22	-137.67
	C_3	2.24	-139.15	2.25	-252.96
	D	1.66	-133.48	1.57	-248.06
Commercial	A	1.75	-158.26	3.93	-161.66
	B_1	1.31	-153.57	3.16	-157.51
	B_2	3.45	-169.44^{-}	6.45**	-299.29^{-}
	B_3	1.34	-154.11	2.32	-156.09
	C_1	3.16	-169.31	3.35	-294.37
	C_2	0.86	-149.24	3.16	-153.03
	C_3	2.88	-162.67	4.5*	-295.44
	D	2.20	-163.44	2.44	-290.93
Transport	A	8.80***	-131.79^{-}	10.56***	-193.63
	B_1	1.86	-123.93	4.89*	-183.39
	B_2	3.21	-130.05	6.36**	-227.47^{-}
	C_1	2.48	-128.01	4.60*	-220.85

Notes. ***, **, * denotes 1%, 5%, 10% level of significance; $^{-}$denotes the minimum BIC per sector. The critical values from Narayan (2005) are presented in Table A.4.

Transport Sector

For the transport sector, we find evidence for cointegration when growth is the dependent variable (Model A) as well as when energy is the dependent variable (Model A, B_1, B_2, C_1). Interestingly, we find evidence for mutual cointegration only in the bivariate case.[13] Once the energy price and / or energy productivity is controlled for, the long-run relationship breaks when growth is the dependent variable. This result indicates that the causal relationship between energy and economic is not at all carved in stone, but can be broken up by efforts to increase the energy productivity of production or by raising the price of energy. The comparison with the other sectors shows that a 'neutralization' of the cointegrating relationship can only be achieved in the transport sector. A possible interpretation of this evidence can be deducted from the fundamental difference between the transport sector and the other sectors: the production process of the transport sector is both inseparable as well as highly energy intensive. On the one hand, there is no potential for offshoring as in the industry sector, which could have distorted the relationship between energy and growth before. Accordingly, changes in energy prices and improvements of the capital to energy ratio immediately affect the relationship between energy and growth. On the other hand, energy is an essential factor input in the transport sector. Compared to the labor intensive commercial sector, developments affecting the energy input thus have a stronger impact on the relationship between energy and growth.

To sum up, the results of the cointegration tests emphasize the need to disentangle the relationship between energy consumption and growth with respect to the aggregation of sectors. As the results from the cointegration tests at the macro level 'hide' the evidence we find on the sector level, we find evidence for Simpson's paradox.

Once the long-term relationships have been established we will test the selected models for evidence for long-run as well as short-run Granger causality in the next step.

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[13] We also analyze the causality between energy consumption in the transport sector and total GDP as discussed in Section 3.2.5 (not reported). We only find evidence for cointegration when energy is the dependent variable (F-statistic: 6.52**), whereas there is no evidence when growth is the dependent variable (F-statistic: 3.0). Accordingly, taking total GDP as a dependent variable may underrate the importance of energy for this sector as well as the overall economy.

3.4.2 Results of the Long-run and Short-run Granger Causality Tests

Macro Level

The results for the long-run and short-run Granger causality tests are reported in Table 3.4. The values in parentheses show the estimated regression coefficient for the $(q-1)$-lagged explanatory variables. The corresponding lag lengths are shown in Table B.3.

The F-Tests on the $(q-1)$-lagged explanatory variables indicate evidence for bi-directional short-run Granger causality. The regression coefficients show that the mutual impact is positive, whereas growth has a stronger effect on energy consumption than the other way around.

Industry Sector

We find evidence for bi-directional short-run Granger causality in the industry sector for Model A. However, the value of the BIC indicates that the fit of the model can be improved if we control for trade, when output is the dependent variable (Model B_3). In this case, the positive effect of energy consumption on growth is almost halved and distributed among energy consumption and trade. The fact that Model B_3 has a better fit leads us to the conclusion that controlling for trade explains economic growth better than (direct) energy consumption alone, given that trade is considered a proxy for the indirect amount of energy consumption. Then, both the direct as well as the indirect amount of energy consumption incorporated in non-energy intermediate imports Granger causes industry output in the short run. So far, policy implications derived from causality analyses have focused mainly on isolated energy policies in the home country. However, as the indirect amount of energy consumption also Granger causes growth, it becomes important for the importing country to internalize energy policies of exporting nations. If, for example, the U.S. government is willing to accept stricter environmental conditions — because its own industry sector has offshored energy intensive parts of the value added chain, it does not necessarily have an incentive to advocate equal standards for all countries. This is especially the case for those countries with a comparative advantage in energy intensive production. Otherwise, too strict regulations for exporting nations could also have a feedback effect on industrial growth in the U.S.

When energy is the dependent variable, the fit of the basic model can be improved by controlling for the capital to energy ratio (Model B_2). The estimates for the regression coefficients indicate that the sign of the effect of energy productivity

Table 3.4 — Results of Restricted ECM

Sector	Depend. variable	Mod.	F-Test on forcing variable(s) ΔEC		ΔY		ΔEP		ΔCAP		$\Delta TRADE$		t-Test on ECT_{t-1}	BIC
Macro	ΔY	A	37.95***	(.58)	—		—		—		—		—	-210.71
	ΔEC	A	—		30.61***	(.85)	—		—		—		—	-196.75
Indust.	ΔY	A	45.89***	(.70)	—		—		—		—		—	-134.55
		B_3	5.15**	(.42)	—		—		—		7.38**	(.38)	—	-144.94
	ΔEC	A	—		6.36**	(.54)	—		—		—		—	-144.20
		B_2	—		1.8	(.03)	—		424.31***	(−1.03);(1.04)	—		—	-261.98
Comm.	ΔY	A	.19	(.07)	—		—		—		—		—	-161.02
		B_2	11.59***	(2.38)	—		—		7.76***	(2.40)	—		—	-161.90
	ΔEC	A	—		.11	(.07)	—		—		—		—	-161.36
		B_2	—		12.36***	(.10)	—		1129.49***	(−1.02);(.85)	—		−.0729***	-306.41
		C_3	—		16.85***	(.10)	—		1018.5***	(−1.02);(.89)	4.74**	(−.02)	−.0828***	-306.11
Transp.	ΔY	A	17.83***	(1.17)	—		—		—		—		−.1726***	-138.80
	ΔEC	A	—		9.41***	(.24)	—		—		—		−.2890***	-197.26
		B_1	—		6.56**	(.22)	1.21	(−.06)	—		—		−.3038***	-190.61
		B_2	—		18.55***	(.15)	—		40.98***	(−.83);(.61)	—		−.1339***	-234.64
		C_1	—		18.94***	(.16)	.00	(−.00)	43.83***	(−.84);(.62)	—		−.1309***	-231.60

***, **, * denotes 1%, 5%, 10% level of significance; coefficient estimates are presented in parentheses (for a maximum lag of 1).

depends on the lag length. In time t the effect of an increase in the capital to energy ratio is negative, while the effect is positive in $t-1$. Thus, we cannot state precisely whether the overall effect is positive or negative. The empirical finding that technological progress positively affects the consumption of energy is known as the 'rebound effect' and was first discovered by William S. Jevons in 1864. In case we control for the capital to energy ratio, we cannot find evidence for short-run Granger causality between energy and output any more. This finding indicates that the effect of growth on energy consumption is not as strong as suggested in Model A. We argued before that, due to the separability of the production process in the industry sector, there are opportunities for bypassing an equal increase in energy consumption if output grows.

Commercial Sector

For the basic model we do not find evidence for Granger causality, both in the long run as well as in the short run. Accordingly, we find evidence for the neutrality hypothesis on all levels of investigation. The neutrality between energy consumption and growth supports our assumption that the transformation of the sectoral composition of the economy is one of the key elements, which distorts the evidence for Granger causality at the macro level. As the commercial sector is the only sector, which has continuously grown over the last decades, it increasingly dominates the economy with respect its share in total GDP. As the growth in the commercial sector is neutral with respect to its energy consumption, there is no equal growth with respect to energy. Altogether, the results indicate that the tertiarization of the economy can be considered one of the reasons why Granger causality tests for the macro level tend to understate the evidence of Granger causality on the sector level.

The fit of the basic model can be marginally increased if we add the energy productivity of capital as a control variable (Model B_2) when output is the dependent variable. We find that energy consumption and the capital to energy ratio Granger-cause growth in the short run. This result indicates that it is rather the replacement of the least energy efficient capital stock than the increase in absolute amounts of energy consumption, which is necessary for growth in the commercial sector.

In case energy is the dependent variable, the ECT is significant at the 1% level, which indicates long-run Granger causality when the capital to energy ratio (Model B_2) and, in addition, when trade (Model C_3) is added to the basic model. The coefficient of the ECT indicates a low speed of adjustment to shocks to the forcing variables (13.7 years in Model B_2; 12.1 years in Model C_3). This finding may be related to the complex and immobile energy infrastructure in the commercial sector. The main energy source consumed in the service serctor is electricity, which necessitates the installation of a complex electricity grid. Comparing Model B_2 and C_3 indicates that the inclusion of trade does not improve the fit of Model B_2. This finding corresponds to the results from Amiti and Wei (2009).[14] The effect of trade on energy consumption is marginally negative. Concerning the short-run Granger causality between the capital to energy ratio, we also find evidence for the rebound effect in both models. However, the effect is smaller than in the industry sector. Although the amount of energy consumption in the commercial sector is comparatively low, our finding suggests that the steady growth of the commercial sector will also raise the energy consumption in the future. As a consequence, the commercial sector may become more dependent on energy.

Transport Sector

We find evidence for bi-directional long-run as well as short-run Granger causality in the transport sector (Model A). The coefficient of the ECT shows that the speed of adjustment to exogenous shocks is much higher than in the commercial sector. Output adjusts to the long-run relationship after 3.5 years, while energy returns to the long-run relationship after 5.8 years. The estimates for the short-run coefficients confirm that growth in the transport sector strongly depends on energy consumption.

In case energy is the dependent variable, the fit of the model can be improved if the capital to energy ratio is included (Model B_2). Again, we find weak evidence for the rebound effect, because the effect of increasing energy productivity on energy consumption is not negative throughout. We also find evidence for cointegration if energy prices are included (Model B_1, C_1), although the fit of the Models B_1 and C_1 is not improved compared to Models A and B_2. We interpret this finding as weak evidence for the dependence of energy consumption on the development of energy prices. However, it is remarkable that energy prices seem to accelerate the recovery of energy consumption after a shock to output (3.3 years in Model B_1, while the capital to energy ratio slows down the recovery (7.5 years in Model B_2; 7.6 years in Model C_1).

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[14] Amiti and Wei (2009) found that service offshoring is likely to be more skill intensive than material intensive. Moreover, service offshoring is only a more recent phenomenon.

3.5 Conclusions

We analyzed the Granger causality between energy and growth in the U.S. for the period from 1970 to 2007 on the macro level as well as for the industry sector, the commercial sector, and the transport sector. For our analysis we used the recently developed ARDL bounds testing approach as proposed by Pesaran and Shin (1999) and Pesaran et al. (2001).

Our paper contributes to the literature in several ways: (1) based on Zachariadis (2007), we analyze the existing energy growth literature for the U.S. with respect to the choice of appropriate variable pairs for causality analyses and discuss why the evidence is ambiguous. We conclude that only sectoral value added together with sectoral final energy consumption covers the same scope of economic activity and that the sector level should be preferred to the macro level. (2) We also emphasize the fundamental differences between goods and service producing industries and its implications for the relationship between energy and growth in each sector. We argue that, due to the inseparability of the production chain of service producing industries, there exists a closer relationship between energy and growth than in goods producing industries. As the energy intensive production of intermediate goods can be offshored to developing countries, the relationship between industry value added (accounted for in national statistics) and energy consumption, whereas the indirect consumption of energy is not accounted for, is weaker. (3) We combine the well-established methodology from the energy growth literature with major findings from the EKC literature as well as its limitations discussed in the literature. We show that augmenting the basic bivariate model with variables controlling for trade and energy productivity significantly improves the fit of several model specifications. (4) We find that Granger causality between energy consumption and economic growth are not always forced by the same (control) variables. This is the case when we do not find cointegration or the BIC is not minimized for the same model where energy and growth are the dependent variables.

In contrast to most bivariate analyses at the macro level, we conclude that the causal relationship between energy consumption and economic growth is much closer than is normally assumed. Our results confirm that long-run Granger causality between energy consumption and economic growth can rather be found on the sectoral level. We find evidence for bi-directional long-run Granger causality in the transport sector. However, once the increasing energy productivity of the capital stock is controlled for, the relationship breaks. In the commercial sector we find evidence for long-run Granger causality from growth to energy, if energy productivity is controlled for. The fundamental difference between goods and service producing industries also shows the differential impact of trade on the relationship between energy and growth. Once trade is controlled for, we find evidence for short-run Granger causality running from energy and trade to growth in the industry sector.

Concerning the implications, which can be drawn from the results, we strongly recommend the choice of an appropriate level of aggregation for Granger causality analyses in the energy growth literature. If evidence for Granger causality cannot be found at the macro level, the implication that no causality exists at all is myopic (Simpson's paradox). Even though no evidence for long-run Granger causality can be found at the macro level, policies which aim at the reduction of energy consumption could, in fact, affect individual sectors, both in the long run as well as in the short run. International policies which aim at stricter environmental regulations for developing countries would also indirectly affect the home country if the indirect consumption of energy is not internalized.

Finally, the long-run relationship between energy and growth is not carved in stone. We show that efforts to increase the energy productivity of the capital stock allow to break the long-run relationship between energy and growth in the transport sector. As long as the 'rebound effect' of increasing energy productivity does not outweigh the conservation of energy, a de-coupling between energy consumption and economic growth is possible. However, for this purpose we have to be aware of the 'real' relationship between energy consumption and growth, which tends to be undervalued in inappropriate model specifications.

4

The Growth of the "Service Economy" and the Energy Paradox of Sectoral Change[1]

4.1 Introduction

The role that energy plays in economic growth is back on the agenda. After the oil price shock of the 1970s, the topic had already attracted much attention. Two new developments have revived this interest. First, since the turn of the millennium, energy prices have begun a secular rise again. A growing energy demand of the newly industrializing countries over-compensates for ongoing energy efficiency gains in the industrialized world. At the same time, it is generally assumed that oil extraction has reached its maximum, nourishing concerns about the depletion of world oil resources (Hubbert, 1949; Campbell and Laherrère, 1998; Campbell and Heapes, 2008). Second, there is a growing awareness of the environmental threats implied by increasing fossil energy consumption and its effect on the CO_2 concentration in the atmosphere (Stern 2008). The possibility of regulatory interventions and rising taxes becomes likely and will drive up the cost of energy utilization even further. If energy costs have a signficant influence on economic growth, a timely question is how the economy will adjust to less cheap energy.

The question has been extensively discussed, yielding rather controversial results

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[1] This chapter is based on Gross, C. and U. Witt, 2012, The Energy Paradox of Sectoral Change and the Future Prospects of the Service Economy, Papers on Economics and Evolution #1209.

(for recent summaries see, e.g., Kilian, 2008; Payne, 2010). However, these studies neglect the structural effects through which changing energy use affects aggregate economic performance (Gross, 2012). In the past decades, economic growth in all OECD economies has been accompanied by an expansion of value added and employment in the service sector relative to the industrial sector (Schettkat, 2007) — a phenomenon often being dubbed the rise of a "service economy". In this process, the service sector has absorbed labor that was laid off in the industrial sector with its much higher labor productivity growth rates. Policy makers and the public therefore often trust that the "service economy" has the potential to align economic growth with high employment rates also in the future. It is not clear, though, whether the patterns of structural change will be the same in the future if energy costs continue to strongly increase and, accordingly, what the future growth prospects of the "service economy" will be.

Since Baumol's (1967) seminal paper on "cost disease" in the service sector, a huge body of literature has focused on the role that productivity differentials between sectors play for economic growth (see Nordhaus, 2008 for a recent summary). However, these studies have hardly ever considered the influence of changing energy costs on the productivity differentials (for an exception see Kander, 2005). In the present paper we will therefore explore the role of energy for explaining the shifts between the value added and employment shares of the respective sectors. More specifcally, we want to highlight the role of the technological conditions of energy use that differ between the sectors. As will be shown, these differences prove to be crucial to understanding how a changing gross energy price (including tax) affects sectoral productivity growth and and drives the ascendancy of the "service economy".

Over much of the second half of the 20th century, the price of energy stagnated, or even fell, relative to the ever increasing price of labor. The falling relative price of energy created incentives to substitute energy for labor in all sectors. Yet, for reasons of their specific technologies, the sectors differ with respect to the extent of substitution and, hence, possible cost savings. In the industrial sector, the production technology allows for a large-scale substitution of both energy and capital for labor. This is not the case in the service sector, with the exception of transport. (When the service sector is divided up into "transport services" and "commercial services" as the remainder, the technology of the transport sector turns out to be characterized by an energy-labor ratio that is even higher than that of the industry sector.) In order to provide commercial services, little energy is needed. Hence, the potential range for substituting energy for labor is severely technologically constrained in that sector.

Based on these observations, we argue that there are technological differences between the sectors in how, and to what extent, energy (plus capital) can be substituted for labor. These differences are a major reason for why productivity increases are significantly higher, in real terms, in sectors with a high energy intensity of production than in those with a low energy intensity. To evaluate this hypothesis empirically, we use U.S. data for the period from 1970 to 2005. By means of the Autoregressive Distributed Lags (ARDL) bounds test developed by Pesaran and Shin (1999) and Pesaran et al. (2001), we test the relationship for the three sectors industry, transport, and commerce, as well as for the macro level. The evidence we find suggests that the soaring use of cheap energy in the "progressive" industry sector has indirectly fueled much of the inflationary development of the "stagnant" commercial service sector in which energy is of only minor quantitative importance. We dub this phenomenon the "energy paradox of sectoral change". By reverse inference, the energy paradox seems to suggest that the "service economy" may not fulfill existing political expectations regarding the attainment of both high economic growth and employment rates, if gross energy prices continue to rise substantially in the future.

We will develop our argument in more detail as follows. Section 2 discusses how the sectors' production technologies differ in their energy utilization and what role labor and capital goods play in their production technologies. Furthermore, we explain why there is a need to distinguish transport from other services. In Section 3, we introduce a simple sectoral production model, based on a modified Cobb-Douglas function. We understand the model as locally approximating the relationships between energy, labor, and capital at different points in time. Following the discussion in the preceding section, we use the model framework to explore the hypothesis mentioned above. Section 4 explains both the data we use for the empirical tests of the working hypothesis and our methodology. In Section 5, we present the empirical results and discuss the energy paradox, including its implications for the growth prospects of the service economy. Section 6 presents some tentative conclusions.

4.2 Energy and Growth — Background and Technological Contingencies

The systematic shift of value added and employment shares between the sectors as a result of economic growth has long been recognized (see Schettkat and Yocarini, 2006 for a recent survey). It is likely to have several causes, and their significance may historically vary.[2] In our analysis, we concentrate on the well known, and more persistent, differential growth of the sectors' labor productivity. This phenomenon has been highlighted by Baumol's diagnosis of a "cost disease" in the service sector. Baumol (1967; see also Baumol, Blackman and Wolff, 1985) observed that, over time, comparatively less labor is needed in the industrial sector. Consequently, labor productivity rises faster in real terms in that sector than in the service sector. With by and large the same wage rate being paid in all sectors, the productivity differential results in the average unit costs of services rising relative to average unit costs in the industrial sector. If the prices of services can be raised sufficiently relative to those of industrial goods, the unit cost differentials can be compensated for. This will induce customers to substitute away from some, but not all, of the ever more expensive services (Baumol and Bowen, 1966). In fact, the service sector has been able to increase not only its employment share but also its value added share over time (see the empirical findings in Nordhaus, 2008).

Using this explanation, differential productivity growth appears as the ultimate reason for the changing sectoral shares. It can be argued, however, that the difference in sectoral productivity growth is itself a result of a more basic causal mechanism. Indeed, we claim that the deeper cause can be largely attributed to the technological conditions of energy use and a changing energy price. To motivate this interpretation, it is helpful to highlight a few technological characteristics of how, and for what purpose, energy (in the language of physics: *free* energy) is used in the different sectors.

In the industrial sector, "production" can be characterized as the transformation and shaping materials, which requires energy in various forms (Buenstorf, 2004). Due to the nature of these processes, the energy-output ratio in the industrial sector is comparatively high. The application of energy (apart from physical work done by human beings) is mediated by specific facilities and equipments, i.e. capital goods. Real capital is "productive" — and can replace human labor — in industrial production processes precisely because it is the medium through which non-anthropogenic energy is transmitted and applied, in a controlled form, at the point of use.[3]

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[2] For instance, changes in international specialization patterns are currently of great interest (outsourcing and/or off-shoring particularly of manufacturing activities, from high to low wage countries, as well as service intensive parts of the value chain concentrating in the most developed economies). However, energy-related factors — on which the present paper focuses — do not seem to play a role in these topical changes. We will therefore exclude them from consideration here.

[3] Another reason is, of course, that, in sufficiently standardized production, the know-how and the skills built into machinery allow for the re-use of human knowledge over and again at a marginal cost close to zero, see Langlois (1999).

By its technical design, in full load use, the capital stock existing in the industrial sector requires a certain energy throughput per period of time. If the energy actually utilized falls short of that nominal throughput, this means that some of the facilities and equipments are left idle or do not run at full load level. In line with this observation we deviate from the literature assuming Cobb-Douglas functions with energy and capital as substitutes for the entire economy (see, e.g., Berndt, 1975; Kuemmel, 1985; Ayres and Watt, 2005). Instead, we submit that, in the short run, energy and capital are limitational inputs. The energy-capital ratio and, hence, the energy intensity of the capital stock can, however, be changed in the longer run by replacing existing facilities and equipment, i.e. by investment. We claim that the short run limitational relationship between capital and energy inputs also holds for the service sector.

In other respects, the production technology of the service sector is obviously a different one, particularly if transport services are separated from the rest of the service sector (to which we attach the label "commercial services"). In transport, passengers or freight are moved from one location to another. By definition this amounts to carrying out physical work. Capital goods in the form of transport vehicles and the energy that fuels their movement represent limitational inputs in the short run. (Vehicles can, of course, be "parked" and their energy consumption thus proportionately saved.) However, unlike in industrial production, a transport service hardly requires any other material input. Not surprisingly, both the energy-capital ratio and the energy-output ratio are therefore even higher in the transport sector than in the industrial sector. (For the empirical facts see the sector statistics for the U.S. for the years 1970 and 2005 in Table 4.1.)

With respect to commercial services the opposite holds. Facilities and equipments utilized in this sector do not typically serve to move or transform things. To a large extent they enable automated and computerized information processing and application. To accomplish this task, little energy is needed. Therefore, the energy-output ratio in this sector is the lowest of all sectors, as is the energy-capital ratio. The difference in the energy intensity is intuitively evident if one considers the role that energy plays, say, in producing an insurance service vs. producing a chemical like chlorine, or shipping a container from Hong Kong to Seattle.

Once these differences are acknowledged, it is quite easy to understand the role of energy for sectoral change in the past and, thus, for the rise of the "service economy". During much of the 20th century, the prices of energy inputs were very low, or even declining (Ayres and Warr, 2005). In contrast, the wage level in the three sectors increased significantly and, as assumed by Baumol, with little difference between

Table 4.1 — Sector Statistics for 1970 and 2005

Sector	Industry	Commercial	Transport
Value added share (macro deflator)	21 (33)	76 (63)	3 (4)
Value added share (sector deflator)	30 (33)	66 (63)	4 (4)
Employment share	21 (35)	76 (61)	3 (4)
Δ Labor productivity (macro deflator)	1.9	1.7	1.7
Δ Labor productivity (sector deflator)	3.1	1.7	2.5
Δ Relative wage level[1]	1.0	1.0	0.8
Energy/Labor ratio	0.56	0.01	1.15
Δ Energy/Labor ratio	1.1	1.0	1.7
Capital/Energy ratio	0.05	0.19	0.08
Δ Capital/Energy ratio	1.9	2.2	1.3
Energy/Output ratio	12.9 (22.0)	1.9 (3.2)	44.1 (43.5)

Note: Values for 2005 (1970); Δ denotes the growth factor (1970=1);
[1]development relative to commercial sector.

sectors (see line 6 in Table 4.1). The decreasing relative price of energy signified a strong incentive to substitute energy (jointly with capital) for labor. However, given the differing significance of energy in their respective production technologies, both the incentives and the extent of energy for labor substitution differed substantially between the sectors. As a result, in real terms labor productivity in industry and transport increased more so than in the commercial sector (see the first two lines in Table 4.1). Hence, according to our explanation of sectoral change, industry and transport appear to be "progressive" sectors simply because they can take advantage of their higher energy intensity. Due to its significantly lower energy requirements this option is not feasible for the commercial service sector.

When wages increase similarly across sectors while the growth of labor productivity strongly differs (in real terms), a soaring wage-productivity gap between sectors seems inevitable. However, this need not be true so long as the price level in the low-productivity sector rises fast enough relative to the price level in the high-productivity sector. Indeed, this is what happened. The relative price of commercial services increased to such an extent that labor productivity in nominal terms was almost equalivalent across sectors.[4] Rising real income apparently enabled customers

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[4] Compare the changes of labor productivity in line 4 and 5 of Table 1 calculated on the basis of a GDP price index and a sector-specific price index respectively; see also the discussion in Henriques and Kander (2010).

to afford the increasing prices of commercial services, allowing the entire sector to actually expand. Thus, a paradoxical effect emerged. To save cost, the energy-intensive sectors made use of their technical capacity to extensively substitute cheap energy for expensive labor. In the commercial service sector where only comparatively little energy is used no such cost saving was possible so that its relative costs increased. Similarly, this sector profited least from the technical progress in energy efficiency, i.e. the falling energy-capital and energy-output ratios in the economy. The combination of these effects establishes what we call the energy paradox of sectoral change, namely that, in monetary terms, energy had the greatest effect on that sector — the commercial sector — where the use of energy is least significant.

4.3 A Sectoral Production Model with Energy-Labor Substitution

In the previous section we argued that the key for understanding the persistent drivers behind the rise of the service economy lies in the sectors' different energy technology. In accounting for these differences in a suitable sectoral production model it has to be recognized, we argued further, that, at any given point in time, energy and capital are limitational factors. Let the sectors of the economy be denoted by the suffix i and time by the suffix t. Let E_{it} give the size of the energy input and $K^*_{it} = u_{it}K_{it}$ that part of the capital stock K_{it} that is active at time t. u_{it} is a utilization rate, $0 \leq u_{it} \leq 1$. Complementarity between these factors can then be expressed by

$$E_{it} = \varepsilon_{it} K^*_{it}. \tag{4.1}$$

The parameter $\varepsilon_{it} > 0$ reflects the energy dependence of a sector's capital stock. The inverse, the energy efficiency $1/\varepsilon_{it}$ of capital at the prevailing technological efficiency boundary, increases over time through technical progress[5].

While we submit that the sectors' production technology is in the short run limitational in energy and capital, this is different for labor. Energy-capital packages of the given technological vintage on the one hand and labor on the other can be assumed to be substitutes. To keep things simple we capture this feature by choosing a Cobb-Douglas production function for each sector with the arguments

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[5] We assume that the energy throughput by the actually used part of the capital stock is always at the energy efficiency boundary. u_{it} fluctuates in historical time without any clear trend. In contrast, ε_{it} decreased in all three sectors in the U.S. over the period 1970 - 2005, most significantly, however, in manufacturing (see Table 1).

$$Y_{it} = A_{it} \left(K^{*}_{it} \right)^{\alpha_i} \left(L_{it} \right)^{1-\alpha_i} . \tag{4.2}$$

Here Y_{it} and A_{it} denote value added[6] and total factor productivity respectively. Labor as the factor input L_{it} warrants some further reflections. Every production technology requires a certain quality of labor services as input. To the extent to which training does not take place on the job, knowledge and skills need to be acquired with a time input L^s_{it}. This input is necessary for making qualified labor available in the labor market, but it is only indirectly compensated for by income earned with the paid labor time L^p_{it} (measured in hours of contracted work time). If the skilling time ratio is denoted by $L^s_{it}/L^p_{it} = \sigma_{it} > 0$, we can write for the factor input

$$L_{it} = \left(1 + \sigma_{it} \right) L^p_{it} \tag{4.3}$$

Inserting Eqs. (4.1) and (4.3) into (4.2) we get

$$Y_{it} = \tilde{A}_{it} \left(E_{it} \right)^{\alpha_i} \left(L^p_{it} \right)^{1-\alpha_i} \tag{4.4}$$

with

$$\tilde{A}_{it} = A_{it} \left(\frac{1}{\varepsilon_{it}} \right)^{\alpha_i} \left(1 - \sigma_{it} \right)^{1-\alpha_i} . \tag{4.5}$$

In the explanatory sketch of the rise of the service economy in the previous section we have emphasized the sector-specific differences in technological opportunities for substituting energy for labor with their impact on labor productivity. Dividing Eq. (4.4) by L^p_{it} and inserting Eq. (4.5) we get the labor quality and energy efficiency augmented labor productivity which, after taking logs, can be written as

$$y_{it} = \underbrace{a_{it}}_{\substack{\text{Unexplained} \\ \text{TFP}}} + \underbrace{\alpha_i b_{it}}_{\substack{\text{Energy} \\ \text{efficiency}}} + \underbrace{\left(1 - \alpha_i \right) c_{it}}_{\substack{\text{Up-} \\ \text{skilling}}} + \underbrace{\alpha_i d_{it}}_{\substack{\text{Energy-labor} \\ \text{substitution}}} \tag{4.6}$$

where $y_{it} = \ln \left(\frac{Y_{it}}{L^p_{it}} \right)$, $a_{it} = \ln A_{it}$, $b_{it} = \ln \left(\frac{1}{\varepsilon_{it}} \right)$, $c_{it} = \ln \left(1 - \sigma_{it} \right)$, $d_{it} = \ln \left(\frac{E_{it}}{L^p_{it}} \right)$.

On the basis of Eq. (4.6) we can now empirically assess the influence which the different variables have on the labor productivity development in the three sectors.

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[6] More specifically, deflated value added, as $Y_{it} = Y^n_{it}/p_{it}$ with p_{it} as the sector-specific output price index and Y^n_{it} as nominal value added measured in current USD.

Following the working hypothesis that has been outlined, we expect that sectoral differences in the energy-labor substitution and increases in energy efficiency are significant for the sectors' labor productivity growth differentials.

4.4 Data and Methodology

Data on GDP as well as sectoral value added are provided by the Bureau of Economic Analysis (2010) for the U.S. and cover the period from 1970 to 2005. In order to transform the output measures into constant U.S. Dollars, we used sector specific deflators for sectoral value added as well as a GDP deflator for total GDP. The deflators are provided by the same source. The NAICS-based data on value added are available for three sectors: industry (including agriculture, mining, manufacturing and construction), commerce (wholesale trade, retail trade, information, finance, insurance, real estate, rental and leasing, professional and business services, educational services, health care and social assistance, arts, entertainment, recreation, accommodation and food services, and government), and transport (transportation and warehousing; we excluded the residential sector from the analysis because the focus of this paper is on the production side of the economy).

Energy data are provided by the Energy Information Administration (2011). They cover the same sectors as the output data. The energy input is measured as final energy consumption in Billion Btu. Data on hours of work as well as capital data used for the calculation of the capital to energy ratio are taken from the EU-KLEMS Growth and Productivity Accounts (2009a; 2009b). The real fixed capital stock is calculated in constant U.S. Dollars. For the calculation of the capital-energy ratio in the commercial sector we excluded real estate.

Data on capacity utilization in the industry sector are provided by the Federal Reserve Board (2011). For the other sectors we proxy the utilization of capital by one minus the unemployment rate. These data are taken from the Bureau of Labor Statistics (2011). We approximate the up-skilling of the labor force by years of schooling. The data are derived from the UNESCO Institute for Statistics database (2011). All variables have been transformed to logs.

For the analysis of our hypothesis we test whether the time series of each sector enter a cointegration relationship. For this purpose we use the ARDL bounds testing procedure recently developed by Pesaran and Shin (1999) and Pesaran et al. (2001). There are several advantages of the ARDL approach over alternatives such as those suggested by Engle and Granger (1987) and Johansen and Joselius (1990). (1) Here, it is not a prerequisite to examine the non-stationarity property and order of integration of the variables; (2) bounds tests produce robust results also for small sample sizes like the present one (Pesaran and Shin 2001) and (3) empirical studies have established that energy market-related variables are either integrated of order 1 [I(1)] or I(0) in nature and one can rarely be confronted with I(2) series (Narayan and Smyth, 2007; 2008), justifying the application of ARDL for our analysis. Narayan (2005) provides tables with critical F values for sample sizes ranging from 30 to 80. As our sample size is within this range, we will use the critical values provided by Narayan. The ARDL bounds testing procedure involves two steps: (1) we conduct a Phillips-Perron test to ensure that the variables are not I(2). (2) we apply an unrestricted error correction model (ECM) to test for cointegration among the variables and display also the short-run dynamics.

The ARDL modeling approach does not require unit root tests to check whether all variables are I(0) or I(1). We conduct the unit root test, nonetheless, in order to ensure that no variable is I(2) or higher. If a variable is found to be I(2), then the critical F-statistics computed by Pesaran et al. (2001) and Narayan (2005) are no longer valid. For stationarity tests we use the semi-parametric Phillips-Perron test, as proposed by Phillips and Perron (1988).

We derive the regression equation from Eq. (4.6). Accordingly, the notation of an unrestricted ECM in first log-differences for the ARDL $(p, q_1, ..., q_3)$ bounds test is:

$$\begin{aligned}\Delta y_{it} &= a_i + \beta_{i1} y_{it-1} + \beta_{i2} b_{it-1} + \beta_{i3} c_{it-1} + \beta_{i4} d_{it-1} \\ &+ \sum_{j=1}^{p-1} \theta_{ij1} \Delta y_{it-j} + \sum_{j=0}^{q_1-1} \theta_{ij2} \Delta b_{it-j} + \sum_{j=0}^{q_2-1} \theta_{ij3} \Delta c_{it-j} + \sum_{j=0}^{q_3-1} \theta_{ij4} \Delta d_{it-j} + \eta_{it}.\end{aligned} \tag{4.7}$$

The residual term η_{it} is assumed to be a white noise error process. The model is tested for i = Macro, Industry, Commercial, and Transport. The lag length of the explanatory variables is denoted by q. The optimal lag order is selected following the minimum values of the Bayesian information criterion (BIC). According to Pesaran et al. (2001), the BIC is generally a preferred choice, since it tends to define more parsimonious specifications. The null hypothesis of 'no cointegration relationship' is tested by means of an F-test of the joint significance of the lagged level coefficients: $H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$. The null hypothesis of no cointegration will be rejected provided the upper critical bound is less than the computed F-statistic.

Table 4.2 — Results of the Phillips-Perron Test

Sector	Variable	Level	First difference
Macro	y	-0.275	-4.560***
	b	0.080	-4.219***
	c	-1.770	-8.175***
	d	-1.270	-4.073***
Industry	y	1.831	-5.469***
	b	-1.388	-3.289**
	d	-1.245	-3.601***
Commercial	y	-0.544	-5.308***
	b	1.223	-5.442***
	d	-1.624	-5.439***
Transport	y	-0.040	-5.882***
	b	0.221	-3.325**
	d	-2.546	-4.994***

Note: ***, **, * denotes 1%, 5%, 10% level of significance, respectively.

4.5 Empirical Results

The results of the stationarity tests (see Table 4.2) show that all of the variables are non-stationary at level. After differencing the variables once, all variables are confirmed to be stationary. As none of the variables is integrated of order two, the ARDL bounds procedure can be used to examine the existence of a cointegration relationship among the variables. The results of the ARDL bounds test (see Table 4.3) show that a long-run relationship between labor productivity and the explanatory variables only exists in the industrial sector and the transport sector, i.e. only in these sectors the F-statistics exceed the critical F-values provided by Narayan (2005)[7]. The fit of the models and the low or insignificant values of the unexplained technological progress indicate that the development of labor productivity is well described by the selected explanatory variables in these two sectors.

In the commercial sector, in contrast, labor productivity neither gains from the substitution of energy for labor nor from an increasing energy productivity of production. This finding also explains the low increase in labor productivity in the

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[7] The critical values for the investigation of the long-run relationship are 6.988, 5.090, 4.274 at the 1%, 5%, 10% level of significance (case IV, p. 1989 in Narayan, 2005).

Table 4.3 — Results of the Cointegration Test

F-test	Macro	Industry	Commmerce	Transport
$\forall\beta = 0$	4.25	5.65**	4.19	5.95**
Const.	-0.3535	-0.3776	5.1328***	-3.1920**
Adj. R^2	0.63	0.37	0.41	0.72
Obs	34	32	34	32

Note: ***, **, * denotes 1%, 5%, 10% level of significance, respectively.

commercial sector. Factors found to be significant for the other two sectors do not affect the development of labor productivity in the commercial sector. As total GDP is dominated by commercial value added, an analysis at a more aggregate level hides the significant diffrences at the sectoral level to which Baumol's cost disease hypothesis refers. Put differently, the impact of energy-related changes on the economy falls victim to an aggregation effect.

Our findings are compatible with the conjecture of an extensive substitution of cheap energy for labor in the "progressive" industry sector (and in transport) where this is technologically feasible. In the "stagnant" commercial sector, in contrast, there is comparatively little room for an energy-for-labor substitution. We therefore infer that cheap energy costs have caused a rise of value added and employment shares in the sector where least energy is is used, the commercial sector. We call this effect the energy paradox of sectoral change.

4.6 Conclusions

In this paper we highlight the role that energy plays in the context of the growth of the "service economy". We distinguish three sectors in our analysis: industry, transport, and commercial services. The "service economy" is characterized by a dominant role of the commercial service sector in terms of value added and employment. In order to understand the importance of energy, disaggregating to the sectoral level is essential. Empirical tests which investigate the causality from energy consumption to economic growth at an aggregate level often reject the hypothesis that there exists a causal link. Our empirical analysis shows, however, that energy-related factors did have an impact on the growth of the U.S. economy over the period 1970-2005 at the sectoral level.

According to this theory, the rise of the "service economy" was driven by technological differences in the substitutability of energy (plus capital) for labor together with the cheap energy of the past. This explains why, in industry and transport (the sectors with a high energy intensity of production), productivity increases are in real terms significantly higher than in the commercial service sector (with low energy intensity). The divergence that occurred between the sectors' labor productivity induced not only a migration of employment from the industry to the commercial service sector. It also generated lasting cost differentials, epitomized by Baumol's cost disease of the service sector. The differentials seem to have largely been compensated by a price level rising faster for commercial services than for industrial products and transport services. In nominal terms, productivity differences between the sectors were thus leveled off and, by the same token, the value added share of commercial services inflated.

To test our hypotheses empirically, we analyze the existence of a cointegration relationship among labor productivity and the variables derived from our model by means of the Autoregressive Distributed Lags (ARDL) bounds test developed by Pesaran and Shin (1999) and Pesaran et al. (2001). We find evidence of cointegration only in the sectors industry and transport, implying that the development of labor productivity in the commercial sector is independent of energy-related parameters.

If our explanation of the role of energy for the rise of the "service economy" is correct, the analysis holds some interesting implications for the future. Since the turn of the millennium energy prices have been rapidly rising. If they continue to do so, it would be rather unlikely that the apparently incessant growth of the commercial sector in terms of value added and employment continues. Productivity increases in the other two, energy-intensive, sectors would likely slow down as the incentive to further substitute energy for labor would fade out there. In the commercial sector, where energy-for-labor substitution did not play much of a role in the past, the development of labor productivity (in real terms) would be less affected by rising energy prices. Consequently, the productivity growth differential between what were "progressive" and "stagnant" sectors may decline or even disappear as would, in that case, Baumol's cost disease. Productivity growth would then slow down economy-wide and so would economic growth.

5

Can Declining Energy Intensity Mitigate Climate Change? Decomposition and Meta-Regression Results[1]

5.1 Introduction

Ever since the First Assessment Report on Climate Change by the Intergovernmental Panel on Climate Change (IPCC) in 1990, there has been an ongoing debate on the quantification of future greenhouse gas emission (e.g. Hoffert et al., 1998; Canadell et al., 2007; Le Quéré et al., 2009). In the economic field, the carbon intensity, i.e., the ratio between carbon emissions and economic production (GDP), is often used to assess the state of an economy in climate change mitigation. An economy that is able to sustain GDP growth without having a negative impact on environmental conditions is said to be decoupled. Exactly how, if, or to what extent this can be achieved is a subject of much debate.

To assess the determinants of carbon intensity analysts often use the Kaya identity, which was originally proposed by the Japanese energy economist Yoichi Kaya (see, e.g., Raupach et al., 2007; Galiana and Green, 2009). The Kaya identity relates the carbon intensity to its main driving factors: the energy intensity of production

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[1] This chapter is based on Bruns, S.B. and C. Gross, 2012, Can Declining Energy Intensity Mitigate Climate Change? Decomposition and Meta-Regression Results, Papers on Economics and Evolution #1211.

(Energy/GDP) as well as the carbon intensity of energy (CO_2/Energy). It plays a core role, e.g., in the IPCC Special Report on Emissions Scenarios (SRES, see Nakicenovic et al., 2000).

In achieving today's lower carbon intensity, however, some argue that the extent to which its main driver, the energy intensity, has declined will not proceed. Still, most SRES scenarios rely on a rapid and ongoing decline in energy intensity (exceeding 1.0% per year). Apart from energy savings due to technological progress, a significant part of the decline can be attributed to structural changes such as sectoral shifts as well as offshoring of industrial production. However, the effect of the described structural changes on the relation between energy and GDP is twofold. Apart from contributing to lower energy intensity, these factors also have biased national statistics (Kander, 2005; Henriques and Kander, 2010; Gross, 2012). All of these effects tend to hide the true relationship, namely that energy and GDP are closely related (Cleveland et al., 1984).

If, in fact, energy and GDP go hand in hand, the energy intensity cannot be arbitrarily reduced. Using meta-significance testing (Stanley, 2005; 2008) for a sample of 44 studies and 534 causality tests, which deal with the causality between energy and GDP, we find that energy and GDP are strongly coupled. In addition, we find support for our reasoning that the described structural changes play a major role in hiding the true relationship.

This finding has some strong implications for emission scenarios based on the Kaya identity, since it does not account for possible interactions among the (explaining) variables. When the described structural changes come to a halt, the decline in energy intensity cannot pass on unchanged. It is more likely that it will converge to a (high) level, as will the carbon intensity in the short term. If the coupling between energy and growth persits, the consumption of energy must further increase to enable economic growth in the future. As a consequence, carbon emissions will catch up unless the carbon intensity of energy has been reduced sufficiently. Similarly, the only strategy to reach our climate targets in the long run is to invest in the decarbonization of energy use today, widely irrespective of the development of energy intensity.

We proceed as follows: in Section 5.2 we discuss the particular role of energy intensity in emission scenarios. In Section 5.3 we present the dataset which we use for meta-significance testing. It is followed by a discussion of the results. Section 5.4 concludes.

Table 5.1 — Values for the Kaya Identity

Income class	CO_2/GDP		CO_2/Energy		Energy/GDP	
Low/Middle	1.77	(2.08)	2.67	(2.07)	0.66	(1.01)
High	0.43	(0.88)	2.35	(2.83)	0.18	(0.31)
World	0.79	(1.21)	2.70	(2.80)	0.29	(0.43)

Note: Values for 2008 (1971) are taken from the World Development Indicators (2012a-c).

5.2 The Role of Energy Intensity in Climate Change Mitigation

In order to assess the trends in decoupling and its economic and technological drivers, we decompose carbon emissions according to the Kaya identity[2] (Nakicenovic et al., 2000; Nakicenovic, 2004):

$$\frac{\mathrm{CO_2}}{\mathrm{GDP}} = \frac{\mathrm{CO_2}}{\mathrm{Energy}} \frac{\mathrm{Energy}}{\mathrm{GDP}}. \tag{5.1}$$

Accordingly, carbon intensity is the product of carbon intensity of energy (measured, e.g., in grams of carbon dioxide released per megajoule of energy consumed) as well as (economic) energy intensity (measured, e.g., in megajoule of energy consumed per Dollar of output). Overall, the decline in carbon intensity over the last decades is mainly driven by the lower energy intensity (Table 5.1). The carbon intensity, in contrast, remains almost constant, since the increase in carbon intensity of energy in Low- and Middle-income countries outweighs the decline in High-income countries (see also Fig. C.1 and C.2).

The declining average carbon intensity of energy over time is referred to as decarbonization. In general terms, it can be achieved through technical progress or a switch to energy sources with lower carbon emissions (e.g., Pacala and Socolow, 2004; Ragauskas et al., 2006; Shinnar and Citro, 2006; Tilman et al., 2006; Muradov and Veziroglu, 2008). Historically, the decarbonization rate of the world's energy system was found to be constant at a rate of about 0.3% per year throughout previous decades (Nakicenovic, 1996). The median of all the SRES scenarios indicates a continuation of the historical trend, with a decarbonization rate of about 0.4% per year,

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[2] Another variant of the decomposition takes population growth into account. It would additionaly scale up projections for the carbon intensity (O'Neill et al., 2010).

which is similar to the trend in the IPCC IS92a baseline scenario (Leggett et al., 1992). Deviating from that, Fig. C.3 indicates even a tendency of re-carbonization ever since the turn of the millennium. This can mainly be explained by the accelerated industrialization of China and India (Raupach et al., 2007).

A timely question therefore is, which factors facilitated the rapid decline in energy intensity — still, the main driver of decoupling. Can the decline in energy intensity persist in the future? First, a distinction must be drawn between economic energy intensity (used for the Kaya decomposition) and technical energy intensity. The overall effect of increasing technical efficiency on energy consumption has been discussed controversially. What is labeled the 'rebound effect' describes the circumstance that a new energy-saving technology may partly, or entirely, offset the initial or direct energy saving due to substitution and income effects (see, e.g., Brännlund et al., 2007; Druckman et al., 2011). Since the relationship between decreasing technical energy intensity and economic energy intensity is not well enough understood (Sorrell, 2009), the primary reliance of most SRES emission scenarios on declining economic energy intensity should be critically scrutinized (Pielke et al., 2008).[3]

Instead of effective energy-saving technological innovations, some argue that structural changes are a major determinant of the recent decline in energy intensity. Particular attention is given to shifts in economic activity from industrial production to less energy consuming services as well as the increasing neglect of indirect energy consumption due to an offshoring of industrial production. With regard to shifts in economic activity, a decline of energy intensity of about 20% (±10%) can be expected (Baksi and Green, 2007). Apart from effective energy savings, it has been argued that the observed decline in energy intensity is overrated (Kander, 2005; Henriques and Kander, 2010). Since the average price of output of most services is inflated, the ratio between GDP and energy diverges even more than solely due to sectoral shifts. With regard to the neglect of indirect energy consumption, the increasing imports of non-energy (intermediate) goods from low-wage countries entails an overvaluation of the value added from goods producing sectors in importing countries as well as a neglect of indirect energy consumption from exporting nations (OTA, 1990; Houseman et al., 2010; Gross, 2012). Hence, the energy intensity recorded by national statistics declines, although the energy consumed for end-use products, and thus the global energy intensity, remains unaffected.

Ultimately, the debate revolves around the core question whether, or to what extent, the coupling between energy and GDP can be broken up. Apart from the po-

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[3] When the term "energy intensity" is used in the remainder, we mean economic energy intensity.

tential to effectively reduce energy intensity, the question is yet unanswered whether there is still an underlying causal relationship between both variables (Ozturk, 2010; Payne, 2010). In a meta-regression analysis of the relationship between energy and GDP, Bruns et al. (2012) find that the relationship between energy and GDP has become noticeably weaker. Card and Krueger (1995) argue that such a finding can have two reasons, either publication bias or structural changes, which hides the true effect between the variables, namely that energy and GDP are closely related (Cleveland et al., 1984).[4]

Accordingly, with regard to the relationship between energy and GDP, we hypothesize that the true effect can only be found, if the relation between energy and GDP has not been distorted by structural changes. If such a causal mechanism exists, energy and GDP are not adequately represented by a ratio in a simplified decomposition analysis. To give an example, if GDP strongly depends on the consumption of energy, a reduction of energy would not necessarily lower the energy intensity. Instead, economic growth would slow down too so that the energy intensity remains constant after all. Since the carbon intensity of energy is fixed in the short term, the carbon intensity would stay constant, too.

5.3 Empirical Analysis

5.3.1 Data Selection and Estimation Strategy

Our empirical analysis is based on 44 studies which investigate the causality between total energy consumption and total GDP according to, e.g., Granger (1969) and Engle and Granger (1987). Most of the studies are recorded in two recently published surveys (Ozturk, 2010; Payne, 2010). In addition, we searched Scopus, EconLit, as well as Google Scholar for combinations of the keywords "Energy", "Growth", "Income", "Output", "Economy", "Causality", "Cointegration", and "Relation".[5] In sum, the sample contains 534 causality tests for 77 different countries.

We use meta-significance testing (MST) to investigate the presence of a true empirical effect (Stanley, 2005, 2008). Given the presence of a true effect, the standardized test statistic of a regression coefficient increases with the square root of the degrees of freedom. If there is no true empirical effect, the test statistic should be independent of the degrees of freedom and vary randomly around zero. This relationship is

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[4] With regard to the first objection, Bruns et al. (2012) argue that, in the case of the literature on energy and GDP, publication bias is negligible. As neutrality between energy and GDP is also considered a relevant finding, those studies with insignificant results have not been systematically excluded from publication.

[5] For a detailed discussion of the data collection see Bruns et al. (2012).

represented by the test regression

$$\ln |t_i| = \beta_0 + \beta_1 \ln df_i + \varepsilon_i, \tag{5.2}$$

where t is the value of the test statistic and df the degrees of freedom. If $\beta_1 > 0$, there is evidence for a true effect. Alternatively, if $\beta_1 = 0$, there is no effect. If $\beta_1 < 0$, the relationship between energy and GDP is subject to structural changes (Card and Krueger, 1995).

We disentangle the impact of structural changes on the relationship between energy and GDP by subsequently dividing the dataset into subsamples. Then, we run the MST regression in each subsample. We drop outliers which lie outside a distance of two standard errors around the mean in both dimensions, namely the test statistic and the degrees of freedom.[6] Following our theoretical considerations, the reductions in energy intensity occured mainly due to sectoral shifts, as well as the neglect of indirect energy consumption due to offshoring.

Almost all countries are characterized by a transition toward services. Hence, we define structural stability as a permanently high industry share in GDP. As the amount of energy required per unit of output is considerably higher in the industries than in the services, the distortion of the link between energy and GDP at the macro level is lower if the industry share remains constantly high. To select the subsample of countries with a high share of industry in GDP we, first, take a high initial industry share in the earliest available period (1960-1980). Subsequently, we break up the subsamples into studies from countries with a sufficiently high share in the latest available period (2005-2010). This procedure allows us to identify those countries with low distortions due to sectoral shifts. Finally, in order to approximate offshoring, we subdivide the resulting subsamples into studies for countries where there is a low share of imports in GDP in the latest available period (2005-2010). We take the first and, respectively, the last values within the described time frames, because the starting and ending date of the times series varies among the countries. By doing so, we assure that we do not loose too many observations. The time frames chosen for early and late values coincide with the usual time frame of the underlying studies. The corresponding data are taken from the World Development Indicators (2012d-e).

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[6] Since we drop outliers in every subsample individually, the sample size of subsamples may not add up to the sample size of the corresponding original sample.

Table 5.2 — Estimations for Beta 1 Coefficients: Energy Causes GDP

Industry share (early)			And industry share (late)			And import share (late)		
> 40%	-0.09	[50]	> 25%	0.53	[39]	> 30%	−0.59	[15]
						< 30%	1.47***	[23]
			< 25%	−0.01	[11]	> 30%	−0.01	[11]
						< 30%		[0]
< 40%	−0.77***	[198]	> 25%	−0.53*	[136]	> 30%	−0.67**	[73]
						< 30%	−0.70·	[61]
			< 25%	−0.79***	[63]	> 30%	−0.41·	[22]
						< 30%	−0.64*	[43]

Note: ***,**,*,· denotes significance at the 1%, 5%, 10%, 15% level; number of observations in squared brackets; inference based on bootstrapping.

5.3.2 Results

The results for MST are listed consecutively as paths of structural change and/or structural stability (Table 5.2). To give an example, a path of structural stability is "Industry share (early) > 40%", followed by "Industry share (late) > 25%", as well as "Import share (late) < 30%". This economy is characterized by an initially high industry share without marked tertiarization: the average industry share of the underlying countries is 58% at the beginning of the period and 42% at the end. In line with our hypothesis, namely that evidence for the true effect can be found in subsamples of structural stability, we find a significantly positive beta coefficient. Accordingly, we conclude that energy consumption causes economic growth, which also implies that energy and GDP are strongly coupled. This subsample of 23 significantly positive causality tests comprises studies which are conducted for China, Japan, and Argentina. On the contrary, even though the late industry share remains high, MST cannot detect a coupling for those countries with a high level of imports.

All countries with a low industry share at the beginning show significantly negative beta coefficients throughout. Since the degrees of freedom coincide with the respective time span of each study, the negative coefficient suggests that structural changes have increasingly confounded the initial coupling between energy and GDP. With regard to the reverse direction of causality, namely from GDP to energy, the results for MST show a fairly similar pattern (Table C.1). However, most of the results are not found to be significant. It indicates that the coupling between energy and GDP tends to be asymmetric.

In addition, we systematically check the robustness of the results. The observed patterns are robust with regard to alternative classifications of subsamples. However, we find that an initially high industry share is needed to identify the true effect. Otherwise, the true effect is overlapped by structural changes already from the outset.

5.3.3 Discussion of Results

Our findings indicate that the true effect, namely that energy and GDP are strongly coupled, is potentially confounded by several structural changes. Apparently, in those countries where the changes occured, it is unlikely that the changes will continue as they did in the past. The (relative) size of the industrial sector cannot be randomly reduced. Similarly, the incentives to further offshore industrial production may disappear when environmental regulations in developing are strengthened or if the labor costs increase. Hence, we infer that the energy intensity will converge to a level considerably larger than zero, since economic growth will continue to be dependent on a sufficient supply of energy. In other words, economic growth cannot be decoupled from energy consumption if the causal link persists.

In a similar vein, the decline of the carbon intensity will not continue to decline unless the carbon intensity of energy is sufficiently reduced. Hence, we should not uncritically rely on the promising decoupling of carbon emissions from GDP observed over the last decades. Not only was the decoupling partly driven by nonrecurring structural changes but these structural changes also resulted in an overvaluation of the decline in energy intensity. Instead, attention should be focused on the decarbonization of energy use, widely irrespective of the development of the energy intensity.

5.4 Conclusions

Starting from the question whether declining energy intensity can mitigate climate change, we decompose the determinants of carbon intensity reduction according to the Kaya identity. A shortcoming of such a simplified decomposition approach, we argue, is that it cannot account for possible interactions between the (explaining) variables. Using meta-significance testing based on 44 studies dealing with the causality between energy and GDP, we find evidence for a strong interdependence between both variables. We conclude that the energy intensity cannot be arbitrarily reduced but may converge to a level, which is likely to be too high to reach our climate targets. In order to effectively mitigate climate change, we should, therefore, not rely on a persistently declining energy intensity. Instead, there is an urgent need to invest in the decarbonization of energy use, widely irrespective of the development of energy intensity.

6

Conclusions and Outlook

This dissertation is another step towards a better understanding of the role of energy in the economy. Although renowned theorists such as Cleveland et al. (1984) and Ayres and Warr (2009) argue that energy and GDP are strongly coupled, the evidence from an empirical perspective is often ambiguous (Ozturk, 2010; Payne, 2010). We address this pressing question from different angles, namely by means of meta-regression techniques, by introducing important findings from strands of literature other than the empirical energy-growth literature, and by augmenting Baumol's cost disease model with energy-related parameters. All in all, we find that the way how the relationship between energy and growth has been investigated often underrates the importance of energy for our economic system.

In Chapter 2 we conclude that the relationship between energy and GDP should be reconsidered from an empirical point of view, because the empirical evidence has systematically moved away from what can be considered a true effect from a theoretical point of view, namely that energy and GDP are closely related (Cleveland et al., 1984; Ayres and Warr, 2009). The systematic decline in empirical evidence is reflected by an overall negative estimation coefficient between the test statistic and the degrees of freedom derived from our meta-significance analysis based on Stanley (2005; 2008). The analysis covers 1020 causality tests between energy consumption and GDP from a total of 75 studies and 108 countries.

Moreover, we find that both the impact of the level of (sectoral) aggregation of output as well as the choice of control variables as well as the development stage significantly affects the results. With regard to the level of sectoral aggregation, we confirm that results from causality tests may be spurious if the level of aggregation is not appropriate, in the sense that the scope of economic activity differs among the explaining variables (Zachariadis, 2007; Gross, 2012). In addition, the inclusion of control variables may affect the causality between energy and GDP, if they are highly correlated with (one of) the explaining variables. The development stage of the economy has an effect insofar as in High income countries the evidence for causality has been significantly more confounded compared to Low income countries. Contrary to frequent conjectures expressed in the literature, the choice of the methodology alone does not affect the finding of causality. We argue that reasons for this can rather be found in contextual aspects of each underlying study. Finally, we find that the differentiation between total energy and single energy sources does not have an effect in High income countries. This, in our view, may lead to problematic policy implications if the relationship between energy and GDP is traced back to a single energy source, although it is highly correlated with total energy consumption.

We emphasize the need to develop a better theoretical foundation for empirical analyses of the relationship between energy and GDP. By bringing insights from the environmental Kuznets curve literature to the causality approach, the study by Gross (2012) takes a new path to account for the nonmonotonic relationship between energy and GDP. We should further disentangle the underlying dynamics so that the relationship between energy and GDP can be adequately assessed.

In Chapter 3 we analyze the Granger causality between energy and growth in the U.S. for the period from 1970 to 2007 on the macro level as well as for the industry sector, the commercial sector, and the transport sector. For our analysis we used the recently developed ARDL bounds testing approach as proposed by Pesaran and Shin (1999) and Pesaran et al. (2001).

Our paper contributes to the literature in several ways: (1) based on Zachariadis (2007), we analyze the existing energy growth literature for the U.S. with respect to the choice of appropriate variable pairs for causality analyses and discuss why the evidence is ambiguous. We conclude that only sectoral value added together with sectoral final energy consumption covers the same scope of economic activity and that the sector level should be preferred to the macro level. (2) We also emphasize the fundamental differences between goods and service producing industries and its implications for the relationship between energy and growth in each sector. We argue that, due to the inseparability of the production chain of service producing industries, there exists a closer relationship between energy and growth than in goods producing industries. As the energy intensive production of intermediate goods can be offshored to developing countries, the relationship between industry value added (accounted for in national statistics) and energy consumption, whereas the indirect consumption of energy is not accounted for, is weaker. (3) We combine the well-established methodology from the energy growth literature with major findings from the EKC literature as well as its limitations discussed in the literature. We show that augmenting the basic bivariate model with variables controlling for trade and energy productivity significantly improves the fit of several model specifications. (4) We find that Granger causality between energy consumption and economic growth are not always forced by the same (control) variables. This is the case when we do not find cointegration or the BIC is not minimized for the same model where energy and growth are the dependent variables.

In contrast to most bivariate analyses at the macro level, we conclude that the causal relationship between energy consumption and economic growth is much closer than is normally assumed. Our results confirm that long-run Granger causality between energy consumption and economic growth can rather be found on the sectoral level. We find evidence for bi-directional long-run Granger causality in the transport sector. However, once the increasing energy productivity of the capital stock is controlled for, the relationship breaks. In the commercial sector we find evidence for long-run Granger causality from growth to energy, if energy productivity is controlled for. The fundamental difference between goods and service producing industries also shows the differential impact of trade on the relationship between energy and growth. Once trade is controlled for, we find evidence for short-run Granger causality running from energy and trade to growth in the industry sector.

Concerning the implications, which can be drawn from the results, we strongly recommend the choice of an appropriate level of aggregation for Granger causality analyses in the energy growth literature. If evidence for Granger causality cannot be found at the macro level, the implication that no causality exists at all is myopic (Simpson's paradox). Even though no evidence for long-run Granger causality can be found at the macro level, policies which aim at the reduction of energy consumption could, in fact, affect individual sectors, both in the long run as well as in the short run. International policies which aim at stricter environmental regulations for developing countries would also indirectly affect the home country if the indirect consumption of energy is not internalized.

Finally, the long-run relationship between energy and growth is not carved in stone. We show that efforts to increase the energy productivity of the capital stock allow to break the long-run relationship between energy and growth in the transport sector. As long as the 'rebound effect' of increasing energy productivity does not outweigh the conservation of energy, a de-coupling between energy consumption and economic growth is possible. However, for this purpose we have to be aware of the 'real' relationship between energy consumption and growth, which tends to be undervalued in inappropriate model specifications.

In Chapter 4 we highlight the role that energy plays in the context of the growth of the "service economy". We distinguish three sectors in our analysis: industry, transport, and commercial services. The "service economy" is characterized by a dominant role of the commercial service sector in terms of value added and employment. In order to understand the importance of energy, disaggregating to the sectoral level is essential. Empirical tests which investigate the causality from energy consumption to economic growth at an aggregate level often reject the hypothesis that there exists a causal link. Our empirical analysis shows, however, that energy-related factors did have an impact on the growth of the U.S. economy over the period 1970-2005 at the sectoral level.

According to this theory, the rise of the "service economy" was driven by technological differences in the substitutability of energy (plus capital) for labor together with the cheap energy of the past. This explains why, in industry and transport (the sectors with a high energy intensity of production), productivity increases are in real terms significantly higher than in the commercial service sector (with low energy intensity). The divergence that occurred between the sectors' labor productivity induced not only a migration of employment from the industry to the commercial service sector. It also generated lasting cost differentials, epitomized by Baumol's cost disease of the service sector. The differentials seem to have largely been compensated by a price level rising faster for commercial services than for industrial products and transport services. In nominal terms, productivity differences between the sectors were thus leveled off and, by the same token, the value added share of commercial services inflated.

To test our hypotheses empirically, we analyze the existence of a cointegration relationship among labor productivity and the variables derived from our model by means of the Autoregressive Distributed Lags (ARDL) bounds test developed by Pesaran and Shin (1999) and Pesaran et al. (2001). We find evidence of cointegration only in the sectors industry and transport, implying that the development of labor productivity in the commercial sector is independent of energy-related parameters.

If our explanation of the role of energy for the rise of the "service economy" is correct, the analysis holds some interesting implications for the future. Since the turn of the millennium energy prices have been rapidly rising. If they continue to do so, it would be rather unlikely that the apparently incessant growth of the commercial sector in terms of value added and employment continues. Productivity increases in the other two, energy-intensive, sectors would likely slow down as the incentive to further substitute energy for labor would fade out there. In the commercial sector, where energy-for-labor substitution did not play much of a role in the past, the development of labor productivity (in real terms) would be less affected by rising energy prices. Consequently, the productivity growth differential between what were "progressive" and "stagnant" sectors may decline or even disappear as would, in that case, Baumol's cost disease. Productivity growth would then slow down economy-wide and so would economic growth.

In Chapter 5 we combine the findings of the previous chapters and transfer them to the recent emission scenarios of the IPCC. Starting from the question whether declining energy intensity can mitigate climate change, we decompose the determinants of carbon intensity reduction according to the Kaya identity. A shortcoming of such a simplified decomposition approach, we argue, is that it cannot account for possible interactions between the (explaining) variables. Using meta-significance testing based on 44 studies dealing with the causality between energy and GDP, we find evidence for a strong interdependence between both variables. We conclude that the energy intensity cannot be arbitrarily reduced but may converge to a level, which is likely to be too high to reach our climate targets. In order to effectively mitigate climate change, we should, therefore, not rely on a persistently declining energy intensity. Instead, there is an urgent need to invest in the decarbonization of energy use, widely irrespective of the development of energy intensity.

At the basis of all these findings, we conclude that energy, indeed, plays a significant role in the economy. Calculations of future energy demands need to take into account that the potential to decouple economic growth from the consumption of energy is limited. Since there are many indications that energy and GDP are causally interlinked, an underprovision of energy supply would entail the risk of lower growth potentials. Since we show that even the growth of the less energy consuming service sector indirectly depends on energy via an energy-related "cost disease", strategies which were intended to reduce the consumption of energy widely failed to break the relationship between energy and GDP. In this respect, rising energy costs may also raise problems to the service economy, still the major driver of economy-wide growth.

Hence, we should take into account that economic growth rates may be considerably lower in the near future if the rise in energy prices persists. In such a case, we might soon be confronted with the choice of two fundamentally different strategies. First, it has been suggested to return to cheap but high-emitting fossil fuels. This would keep the average price of energy low and enable persistent economic growth in a low energy price regime. However, if new technologies to neutralize the resulting emissions — such as Carbon Dioxide Capture and Storage — does not become operational, the carbon intensity of energy would again strongly increase. Our finding that the decline in carbon intensity has been driven almost exclusively by the decline in energy intensity (which may come to a halt in the near future for the reasons discussed in Chapter 5) reiterates the danger of a return to high-emitting fossil fuels. In this respect, a weakness of those mainstream economic growth models becomes apparent, which sensitively rely on high levels of (unexplained) technological progress or widely ignore the importance of energy for economic growth or the environmental impact related to the emission of greenhouse gases.

Since leading climate researchers argue that an increase of the average world temperature of more than two degrees may entail unforeseeable climatic disasters, the focus of any energy policy needs to be concentrated on an alternative strategy, namely the decarbonization of energy use. In this respect, a milestone will be the development of an economic growth theory which resolves the apparent conflict of objectives between high rates of economic growth on the one hand and increasing pollution on the other.

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Appendix A

Table A.1 — Estimations for Beta 1 Coefficients: Non-Macro Energy and Non-Macro GDP

Direction of causality			Energy aggregation			Development stage			Control variables			Cointegrated		
Energy causes growth	−0.01	[85]	Total	0.03	[53]	Low	−0.14	[8]	Yes		[0]	Yes		[0]
												No		[0]
									No	−0.14	[8]	Yes		[$\emptyset$]
												No		[$\emptyset$]
						High	−0.03	[49]	Yes		[0]	Yes		[0]
												No		[0]
									No	−0.03	[49]	Yes	−4.11	[8]
												No	0.36	[42]
			Disaggr.	−0.35	[281]	Low	0.22	[18]	Yes		[0]	Yes		[0]
												No		[0]
									No	0.22	[18]	Yes	−4.12***	[12]
												No	0.47	[4]
						High	2.48*	[13]	Yes	−6.19***	[4]	Yes		[$\emptyset$]
												No		[$\emptyset$]
									No	0.00^a	[9]	Yes		[$\emptyset$]
												No		[$\emptyset$]
Growth causes energy	−0.57**	[90]	Total	−0.81	[55]	Low	−0.75**	[8]	Yes		[0]	Yes		[0]
												No		[0]
									No	−0.75**	[8]	Yes		[$\emptyset$]
												No		[$\emptyset$]
						High	−0.82	[51]	Yes		[0]	Yes		[0]
												No		[0]
									No	−0.82	[51]	Yes	8.03***	[7]
												No	−1.48	[43]
			Disaggr.	−0.62	[31]	Low	−0.05	[19]	Yes		[0]	Yes		[0]
												No		[0]
									No	−0.05	[19]	Yes	0.00	[15]
												No	6.90***	[4]
						High	−0.45	[12]	Yes	70.89	[4]	Yes		[$\emptyset$]
												No		[$\emptyset$]
									No	0.00^a	[9]	Yes		[$\emptyset$]
												No		[$\emptyset$]

Note: ***,**,* denotes significance at the 1%, 5%, 10% level; number of observations in squared brackets; inferences based on bootstrapping; [$\emptyset$] indicates that the number of observations from the previous step is too low; ^{a}MST cannot be applied due to identical *df*.

Appendix B

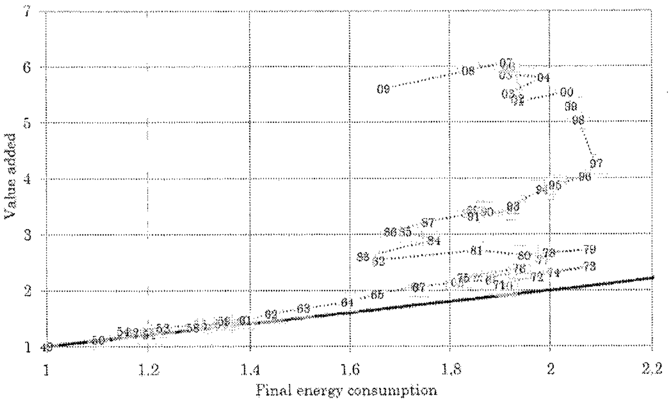

Fig. B.1: Development of value added and final energy consumption in the industry sector, 1949-2009 (1949=1); solid line represents constant energy intensity.

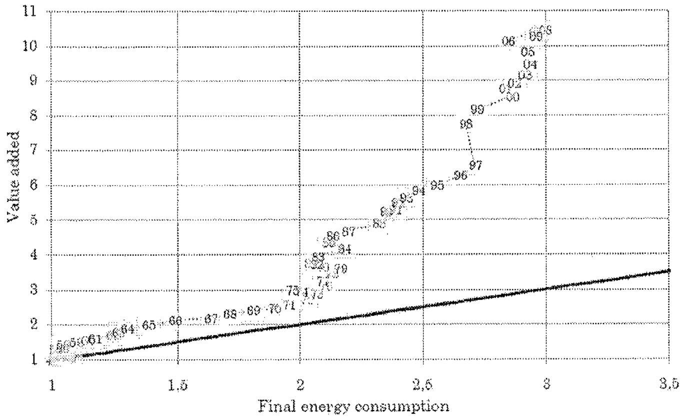

Fig. B.2: Development of value added and energy consumption in the commercial sector, 1949-2009 (1949=1); solid line represents constant energy intensity.

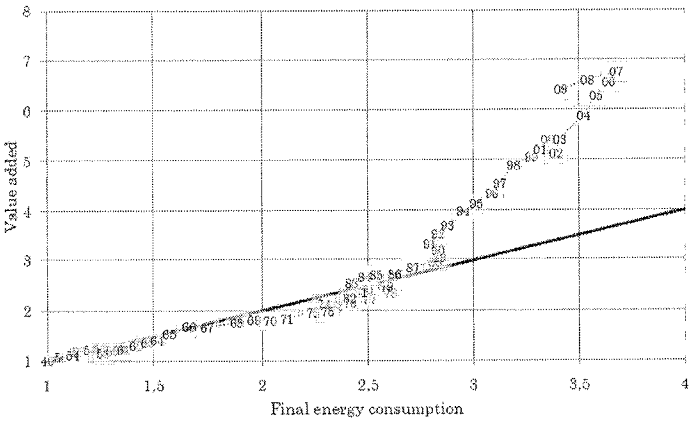

Fig. B.3: Development of value added and energy consumption in the transport sector, 1949-2009 (1949=1); solid line represents constant energy intensity.

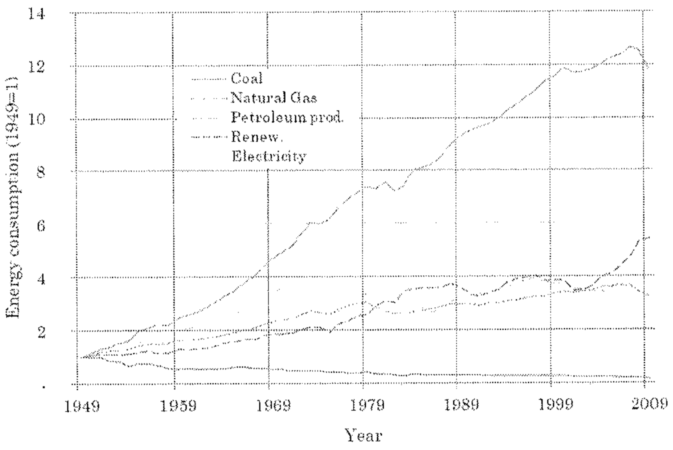

Fig. B.4: Consumption of different energy sources 1949-2009.

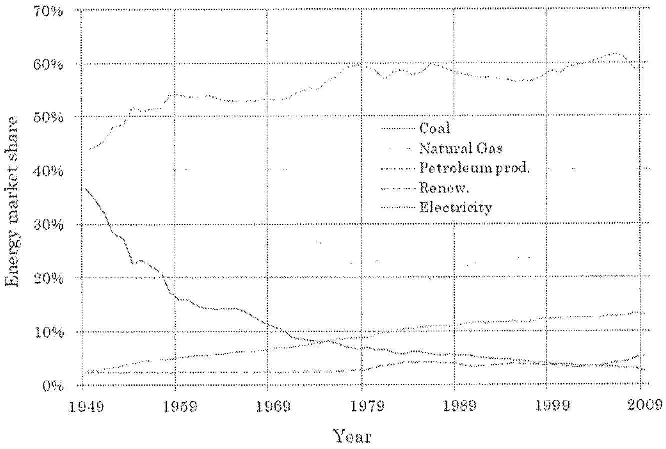

Fig. B.5: Market shares of different energy sources (Btu) 1949-2009.

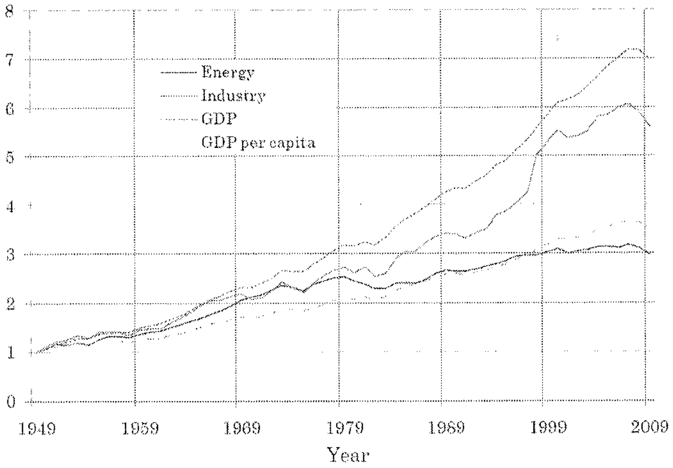

Fig. B.6: Development of energy, manufacturing value added, GDP, and GDP per capita 1949-2009 (1949=1); the industry index is proxied by industry value added.

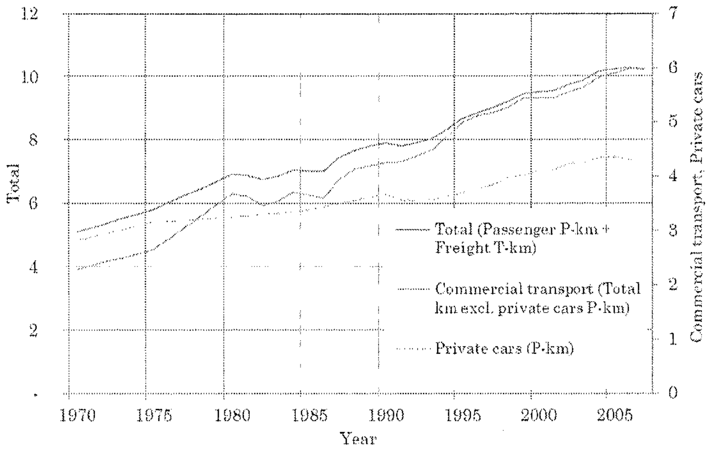

Fig. B.7: Development of Mio total transport km, Mio commercial transport km, and Mio private cars km (1970-2007).

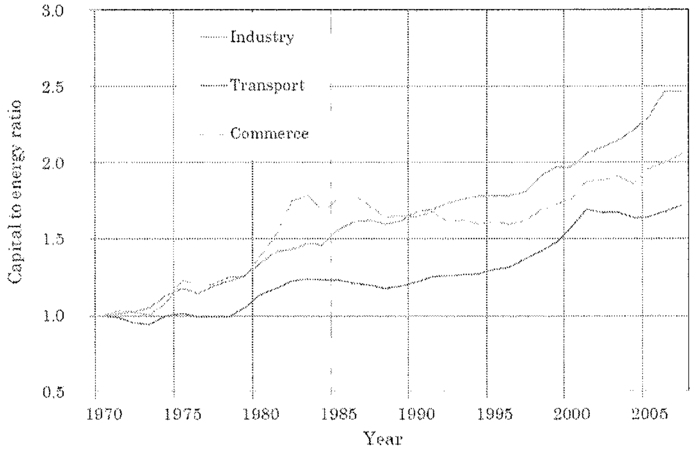

Fig. B.8: Development of the capital to energy ratio in the three sectors, 1970-2007 (1970=1).

Table B.1 — U.S. Energy-Growth Literature

Author(s)	Years	Method(s)	EC	Gr	Y
Kraft and Kraft (1978)	1947-1974	Sims	Total energy	←	GNP
Akarca and Long (1980)	1950-1970	Sims	Total energy	↮	GNP
Yu and Hwang (1984)	1947-1979	Sims	Total energy	↮	GNP
Yu and Choi (1985)	1947-1979	Granger	Total energy	↮	GNP
Abosedra and Baghestani (1991)	1947-1987	Granger	Total energy	←	GNP
Yu and Jin (1992)	1974–1990	Engle-Granger	Total energy	↮	Industry index
Stern (1993)	1947-1990	Granger	Total energy (Divisia)	→	GDP
			Total primary energy	←	GDP
Cheng (1995)	1947-1990	Hsiao	Total energy	↮	GNP
Murry and Nan (1996)	1970-1990	Granger	Electricity	↮	GDP
Zarnikau (1997)	1970-1992	Granger	Total energy & Divisia	↮	GDP
		Instantaneous Granger	Total energy & Divisia	↔	GDP
Stern (2000)	1948-1994	Johansen-Juselius	Total energy (Divisia)	→	GDP
Soytas and Sari (2003)	1950-1992	Engle-Granger	Total energy	↮	GDP per capita
Thoma (2004)	1973-2000^m	Granger	Sector electricity	←	Industry index
Chontanawat et al.(2006; 2008)	1960-2000	Hsiao	Total energy per capita	↮	GDP per capita
Lee (2006)	1960-2001	Toda-Yamamoto	Total energy	↔	GDP per capita
Soytas and Sari (2006)	1960-2004	Johansen-Juselius	Total energy	→	GDP per capita
Soytas et al. (2007)	1960-2000	Toda-Yamamoto	Total energy	↮	GDP
Zachariadis (2007)	1949-2004	ARDL bounds test	Total energy	↮	GDP
		(reported here)	Service energy	←	Service VA
			Manufacturing energy	↮	Manufacturing VA
			Transport energy	←	GDP
Chiou-Wei et al. (2008)	1960-2003	Johansen-Juselius	Total energy	↮	GDP
Narayan and Smyth (2008)	1970-2002	Granger (bootstrapped)	Electricity	↮	GDP
Sari et al. (2008)	2001-2005^m	ARDL bounds test	Single energy sources	←	Industry index
Bowden and Payne (2009)	1949-2006	Toda-Yamamoto	Total primary Energy	↮	GDP
			Service primary Energy	↔	GDP
			Manufact. primary Energy	→	GDP
			Transport primary Energy	↮	GDP
			Residential primary Energy	↔	GDP
Payne (2009)	1949-2006	Toda-Yamamoto	(Non-) renewables	↮	GDP
Payne and Taylor (2010)	1957-2006	Toda-Yamamoto	Nuclear	↮	GDP
Warr and Ayres (2010)	1946-2000	Johansen-Juselius	Exergy	→	GDP

Notes. ^{m}monthly data

Table B.2 — Lag Order Selection for Unrestricted ECM

				Dependent variable							
Sector	Model			ΔY					ΔEC		
Macro	A	(1	3	–	–	–)	(3	0	–	–	–)
Industry	A	(1	0	–	–	–)	(1	0	–	–	–)
	B_1	(1	0	0	–	–)	(1	0	0	–	–)
	B_2	(1	0	–	0	–)	(1	0	–	0	–)
	B3	(1	0	–	–	0)	(1	0	1	–	–)
	C_1	(1	0	0	0	–)	(1	0	1	0	–)
	C_2	(1	0	0	–	0)	(1	0	0	–	0)
	C_3	(1	0	–	0	0)	(1	1	–	1	0)
	D	(1	0	0	0	0)	(1	0	0	1	0)
Commercial	A	(1	0	–	–	–)	(1	0	–	–	–)
	B_1	(1	0	0	–	–)	(1	0	0	–	–)
	B_2	(1	0	–	0	–)	(2	0	–	2	–)
	B_3	(1	0	–	–	0)	(1	0	–	–	0)
	C_1	(1	1	0	0	–)	(2	0	0	2	–)
	C_2	(1	0	0	–	0)	(1	0	0	–	0)
	C_3	(1	0	–	0	0)	(2	0	–	2	0)
	D	(1	0	0	0	0)	(2	0	0	2	0)
Transport	A	(1	0	–	–	–)	(1	0	–	–	–)
	B_1	(1	0	0	–	–)	(1	0	0	–	–)
	B_2	(3	1	–	1	–)	(1	0	–	1	–)
	C_1	(3	1	1	0	–)	(1	0	1	0	–)

Note. Lags for $(\Delta Y, \Delta EC, \Delta EP, \Delta CAP, \Delta TRADE)$ if ΔY is the dependent variable; $(\Delta EC, \Delta Y, \Delta EP, \Delta CAP, \Delta TRADE)$ *vice versa.*

Table B.3 — Lag Order Selection for Restricted ECM

				Dependent variable							
Sector	Model			ΔY					ΔEC		
Macro	A	(1	0	–	–	–)	(1	0	–	–	–)
Industry	A	(1	0	–	–	–)	(1	0	–	–	–)
	B_2			—			(1	0	–	1	–)
	B_3	(1	0	–	–	0)			—		
Commercial	A	(1	0	–	–	–)	(1	0	–	–	–)
	B_2	(1	0	–	0	–)	(2	0	–	2	–)*
	C_3			—			(2	0	–	0	2)*
Transport	A	(1	0	–	–	–)*	(1	0	–	–	–)*
	B_1			—			(1	0	0	–	–)*
	B_2			—			(1	0	–	1	–)*
	C_1			—			(1	0	1	0	–)*

Note. Lags for $(\Delta Y, \Delta EC, \Delta EP, \Delta CAP, \Delta TRADE)$ if output is the dependent variable; $(\Delta EC, \Delta Y, \Delta EP, \Delta CAP, \Delta TRADE)$ *vice versa*;
*Lag order corresponds to cointegrated unrestricted ECM.

Table B.4 — Critical Values for Bounds Test

		Dependent variable																	
		ΔY								ΔEC									
				1%		5%		10%				1%		5%		10%			
Sector	Model	k	n	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$	k	n	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$		
Macro	A	1	38	7.477	8.213	5.233	5.777	4.38	4.867	1	38	7.477	8.213	5.233	5.777	4.38	4.867		
Industry	A	1	38	7.477	8.213	5.233	5.777	4.38	4.867	1	38	7.477	8.213	5.233	5.777	4.38	4.867		
	B_1	2	37	6.328	7.408	4.433	5.245	3.698	4.42	2	36	6.328	7.408	4.433	5.245	3.698	4.42		
	B_2	2	37	6.328	7.408	4.433	5.245	3.698	4.42	2	36	6.328	7.408	4.433	5.245	3.698	4.42		
	B_3	2	38	6.328	7.408	4.433	5.245	3.698	4.42	2	38	6.328	7.408	4.433	5.245	3.698	4.42		
	C_1	3	37	5.654	6.926	3.936	4.918	3.29	4.176	3	36	5.654	6.926	3.936	4.918	3.29	4.176		
	C_2	3	37	5.654	6.926	3.936	4.918	3.29	4.176	3	37	5.654	6.926	3.936	4.918	3.29	4.176		
	C_3	3	38	5.654	6.926	3.936	4.918	3.29	4.176	3	36	6.328	7.408	4.433	5.245	3.698	4.42		
	D	4	37	5.147	6.617	3.578	4.668	3.035	3.997	4	36	5.147	6.617	3.578	4.668	3.035	3.997		
Commercial	A	1	38	7.477	8.213	5.233	5.777	4.38	4.867	1	38	7.477	8.213	5.233	5.777	4.38	4.867		
	B_1	2	37	6.328	7.408	4.433	5.245	3.698	4.42	2	37	6.328	7.408	4.433	5.245	3.698	4.42		
	B_2	2	37	6.328	7.408	4.433	5.245	3.698	4.42	2	35	6.328	7.408	4.433	5.245	3.698	4.42		
	B_3	2	38	6.328	7.408	4.433	5.245	3.698	4.42	2	35	6.328	7.408	4.433	5.245	3.698	4.42		
	C_1	3	37	5.654	6.926	3.936	4.918	3.29	4.176	3	35	5.654	6.926	3.936	4.918	3.29	4.176		
	C_2	3	37	5.654	6.926	3.936	4.918	3.29	4.176	3	37	5.654	6.926	3.936	4.918	3.29	4.176		
	C_3	3	37	5.654	6.926	3.936	4.918	3.29	4.176	3	35	5.666	6.988	4.048	5.09	3.378	4.274		
	D	4	37	5.147	6.617	3.578	4.668	3.035	3.997	4	35	5.147	6.617	3.578	4.668	3.035	3.997		
Transport	A	1	38	6.893	7.537	5.013	5.547	4.23	4.73	1	38	6.893	7.537	5.013	5.547	4.23	4.73		
	B_1	2	37	6.328	7.408	4.433	5.245	3.698	4.42	2	37	6.328	7.408	4.433	5.245	3.698	4.42		
	B_2	2	36	6.328	7.408	4.433	5.245	3.698	4.42	2	36	5.666	6.988	4.048	5.09	3.378	4.274		
	C_1	3	36	5.654	6.926	3.936	4.918	3.29	4.176	3	36	5.654	6.926	3.936	4.918	3.29	4.176		

Notes. The critical values for the bounds test are taken from Narayan (2005), Case IV (unrestricted intercept and restricted trend); k denotes number of regressors; n denotes number of observations.

Appendix C

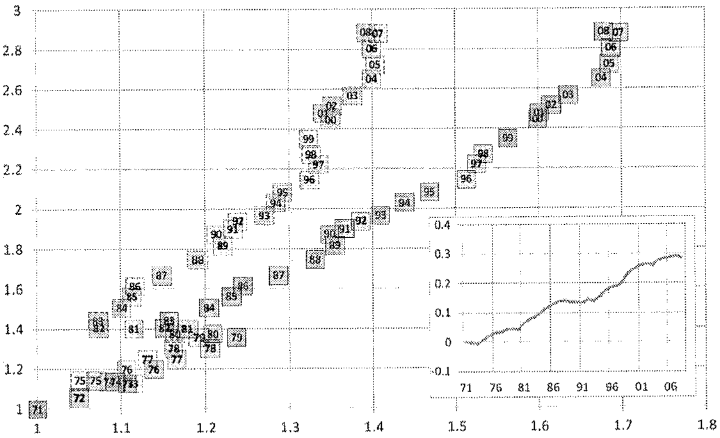

Fig. C.1: GDP as a function of CO_2 emissions (dashed boxes) and energy (solid boxes) for high income countries, 1971-2008 (1971=1); small graph shows decarbonization factor relative to 1971.

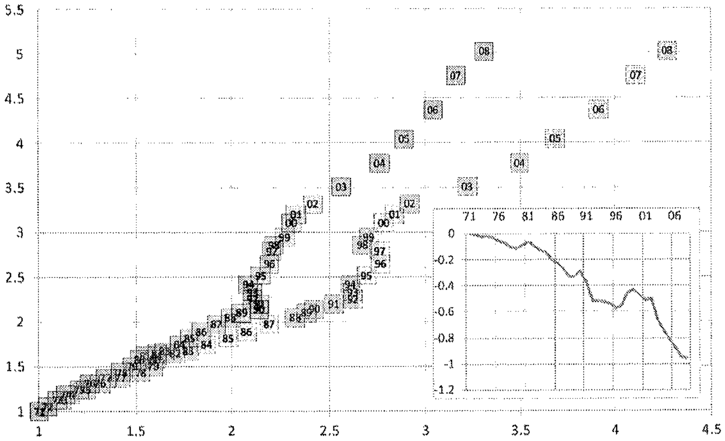

Fig. C.2: GDP as a function of CO_2 emissions (dashed boxes) and energy (solid boxes) for low and middle income countries, 1971-2008 (1971=1); small graph shows decarbonization factor relative to 1971.

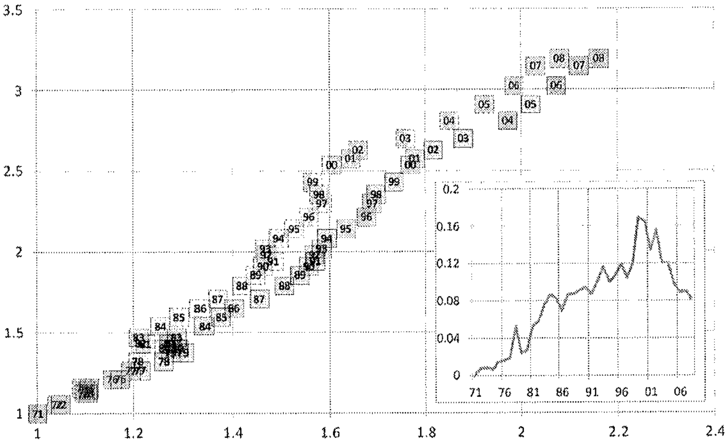

Fig. C.3: GDP as a function of CO_2 emissions (dashed boxes) and energy (solid boxes) for the world, 1971-2008 (1971=1); small graph shows decarbonization factor relative to 1971.

Table C.1 — Results for Meta-Significance Testing: GDP Causes Energy

Industry share (early)			Industry share (late)			Import share (late)		
> 40%	−0.12	[50]	> 25%	−0.03	[38]	> 30%	−0.32	[15]
						< 30%	0.38	[22]
			< 25%	0.37	[10]	> 30%	0.37	[10]
						< 30%	–	[0]
< 40%	−0.28*	[197]	> 25%	−0.26	[138]	> 30%	−0.45*	[73]
						< 30%	−0.03	[62]
			< 25%	−0.32	[61]	> 30%	−0.65	[22]
						< 30%	−0.36*	[42]

Note: ***,**,*,· denotes significance at the 1%, 5%, 10%, 15% level; number of observations in squared brackets.