Universidade de Lisboa

Faculdade de Ciências

Departamento de Engenharia Geográfica, Geofísica e Energia

Three-level energy decoupling:

Energy decoupling at the primary, final and useful levels of energy use

Zeus Hiram Zamora Guevara

Doutoramento em Sistemas Sustentáveis de Energia

2014

Universidade de Lisboa

Faculdade de Ciências

Departamento de Engenharia Geográfica, Geofísica e Energia

Three-level energy decoupling:

Energy decoupling at the primary, final and useful levels of energy use

Zeus Hiram Zamora Guevara

Tese orientada pelo Doutor Tiago Morais Delgado Domingos e pelo Doutor João Manuel de Almeida Serra, especialmente elaborada para a obtenção do grau de doutor em Sistemas Sustentáveis de Energia

2014

"... Delante está el campo, ya verde. Frente al cielo inmenso y puro, de un incendiado añil, mis ojos - ¡tan lejos de mis oídos!- se abren noblemente, recibiendo en su calma esa placidez sin nombre, esa serenidad armoniosa y divina que vive en el sinfín del horizonte..."

Juan Ramón Jiménez

Abstract

Reducing the energy intensity of the economy (energy decoupling) is one of the top priorities of the sustainability agenda. As energy is fundamental for every economic activity, any measure to reduce its consumption must be adequately designed so as not to negatively affect economic growth. Primary energy intensity, which is the standard indicator for energy decoupling analysis, has a high degree of aggregation and therefore is unable to give enough information about its components. A close look at this indicator suggests that the analysis of energy decoupling can be improved with an adequate characterization of energy flows. The objective of this thesis is to improve the understanding of energy decoupling by including in the analysis a detailed characterization of the transformation and use of energy flows in the economy. The work consisted of building models that disentangle economic and energy components from primary energy use. To do so, several methodological tools were used: useful work accounting, decomposition techniques, and input-output analysis. The proposed models successfully deconstruct primary energy use into several components: 1) structure and efficiency of the primary-to-final conversion; 3) structure and efficiency of the final-to-useful conversion; 3) useful exergy demand composition and intensity; 4) economic structure; and 5) final demand of non-energy goods and services. Through these models, it is possible to analyze the relative contribution of each factor on energy decoupling (or coupling) in economic systems. The models were applied to evaluate the trends of primary energy use and energy decoupling in Portugal between 1995 and 2010. The country experienced a relative decoupling driven by three main forces: improvements in primary-to-final energy conversion efficiencies, reductions in useful exergy intensity and economic structural changes. This study shows that the analysis of energy decoupling can be improved by the inclusion of three levels of energy use, i.e. primary, final and useful. The present thesis contributes to the literature of energy decoupling, energy input-output analysis and energy-related decomposition studies.

Acknowledgements

I am grateful to my supervisor, Tiago Domingos, who opened the doors of his research group and provided me with opportunities to conclude this Ph.D. thesis. His trust, advice and encouragement allowed me developing my academic skills and discovering my research path. I would also like to thank Tânia Sousa for her constant support and, especially, for her patience in hearing my ideas in chaotic form and helping me put them into sense. In addition, I thank João Rodrigues, who helped me develop the PF model in Chapter 4 and the study in Chapter 7 and solved most of my doubts about input-output analysis. Without these three persons this work would not have been possible.

This thesis was supported Fundação para a Ciência e Tecnologia and the MIT Portugal Program that provided funding for this Ph.D. research work through scholarship SFRH/BD/51297/2010. I also recognize the financial support by Agência de Inovação through the project Energy Wars (QREN7929).

I would also like to thank João Serra and Miguel Brito for their support, especially in the first years of my program. I know the difficulties that you faced while trying to set me in the right path. Moreover, I thank Michal Monit, my classmate, flat-mate and comrade of various battles, many of which, we failed.

I am very thankful to all other members of the Environmental and Energy Research Group at Instituto Superior Técnico for welcoming me as your college and friend. Sorry, for disrupting your life with my Mexican ways. I thank the master students I co-supervised, André Silvério and Miguel Palma. I am glad that I was able to contribute to your work. Additionally, I would like to thank the members of the Center for Sustainable Energy Systems at Universidade de Lisboa, the MIT Portugal Program community, Terraprima workforce, the Singularity University network and colleagues from the scientific community, with whom I shared valuable time, coursework, conferences, conversations and friendship. Thank you, Alexandra Marques, Ana Gonçalves, André Augusto, André Folgado, André Serrenho, Carlos Silva, Carlos Teixeira, Cristina Marta, Daniel Wiesmann, David Pera, Divya Sornaraja, Esra Khaleel, Filipa Amorim, Filipa Reis, Filipe Serra, Gonçalo Marques (honorary Mexican), Helena Martins, Hugo Campaniço, Isabel Rodrigues, Ivo Costa, Jorge Palma, Joana Abreu, João Santos, Joyce Bettencourt, Lia Laporta, Mário Brito, Miguel Carmo, Nuno Sarmento, Olga Carvalho, Pedro Nunes, Patrícia Pereira da Silva, Paul Brockway, Pierre Bellanger, Pragnya Alekal,

Rafael Topete, Ricardo Vieira, Sara Manso, Sofia Henriques, Tatiana Valada, Vânia Proença and others that I might forget.

Furthermore, I am grateful to this beautiful country that hosted me for the last four years. I also thank all the people that turn my stay in a valuable learning experience, those I love those I hate. Many thanks to the Mexican community, which helped me endure the difficulties of the distance, and to many domestic and foreign friends, which shared with me their smile.

Finalmente, agradezco a mi familia, especialmente a mis tres mujeres-ternura, los pilares de mi existencia. Ustedes son la razón para despertar cada mañana, para haber llegado hasta donde me encuentro, para caer y luchar, para tener esperanza…

Cada palabra de esta tesis es una oración de amor en su nombre.

Contents

List of Figures

List of Tables

Acronyms

AARG	Annual Average Growth Rate
CPA	European Classification of Products by Activity
CTA	Commodity Technology Assumption of the input-output model
D&L	Dietzenbacher & Los approach to structural decomposition analysis
EEE	Economic Energy Efficiency indicators
ETEE	Economic Thermodynamic Energy Efficiency indicators
EU	European Union
GDP	Gross Domestic Product
GVA	Gross Value Added
HTH	High Temperature Heat uses
IDA	Index Decomposition Analysis
ISEC	Import of Secondary Energy Carriers
ITA	Industry Technology Assumption of the input-output model
LMDI	Logarithmic Mean Divisia Index approach to decomposition analysis
LTH	Low Temperature Heat uses
MTH	Medium Temperature Heat uses
NACE	European Classification of Economic Activities
NAFTA	North-America Free Trade Agreement
OE	Other Electric uses
PCM	Physical Content Method
PEU	Primary Energy Use
PF	Primary-to-Final energy input-output model
PFES	Primary Fossil Energy Sources
PFU	Primary-to-Final-to-Useful energy input-output model

PFUS Primary-to-Final-to-Useful-to-Service energy use model

PSM Partial Substitution Method

PTEE Physical Thermodynamic Energy Efficiency indicators

PU Primary-to-Useful energy IDA model

SDA Structural Decomposition Analysis

TEE Thermodynamic Energy Efficiency indicators

UW Useful Work

UWA Useful Work Accounting

Notation

General

$\boldsymbol{x}$, $\boldsymbol{g}$... A bold lower case Latin letter corresponds to a vector

$\boldsymbol{Z}$, $\boldsymbol{T}$... A bold upper case Latin letter describes a matrix.

$\boldsymbol{\alpha}$, $\boldsymbol{\pi}^*$... A bold Greek letter describes a matrix.

x_i , n... Non-bold lower case Latin letters represent scalars or elements of a vector

Z_{ij}... Non-bold upper case Latin letters represent scalars or elements of a matrix

ν, ϕ... Non-bold Greek letters describes a scalar or elements of a matrix.

$\hat{\boldsymbol{x}}$ A vector with a hat represents a diagonal matrix, whose diagonal is vector $\boldsymbol{x}$.

$\boldsymbol{x}'$, $\boldsymbol{Z}'$... An apostrophe on a vector or matrix denotes the vector or matrix transpose.

$\boldsymbol{i}$ Vector of ones (or summation vector)

$\boldsymbol{x}^*$ The superscript * refers to a variable in hybrid units

$\boldsymbol{x}^M$ The superscript M refers to a measure in monetary units

$\boldsymbol{x}^S$ The superscript S refers to a measure of producing sectors

$\boldsymbol{x}^R$ The superscript R refers to a measure of non-producing sectors

$\otimes$ Hadamard or element-wise matrix product

Q Output (in gross output, GDP or GVA)

Chapter 1

η_{ex} Exergy or second-law efficiency

η First-law efficiency

ϕ Exergy factor

Chapter 3

Section 3.1

B Exergy content of final carriers (B_i – allocated to useful work category i)

U Useful work amount (U_i – of useful work category i and U_T – economy-wide)

ϵ Second-law final-to-useful efficiency or technical efficiency (η_{ex} of the final-to-useful energy conversion stage) (ϵ_T – economy-wide)

θ_0 Environment reference temperature

θ_2 Temperature at which heat transfer occurs

r Engine compression ratio

γ Specific heat ratio

Section 3.2

$\boldsymbol{x}$ Total output by industry vector

$\boldsymbol{Z}$ Total interindustry transactions matrix

$\boldsymbol{A}$ Matrix of technical coefficients (A_{ij})

$\boldsymbol{B}$ Product-by-industry matrix of technical coefficients (B_{ij})

$\boldsymbol{f}$ Final demand vector

$\boldsymbol{w}$ Value added by industry vector

n Number of industries

r Number of energy industries ($r < n$)

m Number of products /commodities

$\boldsymbol{L}$ Leontief or total requirements matrix

$\boldsymbol{U}$ Use matrix

$\boldsymbol{V}$ Make matrix

$\boldsymbol{y}$ Final demand by product vector

$\boldsymbol{q}$ Total output by product vector

$\boldsymbol{D}$ Product-output proportions matrix

$\boldsymbol{C}$ Industry output proportions matrix

$\boldsymbol{E}$ Matrix of interindustry energy transactions

$\boldsymbol{g}$ Total energy use vector

$\boldsymbol{h}$ Energy deliveries to final demand vector

$\boldsymbol{\alpha}$ Total energy requirements matrix of the hybrid-unit energy input-output model

$\boldsymbol{\beta}$ Total energy requirements matrix of the direct impact coefficient energy input-output model

$\boldsymbol{K}$ Bridge matrix to select energy industry rows from the hybrid $\boldsymbol{L}^*$

$\boldsymbol{T}$ Direct energy intensity matrix

$\widetilde{\boldsymbol{Q}}$ Inverse prices to final demand matrix

$\boldsymbol{\theta}^*$ $\boldsymbol{L}^*$ sub-matrix of energy transactions between energy industries per final energy demand

$\boldsymbol{\tau}^*$ $\boldsymbol{L}^*$ sub-matrix of direct energy use by non-energy industries per final demand

$\boldsymbol{\pi}^*$ $\boldsymbol{L}^*$ sub-matrix of transactions from non-energy to energy industries per final energy demand

$\boldsymbol{\psi}^*$ $\boldsymbol{L}^*$ sub-matrix of interindustry transactions between non-energy industries per final demand

Section 3.3

V Aggregate variable (V_k – of sector k)

$\boldsymbol{v}$ Aggregate variable vector

x_i Exogenous factors of V ($x_{i,k}$ – of sector k)

$\boldsymbol{X}_i$ Exogenous factors of $\boldsymbol{v}$

DV_{x_i} Decomposition coefficient of factor x_i with respect to V, i.e. the effect of changes in factor x_i on changes in V

$D\boldsymbol{v}_{\boldsymbol{X}_i}$ Decomposition coefficient of factor $\boldsymbol{X}_i$ with respect to $\boldsymbol{v}$

y_i Partial derivative of V with respect to factor x_i (exception to the general notation)

α_i Parameters of approximation functions under linear path conditions (α_{ij} in SDA)

β_i Parameters of approximation functions under logarithmic path conditions (β_{ij} in SDA)

n Number of exogenous factors

m Number of sectors

t Time (t_1 and t_2 – initial and final instant)

E Energy use aggregate (E_k – of sector k)

M Activity mix factor of energy-related IDA

I Sectoral energy intensity factor of energy-related IDA

Chapter 4

$\boldsymbol{U}^E$ Energy use matrix

$\boldsymbol{V}^E$ Energy make matrix

$\boldsymbol{Y}^E$ Matrix of direct energy demand by carrier and by direct demand category

$\boldsymbol{d}^E$ Vector of domestic production of primary energy carriers

$\boldsymbol{m}^E$ Vector of imports of primary and final energy carriers

$\boldsymbol{w}^E$ Vector of energy conversion losses

$\boldsymbol{q}^E$ Vector of total energy output by energy carrier

$\boldsymbol{x}^E$ Vector of total energy output by energy technology / industry

n Number of industries

r Number of energy technologies / industries ($r < n$)

m Number of products /commodities

n_T Number of energy technologies / industries

n_E Number of energy carriers

n_F Number of non-energy sectors of direct energy demand

n_E Number of energy carriers

n_P Number of primary energy carriers

n_C Number of final energy carriers

n_N Number of non-energy-use energy carriers

$\boldsymbol{p}$ Primary energy use vector ($\boldsymbol{p}^S$ & $\boldsymbol{p}^R$ – production-related and residential)

$\boldsymbol{L}^E$ Total requirements matrix of the energy sector (Structure and efficiency of the primary-to-final conversion stage)

$\boldsymbol{C}^E$ Demand composition of direct (final or secondary) energy matrix ($\boldsymbol{C}^{E,S}$ & $\boldsymbol{C}^{E,R}$ – production-related and residential)

$\boldsymbol{T}^E$ Direct energy intensity matrix

$\boldsymbol{T}^P$ Primary energy intensity matrix

$\boldsymbol{L}^M$ Total requirements matrix of the rest of the economy (non-energy producing sectors)

$\boldsymbol{C}^M$ Final demand composition matrix

$\boldsymbol{s}^M$ Total final demand or economic scale vector

$\boldsymbol{K}^P$ Bridge matrix to select primary energy carrier's rows from $\boldsymbol{L}^E$

$\boldsymbol{r}^E$ Direct or final energy demand vector ($\boldsymbol{r}^{E,S}$ & $\boldsymbol{r}^{E,R}$ – production-related and residential)

$\boldsymbol{x}^S$ Total output of non-energy producing sectors vector

$\boldsymbol{e}$ Final energy use vector ($\boldsymbol{e}^S$ & $\boldsymbol{e}^R$ – production-related and residential)

$\widetilde{\boldsymbol{Q}^E}$ Inverse prices to final demand matrix

$\widetilde{\boldsymbol{Q}}^P$ Matrix of primary energy embodied in residential energy demand per energy expenditures

$\boldsymbol{a}$ Vector of primary energy equivalent coefficients of renewables and imports of final carriers

$\delta \boldsymbol{X}$ Decomposition coefficient of factor $\boldsymbol{X}$ with respect to PEU (equivalent to $D\boldsymbol{p_X}$)

Chapter 5

Section 5.1

Notation of Chapter 4 and

$\boldsymbol{Y}^U$ Matrix of direct useful work demand ($\boldsymbol{Y}^{U,W}$ – by type of useful work flow)

$\boldsymbol{\epsilon}^U$ Matrix of final-to-useful conversion efficiency ($\boldsymbol{\epsilon}^{U,W}$ – by type of useful work flow)

$\boldsymbol{L}^U$ Total requirements matrix of the extended energy sector (Structure and efficiency of the final-to-useful conversion stage)

$\boldsymbol{Y}^X$ Matrix of direct exergy demand ($\boldsymbol{Y}^{X,W}$ – by type of useful work flow and $\boldsymbol{Y}^{X,E}$ – by carrier)

$\boldsymbol{G}^{EC}$ Bridge matrix between values by type of useful work flow and by carrier

$\boldsymbol{\phi}^E$ Vector of energy factors by carrier

$\boldsymbol{C}^U$ Demand Composition of direct useful work matrix ($\boldsymbol{C}^{U,S}$ & $\boldsymbol{C}^{U,R}$ – production-related and residential)

$\boldsymbol{r}^U$ Useful work demand vector ($\boldsymbol{r}^{U,S}$ & $\boldsymbol{r}^{U,R}$ – production-related and residential)

$\boldsymbol{T}^U$ Direct useful work intensity matrix

Section 5.2

P Primary energy use (P^S & P^R – production-related and residential)

E Final or direct energy use (E^S & E^R – production-related and residential)

U Final or useful work use (U^S & U^R – production-related and residential)

A Residential activity level

k Industry index

h Household index

$\bar{v}$ Average primary-to-final conversion efficiency

ϕ Exergy factor

$\overline{\epsilon\phi}$ Average final energy to useful work conversion efficiency

M Activity mix factor of energy-related IDA

UI Direct useful work intensity factor of energy-related IDA

L Production technology factor of energy-related IDA

F Final demand mix factor of energy-related IDA

f Economic scale or total final demand factor of energy-related IDA

Chapter 6

Notation of Section 3.1, Section 3.3 and Section 5.2

Chapter 7

Notation of Chapter 4 and

$\boldsymbol{c}^E$ Household energy demand composition vector

b^H Aggregate energy price

c^H Share of energy expenditure in total household expenditure

s^H Total household expenditure

$\delta\boldsymbol{\pi}^M$ Effect of the non-energy transactions of the energy sector on primary energy use

$\delta\boldsymbol{\psi}^M$ Effect of transactions between non-energy industries on primary energy use

Chapter 8

Notation of Chapter 4, Section 5.1, Section 5.2 and

d Decoupling index

m_{kj} Number of producing sub-sectors

m_j Number of producing sectors

Chapter 9

Notation of Section 5.2 and

$\bar{\mu}$ Average non-dissipation efficiency of passive systems

W Productive useful work (W^S & W^R – production-related and residential)

b Average unit price of products (p_k)

b^E Average energy price

Y Total output in physical units

S Energy service requirements, i.e. the ratio of productive useful work used per unit of energy services in physical units

N Physical energy intensity (N^U – at the useful level of energy use)

1 Introduction

Any economic system "could not exist without large and incessant flows of energy" (Smil, 2003) as energy is the driving force of any activity and process in nature (Stern, 2011). It is obvious then that when there is no energy, there will not be any economic activity; and when there is energy, it is possible to carry out economic activities. However, the relationship between energy use and the output of these activities is not simple (Ockwell, 2008; Smil, 2000).

Empirical studies have found that, especially after the industrial revolution, the growth of economic output and the increase in energy consumption are strongly linked, i.e. an increase in output corresponds to a proportional increase in energy use (Alam, 2009; Fiorito, 2013; Stern, 2011). Nevertheless, in the last decades, this link has become weaker meaning that economic output grows at a larger rate than energy use (Bithas and Kalimeris, 2013; Goldemberg and Siqueira Prado, 2011; Markandya et al., 2006; Mulder and de Groot, 2004). The latter phenomenon has been referred to as energy – economic growth decoupling (hereby called energy decoupling), which is formally defined as the reduction of the rate of use of primary energy use per unit of economic activity (UNEP, 2011)

Energy decoupling can help reduce the environmental impact associated to the use of energy resources, which is significant at a global scale since energy use accounts for the largest share of anthropogenic greenhouse gas emissions (IPCC, 2007), and has multiple other positive environmental impacts. As most countries (including the largest energy consumers) are dependent on foreign fossil energy sources (IEA, 2010, 2012a), it can also help reduce this dependency, increasing energy security. Moreover, energy decoupling contributes to long term development by reducing the pressure on the limited global reserves of fossil fuels (predominant in primary energy use). In addition, it can also increase the economic competitiveness of an economy (Smil, 2003). Because of these benefits, energy decoupling has become one of the top priorities of the sustainability agenda (Smil, 2000).

Two types of decoupling are distinguished (UNEP, 2011; Wang, 2011): 1) Relative decoupling is when the growth rate of primary energy use is positive but relatively smaller than the growth rate of economic activity; and 2) absolute decoupling when the use of energy resources decreases while economic activity grows. The distinction is relevant since only the latter is related to an absolute reduction of primary energy use (Smil, 2000; UNEP, 2011).

The standard indicator of energy decoupling analysis is primary energy intensity, which is defined as the ratio of primary energy use per unit of economic activity (usually GDP). The use of this indicator for energy decoupling analysis has been criticized on the basis that a single indicator cannot describe the complex relationship between energy use and economic growth (Bithas and Kalimeris, 2013; Coccia, 2010; Fiorito, 2013; Smil, 2003; Sorman and Giampietro, 2011). Another issue regarding this indicator is that it is constructed with two aggregate variables, i.e. total primary energy use and GDP, that have accounting problems on their own (Patterson, 1993; Smil, 2003; Sorman and Giampietro, 2011).

Primary energy intensity contains (in a highly aggregated form) the characteristics of all economic transactions and all physical processes, including energy conversion and use, in the economy. It can provide a general insight on energy decoupling of an economy (Lightfoot, 2007; Smil, 2003). However, it cannot provide information about its components and therefore it can neither act as a reliable predictor of energy decoupling or as a comparison measure between economies (Fiorito, 2013; Smil, 2003).

Smil (2003) argues that the

> *deconstruction of the measure [primary energy intensity] offers a deeper understanding of underlying realities, uncovers a number of serious data limitations, leads to a careful interpretation of differences in levels and trends, and helps to avoid simplistic, and hence potentially counterproductive, conclusions.*

This deconstruction consists of evaluating the main determinants of primary energy intensity, which are eight, based on Liddle (2010), Patterson (1996), Percebois (1979) and Smil (2003): 1) economic structure; 2) degree of energy self-sufficiency; 3) composition of primary energy supply; 4) composition of direct energy use in production; 5) patterns of residential energy use; 6) efficiency in the conversion and end-use of energy; 7) country size and climate; and 8) others, e.g. defense spending. Only the analysis of all determinants can give an explanation of the level and changes in primary energy intensity of an economy (Smil, 2003).

Four of the eight determinants of primary energy intensity are directly related to the transformations and use of energy flows in the economy (determinants 3-6). This suggests that the analysis of energy decoupling can be improved if an adequate characterization of energy flows is included in the analysis.

Therefore the objective of this thesis is to improve the understanding of energy decoupling by addressing the following research question:

What is the effect on energy decoupling of the characteristics of the transformation and use of energy flows in an economy?

To answer this research question, I focus on the numerator of the primary energy intensity (i.e. primary energy use/supply). Thus the present work consists of building models that disentangle the factors related to energy transformation and use from the primary energy use. Three methodological tools were used for the construction of these models: useful work accounting, decomposition techniques and input-output analysis.

The proposed models successfully deconstruct primary energy use into several components: 1) Structure and efficiency of primary-to-final conversion; 3) structure and efficiency of final-to-useful conversion; 3) useful exergy demand composition and intensity; 4) economic structure; and 5) final demand of non-energy goods and services. It is worth to notice that the models include economic factors that are also considered determinants of primary energy intensity (e.g. economic structure). Moreover, the main contribution of this thesis is that the proposed models allow the analysis of the effect of the different factors on primary energy use and on energy decoupling, which was not possible with existing models in literature.

This thesis is organized in ten chapters, which are briefly described as follows:

Chapter 2 describes the energy flows in the economy according to the primary, final, useful and service levels of energy use. Moreover, the exergy concept is introduced, which allows evaluating the quality of energy flows.

Chapter 3 describes the methodological framework of the present thesis, which consists of three methodologies: 1) useful work accounting; 2) input-output analysis; and 2) decomposition analysis. In addition, this chapter analyzes the conventional approaches to energy-related topics of the two latter methodologies.

Chapter 4 presents the development of the primary-to-final energy input-output model. The model allows the evaluation of energy transactions in the economy at the primary and final level of energy use.

Chapter 5 introduces two energy models, which include the useful level of energy use: The primary-to-useful IDA model and the primary-to-final-to-useful energy input-output model (an extension of the model in the previous chapter).

Chapter 6 presents an approach to evaluate energy efficiency trends applied to Mexico 1971-2009. In this chapter, one of the most used approaches to evaluate energy efficiency trends in the literature is improved by including the useful level of energy use.

Chapter 7 presents the analysis of primary energy use in Portugal 1995-2010 with the model in Chapter 4. The analysis gives insight on the effect of energy and economic transitions in the country.

Chapter 8 extends the analysis in Chapter 7 and presents the evaluation of energy decoupling in Portugal 1995-2010 at the primary, final and useful levels of energy use.

Chapter 9 describes two specific areas for future research: the extension to the service level and a generic model of energy efficiency indicators. In addition, it presents other general areas for future work.

Finally, Chapter 10 presents the main conclusions obtained from this research.

2 Levels of energy use

Every modern industrial society depends on a series of conversion stages of energy resources in nature from less to more usable forms. These conversion stages are carried out to produce a wide variety of goods and services (Alam, 2009; Nakićenović and Grübler, 1993; Smil, 1994; Summers, 1971).

The evolution of these societies is, therefore, linked to the type of available energy resources, the structure of conversion stages and the patterns of energy end-uses. Consequently, the analysis of these societies should be able to capture the complexity of energy flows (Nakićenović and Grübler, 1993).

Traditionally, the complexity of energy flows is simplified by differentiating three levels of energy use, i.e. primary, final and useful (Section 2.1) (Ma et al., 2012; Nakićenović et al., 1996; Orecchini, 2006; Summers, 1971). Additionally, further insights can be achieved by analyzing energy flows under different energy metrics, e.g. the capacity to produce work or the heat content (Section 2.2) (Ayres, 1998; Nakićenović et al., 1993).

2.1 The levels of energy use in the economy

The levels of energy use describe the flow of energy along all stages of energy conversion and use in the economy. These levels are defined based on the metabolism approach, which describes the economy as a physical input-output system drawing energy from the environment, performing internal physical processes (i.e. energy conversion or transfer) and dissipating low-grade waste heat to the environment (Haberl, 2006).

As mentioned before, energy flows are traditionally classified into three levels of energy use: primary, final and useful with two stages of energy conversion: primary-to-final and final-to-useful. However, Nakićenović and Grübler (1993) argue that this classification truncates the analysis at the last stage of energy conversion and hence does not include actual delivered energy services, see also Haas et al. (2008), Pachauri and Spreng (2004), and Wirl (1995). Therefore, a service level of energy use and a useful-to-service transition stage should be included (Section 2.1.4, Figure 2-1).

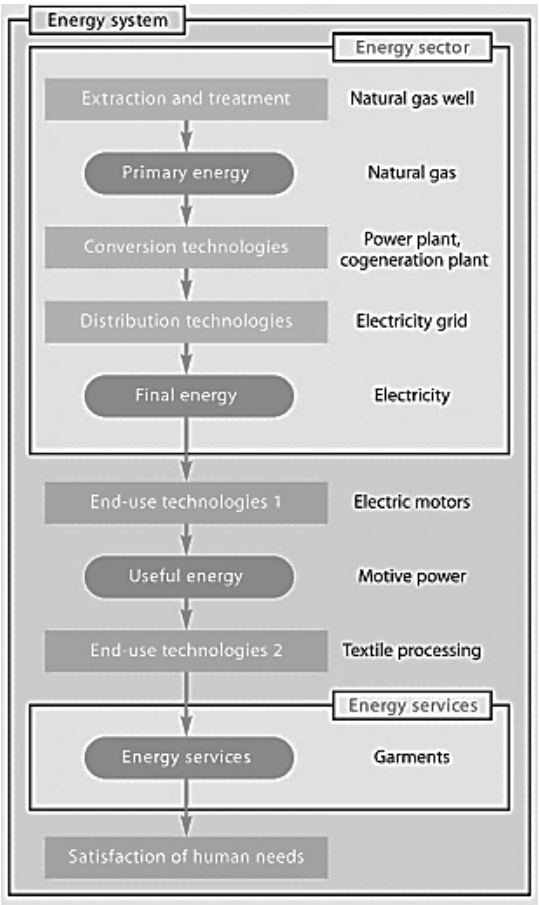


Figure 2-1 Diagram of energy flows with major energy- and efficiency-related terms
Note: From UNDP (2000) and UNDP (2004)

UNDP (2000) and Cullen and Allwood (2010a) place the service level in flow diagram of an energy system as the output of a dissipative energy transfer performed by a pas*sive system* (i.e. end-use device which dissipates most of the energy it receives, explained in Section 2.1.4).

Furthermore, Cullen and Allwood (2010a) and Ma et al. (2012) built technically-focused energy Sankey diagrams (Schmidt, 2008a) that show the levels of energy use from primary energy resources to energy services (e.g. Figure 2-2). These diagrams highlight the importance of the levels of energy use for the analysis of energy performance of an economy. Vertically, the energy flows and potential efficiency improvements by level can be compared in absolute terms. On the other hand, horizontally, the entire flow chain from primary to service and the effect of sequential improvements in efficiency can be tracked (Cullen and Allwood, 2010a).

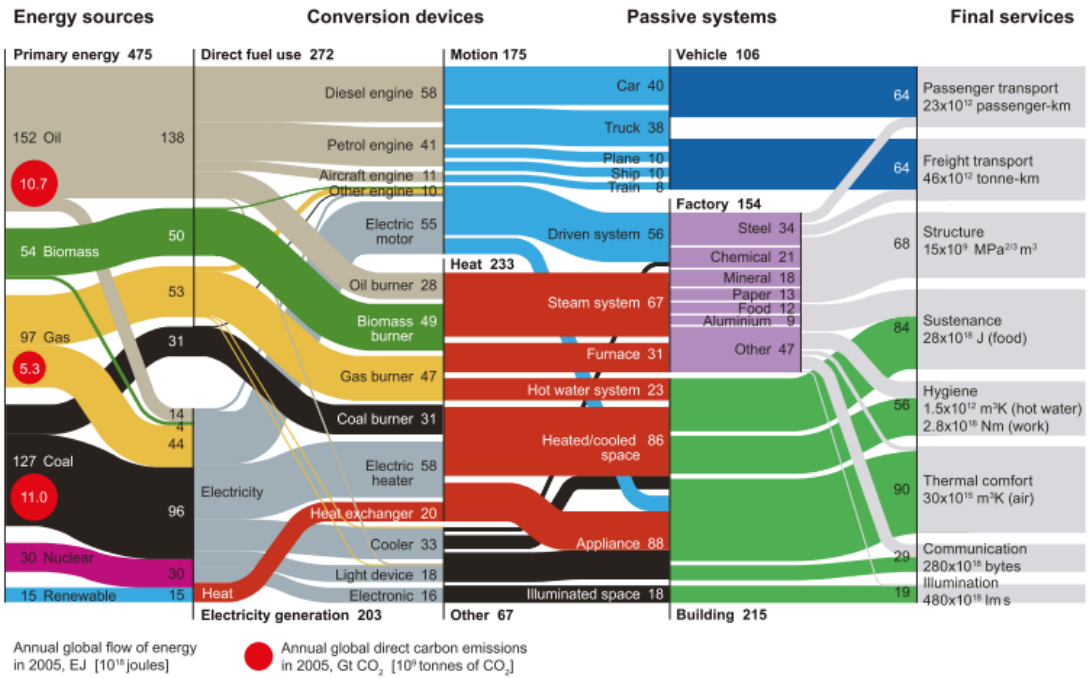


Figure 2-2 Global energy flow from the primary to service levels of energy use
Note: From Cullen and Allwood (2010a). Conversion losses and dissipative degradation are included

In the following sections, the levels of energy use and the transition stages between them are explained in detail.

2.1.1 Primary level of energy use

Primary energy corresponds to energy carriers as they are recovered or gathered from the natural environment (Haberl, 2001a; Nakićenović and Grübler, 1993), i.e. natural resources such as mined coal, collected biomass or crude oil. As there are many forms of energy carriers in the natural environment, primary energy is given in terms of the energy content of these energy carriers, which leads to consistency issues (Serrenho, 2013).

In the case of fossil fuels, the energy content is usually determined by the enthalpy or heating thermodynamic potential (IEA, 2011a; Serrenho, 2013). In the case of renewable and non-conventional energy carriers, the energy content (or primary energy equivalent) is estimated according to two accounting methods (Bhattacharyya, 2011; Cegonho et al., 2012; IEA, 2014; Lightfoot, 2007; UN, 1982):

The *partial substitution method* (PSM) transforms the flows of non-conventional and renewable heat and electricity into the equivalent heat content of fossil fuels that would be needed if the same amount of electricity or heat had been produced by 1) a standard thermal technology and 2) an existing domestic thermal technology. The PSM is suitable for the analysis of the substitution of conventional carriers by renewables in terms of the fossil fuels avoided by the introduction of renewables. This method is not recommended for countries with a large share of renewables (IEA, 2014).

The *physical content method* considers the physical energy content of the first usable energy form (i.e. electricity or heat) as the equivalent primary energy of non-conventional and renewable energy carriers (hereby referred to as PCM-I). However, as pointed out by Cegonho

et al. (2012) and Serrenho (2013), the first usable energy form can also be that of the natural resources themselves (e.g. wind flow and solar irradiation) hence the equivalent primary energy will correspond to the physical energy content of natural resources, e.g. the kinetic energy of the wind flow and solar irradiation energy (hereby referred to as PCM-II). The PCM's are suitable for the analysis of renewable transition in the economy (see Section 7.4.5.1).

2.1.2 Final level of energy use and the primary-to-final conversion

Final or secondary energy is the flow of energy carriers that is available for direct use by consumers. A consumer is a unit of the economic system (i.e. industries and households) that requires energy services for production or consumption, e.g. industries or households (Haberl, 2001a).

The final level of energy use mainly accounts for the energy content in output products of the energy sector, e.g. oil derivatives, electricity, biodiesel or geothermal heat. It also accounts for energy carriers in secondary form produced by decentralized generation systems, which are not part of the energy sector, e.g. residential solar thermal boilers or stand-alone wind turbines. Additionally, the International Energy Agency does not include the direct use of secondary energy carriers by the energy sector as final energy flows (IEA, 2011a). IEA's distinction is followed in this work. It is worth mentioning that the measurement of the energy content of final energy flows is more consistent than for primary energy flows, though there are still different options, depending on the selection of thermodynamic potential e.g. the low or high heating value (Serrenho, 2013).

The primary-to-final conversion is the first energy transformation stage in the economy, where primary energy sources are upgraded into more useful forms of energy through conversion processes (Cullen et al., 2011). In addition to conversion process, such as oil refining and coal-fuelled electric generation, this conversion stage usually includes other operation processes of the energy sector, e.g. extraction, storage and distribution (Orecchini and Naso, 2012; Serrenho, 2013; UNDP, 2000).

2.1.3 Useful level of energy use and the final-to-useful conversion

Useful energy (mainly heat, motion, and light) is the last form of energy flows that is directly used to provide energy services (Cullen et al., 2011). It is obtained from the conversion of secondary energy carriers by end-use conversion devices, for example, motor engines, boilers, ovens and lamps (Nakićenović and Grübler, 1993). Because useful energy is situated immediately before the level of satisfied energy needs and is independent from the evolution of energy conversion technology, it is should be included in economy-wide energy accounting (Haberl, 2001a; Percebois, 1979; Serrenho, 2013).

The final-to-useful conversion is the second and last energy conversion stage in the economy. This stage is usually carried in the exact location where energy services are required (in the household or in a factory). The final-to-useful conversion stage consists of a large share of one-step conversions, e.g. electricity into motion by an electric motor or natural gas into steam by a boiler, and of two-step conversions, e.g. gasoline into motion by a car engine into air conditioning low temperature heat. Moreover, this conversion stage is difficult to estimate since every sector, every energy carrier, every conversion device and every energy service must be considered (Nakićenović et al., 1996).

2.1.4 Service level of energy use and the useful-to-service dissipative transfer

Haberl (2001a) defines energy services as immaterial services, whose provision involves the use of energy[1]. For example, heating of a room, moving commodities from one point to another in a defined time period, or transforming material inputs into a piece of furniture. In addition to energy, these services also involve inputs of technology, capital (human and physical) and non-energy resources (Haas et al., 2008).

The problem with these definitions is that it is not possible to distinguish energy services from other goods and services in the economy (Pachauri and Spreng, 2004) (everything needs energy to be produced). Consequently, energy services sometimes are classified into two categories (Haas et al., 2008; Pachauri and Spreng, 2004): 1) direct, such as lighting, ironing, drilling, melting sands to form glass, etc.; and 2) indirect, i.e. the energy embodied in food, shoes, building, vehicles, etc. Nevertheless, as consumers do not consume non-energy products and services due to their embedded energy, the indirect services are evaluated in terms of the direct energy services used to produce them. Therefore, only direct energy services are considered part of the service level of energy use.

The definition of direct energy services, because of their many forms, is complex (Cullen and Allwood, 2010a; Nakićenović et al., 1996). Moreover, at this level of energy use, other human behavioral and lifestyle characteristics (voluntary or not) are also involved (Cullen et al., 2011; Nakićenović and Grübler, 1993), which increases the complexity. However, these issues can be addressed by an understanding of the stage of transition between useful energy and energy services (see below).

This level of energy use and its preceding transition stage from the useful level is fundamental for the analysis of energy performance of an economy because it appears to be the "weakest link" of the energy chain from primary to services (Nakićenović and Grübler, 1993) so the largest improvements are expected to be at the useful-to-service transition stage (Nakićenović et al., 1996).

Useful-to-service dissipative transfer

The transition between the useful and the service levels of energy use consists of a series of dissipative processes (Haberl, 2001a). These processes are performed by passive systems that "holds or traps useful energy for a time to provide a level of final service" (Cullen et al., 2011).

A passive system is a last technical component of the energy chain, whose purpose is not converting the flow of useful energy into another energy form. In providing energy services, useful energy is eventually dissipated to the natural environment as low-grade heat (Cullen and Allwood, 2010a). Therefore, a passive system requires a continuous supply of useful energy to maintain a constant level of service. The most efficient passive system is the one that minimizes dissipation, i.e. retains useful energy for longer periods (Cullen et al., 2011). Additionally, in the production of material products, a part of useful energy is dissipated to the

[1] In this case, energy services do not correspond to the services that energy companies provides as in Bandi (2010) and EU (2006)

environment while the rest is contained in the product in the form of changes in chemical and physical properties (Cullen et al., 2011).

The definition of boundaries of the passive system with respect to end-use conversion devices and other external systems are not simple (Cullen and Allwood, 2010a). For example, a car could be considered as formed by a conversion device (the engine) and a passive system (the rest of the car). However in providing a transportation service the car interacts with the road infrastructure (road, signals, etc.) Most of the dissipation of useful energy (i.e. friction) is caused by this interaction; hence the passive system should be defined as the car (except the engine) plus the road infrastructure. In addition, the boundaries of the passive system also depend on a clear, though arbitrary, definition of the energy service. The conditioning of a building can be thought as warming indoor air into a desired temperature (a closed passive system) or as providing an air flow with desired characteristics for a time period (an open passive system).

Furthermore, the service level of energy use also involves the direct or indirect participation of the end-user. A user has a direct participation when its interaction with the passive system affects the performance of this system, i.e. the capacity of the passive system to retain useful energy is affected. For example, a bad driver can significantly increase the dissipation in a transportation service hence the user operation might as well be considered part of the passive system. An indirect participation is when the user does not affect the performance of the passive system, for example, setting the indoor heating system at an ideal workspace temperature or leaving the lights on in an empty room. In this case, the indirect participation determines how much of the energy services are turned into real benefits for the user. In the example of leaving the light on in an empty room, the lighting service is provided by the room and the lamp but does not have any productive use or benefit for the user. In summary, the direct participation is related to the operation of passive systems at the useful-to-service transition stage while indirect participation is related to the consumption behavior at the service level.

Because of the issues in the definition of each energy service and the boundaries of its passive system, the service level has been excluded in most studies (Nakićenović and Grübler, 1993). Once the energy service and its associated passive system are defined, the non-dissipative efficiency, also called service factor by Nakićenović et al. (1996), of passive systems can be defined (see Section 9.1.2.2).

2.2 Approaches to the analysis of energy flows

There are two main approaches to the analysis of energy use in engineering and economic systems[2], i.e. the so-called energy and exergy approaches (Figure 2-3) (Dincer and Rosen, 2012; Wall and Gong, 2001). On the one hand, energy analysis is focused on the energy content[3] of energy flows and framed under the first law of thermodynamics (In the previous section, the levels of energy use are described according to this approach). On the other hand, exergy analysis is focused on the exergy (explained below) of energy flows and framed under the second law of thermodynamics. This latter approach, as opposite to the former, provides a context-dependent understanding of system's energy performance[4].

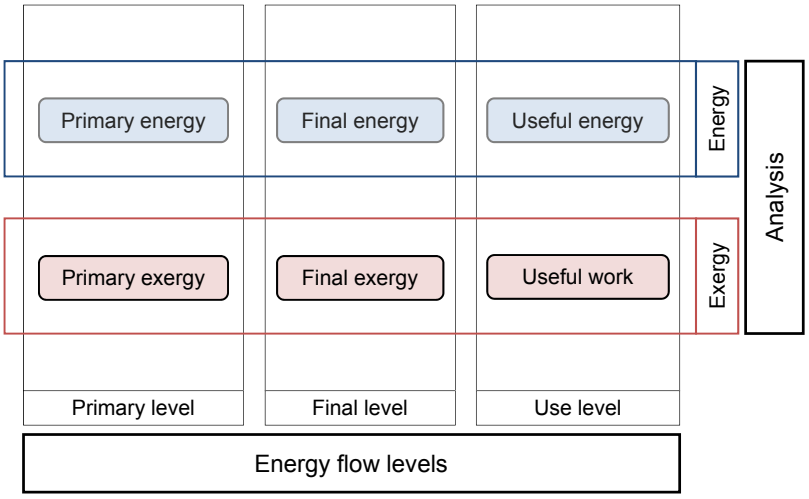


Figure 2-3 Levels of energy flows (primary to useful) and analysis approaches

Exergy

The concept of exergy stems from the second law of thermodynamics, which establishes the fundamental property entropy (Dincer and Rosen, 2012). This law also explains that every process of an isolated system will tend to maximize the system's entropy, i.e. entropy must increase in any process of energy transfer or conversion. Therefore, the state of thermodynamic equilibrium of a system is characterized by relative maximum entropy, i.e. no further increases in entropy are possible without external means (Dincer and Rosen, 2012; Moran et al., 2006; Wall, 2009).

Exergy is the maximum work that can be theoretically obtained from a system or a heat/matter flow as it is brought into equilibrium with a reference environment by means of a

[2] The analysis of the financial value of energy flows can also be considered a level of analysis of energy use mainly in economic systems (Cleveland et al., 2000; Dincer and Rosen, 2012; Stern, 2010, 2011).

[3] The energy content can be measured by one of the different thermodynamic potentials (e.g. internal energy, enthalpy, Helmholtz or Gibbs potentials) (Moran et al., 2006). The selection of the potential is arbitrary though enthalpy or heating potential is usually used for the analysis of energy flows (Serrenho, 2013).

[4] It is commonly assumed for simplicity that energy analysis is not dependent on the context, see (Dincer and Rosen, 2012). However, the values of some of the thermodynamic potentials, mentioned in the Footnote 3, vary with context-dependent properties, e.g. the Helmholtz and the enthalpy potentials depend on the temperature and the pressure of the system, respectively.

reversible process[5] (Moran et al., 2006; Rosen, 2004). It can alternatively be defined as the minimum work required to bring a system from an equilibrium to a desired state (Moran et al., 2006). Moreover, exergy is considered a measure of energy quality since it establishes the ability of an energy source to produce work between an initial and the equilibrium states (Wall, 2009).

Exergy has the following properties (Dincer and Rosen, 2012; Moran et al., 2006; Wall, 2009):

- Exergy depends on the properties of the system/flow and the environment together;
- The value of exergy is always positive;
- Exergy is not conservative, i.e. it is destroyed or consumed along a process due to irreversibilities;
- Exergy is zero at a state of thermodynamic equilibrium with the environment;
- Exergy increases as the system deviates from the environment, i.e. energy flows with low entropy content (e.g. electricity) have more exergy that those with high entropy content (e.g. low temperature heat);
- High exergy systems/flows are usually more valued than low exergy.

Exergy has been widely applied to several areas of engineering systems, for example: 1) the analysis of thermal processes; 2) the design of energy conversion systems; 3) the estimation of practical limits for efficiency improvements; and 4) the evaluation of the impact of energy use on the environment and on sustainable development (Dincer and Rosen, 2012; Gong and Wall, 2001). In addition, exergy has been also applied to the analysis of materials flows as a measure of resource quality (De Meester et al., 2006; Dincer and Rosen, 2005; Ertesvåg, 2005; Gong and Wall, 2001).

Three exergy-related concepts are further described:

1. The reference environment

The choice of the reference environment constitutes the major methodological issue in exergy analysis (Wall and Gong, 2001). Generally, the reference environment is modelled as the actual environment (where the system or flow is contained[6]) in a perfect state of equilibrium, i.e. without changes in intensive properties (e.g. temperature, pressure and chemical composition) (Dincer and Rosen, 2012; Wall, 2004).

Nevertheless, depending on the scope of the analysis, the actual environment cannot be assumed as chemically unreactive or invariable with space and time. In these cases, a standard environment is defined with the average properties of the actual environment or a set of different reference environments are defined to account for time and spatial differences.

[5] A reversible process is the process, along which entropy of the system or flow remains constant. It is theoretical since it does not occur in nature

[6] The environment and *immediate surroundings* of a system must be differentiated since intensive properties of the latter can significantly vary through interactions with the system. Therefore, the properties of the environment are defined at a relatively long distance from the system (Moran et al., 2006).

2. Exergy efficiency

Exergy efficiency or second-law efficiency represents the fraction of an exergy flow that is converted into work or into another form of exergy flow (Cullen and Allwood, 2010b; Wall, 2009). Ford et al. (1975) provided detail to the definition as:

$$\eta_{ex} = \frac{\begin{matrix}\text{Minimum amount of work/exergy} \\ \text{required to produce the desired energy transfer/conversion}\end{matrix}}{\begin{matrix}\text{Maximum amount of work/exergy} \\ \text{that could be produced from the relevant energy input}\end{matrix}} \quad (2.1)$$

This efficiency quantifies the distance between the results of real and ideal theoretical processes. It also serves to evaluate the effectiveness of improvements in energy conversion systems (Dincer and Rosen, 2012; Moran et al., 2006).

Exergy efficiency differs from energy efficiency or first-law efficiency[7] (η) because the former gives a figure of merit, i.e. quality and closeness to ideal, and has a strict range of $0 \leq \eta_{ex} \leq 1$ for any process of energy use, which allows the comparison between different processes . On the other hand, η does not provide a figure of merit and can take values larger than 1 for processes that involve an energy contribution from the environment (e.g. heat pumps) (Dincer and Rosen, 2012; Wall, 2009).

3. The exergy of combustible energy carriers

The exergy content of energy carriers is calculated by the thermodynamic analysis of a closed system, which produces work through an isobaric and adiabatic combustion reaction till the combustion products reach a state of equilibrium with the environment. The exergy content then corresponds to the absolute change of the system's heating thermodynamic potential (i.e. enthalpy of combustion) plus/minus a term that accounts for the chemical exergy of combustion products. This chemical exergy results from the contrast of the composition of the combustion products and the composition of the reference environment (Ayres and Masini, 2004; Rosen, 2004). Moreover, the enthalpy of combustion for this combustion process corresponds to the maximum heat content of an energy carrier, also known as high heating value (Moran et al., 2006).

The values of the exergy of most combustible energy carriers are presented in the literature in the form of exergy factors, e.g. see Ertesvåg and Mielnik (2000), Nakićenović et al. (1996) and Serrenho et al. (2012). The exergy factor (ϕ) is defined as the ratio of exergy content and the minimum heat content, i.e. low heating value[8] (as most energy databases are in terms of the low heating value).

[7] The first-law efficiency (η) is defined as the ratio of desired energy output (transfer or conversion) and the relevant energy input (Ford et al.).

[8] The enthalpy of combustion of an isobaric combustion reaction in a closed system, whose final state is defined by the end of the combustion reaction, i.e. the combustion products are at the temperature of the reaction. The high heating value exceeds the low heating value by the amount of energy needed to condense the water product and cool other combustion products from the reaction temperature to the ambient temperature (Moran et al., 2006) Note: the latent heat of water vapor accounts for the largest share of this difference.

Exergy vs. energy analysis

Exergy and energy variables are used for the same applications in engineering, though the insights that are obtained from the exergy approach instead of the energy approach can be significantly different. The main advantage of exergy analysis, compared to energy analysis, is that it allows accounting for the quality of energy flows rather than only quantity. Moreover, it provides information of energy degradation within the system, provides insights on potential system's improvements and allows for the comparison of energy flows[9], which are different in physical sense, according to a common standard of value (Dincer and Rosen, 2012).

Exergy is also convenient for the analysis of economic systems on the basis that this variable is related to the actual purpose of using an energy flow in the economy, i.e. work in the form of energy services (Ayres and Warr, 2009; Nakićenović and Grübler, 1993). Because of this, exergy analysis should be preferred for energy policy-making (Dincer, 2002). Nevertheless, when the scope of the analysis is an economy, the issue of selection of the reference environment can become more significant. This issue can lead to an unreliable economy-wide standard of energy quality if not addressed properly (Gaudreau et al., 2009; Valero, 2006), see Section 3.1.2-Issue 1.

Finally, exergy analysis, as opposed to energy, can also be extended to the accounting of material flows in the economy, which is particularly important for the analysis of socioeconomic metabolism (Haberl, 2001a). However, this thesis is only focused on energy flows since the application of exergy to non-energy flow analysis requires further development to become more consistent (Gaudreau et al., 2009).

[9] For example, exergy provides a better standard for comparing uranium supplies or imported electricity with primary fossil fuels (Cullen and Allwood, 2010a)

3 Methodological framework

This chapter introduces the methodological framework of the present thesis. This framework consists of three methodologies: useful work accounting, input-output analysis and decomposition analysis.

3.1 Useful work accounting

Useful work accounting (UWA) is an exergy accounting methodology (Grubler, 2012; Valero, 2006) at the useful level of energy use (Section 2.1.3). This methodology was developed departing from the work of Ayres et al. (2003) who introduced the concepts of useful work and second law final-to-useful efficiency in long-term energy transition studies[10].

Useful work (U) measures the effective amount of exergy (B) from final energy carriers that is delivered to a final function (Ayres and Warr, 2009) , e.g. the mechanical work from electricity used by an elevator motor or the exergy of the heat provided by a gas heater. It is therefore closely related to energy services in the economy.

$$U = \epsilon B \tag{3.1}$$

On the other hand, the second law final-to-useful efficiency (ϵ) represents the fraction of an exergy input that is converted into useful work (Section 2.2). The value of ϵ is a characteristic of each end-use device and is subject to thermodynamic limits (Lovins, 2004).

The main advantage of useful work-based studies (compared to other studies e.g. Apergis and Payne (2010), Recalde and Ramos-Martin (2012), Chontanawat et al. (2008), Costantini and Martini (2010) , Imran and Siddiqui (2010), Jiang and Lin (2012), and Wolde-Rufael (2005)) is that it focuses on the productive role of energy within an economy (what it is used for) instead of focusing on energy carriers (where it comes from) (Ayres and Warr, 2009). This allows including energy uses into energy transition studies, which can significantly improve conclusions (Grubler, 2012; Percebois, 1979; Rubio and Folchi, 2012; Warr et al., 2010).

[10] Useful work accounting can be considered an equivalent, though more detailed, methodology to account for useful exergy in the economy as the one applied by Nakićenović et al. (1993) and Nakićenović et al. (1996).

The results from initial useful work accounting studies for the U.S. (Ayres et al., 2003), U.K. (Serrenho, 2013; Warr et al., 2008), Austria & Japan (Warr et al., 2010), Portugal (Serrenho et al., 2012) and EU-15 (Serrenho et al., 2013) have shown that the trend of useful work intensity is mainly influenced by structural transitions, e.g. industrialization or the transition from a protectionist to an export-led economy. These studies also reported significant differences between the trends of useful work intensity (useful work/GDP) and final exergy intensity. For example, Serrenho et al. (2012) found that useful work intensity varied by only ±20% around its 154-year average while final exergy intensity experienced a stable decline. In addition, economic growth can be better explained with the introduction of useful work as a factor of production (Ayres, 2008; Ayres and Warr, 2005, 2009; Santos, 2013; Warr and Ayres, 2010, 2012). These findings suggest that the analysis of useful work can give further insights on the relationships between energy and economic growth, namely concerning energy decoupling.

3.1.1 The methodology

The basic methodology for useful work accounting was mainly developed by Ayres et al. (2003) Warr et al. (2008) and Warr et al. (2010), who accounted for useful work by allocating the direct use of exergy into several categories of useful work (e.g. heat and mechanical drive) and estimating process parameters (i.e. efficiency, temperature, etc.) of the final-to-useful conversion of exergy. In this initial methodology, electricity was considered a separate category of useful work and the allocation of direct use of exergy had little sectoral detail. Serrenho (2013) addressed these issues by breaking down electricity uses, improving second law efficiency estimates and allocating direct exergy use at a more detailed sectoral level. More recently, Palma (2014) and Brockway et al. (2014) added further detail to the allocation into useful work categories and improved the estimation of process variables of the final-to-useful conversion.

The methodology used in this work, which comprises four steps (Figure 3-1), is mainly based in the work of Serrenho (2013):

3.1.1.1 Conversion of existing final energy data to final exergy values (Step 1)

Collecting energy data

Energy datasets are collected from available information of reliable institutions (e.g. IEA, World Bank, etc.). For a comprehensive accounting, data should include non-conventional energy carriers (exergy sources) such as food for humans, feed for draft animals and early renewables (e.g. wind for mills and boats), which had a significant role in the pre-industrialized era and in rural-based economies (Haberl, 2001a, b).

The following groups of final energy carriers are considered: Coal and coal products, Oil and oil products, Natural gas, Combustible renewables, Electricity, Food and feed, and Other non-conventional

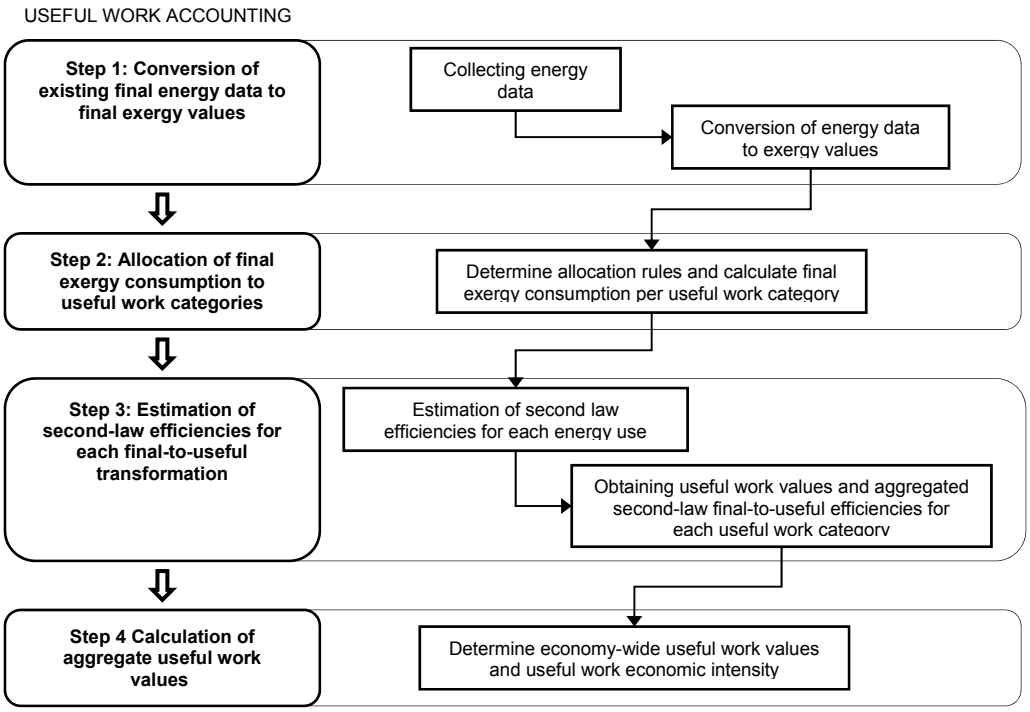


Figure 3-1 Useful work accounting methodology: Flow diagram

Conversion of energy data to exergy values

The conversions of energy to exergy values of energy carriers is given by the exergy factor (Section 2.2, Table 3-1):

Table 3-1 Exergy factors by energy carrier from Serrenho et al. (2012)

Energy carrier	Exergy factor
Coal and coal products	1.06
Oil and oil products	1.06
Natural gas	1.04
Combustible renewables	1.11
Electricity	1
Food and feed	1
Other non-conventional	1

3.1.1.2 Allocation of final exergy consumption to useful work categories (Step 2)

Final exergy consumption values per energy carrier[11] are allocated to five useful work categories[12]: heat, mechanical drive, light, other electric uses and muscle work (Serrenho et al., 2012).

[11] Non-energy uses are not included since, according to Ayres et al. (2003), the share of final exergy for non-energy uses in the economy is several orders of magnitude smaller than for energy uses, hence negligible. Non-energy uses comprise all uses that exploit other properties of an energy carrier rather than its energy content. For example, oil derivatives (paints, lubricants and plastics) or wooden furniture.

Heat: This category includes all heat used in the economy by processes and devices. It is subdivided in three types of use, based on temperature ranges of the hot reservoir (Ayres et al., 2003): 1) High temperature heat (HTH)(>600˚C) for most processes of heat-intensive industries such as iron, steel, cement, glass and oil refining industries (Harvey, 2010); 2) Medium temperature heat (MTH)(120-600˚C) for some processes of the metallurgical, chemical and energy industries (Harvey, 2010), e.g. the digestion process of aluminum production; and 3) Low temperature heat (LTH)(<120˚C) for residential and industrial hot water, cooking and space heating and other low temperature industrial processes e.g. pressing for paper production and canning for food preservation (Harvey, 2010).

Mechanical drive: This category consists of mechanical work, i.e. any conversion to drive and movement by a mechanical device regardless of the final exergy carrier. Examples of this category are energy uses through internal combustion engines, motors of household appliances (including those of HVAC and refrigeration devices[13]) and other electric motors.

Light: Includes the total lighting for industrial and residential use from any energy carrier. In modern / urban economies, most lighting services are produced by electricity. However in developing / rural economies, lighting was also obtained from oil products, fat or "town gas".

Other electric uses: This category includes others uses for electricity not mentioned in the previous categories. According to Serrenho et al. (2012), this category is divided into two subcategories: 1) Communication, electronic and electric devices and 2) electrochemical processes.

Muscle work: Comprises useful work from ingested final gross exergy of food and feed by humans and animals, respectively.

3.1.1.3 Estimation of second-law efficiencies for each final-to-useful transformation (Step 3)

Heat: According to Ford et al. (1975), ϵ_{heat} is obtained through

$$\epsilon_{heat} \approx \eta \left(1 - \frac{\theta_0}{\theta_2}\right) \tag{3.2}$$

where η is the first-law efficiency, which represents the technological level of heat end-use devices (e.g. exchangers, furnaces, boilers, etc.); θ_0 is the environment reference temperature, which refers to specific environmental conditions at the location where each heat conversion process is carried on; and θ_2 is the temperature at which heat transfer occurs.

Mechanical drive: Gasoline engines, diesel engines and electric motors perform most of the mechanical work in every sector of the economy. Therefore the second law efficiencies of these devices are considered.

[12] Palma (2014) has proposed a sixth useful work category "Heat extraction", which would include HVAC cooling and refrigeration (e.g. from electric heat pumps or steam absorption chillers). However the estimation of heat extraction data is still unreliable at the macro-scale.

[13] HVAC and refrigeration devices are included in mechanical drive because available data corresponds to the electricity use by their motors rather than to their heat extraction output (see Footnote 12).

1. Gasoline engines: $\epsilon_{gasoline}$ of these engines is obtained from that of the Otto thermodynamic cycle (Ford et al., 1975):

$$\epsilon_{gasoline} \approx \eta_{max} \prod_{i=1}^{6} \alpha_i \tag{3.3}$$

where $0 \leq \alpha_i \leq 1, \forall\, i$ are coefficients that account for deviations from the ideal process and $\eta_{max} = 1 - (1/r)^{\gamma-1}$, which is the maximum theoretical efficiency of the engine. It depends on the compression ratio (r) and the specific heat ratio $\gamma = C_p/C_v \approx 1.4$.

2. Diesel engines: For the purpose of this work, ϵ_{diesel} for diesel motors can be considered 25% higher than that of gasoline engines since diesel engines have better compression ratios and better fuel-burning efficiencies (Ford et al., 1975).

$$\epsilon_{diesel} \approx 1.25\, \epsilon_{gasoline} \tag{3.4}$$

3. Electric motors: ϵ_{mech} is estimated from technical specifications and estimates in the literature, e.g. Ayres et al. (2005).

Light: Final-to-useful efficiency for a lighting technology differs from the others since it is determined based on a non-energy unit, i.e. lumens. It is defined as the ratio of generated lumens per watt by a lighting technology (e.g. kerosene lamp or a fluorescent bulb) and a reference value of maximum lumens per watt generated by an ideal light source [14].

$$\epsilon_{light} = \frac{\text{Generated light by a lighting technology} \left[{}^{\text{lm}}/_{\text{W}}\right]}{\text{Reference light generated by an ideal light source} \left[{}^{\text{lm}}/_{\text{W}}\right]} \tag{3.5}$$

Consequently, the useful work of a lighting technology represents the quantity of exergy that this ideal light source would consume to generate the same amount of lumens as those generated by the lighting technology. This approach to ϵ_{ligth} is supported by most lighting and efficiency literature, e.g. Ayres et al. (2005), Fouquet and Pearson (2006) and Nordhaus (1997).

Other electric uses: $\epsilon_{other\ electric}$ is calculated according to Equation (2.1). It accounts for the exergy losses of circuits and components of electric / electronic devices. This efficiency is estimated from available data and historical studies of second-law efficiencies of these devices (e.g. Ayres et al. (2005)).

Muscle work: ϵ_{muscle} corresponds to the efficiency of human and animals to convert food and feed final gross exergy[15] into muscle work (Serrenho et al., 2012). ϵ_{muscle} accounts for incomplete absorption / digestion, for body growth and other body energy uses, for physiological state of the system, etc. (FAO, 2003).

[14] Nevertheless, considerations about the value of the reference value in lumens per watt (ln/W) for 100% lighting efficiency differ: e.g. Ayres et al. (2005) considered 400 ln/W, while Serrenho et al. (2012) took 683 ln/W, associated to the wavelength of 555nm (green light range) to which the human eye is most sensitive.

[15] Final gross exergy approximately corresponds to the maximum amount of heat obtained from complete combustion of a certain food in a bomb calorimeter (FAO, 2003).

3.1.1.4 2.4 Calculation of aggregate useful work values (Step 4)

Aggregate useful work figures per categories and sub-categories of useful work are calculated with Equation (3.1) and then aggregated to obtain economy-wide useful work (U_T) and second-law final-to-useful efficiency (ϵ_T)

$$\frac{U_T}{B_T} = \frac{\sum_i U_i}{\sum_i B_i} \tag{3.6}$$

where U_i is the consumption of useful work category i and B_i is the total final exergy allocated to useful work category i. ϵ_T, also referred as *technical efficiency*, represents all improvements in the technology of end-use devices in the economy.

Additionally, useful work economic intensity is calculated as:

$$\frac{U_T}{Q} = \frac{\sum_i U_i}{Q} \tag{3.7}$$

where Q is an output indicator in constant prices, e.g. gross output, GDP or GVA.

3.1.2 Conceptual issues

Issue 1: Validity of assumptions

The data required to perform economy-wide useful work accounting is never complete hence assumptions about allocation of direct energy uses into useful work categories and parameters of final-to-useful conversion must be done. The validity of these assumptions determines the level of closeness to reality of estimated useful work values and the suitability of conclusions obtained. This issue can be addressed by performing a sensitivity analysis of these assumptions, for example, Palma (2014) and Brockway et al. (2014).

Issue 2: Context specific

Exergy is a concept that is sensitive to the reference environment (Section 2.2). The boundaries of this reference environment are determined by the researcher rather than by the concept itself (Gaudreau et al., 2009), which could add bias to estimated useful work values. The consequences of this issue can be reduced by: 1) evaluating different perspectives of the reference environment; and 2) performing the analysis at the lowest possible level of aggregation.

3.2 Input-output analysis

Input-output analysis is a method for economic analysis (Christ, 1955; Miller and Blair, 2009), which was originally developed by Wassily Leontief in the 1930's (Leontief, 1936). Leontief built an empirical model of the U.S. economy for the year 1919 based on the concept of general interdependence among elements of the economic system[16].

[16] The first system on general interdependence (*Tableau Economique*) was developed by Frangois Quesnay in 1758 (Phillips, 1955). His table represented the regeneration of income due to the expenditure of a member of the proprietor class. Leontief (1936) establishes that his methodology is an

The advantages of the input-output method rely on the simplicity of the representation of the economic system (Christ, 1955; Leontief, 1955). Because of this, it has been applied to many areas of economic theory (Dietzenbacher et al., 2013; Leontief, 1986; Miller and Blair, 2009; Rose and Miernyk). Notably, environmental applications have expanded in recent decades (Dietzenbacher et al., 2013; Duchin and Steenge, 1999; Suh, 2009). For example, analyses of the impact of the economic structure on emissions, energy use, pollution and material use.

This section presents the basis of the input-output method and ends with the description of the application of this method to energy use studies.

3.2.1 The basic input-output model

The input-output framework describes the flows of products within an economic system. It accounts for product transactions between industries and between industries and final consumers.

An industry, or producing sector, represents a segment of the economic system. Each industry has a double role: it produces goods and services; and it uses products from other industries as inputs for production. On the other hand, final consumers are non-producing units of the economic system. They are considered exogenous purchasers, which means that their demand for products is unrelated to the amount of products produced by industries.

		Industries				Final Demand	Total output
		1	2	⋯	n		
Industries	1	Z_{11}	Z_{12}	⋯	Z_{1n}	f_1	x_1
	2	Z_{21}	Z_{22}	⋯	Z_{2n}	f_2	x_2
	⋮	⋮	⋮	⋱	⋮	⋮	⋮
	n	Z_{n1}	Z_{n2}	⋯	Z_{nn}	f_n	x_n
				$\boldsymbol{Z}$		$\boldsymbol{f}$	$\boldsymbol{x}$
Value added		w_1	w_2	⋯	w_n		
				$\boldsymbol{w}$			
Total inputs		x_1	x_2	⋯	x_n		
				$\boldsymbol{x}'$			

Figure 3-2 Input-output table of interindustry flows of goods

Input and output data is built with existing economic data, organized in an interindustry transactions table (Figure 3-2). Interindustry transactions are recorded in either monetary or physical units. Monetary units correspond to the euro/dollar value of sales of a specific product, while physical units correspond to the amount in tons, meters, etc. of sales of that product.

Within this framework, the total output (production) of an industry can be represented by the sum of sales to other industries and the final demand for that industry.

$$x_i = Z_{i1} + Z_{i2} + Z_{i3} + \ldots + Z_{in-1} + Z_{in} + f_i \tag{3.8}$$

attempt to build a *Tableau Economique* for the U.S. economy hence emphasizing the link between both methods (Maital, 1972; Phillips, 1955).

There are similar equations for every industry $i = 1,2,3 \dots n$ of the economic system. They can be arranged as a matrix system of n linear equations

$$\boldsymbol{x} = \boldsymbol{Z}\boldsymbol{i} + \boldsymbol{f} \tag{3.9}$$[17]

where matrix $\boldsymbol{Z}$ of size $n \times n$ represents the total interindustry transactions, vector $\boldsymbol{x}$ of length n is the total output and vector $\boldsymbol{f}$ of length n corresponds to final demand. Notice that column j of matrix $\boldsymbol{Z}$ describes the input structure of industry j. In addition, industry j also uses other items as inputs, such as labor and capital, which are accounted for by the value *added* vector ($\boldsymbol{w}$) (Figure 3-2). Equation (3.9) represents the flows of the economy.

To explain how changes in final demand would affect the level of production of the economy the interindustry transaction matrix ($\boldsymbol{Z}$) must be defined in terms of $\boldsymbol{x}$ and/or $\boldsymbol{f}$ because increasing a unit in the final demand of a product will proportionally increase the production of other goods.

The amount of inputs from industry i to the industry j will increase with the total output of industry j .

$$Z_{ij} = \alpha_{ij}(x_j) \tag{3.10}$$

Function α_{ij} is a component of the production function for industry j. It is assumed that this production function is of perfect complements (i.e. there is no substitution between inputs) and has constant returns to scale (Miller and Blair, 2009). Under these assumptions

$$Z_{ij} = A_{ij}x_j \tag{3.11}$$

where the constant term $A_{ij} = \frac{Z_{ij}}{x_j}$ is known as the technical coefficient, which describes the amount of inputs from industry i per unit of output of industry j.

Introducing the technical coefficients in the expression for total output of industry i (Equation (3.8)), we obtain

$$x_i = A_{i1}x_1 + A_{i2}x_2 + \cdots + A_{in}x_n + f_i \tag{3.12}$$

which reinforces the notion of how interindustry transactions are related to total output of every industry.

Analogously, there are n similar equations for every industry $i = 1,2,3 \dots n$ that are arranged in matrix form as

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{f} \tag{3.13}$$

where matrix $\boldsymbol{A}$ of size $n \times n$ is the technical of direct input coefficient matrix, which is related to the interindustry transactions matrix as $\boldsymbol{A} = \boldsymbol{Z}\hat{\boldsymbol{x}}^{-1}$.

[17] Hereinafter: A bold lower case letter ($\boldsymbol{x}$) corresponds to a vector. A bold capital letter ($\boldsymbol{Z}$) describes a matrix. Non-bold lower case and capital letters (x_i and Z_{ij}) represent scalars. A vector with a hat ($\hat{\boldsymbol{x}}$) represents a diagonal matrix, whose diagonal elements are the elements of vector $\boldsymbol{x}$. An apostrophe on a vector or matrix ($\boldsymbol{x}'$ and $\boldsymbol{Z}'$) denotes the vector or matrix transpose. $\boldsymbol{i}$ is a vector of ones of a consistent length (or summation vector). Refer to the Notation Index of this thesis.

Equation (3.13) is then solved for the vector of total output $\boldsymbol{x}$

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} = \boldsymbol{L}\boldsymbol{f} \tag{3.14}$$

where the matrix $\boldsymbol{L}$ of size $n \times n$ is the Leontief or total requirements matrix, whose elements L_{ij} represent the amount of output by industry i that is directly and indirectly needed to provide a unit of product of industry j to final demand. Equation (3.14) is the basic input-output model.

The main assumptions of input-output analysis are listed below (mainly based on EUROSTAT (2008b), (Leontief, 1955), Miller and Blair (2009) and Suh (2009)) with a small discussion of the most relevant:

- Technical coefficients (A_{ij}) are fixed. Fixed coefficients imply that the cost of each input is directly proportional to the quantity of output hence price effects are neglected (Rose and Miernyk, 1989). This assumption is the most controversial and is followed for the sake of simplicity (Leontief, 1955; Rose and Miernyk, 1989). However, it is less relevant in structural decomposition analysis (Rose, 1999), see Section 3.3.3.
- Constant returns to scale are considered, which equates the marginal to the average input from industry i per output of industry j, i.e.

$$A_{ij} = \underbrace{\frac{Z_{ij}}{x_j}}_{\text{Average}} = \underbrace{\frac{\Delta Z_{ij}}{\Delta x_j}}_{\text{Marginal}} \tag{3.15}$$

  This assumption reduces the forecasting power of the input-output method by neglecting economies of scale.
- There is no substitution between inputs to the production process, i.e. all inputs are perfect complements. This assumption is also controversial (Christ, 1955) though less relevant in structural decomposition analysis, see Section 3.3.3.
- Industries produce one and only one product, which does not correspond to the reality of most economies.
- Resources are not constrained, i.e. supply is infinite and perfectly elastic, and are not underused, i.e. efficient use of resources.
- The model is static hence it only takes into account the flows of inputs and outputs of a given time unit.
- Final demand is considered exogenous.
- Data is diligently prepared. However given the size of data requirements, there are issues about availability, aggregation, accuracy and indirect estimations.

3.2.2 The product-by-industry approach to input-output analysis

As discussed in the previous section, the basic input-output model assumes that each industry produces one single product. However, industries also produce secondary products and/or by-products. The product-by-industry approach provides a framework to account for these additional products in the economy (EUROSTAT, 2008b; Miller and Blair, 2009; Rodrigues and Rueda-Cantuche, 2013).

Each industry uses input products to make one or more type of products. Final demand for products is also considered exogenous. This information is ordered into a make-use table framework (Figure 3-3). This framework is in accordance to a broader system of national accounts (UN, 1993, 2009) and it has become the standard accounting method for interindustry transactions in the European Union (EUROSTAT, 2014a).

The system consists of n industries that use and produce m different products. Industries are characterized by one or more primary products. However, if there is one primary product per industry, the system is square (i.e. $n = m$).

		Products				Industries				Final Demand	Total output	
		1	2	⋯	m	1	2	⋯	n			
Products	1					U_{11}	U_{12}	⋯	U_{1n}	y_1	q_1	
	2					U_{21}	U_{22}	⋯	U_{2n}	y_2	q_2	
	⋮					⋮	⋮	⋱	⋮	⋮	⋮	$\boldsymbol{q}$
	m					U_{m1}	U_{m2}	⋯	U_{mn}	y_m	q_m	
						$\boldsymbol{U}$				$\boldsymbol{y}$		
Industries	1	V_{11}	V_{12}	⋯	V_{1m}						x_1	
	2	V_{21}	V_{22}	⋯	V_{2m}						x_2	
	⋮	⋮	⋮	⋱	⋮						⋮	$\boldsymbol{x}$
	n	V_{n1}	V_{n2}	⋯	V_{nm}						x_n	
		$\boldsymbol{V}$										
Value added						w_1	w_2	⋯	w_n			
						$\boldsymbol{w}'$						
Total inputs		q_1	q_2	⋯	q_m	x_1	x_2	⋯	x_n			
		$\boldsymbol{q}'$				$\boldsymbol{x}'$						

Figure 3-3 Make-use framework for product-by-industry data
Note: $\boldsymbol{U}$ – Use matrix, $\boldsymbol{V}$ – Make matrix, $\boldsymbol{y}$ – Final demand by product, $\boldsymbol{w}$ – value added by industry, $\boldsymbol{q}$ – Total output by product and $\boldsymbol{x}$ – Total output by industry,

3.2.2.1 The use and make matrices U and V

The use matrix accounts for interindustry transactions of products. Row i of $\boldsymbol{U}$ represents the sales of product i to be used as input to producing industries. Column j of matrix $\boldsymbol{U}$ describes the input structure of products of industry j

As in Section 3.2.1, the amount of inputs of product i to the industry j (U_{ij}) is directly proportional to the total output of industry (x_j):

$$U_{ij} = B_{ij}x_j \tag{3.16}$$

where the constant term $B_{ij} = \frac{U_{ij}}{x_j}$ corresponds to the product-by-industry technical coefficient, analogous to the technical coefficients A_{ij}.

In matrix notation, Equation (3.16) is

$$\boldsymbol{U} = \boldsymbol{Bx} \tag{3.17}$$

The make matrix show the way industries make products. The total output of industry j is the summation of the value of output of every product that it produces, i.e.

$$x_j = V_{1j} + V_{2j} + V_{3j} + \ldots + V_{(m-1)j} + V_{mj} \tag{3.18}$$

or in matrix notation,

$$\boldsymbol{x} = \boldsymbol{V}\boldsymbol{i} \tag{3.19}$$

In addition, the summation the column i of the make matrix gives the total output of product i (q_i), which is represented in matrix notation as

$$\boldsymbol{q} = \boldsymbol{V}'\boldsymbol{i} \tag{3.20}$$

3.2.2.2 The total requirements matrix

The total output of product i can be represented by the sum of all purchases of this product by n industries and by final demand as

$$q_i = U_{i1} + U_{i2} + U_{i3} + \ldots + U_{in-1} + U_{in} + y_i \tag{3.21}$$

There are similar equations for every product $i = 1,2,3 \ldots m$, whichcan be arranged as a matrix system of m linear equations,

$$\boldsymbol{q} = \boldsymbol{U}\boldsymbol{i} + \boldsymbol{y} \tag{3.22}$$

Introducing B_{ij} coefficients from Equation (3.16)

$$\boldsymbol{q} = \boldsymbol{B}\boldsymbol{x} + \boldsymbol{y} \tag{3.23}$$

Notice that, in this case, it is not possible to calculate a total requirements matrix, as in Section 3.2.1, i.e. it is neither possible to solve Equation (3.23) for $\boldsymbol{q}$ nor for $\boldsymbol{x}$ since they represent different quantities.

Alternatively, there are two conventional assumptions to build a symmetric total requirements matrix from Equation(3.23): the Industry Technology Assumption (ITA) and the Commodity Technology Assumption (CTA). The ITA establishes that all products made by an industry share the same input structure while the CTA establishes that each product has the same input structure in every producing industry. (EUROSTAT, 2008b; Guo et al., 2009; Miller and Blair, 2009; UN, 1999).

Industry Technology Assumption

A product-output proportions matrix ($\boldsymbol{D}$) is derived from the make table as

$$\boldsymbol{D} = \boldsymbol{V}\hat{\boldsymbol{q}}^{-1} \tag{3.24}$$

where each entry of $\boldsymbol{D}$, D_{ij}, is the share of product i that is produced by industry j.

If this equality is post-multiplied by the total product output and combined with Equation (3.19) we obtain

$$\boldsymbol{D}\boldsymbol{q} = \boldsymbol{V}\hat{\boldsymbol{q}}^{-1}\boldsymbol{q} = \boldsymbol{V}\boldsymbol{i} = \boldsymbol{x} \tag{3.25}$$

Introducing the latter expression into Equation (3.23) and solving for $\boldsymbol{q}$ or for $\boldsymbol{x}$, the following expressions are obtained:

$$\boldsymbol{q} = (\boldsymbol{I} - \boldsymbol{BD})^{-1}\boldsymbol{y} \tag{3.26}$$

$$\boldsymbol{x} = \boldsymbol{D}(\boldsymbol{I} - \boldsymbol{BD})^{-1}\boldsymbol{y} \tag{3.27}$$

,where $\boldsymbol{D}(\boldsymbol{I} - \boldsymbol{BD})^{-1}$ corresponds to the industry-by-product total requirements matrix and $(\boldsymbol{I} - \boldsymbol{BD})^{-1}$ to the product-by-product total requirements matrix under the ITA.

Note: The distinction between the industry-by-product and product-by-product total requirements matrices is introduced by the make-use framework. The former matrix (of size $n \times m$) transforms final demand by product into total output by industry while the latter matrix (of size $m \times m$) transofrms the final demand by product into total output by product. Moreover, in this respect, the total requirements matrix of the basic input-output model (Equation (3.14)) can be calssified as an industry-by-industry total requirements matrix as it transforms final demand by industry into total output by industry.

Commodity Technology Assumption

An industry output proportions matrix ($\boldsymbol{C}$) is derived from the make table as

$$\boldsymbol{C} = \boldsymbol{V}'\widehat{\boldsymbol{x}}^{-\boldsymbol{1}} \tag{3.28}$$

where the entries C_{ij} correspond to the share of industry i's output which is obtained through product j.

If this equality is post-multiplied by the total industry output and combined with Equation (3.25) we obtain

$$\boldsymbol{Cx} = \boldsymbol{V}'\boldsymbol{i} = \boldsymbol{q} \tag{3.29}$$

Introducing the latter expression into Equation (3.23) and solving for $\boldsymbol{q}$ and $\boldsymbol{x}$, the following expressions are obtained:

$$\boldsymbol{q} = (\boldsymbol{I} - \boldsymbol{BC}^{-1})^{-1}\boldsymbol{y} \tag{3.30}$$

$$\boldsymbol{x} = \boldsymbol{C}^{-1}(\boldsymbol{I} - \boldsymbol{BC}^{-1})^{-1}\boldsymbol{y} \tag{3.31}$$

where $\boldsymbol{C}^{-1}(\boldsymbol{I} - \boldsymbol{BC}^{-1})^{-1}$ corresponds to the industry-by-product total requirements matrix and $(\boldsymbol{I} - \boldsymbol{BC}^{-1})^{-1}$ to the industry-by-product total requirements matrix under the CTA. Notice that these matrices can only be obtained when the industry output proportions matrix ($\boldsymbol{C}$) is square (i.e. $m = n$, there are the same number of industries and products).

Selection between Industry and Commodity Technology Assumption

Jansen and Ten Raa (1990) evaluated approaches to obtain input-output coefficient matrices (including the ITA and CTA approaches). They singled out the CTA for complying with most desirable properties (e.g. material balance, scale invariance, financial balance and price invariance). Complementarily, Ten Raa and Rueda-Cantuche (2003) identified that the ITA needs restrictive conditions on the data sets in order to comply with the desirable properties. Nevertheless, the CTA occasionally constructs negative coefficients and can only be applied to

square systems (i.e. $m \neq n$). On the one hand Miller and Blair (2009) and Guo et al. (2009) define some techniques to reduce the incidence of negative coefficients. On the other hand, as there are no alternatives for the square condition of the CTA, the ITA or other approaches should be used (EUROSTAT, 2008b).

3.2.3 Energy input-output model

Energy input-output models are designed to account for the energy flows in the economy (Bullard and Herendeen, 1975a; Casler and Wilbur, 1984; Miller and Blair, 2009). These models also enable the analysis of: 1) direct and indirect energy requirements of the economy, i.e. Net energy analysis (Bullard et al., 1978); 2) the energy cost of goods and services for final demand (Krenz, 1974; Wright, 1974); 3) the effect of alternative energy conversion technologies (Miller and Blair, 2009; Park, 1982); and 4) changes in energy use through structural decomposition (see Section 3.3.3).

Energy input-output models are built according to two approaches: the *hybrid-unit approach* and the *direct impact coefficient approach* (also known as *energy intensity approach*).

3.2.3.1 The hybrid-unit approach

The hybrid unit approach was originally developed by Bullard and Herendeen (1975a, b)[18] based on the conservation of embodied energy, which establishes that energy embodied in the output of and industry is equal to the energy embodied in input products plus any external energy input to this industry.

This approach is considered the standard for energy input-output models (Casler and Wilbur, 1984; Griffin, 1976; Hawdon and Pearson, 1995; Miller and Blair, 2009). Some examples of its application can be found in Cohen et al. (2005); Hannon (2010); Hannon et al. (1983); Kagawa and Inamura (2001); Lindner et al. (2011); Machado et al. (2001); Machado (2000); Park and Heo (2007); Reinders et al. (2003); Santos et al. (2009) and Treloar (1997).

The hybrid unit approach starts from the basic input-output identity, i.e. $\boldsymbol{x} = \boldsymbol{Zi} + \boldsymbol{f}$. The n industries, represented in $\boldsymbol{Z}$, consist of r energy industries and $n - r$ non-energy industries (for convenience, energy industries are placed first in the index of industries).

It is possible to determine a similar identity for energy flows in physical units, as

$$\boldsymbol{g} = \boldsymbol{Ei} + \boldsymbol{h} \tag{3.32}$$

where vector $\boldsymbol{g}$ of length r is the total energy use (i.e. output of energy industries); matrix $\boldsymbol{E}$ of size $r \times n$ represents the energy flows from energy industries to all producing industries (energy and non-energy); and vector $\boldsymbol{h}$ of length r represent the energy deliveries to final demand.

[18] The work of Bullard and Herendeen (1975a) was contemporary to other attempts to build a consistent energy input-output model by for example Krenz (1974), Wright (1974) and Wright (1975).

The monetary-unit rows of energy industries in $\boldsymbol{Z}$, $\boldsymbol{f}$ and $\boldsymbol{x}$ are substituted by the corresponding physical-unit rows of $\boldsymbol{E}$, $\boldsymbol{h}$ and $\boldsymbol{g}$, respectively (Figure 3-4), in order to construct a system of hybrid-units:

$$\boldsymbol{x}^* = \boldsymbol{Z}^*\boldsymbol{i} + \boldsymbol{f}^* \tag{3.33}$$[19]

where $\boldsymbol{x}^*$ is the hybrid vector of length n of total industrial output, $\boldsymbol{Z}^*$ is the hybrid matrix of size $n \times n$ of interindustry flows; and $\boldsymbol{f}^*$ is the hybrid vector of length n of final demand.

The model in Equation (3.33) is then solved for $\boldsymbol{x}^*$ in the same way as in Section 3.2.1.

$$\boldsymbol{x}^* = (\boldsymbol{I} - \boldsymbol{A}^*)^{-1}\boldsymbol{f}^* = \boldsymbol{L}^*\boldsymbol{f}^* \tag{3.34}$$

where $\boldsymbol{A}^*$ and $\boldsymbol{L}^*$ are the hybrid unit versions of matrices $\boldsymbol{A}$ and $\boldsymbol{L}$ in Equation (3.14).

			Industries: Energy			Industries: Non-energy			Final demand	Total output
			1		r	$r+1$	$\cdots$	n		
	Energy	1	E_{11}	$\cdots$	E_{1r}	$E_{1(r+1)}$	$\cdots$	E_{1n}	h_1	g_1
		$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$
		r	E_{r1}	$\cdots$	E_{rr}	$E_{r(r+1)}$	$\cdots$	E_{rn}	h_r	g_r
Industries	Non-energy	$r+1$	$Z_{(r+1)1}$	$\cdots$	$Z_{(r+1)r}$	$Z_{(r+1)n}$	$\cdots$	$Z_{(r+1)n}$	$f_{(r+1)}$	$x_{(r+1)}$
		$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$
		n	Z_{n1}	$\cdots$	Z_{nr}	Z_{nn}	$\cdots$	Z_{nn}	f_n	x_n
						$\boldsymbol{Z}^*$			$\boldsymbol{f}^*$	$\boldsymbol{x}^*$

Rules of substitution

Rows	$\boldsymbol{Z}^*$	$\boldsymbol{f}^*$	$\boldsymbol{x}^*$
$1 \le i \le r$	$Z^*_{ij} = E_{ij}$	$f^*_i = h_i$	$x^*_i = g_i$
$r < i \le n$	$Z^*_{ij} = Z_{ij}$	$f^*_i = f_i$	$x^*_i = x_i$

Figure 3-4 Graphical representation of the hybrid-unit identity in Equation (3.33).
Note: In hybrid-unit systems the column sums of $\boldsymbol{Z}^*$ are meaningless (see Section 3.2.3.4-Issue 7).

Equation (3.34) is a hybrid version of the basic input-output model. However, the objective of energy input-output analysis is to have a total energy requirements matrix $\boldsymbol{\alpha}$ that enables the calculation of the energy requirements to meet final demand, i.e. the matrix that solves the equation:

$$\boldsymbol{g} = \boldsymbol{\alpha}\boldsymbol{f}^* \tag{3.35}$$

As seen in Figure 3-4, $x^*_i = g_i$ for $1 \le i \le r$, so it is possible to establish a simple relationship, $\boldsymbol{g} = \boldsymbol{K}\boldsymbol{x}^*$, where $\boldsymbol{K}$ is a bridge matrix of size $r \times n$ with entries $K_{ij} = 1$ for $i = j$ (i.e. energy industries) and $K_{ij} = 0$ for $i \ne j$. $\boldsymbol{K}$ extracts the elements of $\boldsymbol{x}^*$ that correspond to the output of energy industries.

[19] Hereinafter, the superscript * on a variable denotes a hybrid-unit version of that variable.

Consequently, the total energy requirements matrix ($\boldsymbol{\alpha}$) can be calculated as

$$\boldsymbol{\alpha} = \boldsymbol{K}(\boldsymbol{I} - \boldsymbol{A}^*)^{-1} = \boldsymbol{K}\boldsymbol{L}^* \quad (3.36)$$ [20]

Furthermore, the product-by-industry or make-use approach (Section3.2.2) enables to account for secondary products in the construction of the total energy requirements matrix, see also Casler and Wilbur (1984). Table 3-2 summarizes the expressions to determine matrix $\boldsymbol{\alpha}$ under the Industry and the Commodity Technology Assumptions (CTA and ITA).

Under the make-use framework, the non-energy products that energy industries produce (e.g. engineering services) and energy carriers that non-energy industries produce (e.g. residual biomass from agriculture) can be included. As energy carriers are in physical units and non-energy products in monetary units, these cannot be added together in the total output by industry ($\boldsymbol{x}^*$), i.e.only the total output per product ($\boldsymbol{q}^*$) is consistent. Therefore, $\boldsymbol{\alpha}$ represents a product-by-product (instead of an industry-by-product) energy technology matrix. This is to avoid the aggregation of energy and non-energy outputs of energy industries (e.g. gasoline vs. engineering services) or of non-energy industries (e.g. agricultural products vs. residual biomass for boilers).

Table 3-2 The product-by-industry energy input-output model under the ITA and CTA

Hybrid-unit matrices	ITA	CTA
Use	$\boldsymbol{U}^*$	
Make	$\boldsymbol{V}^*$	
Inputs per industry output	$\boldsymbol{B}^* = \boldsymbol{U}^*(\widehat{\boldsymbol{x}}^*)^{-1}$	
Product output proportions	$\boldsymbol{D}^* = \boldsymbol{V}^*\widehat{\boldsymbol{q}}^{-1}$	
Industry output proportions		$\boldsymbol{C}^* = (\boldsymbol{V}^*)'(\widehat{\boldsymbol{x}}^*)^{-1}$
Product-by-product total requirements	$\boldsymbol{\alpha} = \boldsymbol{K}(\boldsymbol{I} - \boldsymbol{B}^*\boldsymbol{D}^*)^{-1}$	$\boldsymbol{\alpha} = \boldsymbol{K}\left(\boldsymbol{I} - \boldsymbol{B}^*\,\boldsymbol{C}^{*-1}\right)^{-1}$

3.2.3.2 The direct impact coefficient approach

The direct impact coefficient approach was developed in the 1960's (Miller and Blair, 2009; Rose and Casler, 1996). It is simpler and requires less detailed data than the hybrid-unit approach. Because of this, it is still widely supported and used (Ardent et al., 2009; Cruz, 2002; Hawdon and Pearson, 1995; Proops, 1977) even though it is less consistent than the hybrid – unit approach, see Section 3.2.3.4-Issue 4 and (Miller and Blair, 2009). Some examples of its application can be found in Chai et al. (2009); Gould and Kulshreshtha (1986); Kahrl and Roland-Holst (2008, 2009); Liang et al. (2010); Limmeechokchai and Suksuntornsiri (2007); Östblom (1982); Park (1982); Proops (1984); Wachsmann et al. (2009); Weber (2009) and Wu and Chen (1990)

[20] This is a pragmatic and intuitive approach to matrix $\boldsymbol{\alpha}$. Bullard and Herendeen (1975a) and Miller and Blair (2009) obtain an equivalent expression by solving the embodied energy conservation equation $\alpha_{kj}x_j = \sum \alpha_{ki}x_i + g_{kj}$. This equation states that the energy of type k embodied in the output of industry j ($\alpha_{kj}x_j$) is equal to the energy embodied in the inputs of this industry ($\alpha_{ki}x_i$) plus any exogenous energy input (g_{kj}).

The model starts by calculating a direct energy intensity matrix $(\boldsymbol{T})$,

$$\boldsymbol{T} = \boldsymbol{E}\hat{\boldsymbol{x}}^{-1} \tag{3.37}$$

whose elements T_{kj} correspond to the direct use of energy of type k ($1 \leq k \leq r$) to produce a monetary unit of output of industry j ($1 \leq j \leq n$).

Therefore, from Equations (3.32) and (3.14)

$$\boldsymbol{g} - \boldsymbol{h} = \boldsymbol{T}\boldsymbol{x} = \boldsymbol{T}\boldsymbol{L}\boldsymbol{f} \tag{3.38}$$

where matrix $\boldsymbol{TL}$ of size $r \times n$ is the total interindustry energy coefficient matrix.

To account for the energy deliveries to final demand $\boldsymbol{h}$, Miller and Blair (2009) (similar to Cruz (2002) and Proops (1977)) propose a relationship with final demand as: $\boldsymbol{h} = \widetilde{\boldsymbol{Q}}\boldsymbol{f}$ where $\widetilde{\boldsymbol{Q}}$ is the matrix of size $r \times n$ of inverse prices of energy of type k to final demand (p_{kj}), whose element $\tilde{q}_{kj} = 1/p_{kj}$ for $i = j$ (i.e. energy carriers) and $\tilde{q}_{kj} = 0$ for $i \neq j$.

Total energy use is therefore obtained as

$$\boldsymbol{g} = \left(\boldsymbol{TL} + \widetilde{\boldsymbol{Q}}\right)\boldsymbol{f} = \boldsymbol{\beta}\boldsymbol{f} \tag{3.39}$$

where $\boldsymbol{\beta}$ is the matrix of total energy requirements (analogous to $\boldsymbol{\alpha}$) obtained through the direct impact coefficient approach.

3.2.3.3 Structure of total energy requirements matrices α and β

The hybrid-unit energy total energy requirements matrix $\boldsymbol{\alpha}$

To describe the structure of $\boldsymbol{\alpha}$, the structure of the hybrid-unit Leontief matrix $(\boldsymbol{L}^*)$ should be discussed first.

$\boldsymbol{L}^*$ is composed by four sub-matrices $\boldsymbol{\theta}^*$, $\boldsymbol{\tau}^*$, $\boldsymbol{\pi}^*$ and $\boldsymbol{\psi}^*$ (Figure 3-5), see Bullard and Herendeen (1975a) and Casler and Wilbur (1984).

1. $\boldsymbol{\theta}^*$ is the sub-matrix of energy transactions between energy industries per unit of final energy demand. The element θ^*_{kl} represents the amount of energy use of carrier type k (i.e. from energy industry) by the energy industry l per unit of final demand of energy industry l.
2. $\boldsymbol{\tau}^*$ is the sub-matrix of direct energy use by non-energy industries per unit of final non-energy demand. The element τ^*_{kj} corresponds to the energy use of carrier type k by non-energy industry j per unit of final demand of this non-energy industry.
3. $\boldsymbol{\pi}^*$ is the sub-matrix of non-energy transactions from non-energy to energy industries per unit of final energy demand. The element π^*_{il} represents the input from industry i to energy industry l per unit of final demand of that energy industry.
4. $\boldsymbol{\psi}^*$ is the sub-matrix of Interindustry transactions between non-energy industries per unit of final demand. The element ψ^*_{ij} accounts for the inputs from industry i to non-energy industry j per unit of final demand of this non-energy industry.

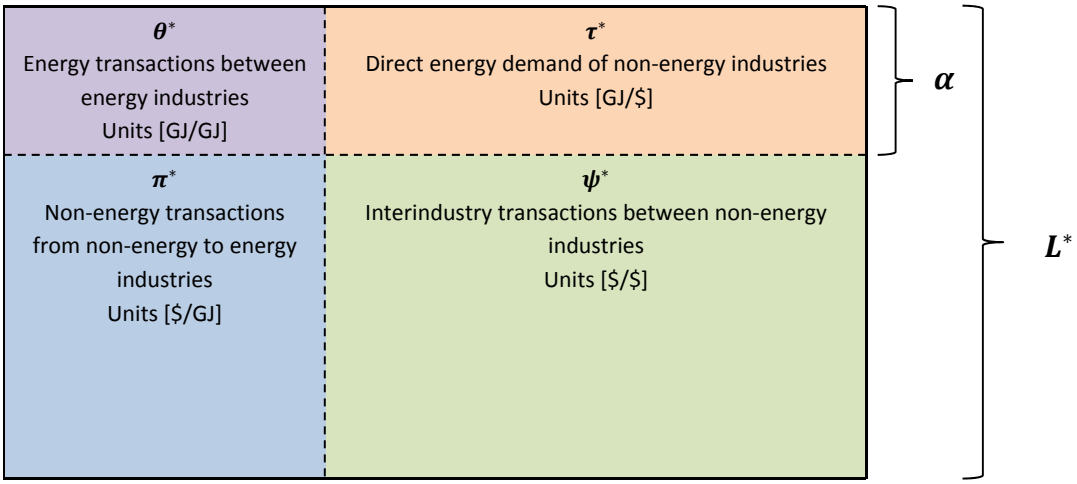


Figure 3-5 The sub-matrices of the hybrid-unit total requirements matrix L^*

As explained in the previous section, the total energy requirements matrix of the hybrid-unit model ($\boldsymbol{\alpha}$) corresponds to the rows of energy industries of the $\boldsymbol{L}^*$. This indicates that $\boldsymbol{\alpha}$ is only composed by the sub-matrices $\boldsymbol{\theta}^*$ and $\boldsymbol{\tau}^*$ (Figure 3-5). Consequently, non-energy transactions in the economy in $\boldsymbol{\pi}^*$ and $\boldsymbol{\psi}^*$ are internalized (indirectly accounted for) by $\boldsymbol{\alpha}$.

The sum of the column l of sub-matrix $\boldsymbol{\theta}^*$ corresponds to the total energy inputs required to produce a unit of energy output to final demand of energy industry l. This is similar to inverse of the concept of energy conversion efficiency, i.e. the ratio of energy output per energy input in a conversion process. Therefore, $\boldsymbol{\theta}^*$ represents the conversion technology of an energy sector that only serves final demand. In addition, this sub-matrix $\boldsymbol{\theta}^*$ and $\boldsymbol{\pi}^*$ together describe the total production function of this energy sector that only serves final demand.

The sub-matrix $\boldsymbol{\tau}^*$ can be represented as the matrix product

$$\boldsymbol{\tau}^* = \boldsymbol{C}\boldsymbol{T}|_f \tag{3.40}$$

where matrix $\boldsymbol{C}$ is the composition of direct energy demand of non-energy industries, whose element C_{kj} accounts for the share of energy type k in the total energy use by the non-energy industry j, and the diagonal matrix $\boldsymbol{T}|_f$ is the energy use (direct and indirect) per unit of final demand (hence the subscript f), i.e. the energy intensity with respect to final demand, whose diagonal element $T_{jj}\big|_f$ corresponds to the total energy use per unit of output to final demand of industry j.

Moreover, as the vector of total energy use ($\boldsymbol{g}$) usually includes the primary energy sector, $\boldsymbol{\tau}^*$ also accounts for the conversion processes of an energy sector that only serves non-energy industries (given by the difference between the final and the primary energy rows of $\boldsymbol{\tau}^*$), see Miller and Blair (2009).

Concluding, $\boldsymbol{\alpha}$ accounts for every transaction in the economy. However, it is not able to separate the effect of energy (i.e. conversion efficiency or direct energy intensity) from non-energy transactions, i.e. both energy and non-energy production processes are aggregated together.

The direct impact coefficient energy total energy requirements matrix $\boldsymbol{\beta}$

The total energy requirements matrix ($\boldsymbol{\beta} = \boldsymbol{TL} + \widetilde{\boldsymbol{Q}}$) combines two variables that are conceptually and technically different: direct and indirect energy embodied in final demand in $\boldsymbol{TL}$ and energy prices $\widetilde{\boldsymbol{Q}}$. Therefore, in the direct impact coefficient model, it is better to analyze separately the production-related energy use (through $\boldsymbol{TL}$) and the energy deliveries to final demand (through $\widetilde{\boldsymbol{Q}}$ or alternative variables) as done, for example, in Chapter 4 and by Cruz (2002), Wachsmann et al. (2009) and Chai et al. (2009). An advantage of the direct impact coefficient model with respect to the hybrid-unit model is that it can separately account for an energy performance indicator, i.e. the direct energy intensity ($\boldsymbol{T}$).

3.2.3.4 Conceptual issues of energy input-output models

Issue 1: Constant returns to scale and fixed technical coefficients

Energy input-output analysis shares the analytical problems of standard input-output analysis (Casler and Wilbur, 1984). The most significant are the assumption of constant return to scale and fixed technical coefficients, which equate the average to the marginal energy intensities (Bullard and Herendeen, 1975a), see Section 3.2.1. This is not true for most producing sectors because there is a share of direct energy use that is independent from production (e.g. lighting and powering security systems) (Eichhammer, 2004).

Issue 2: Accounting for primary, direct or useful energy

The hybrid-unit model and the direct impact coefficient model can account for the primary and/or direct energy use. The selection between these two levels of energy use depends on the aim of the study, the definition of the elements of the identity $\boldsymbol{g} = \boldsymbol{Ei} + \boldsymbol{h}$ and the detail and quality of energy industries in the input-output data (see *Issue 6*).

If a clear representation of primary energy industries is not available, average primary-to-final conversion efficiencies can be used to estimate total primary energy use, as done for example by Hannon et al. (1983) and Cruz (2002). In addition, to account for useful energy, additional data should be included in the construction of the total energy requirements matrix ($\boldsymbol{\alpha}$ or $\boldsymbol{\beta}$) (see Section 5.1).

Issue 3: Energy conservation principle

Miller and Blair (2009) prove that the hybrid-unit model complies with the energy conservation principle while this is not always true for the direct impact coefficient model. They show that the latter model presents sensible results if energy prices are homogenous to all energy consuming sectors, including final demand.

Issue 4: Energy conversion and energy efficiency

The total energy requirement matrices ($\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$) are not able to provide detailed information about energy conversion processes in the economy, separately (i.e. primary-to-final, final-to-useful and useful-to-service, see Section 2.1). These matrices include in aggregated form all conversion efficiencies and the efficiency of energy use i.e. most indicators of energy

performance in the economy cannot be isolated. Consequently, they oversimplify the mechanisms through which energy is used in the economy, see section 2.1.

Issue 5: Substitution of energy transactions in monetary units to physical units

There are two techniques to perform this substitution:

The first technique involves the use of energy prices (in monetary value per physical energy units) to directly transform energy transactions in monetary units in the conventional input-output model (Bullard et al., 1978). This technique becomes complex and requires large amount of data if energy prices are not homogenous across energy consuming sectors. In addition, it only accounts for energy inputs that have been assigned a market value, i.e. uses of non-marketed energy carriers such as industrial waste and traditional biomass are ignored.

The second technique substitutes the transactions of energy industries (rows 1 to r of $\boldsymbol{Z}$, $\boldsymbol{f}$ and $\boldsymbol{x}$) with existing data in physical units of energy flows. These data are generally obtained from national and international energy balances, e.g. IEA (2012b), DGEG (2012), EIA (2011a) and SENER (2013). This technique is preferred since it includes all forms of energy flows (marketed and non-marketed) and does not depends on a detail dataset or assumptions about energy prices to each energy consuming sector.

Furthermore, the energy sector also provides services (i.e. technical studies, engineering design, etc.) to industries and to final demand. These services are also included in the monetary transactions of the energy sector. In this respect, both techniques do not properly account for these services: The first technique transforms every monetary transaction (including services) to a certain amount of energy carriers while the second neglects services of the energy sector. Nevertheless, the amount of services provided by the energy sector is usually insignificant compared to the amount of energy transactions. Therefore the effect of neglecting these services is small.

Issue 6: Representation of the energy sector in input-output data

The quality of analysis of energy flows through the input-output greatly depends on the detail of the representation of the industries in the energy sector (related to *Issue 2*). In this respect, the energy sector in most available input-output databases is highly aggregated. For example, the 1995-2010 make and use EUROSTAT tables for EU countries (EUROSTAT, 2014a) include only two energy products: 1) Electricity, gas, steam and hot water and 2) Coke and refined petroleum products. Furthermore for economies that import most of their primary energy sources, there is no clear representation of primary energy industries in input-output data.

Issue 7: The balance of physical and monetary flows in the hybrid-unit

The hybrid-unit matrices $\boldsymbol{A}^*$ and $\boldsymbol{L}^*$ differ from their corresponding matrices in the basic input-output model (in monetary units). Therefore, the column sums of these matrices are meaningless (units are not consistent) (Miller and Blair, 2009). Moreover, the monetary flows of the whole economy are unbalanced since the monetary flows of the energy sector are substituted by energy flows in physical units. On the contrary, the energy flows can be balanced (Hoekstra, 2005).

3.3 Decomposition analysis

Decomposition analysis is a procedure that allows identifying the driving factors of changes in economic, environmental or socio-economic variables of the economy (Hoekstra and van den Bergh, 2003; Miller and Blair, 2009; Rose and Casler, 1996). This procedure is helpful to evaluate the effectiveness of past policies (Liu and Ang, 2007) and determine future policy interventions (Ang et al., 2003; Hoekstra and van den Bergh, 2002; Liu and Ang, 2007). Moreover, it has been applied to energy-related studies since the 1970's (Ang and Zhang, 2000; Hoekstra and van den Bergh, 2002) and it is now a widely recognized tool for energy policy analysis (Su and Ang, 2012b; Xu and Ang, 2013).

There are two conventional decomposition approaches: Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA). The main differences between these concern their theoretical foundations, input data and scope of results. IDA is based to a large extent on the theory of index numbers (Fisher, 1922), needs time-series of sectoral data –relatively easier to collect– and provides results that are more suitable for long-time historical evaluations. SDA is based on input-output analysis (Miller and Blair, 2009) hence requires input-output data and provides more detailed results for the whole economy. SDA and IDA have evolved independently (Hoekstra and van den Bergh, 2003; Su and Ang, 2012b)

This section gives a brief explanation of the basis of decomposition analysis and explores in detail the IDA and SDA applied to energy issues.

3.3.1 The basis of decomposition analysis

Assume that there is an aggregate variable V that characterizes an economic system. This aggregate variable is defined by the product of n factors

$$V = \prod_{i=1}^{n} x_i \tag{3.41}$$

where $V = V(t)$ and $x_i = x_i(t)$.

To evaluate the variation of V in time, the previous equation is derived with respect to t.

$$\frac{dV}{dt} = \frac{\partial V}{\partial x_1}\frac{dx_1}{dt} + \frac{\partial V}{\partial x_2}\frac{dx_2}{dt} + \cdots + \frac{\partial V}{\partial x_n}\frac{dx_n}{dt} = \sum_{i=1}^{n}\frac{\partial V}{\partial x_i}\frac{dx_i}{dt} \tag{3.42}$$

Furthermore, the partial derivation of V with respect to x_i (named y_i) can be represented as

$$y_i = \frac{\partial V}{\partial x_i} = x_1 x_2 \dots x_{i-1} x_{i+1} \dots x_n = \prod_{j=1}^{n} x_j \,, \forall\, j \neq i \tag{3.43}$$

The total differentiation in Equation (3.42) is therefore established as

$$\frac{dV}{dt} = \sum_{i=1}^{n} y_i \frac{dx_i}{dt} \tag{3.44}$$

Suppose that this function is evaluated between an initial and final instant (t_1 and t_2). The total change of V is obtained by the integration with respect to time

$$\Delta \mathrm{V} = \int_{t_1}^{t_2} \sum_{i=1}^{n} y_i \frac{dx_i}{dt} dt \tag{3.45}$$

which can be rewritten as

$$\Delta V = \sum_{i=1}^{n} \int_{t_1}^{t_2} y_i \frac{dx_i}{dt} dt \tag{3.46}$$

The total change in V along the time period $t_1 - t_2$ is decomposed into the summation of terms that depend on the variation with respect to time of every factor x_i (known as *additive decomposition)*. Each term represents the effect on or the contribution to changes in the aggregate variable V of changes in factor x_i (also referred to as *decomposition coefficients* and represented as DV_{x_i}), i.e.

$$DV_{x_i} = \int_{t_1}^{t_2} y_i \frac{dx_i}{dt} dt \tag{3.47}$$

The integral can be solved if the explicit functions of y_i and x_i are defined. However these functions are in most cases undefined. As we have only the extreme points of the functions at time t_1 and t_2, there is an infinite number of possible paths between these extreme points (Liu et al., 1992). Therefore, the objective of decomposition analysis is to estimate the value of DV_{x_i}'s by determining a path for the functions y_i and x_i between the extreme points $\left(y_i^{t_1}, x_i^{t_1}\right)$ and $\left(y_i^{t_2}, x_i^{t_2}\right)$.

Liu et al. (1992) established that under the path conditions

$$\begin{gathered} \min\left(y_i^{t_1}, y_i^{t_2}\right) \leq y_i^{\tau} \leq \max\left(y_i^{t_1}, y_i^{t_2}\right) \\ \min\left(x_i^{t_1}, x_i^{t_2}\right) \leq x_i^{\tau} \leq \max\left(x_i^{t_1}, x_i^{t_2}\right) \\ t_1 \leq \tau \leq t_2 \end{gathered} \tag{3.48}$$

known as linear or average path conditions, the integral function can be approximated by a discrete parametric function,

$$DV_{x_i} = \int_{t_1}^{t_2} y_i \frac{dx_i}{dt} dt = f\left(\alpha_i, x_i^{t_1}, x_i^{t_2}\right) \Delta x_i \tag{3.49}$$

Additionally, considering logarithmic path conditions (Ang, 1999; Ang and Lee, 1994), the integral function can be approximated by

$$DV_{x_i} = \int_{t_1}^{t_2} y_i \frac{dx_i}{dt} dt = g\left(\beta_i, x_i^{t_1}, x_i^{t_2}\right) \Delta \ln x_i \tag{3.50}$$

In Equations (3.49) and (3.50), α_i and β_i are parameters that represent an average change of V from t_1 to t_2, i.e. similar to index numbers (Fisher, 1922)[21]. Therefore the problem of the undefined integral path in decomposition analysis is analogous to the problem of index number selection (Liu et al., 1992).

For example, consider the special form of function $f\left(\alpha_i, x_i^{t_1}, x_i^{t_2}\right)$ in Liu et al. (1992)

$$f\left(\alpha_i, x_i^{t_1}, x_i^{t_2}\right) = \left[(1-\alpha_i)y_i^{t_1} + \alpha_i y_i^{t_2}\right] \tag{3.51}$$

leads to the Laspeyres ($\alpha_i = 0$), Paasche ($\alpha_i = 1$) and Marshall-Edgeworth ($\alpha_i = 0.5$) indices when $n = 2$ (Hoekstra and van den Bergh, 2002).

Furthermore, as seen from Equations (3.49), (3.50) and (3.51), the parameterization of the integral path decomposes the change in V over the period $t_1 - t_2$ into a set of comparative static changes in factors, i.e. Δx_i or $\Delta \ln x_i$ (Rose and Casler, 1996).

The form of the parametric functions $f\left(\alpha_i, x_i^{t_1}, x_i^{t_2}\right)$ and $g\left(\beta_i, x_i^{t_1}, x_i^{t_2}\right)$ and the selection of index numbers for energy-related decomposition analysis are discussed in the next sections.

3.3.2 Index decomposition analysis

The index approach has been applied to energy studies since the 1970's (Ang and Zhang, 2000). It relies on the theory of index numbers, uses time series of sectoral information and is able to evaluate changes in absolute, intensity and elasticity aggregate variables (Hoekstra and van den Bergh, 2003).

IDA has several energy-related application areas as identified by Ang (2004):

1) Studies on energy demand and supply of specific sectors of the economy;
2) Analysis of energy-related greenhouse gas emissions, see Xu and Ang (2013) for a complete review on this topic;
3) Evaluation of materials flows and dematerialization, in which energy flows are considered material flows into the economy;
4) Monitoring of economy-wide or sectoral energy efficiency trends;
5) Cross-country comparisons.

Additionally, IDA is especially suitable for the analysis of historical changes because of its lower data requirements, compared to SDA (Section 3.3.3) (Ang and Liu, 2007a; Hoekstra and van den Bergh, 2003).

[21] Fisher (1922) was the main contributor to the theory of Index Numbers by comparing the performance of many different indexes. He concluded that no single index number was mathematically able to have all desirable properties and hence the characteristics of the problem would determine index selection.

3.3.2.1 Calculation of decomposition coefficients

Traditionally, IDA mainly uses two types of indices (Ang, 2004): 1) The Laspeyres-type indices quantify the percentage change of different factors, using weights that correspond to a base year value (see Section 3.3.1 and Hoekstra and van den Bergh (2003)). 2) The Divisia-type indices measure the sum of logarithmic growth rates, using weights that correspond to the share of each factor's total value in integral form (Ang, 1999, 2004; Hoekstra and van den Bergh, 2002).

Ang (2004) evaluated several IDA indices based on their theoretical foundation, adaptability, ease of use and ease of result interpretation. He concluded that the Logarithmic Mean Divisia Index (LMDI), developed by Ang et al. (1998) and Ang and Liu (2001), is the best choice for general use in energy policy-making. The conclusion is based on the fact that the LMDI provides a complete decomposition (no residual term), passes the factor reversal test, and both multiplicative and additive forms are linked by a simple relationship.

Further developments, e.g. (Ang et al., 2009; Ang and Liu, 2007a, b; Choi and Ang, 2012), allowed LMDI to be applied to any decomposition situation, including SDA, see Section 3.3.3, Hoekstra and van den Bergh (2003) and Su and Ang (2012b). In the last decade, the LMDI has become the dominant index for IDA of energy-related issues (Xu and Ang, 2013).

The general LMDI formulation is obtained from Equation (3.50) where function $g\left(\beta_i, x_i^{t_1}, x_i^{t_2}\right)$ is defined as the logarithmic mean function (Ang and Lee, 1994)

$$g\left(\beta_i, x_i^{t_1}, x_i^{t_2}\right) = \frac{V^{t_2} - V^{t_1}}{\ln V^{t_2} - \ln V^{t_1}} \tag{3.52}$$

Therefore, the decomposition coefficient of factor x_i can be determined by

$$DV_{x_i} = \frac{V^{t_2} - V^{t_1}}{\ln V^{t_2} - \ln V^{t_1}} \ln\left(\frac{x_i^{t_2}}{x_i^{t_1}}\right) \tag{3.53}$$

The previous formulation can be extended to a sectoral level with m sectors (Ang, 2005), for which the aggregate variable V is defined as

$$V = \sum_{k=1}^{m} V_k = \sum_{k=1}^{m} \prod_{i=1}^{n} x_{i,k} \tag{3.54}$$

where V_k and $x_{i,k}$ correspond to the aggregate variable and factor i of sector k. Within this setting, the decomposition coefficient of factor x_i is obtained by

$$DV_{x_i} = \sum_{k=1}^{m} \frac{V_k^{t_2} - V_k^{t_1}}{\ln V_k^{t_2} - \ln V_k^{t_1}} \ln\left(\frac{x_{i,k}^{t_2}}{x_{i,k}^{t_1}}\right) \tag{3.55}$$

Notice that the use of logarithms implies limitations when dealing with zero or negative data points. Ang and Liu (2007a, b) provide some techniques to cope with these situations.

3.3.2.2 The IDA model of energy use and intensity

The basic models of aggregate energy use E and energy intensity (E/Q) for the IDA are given as

$$E = \sum_{k=1}^{m} E_k = \sum_{k=1}^{m} Q \frac{Q_k}{Q} \frac{E_k}{Q_k} = \sum_{k=1}^{m} Q M_k I_k \tag{3.56}$$

and

$$\frac{E}{Q} = \sum_{k=1}^{m} M_k I_k \tag{3.57}$$

where E_k is the energy use of sector k (either primary or direct), Q_k is the output of sector k and Q is the total output.

Factor Q, the *Activity*, measures the effect of the activity level on E changes. Factor M_k, the *Activity Mix*, quantifies the share of each sector's output in the total aggregate output and reflects the structural effect on changes in E and E/Q . I_k, the *Sectoral Energy Intensity*, measures the energy consumed by each sector per unit of economic output and corresponds to the technological effect on changes in E and E/Q.

The models can be improved by the application of a sub-sectoral aggregation (if suitable), which ensures more reliable results (Liu and Ang, 2007).

$$E = \sum_{k=1}^{m} E_k = \sum_{k=1}^{m} \sum_{l} Q_k \frac{Q_{kl}}{Q_k} \frac{E_{kl}}{Q_{kl}} = \sum_{k=1}^{m} \sum_{l} Q_k M_{kl} I_{kl} \tag{3.58}$$

where Q_{kl} and E_{kl} are respectively the output and energy use of sub-sector l of sector k and Q_k is the total output of sector k.

As explained in the Section 3.3.1, the total change in the aggregate variable in the period $[t_1 - t_2]$ can be decomposed into static changes of involved factors:

$$\Delta E = E^{t_2} - E^{t_1} = DE_Q + DE_S + DE_I \tag{3.59}$$

where the decomposition coefficients DE_Q, DE_S and DE_I are the change in aggregate energy consumption due to changes in Activity, Activity Mix and Sectoral Energy Intensity, respectively.

These models for aggregate energy use and intensity have been extensively used in literature. Thorough reviews of existing studies can be found in Ang and Zhang (2000), Liu and Ang (2007) and Xu (2013).

3.3.2.3 Issues of the IDA model of energy use and intensity

Issue 1: Data aggregation

Weber (2009) showed that the level of sectoral and sub-sectoral data aggregation significantly affects the value of the decomposition coefficients for the Activity Mix and Sectoral Energy Intensity (DE_S and DE_I, respectively). For highly aggregated sectoral data, the Sectoral Energy

Intensity was the main driving factor of changes in energy use while, for low aggregated data, the Activity Mix was the main driving factor.

Issue 2: Energy intensity as an energy efficiency indicator

IDA is considered one of the most rigorous approaches to address energy efficiency issues and to evaluate economy-wide and industry-wide efficiency trends (Liu and Ang, 2007). Especially, because the Sectoral Energy Intensity is a better indicator for energy efficiency than the aggregate energy intensity (Ang and Zhang, 2000). However, energy intensity must be used with caution as an energy efficiency indicator (Patterson, 1996; Smil, 2003)(Section 6.1).

Recently, this issue has been addressed by including physical-thermodynamic energy efficiency indicators, for example, Ang and Xu (2013), Cahill et al. (2010), ADEME (2012b) and Xu and Ang (2014), see Section 6.1. Nevertheless, the Sectoral Intensity Factor (I_k / I_{kl}) of the energy-related IDA in Equations (3.56) and (3.57) remains the standard in the majority of literature (Liu and Ang, 2007; Xu and Ang, 2013).

Issue 3: Levels of energy use

Most IDA studies account for economy-wide and industry-wide direct energy use, i.e. the primary, useful and service levels of energy use (Section 2.1) are not included. Consequently, the physical processes through which energy is used in the economy are not adequately represented, see Sections 3.2.3.4-Issue 2.

Issue 4: Producing and non-producing energy use

The energy use and intensity models (Equations (3.56) and (3.57)) are only applicable to energy use by producing sectors of the economy. Accounting for energy demand by non-producing sectors, i.e. residential energy demand, is carried out by substituting the output-related variables (Q, Q_k and Q_{kl}) in these models for other activity indicators, e.g., population, number of households and floor space (Xu and Ang, 2014)

Issue 5: Value added versus gross output

Output variables of producing sectors in the standard model are usually measured as either value added or gross output. Value added has been used more extensively in industry-wide IDA studies (Liu and Ang, 2007). However, the selection of gross output enables the use of physical-thermodynamic energy efficiency indicators (Ang and Xu, 2013).

3.3.3 Structural decomposition analysis

SDA is a specific decomposition methodology for the input-output model (Section 3.2) hence it is able to capture structural effects that arise from changes in the interlinkages between different sectors in the economy. Even though SDA has more complex data requirements than IDA, it provides more detailed results, for example; 1) it distinguishes the effects of production technology and final demand; it includes indirect demand effects; and 3) it can account for the primary and direct level of energy use (Hoekstra and van den Bergh, 2003; Su and Ang, 2012b). In addition, SDA can overcome the issues of the static input-output model related to the assumptions of fixed technical coefficients and constant returns to scale (Rose, 1999) , because it accounts for changes in technical coefficients from one year to another.

3.3.3.1 Calculation of decomposition coefficients

For the case of SDA, the mathematical expressions in Section 3.3.1 are expressed in matrix form.

1. The aggregate variable $\boldsymbol{v}$ (vector or scalar) as a function of matrix factors $\boldsymbol{X}_i$

$$\boldsymbol{v} = \prod_{i=1}^{n} \boldsymbol{X}_i \tag{3.60}$$

2. The integral form of the decomposition coefficient i

$$D\boldsymbol{v}_{\boldsymbol{X}_i} = \int_{t_1}^{t_2} \left(\prod_{j=1}^{i} \boldsymbol{X}_j \right) \frac{d\boldsymbol{X}_i}{dt} \left(\prod_{j=i+1}^{n} \boldsymbol{X}_j \right) dt \tag{3.61}$$

3. The parametric approximation to $D\boldsymbol{V}_{\boldsymbol{X}_i}$ under conditions of linear path (Liu et al., 1992) or logarithmic path (Ang et al., 1998).

$$D\boldsymbol{v}_{\boldsymbol{X}_i} = F\left(\alpha_{ij}, \boldsymbol{X}_j^{t_1}, \boldsymbol{X}_j^{t_2}, \Delta\boldsymbol{X}_i\right) \; or \; G\left(\beta_{ij}, \boldsymbol{X}_j^{t_1}, \boldsymbol{X}_j^{t_2}, \Delta \ln \boldsymbol{X}_i\right) \tag{3.62}$$

There are different mathematical techniques to determine the value of the $D\boldsymbol{v}_{\boldsymbol{X}_i}$ in Equation (3.62). Su and Ang (2012b) evaluated these techniques based on desirable properties (Ang, 2004). They singled out the D&L (see below) and LMDI techniques as equally good choices for general use in energy and emission studies. Nevertheless, in this work the D&L technique is preferred.

Dietzenbacher and Los (1998) use a parametric function defined under average path conditions for n factors, analogous to Equation (3.51):

$$D\boldsymbol{v}_{\boldsymbol{X}_i} = \left(\prod_{j=1}^{i} \left[\left(1 - \alpha_{ij}\right)\boldsymbol{X}_j^0 + \alpha_{ij}\boldsymbol{X}_j^T \right] \right) \Delta\boldsymbol{X}_i \left(\prod_{j=i+1}^{n} \left[\left(1 - \alpha_{ij}\right)\boldsymbol{X}_j^0 + \alpha_{ij}\boldsymbol{X}_j^T \right] \right) \tag{3.63}$$

where α_{ij} is a parameter that represents an average change of $\boldsymbol{v}$ associated to changes in factor $\boldsymbol{X}_i$ with respect to X_j, $\forall\, j \neq i$, from t_1 to t_2. Dietzenbacher and Los defined the α_{ij} by a Laspeyres-Paasche and Paasche-Laspeyres index combination (i.e. $\alpha_{ij} = 0 \; or \; 1$) (Hoekstra and van den Bergh, 2002).

The distribution of α_{ij}'s is defined for different paths along the edges of a hyper-rectangle, whose extreme points are $\boldsymbol{v}^{t_1}$ and $\boldsymbol{v}^{t_2}$. Each path $\boldsymbol{v}^{t_1} \rightarrow \boldsymbol{v}^{t_2}$ corresponds to one decomposition form with a set of α_{ij}'s, leading to $n!$ possible decomposition forms of $D\boldsymbol{v}_{\boldsymbol{X}_i}$ (Dietzenbacher and Los, 1998).

SDA results are obtained through the average of all $n!$ decomposition forms. By doing so, the D&L technique provides a complete decomposition (no residual term) and a distribution of the values of $D\boldsymbol{v}_{\boldsymbol{X}_i}$ (minimum, maximum and a standard deviation). Because of these characteristics and the fact that the D&L technique is zero-value and negative-value robust, this technique has become the most used in SDA (Su and Ang, 2012b).

A disadvantage of this technique is that for large number of factors ($n > 5$) the formulation becomes cumbersome and computer intensive (Su and Ang, 2012b). However, an important development was the combinatorial approach to the D&L technique by Seibel (2003), based on previous work by De Haan (2001), which simplifies the formulation and reduces computational requirements. In addition, De Haan (2001) found (numerically) that the average of two polar decomposition forms[22] do not significantly differ from the average of $n!$ decomposition forms, which is known as the approximate D&L technique (Hoekstra and van den Bergh, 2003).

3.3.3.2 The SDA model of energy use

The two conventional energy input-output models (the hybrid-unit and direct impact coefficient models, described in Section 3.2.3) are usually applied to SDA (Rose and Casler, 1996). The details of the basic decomposition under these models are explained below:

Hybrid-unit model

The total change in vector $\boldsymbol{g}$ of economy-wide energy use over the period $[t_1 - t_2]$ can be decomposed into static changes of involved factors:

$$\Delta \boldsymbol{g} = \boldsymbol{g}^{t_2} - \boldsymbol{g}^{t_1} = D\boldsymbol{g}_{\boldsymbol{\alpha}} + D\boldsymbol{g}_{\boldsymbol{f}^*} \tag{3.64}$$

where

- $D\boldsymbol{g}_{\boldsymbol{\alpha}}$ is the effect of changes in the total energy requirements matrix ($\boldsymbol{\alpha}$). This coefficient accounts for the evolution of the production functions, i.e. the structure of interindustry transactions. In addition as $\boldsymbol{\alpha}$ includes primary energy industries, $D\boldsymbol{g}_{\boldsymbol{\alpha}}$ also accounts for the primary-to-final conversion processes of the energy sector.
- $D\boldsymbol{g}_{\boldsymbol{f}^*}$ accounts for the effect of changes in the hybrid –unit vector of final demand. Moreover, this coefficient can be decomposed into demand composition and scale effects, as described by Dietzenbacher and Stage (2006) (see Section 3.3.3.3-Issue 6).

Direct impact coefficient model

$$\Delta \boldsymbol{g} = \boldsymbol{g}^{t_2} - \boldsymbol{g}^{t_1} = D\boldsymbol{g}_{\boldsymbol{T}} + D\boldsymbol{g}_{\boldsymbol{L}} + D\boldsymbol{g}_{\tilde{\boldsymbol{Q}}} + D\boldsymbol{g}_{\boldsymbol{f}} \tag{3.65}$$

where

- $D\boldsymbol{g}_{\boldsymbol{T}^E}$ is the effect of changes in the direct energy intensity. This coefficient is analogous to the sectoral energy intensity factor in the IDA.
- $D\boldsymbol{g}_{\boldsymbol{L}}$ accounts for the contributions of changes in the total requirements matrix. This effect is also known as the technology effect or economic structure effect.
- $D\boldsymbol{g}_{\tilde{\boldsymbol{Q}}}$ corresponds to the effect of changes in energy prices to non-producing sectors.
- $D\boldsymbol{g}_{\boldsymbol{f}}$ is the effect of changes in final demand in monetary terms. This coefficient can be decomposed into a demand composition and scale effects, as in for example Nie and Kemp (2013) and Wachsmann et al. (2009) (see Section 3.3.3.3, Issue 6).

[22] A polar pair of decomposition forms consists of two decompositions paths A and B, whose sets of parameters $\alpha_{ij}\big|_A$ and $\alpha_{ij}\big|_B$ are orthogonal, i.e., if these sets of parameters are arranged as vectors ($\boldsymbol{\alpha}|_A$ and $\boldsymbol{\alpha}|_B$), the dot product $\boldsymbol{\alpha}|_A \cdot \boldsymbol{\alpha}|_B = 0$.

A literature review of energy and emission SDA studies since 1995 was performed to assess the relative use of the two conventional approaches to energy input-output analysis[23]. 79 SDA studies were found (Table 3-3).

Even though the hybrid-unit approach is considered the best option (Casler and Wilbur, 1984; Miller and Blair, 2009), it is less used in literature: Only ten out of 28 SDA studies of energy (i.e. energy and intensity) used the hybrid-unit approach while the difference is even larger for emission studies, i.e. 46 out of 51 used the direct impact coefficient model.

Table 3-3 Energy and emission SDA studies in the literature (1995-2014) according to the aggregate indicator and energy input-output model used

Type	Variable	Hybrid-unit	Direct impact coefficient
Energy	Absolute	(Ferreira Neto et al., 2014; Kagawa and Inamura, 2001, 2004; Lin and Polenske, 1995; Mukhopadhyay and Chakraborty, 1999; Xie, 2014)	(Cao et al., 2010; Cellura et al., 2012; de Nooij et al., 2003; Jacobsen, 2000; Liu et al., 2010; Okushima and Tamura, 2007, 2010, 2011; Park and Heo, 2007; Thi Anh Tuyet and Ishihara, 2006; Wachsmann et al., 2009; Weber, 2009; Zhang and Lahr, 2014b)
	Intensity	(Chai et al., 2009; Garbaccio et al., 1999; Liao et al., 2013; Shirvani-Mahdavi, 1999)	(Alcántara and Duarte, 2004; Ben Hammamia et al., 2014; Nie and Zhang, 2013; Nie and Kemp, 2013; Zeng et al., 2014)
Emissions	Absolute	(Casler and Blair, 1997; Casler and Rose, 1998; Das and Paul, 2014; Gerilla et al., 2005)	(Akpan et al., 2014; Baiocchi and Minx, 2010; Brizga et al., 2014; Butnar and Llop, 2011; Chang et al., 2008; Chang and Lin, 1998; Chung and Rhee, 2001; De Haan, 2001; Dong et al., 2010; Guan et al., 2008; Guan et al., 2009; Hasegawa, 2006; Hoen and Mulder, 2003; Lee and Lin, 2001; Lim et al., 2009; Martin and Becuwe, 2014; Mukhopadhyay, 2002; Mukhopadhyay and Forssell, 2005; Munksgaard et al., 2000; Peng and Shi, 2011; Peters et al., 2007; Rhee and Chung, 2006; Roca and Serrano, 2007; Seibel, 2003; Su and Ang, 2013, 2014; Tian et al., 2013; Wang et al., 2013; Wang et al., 2014a; Wang et al., 2014b; Wier, 1998; Wier and Hasler, 1999; Wood, 2009; Wood and Lenzen, 2009; Wu et al., 2007; Xu et al., 2011; Xu and Dietzenbacher, 2014; Yabe, 2004; Yamakawa and Peters, 2011; Yuan, 2012; Yun and Xiuzhen, 2011; Zhang, 2009, 2010)
	Intensity	(Piantanakulchai and Inamura, 1999)	(Cruz and Dias, 2014; Llop, 2007; Zhang and Lahr, 2014a)

3.3.3.3 Issues of the SDA model of energy use

Issue 1: Data aggregation

As in IDA studies, the sectoral aggregation of input-output data affects the value of decomposition coefficients. In the case of the hybrid-unit model, a highly aggregated dataset does not significantly affect the value of the coefficients $D\boldsymbol{g_{\alpha}}$ and $D\boldsymbol{g_{f^*}}$ because of the small number of factors, as seen in Dietzenbacher and Los (1998). In the case of the direct impact coefficient model, the level of sectoral aggregation significantly affects the value of the decomposition coefficients $D\boldsymbol{g_T}$, $D\boldsymbol{g_L}$ and $D\boldsymbol{g_f}$ (Su and Ang, 2012a; Weber, 2009).

[23] There are extensive reviews of SDA studies of energy and emissions. Hoekstra and van den Bergh (2002) and Su and Ang (2012b) summarized SDA studies from 1972 to 2000 and from 1999 to 2010, respectively. However they do not indicate the type of energy input-output model used in these studies (hybrid-unit or direct impact coefficient), as done by Rose and Casler (1996).

Issue 2: Absolute versus intensity aggregate indicators

The SDA approach is usually restricted to the analysis of absolute indicators, e.g. total energy use and emissions (Hoekstra and van den Bergh, 2003). However, there are few energy and emission-related studies in literature that evaluate intensity indicators (Su and Ang, 2012b), for example, Garbaccio et al. (1999), Alcántara and Duarte (2004), Chai et al. (2009), Zhang (2009) and Zhang and Lahr (2014a).

Issue 3: Structure of the total energy requirements matrix

The effect of the total energy requirements matrix of the hybrid-unit model ($D\boldsymbol{g}_{\boldsymbol{\alpha}}$) accounts indirectly for the non-energy interindustry transactions since these are internalized in the transactions of the energy sector (Section 3.2.3.3). Therefore, the effect of energy and non-energy transactions cannot be accounted for separately. Lin and Polenske (1995) and Kagawa and Inamura (2001) addressed this issue by modifying the hybrid-unit model for SDA. These studies successfully isolate the effect of overall changes in non-energy and energy transactions. However they are not able to estimate the effect of other variables associated to energy transactions (e.g. conversion efficiency or energy intensity).

Issue 4: Indicator of energy efficiency

There is no specific factor to account for energy efficiency in the hybrid-unit model. As discussed previously, the interindustry transactions and the efficiencies of energy conversion and use are accounted for together by the total energy requirements matrix ($\boldsymbol{\alpha}$). On the other hand, the direct impact coefficient model has the direct energy intensity factor, which must be taken with caution as an indicator of energy efficiency, as discussed above (Section 3.2.3.4-Issue 2).

Issue 5: Levels of energy use

The hybrid-unit model can account for the primary-to-final conversion processes of energy use, either by including primary energy industries in the hybrid-unit input-output matrices or by making assumptions on primary-to-final conversion efficiencies (Casler and Wilbur, 1984; Hannon et al., 1983; Miller and Blair, 2009). The latter practice is also used in the direct impact coefficient model. Nevertheless, these practices do not account in detail for the actual processes of energy conversion in the economy and do not include the useful and service levels of energy use.

Issue 6: Composition of final demand

The decomposition of final demand into demand composition and demand scale factors is simple for the direct impact coefficient model: i.e. final demand in monetary terms can be represented as

$$\boldsymbol{f} = \boldsymbol{C}\boldsymbol{s} \tag{3.66}$$

where $\boldsymbol{C}$ is the demand composition matrix, whose columns sum to unity and which contains the share of each product in the total final demand of a non-producing sector, and $\boldsymbol{s}$ is the

demand scale vector that corresponds to the total demand for products of every non-producing sector.

In the case of the hybrid-unit model, it is not suitable to build the demand composition matrix since monetary and physical units cannot be summed. Dietzenbacher and Stage (2006) explain the procedure to address this issue in this model. However they also point out that the decomposition results can be significantly different for different energy units (BTU, TJ, KWh). Because of this, the decomposition analysis of the effect of the demand composition with the hybrid-unit model should be avoided.

4 A structural decomposition model of primary energy use: Primary to final

The objective of this chapter is to build an alternative hybrid energy input-output model that is able to account in detail for the processes of energy conversion and direct / indirect energy use to meet final demand in the economy. To do so, an independent input-output model of the energy sector in physical units is built and then coupled to the input-output model of the rest of the economy in monetary units. Furthermore, the application of the model to SDA is discussed.

4.1 An input-output model of the energy sector

A product-by-industry approach (Section 3.2.2) is used to build an isolated input-output model of the energy sector. For this approach, energy technologies (e.g. cogeneration, oil refinery or geothermal power generation) use energy carriers (e.g. diesel or coal) in conversion processes to produce one or more energy carriers for consumption of energy technologies and direct energy demand.

Data on energy flows in physical units from energy balances (e.g. IEA (2011a)) are arranged into a make-use table framework (Figure 4-1) (Section 3.2.2).

The energy use matrix ($\boldsymbol{U}^E$) represents the amount of a specific energy carrier that is used as an input by an energy technology and also the amount that is delivered to direct energy demand (i.e. energy use by non-energy sectors). The energy make matrix ($\boldsymbol{V}^E$) shows the total supply of all energy commodities that are produced by a particular energy technology. $\boldsymbol{Y}^E$ is the matrix of direct energy demand by carrier and by direct demand category. $\boldsymbol{d}^E$ corresponds to the domestic production of primary energy carriers while $\boldsymbol{m}^E$ accounts for imports of primary and final energy carriers. The vector $\boldsymbol{w}^E$ represents the energy conversion losses in the production processes of energy technologies (all elements of this vector have a negative value). Finally, $\boldsymbol{q}^E$ and $\boldsymbol{x}^E$ are the vectors of total energy output by carrier and by technology, respectively.

		Energy carriers				Energy technologies				Direct Demand			Total output	
		1	2	⋯	n_E	1	2	⋯	n_T	1	⋯	n_F		
Energy carriers	1					U^E_{11}	U^E_{12}	⋯	$U^E_{1n_T}$	Y^E_{11}	⋯	$Y^E_{1n_F}$	q^E_1	
	2					U^E_{21}	U^E_{22}	⋯	$U^E_{2n_T}$	Y^E_{21}	⋯	$Y^E_{2n_F}$	q^E_2	
	⋮					⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	$\boldsymbol{q^E}$
	n_E					$U^E_{n_E1}$	$U^E_{n_E2}$	⋯	$U^E_{n_En_T}$	Y_{n_E1}	⋯	$Y^E_{n_En_F}$	$q^E_{n_E}$	
						$\boldsymbol{U^E}$				$\boldsymbol{Y^E}$				
Energy technologies	1	V^E_{11}	V^E_{12}	⋯	$V^E_{1n_E}$								x^E_1	
	2	V^E_{21}	V^E_{22}	⋯	$V^E_{2n_E}$								x^E_2	
	⋮	⋮	⋮	⋱	⋮								⋮	$\boldsymbol{x^E}$
	n_T	$V^E_{n_T1}$	$V^E_{n_T2}$	⋯	$V^E_{n_Tn_E}$								$x^E_{n_T}$	
		$\boldsymbol{V^E}$												
Domestic primary production		d^E_1	d^E_2	⋯	$d^E_{n_E}$									
		$\boldsymbol{d^E}$												
Primary / final imports		m^E_1	m^E_2	⋯	$m^E_{n_E}$									
		$\boldsymbol{m^E}$												
Conversion losses						w^E_1	w^E_2	⋯	$w^E_{n_T}$					
						$\boldsymbol{w^E}$								
Total inputs		q^E_1	q^E_2	⋯	$q^E_{n_E}$	x^E_1	x^E_2	⋯	$x^E_{n_T}$					
		$(\boldsymbol{q^E})'$				$(\boldsymbol{x^E})'$								

Figure 4-1 Make-use framework for product-by-industry data of the energy sector

The system consists of n_T energy technologies (e.g. oil refineries or wind power generation), n_E energy carriers (e.g. crude oil or electricity) and n_F non-energy sectors of direct energy demand (e.g. household or iron and steel industry). Furthermore, the total of n_E energy carriers are classified into three categories: (1) n_P primary energy carriers, endogenous and imported raw energy sources for conversion into final energy carriers (e.g. wind or crude oil); (2) n_C final energy carriers, energy products for direct use of economic sectors (e.g. electricity or fueloil); and (3) n_N non-energy-use energy carriers, outputs of the energy sector with non-energy uses (e.g. lubricant or paraffin).

4.1.1 Total requirement primary-to-final energy matrix

Applying a similar procedure as in Section 3.2.3, the relationship between the total energy use by carrier and the direct energy demand is determined under the Industry Technology Assumption as

$$\boldsymbol{q}^E = \left(\boldsymbol{I} - \boldsymbol{U}^E(\hat{\boldsymbol{x}}^E)^{-1}\boldsymbol{V}^E\widehat{\boldsymbol{q}^E}^{-1}\right)^{-1}\boldsymbol{Y}^E\boldsymbol{i} \tag{4.1}$$

where $\boldsymbol{Y}^E\boldsymbol{i}$ is the direct demand for energy carriers.

The energy carrier output vector $(\boldsymbol{q}^E)$ includes every type of energy carrier (i.e. primary, final and non-energy-use). Primary energy carriers must be isolated to determine a total primary energy requirements matrix of the energy sector. To do so, $\boldsymbol{q}^E$ is pre-multiplied by a bridge matrix $(\boldsymbol{K}^P)$ of size $n_p \times n_E$, whose elements K^P_{ii} are nonzero for primary energy carriers (see Section 3.2.3.1). Finally, the input-output model of the energy sector accounts for the

transformation between total primary energy and the final energy use by the rest of the economy:

$$\boldsymbol{p} = \boldsymbol{K}^{P}\left(\boldsymbol{I} - \boldsymbol{U}^{E}(\hat{\boldsymbol{x}}^{E})^{-1}\boldsymbol{V}^{E}\widehat{\boldsymbol{q}^{E}}^{-1}\right)^{-1}\boldsymbol{Y}^{E}\boldsymbol{i} = \boldsymbol{L}^{E}\boldsymbol{Y}^{E}\boldsymbol{i} \tag{4.2}$$

where

- vector $\boldsymbol{p}$ of length n_C is the vector of use (output) of primary energy carriers of the energy sector,
- matrix $\boldsymbol{L}^{E}$ of size $n_C \times n_E$ is the (dimensionless) total primary energy requirements matrix of the energy sector (Described in detail in Section 4.1.1),
- vector $\boldsymbol{Y}^{E}\boldsymbol{i}$ of length n_E is the direct energy demand.

The model has the same form as the basic input-output model (Section 3.2.1) hence direct energy demand ($\boldsymbol{Y}^{E}\boldsymbol{i}$) is assumed to be exogenous from the energy sector, i.e. the energy sector has a high degree of independence from the rest of the economy (hereinafter referred to as the *energy sector independence assumption*).

4.1.2 Direct energy demand

The vector of aggregated direct energy demand of non-energy sectors ($\boldsymbol{Y}^{E}\boldsymbol{i}$) can be also represented as

$$\boldsymbol{Y}^{E}\boldsymbol{i} = \boldsymbol{C}^{E}\boldsymbol{r}^{E} \tag{4.3}$$

where matrix ($\boldsymbol{C}^{E}$) of size $n_E \times n_F$ is the (dimensionless) composition of direct energy demand. Vector $\boldsymbol{r}^{E}$ of length n_F is the total direct demand (in physical units) of final energy by non-energy sectors (see Section 3.3.3.3, Issue 6).

Furthermore, direct energy demand can be decomposed in direct energy demand of producing non-energy sectors ($\boldsymbol{Y}^{E,S}$)[24], e.g. energy use in agriculture or transport industries, and direct energy demand of non-producing non-energy sectors (i.e. final demand for energy carriers) ($\boldsymbol{Y}^{E,R}$), e.g. residential energy demand and energy exports, as

$$\boldsymbol{Y}^{E}\boldsymbol{i} = \boldsymbol{Y}^{E,S}\boldsymbol{i} + \boldsymbol{Y}^{E,R}\boldsymbol{i} \tag{4.4}$$

or alternatively

$$\boldsymbol{Y}^{E}\boldsymbol{i} = \boldsymbol{C}^{E,S}\boldsymbol{r}^{E,S} + \boldsymbol{C}^{E,R}\boldsymbol{r}^{E,R} \tag{4.5}$$

Finally, primary energy use can be represented by a component of production-related primary energy use ($\boldsymbol{p}^{S}$) component and a component of final energy demand ($\boldsymbol{p}^{R}$).

$$\boldsymbol{p} = \boldsymbol{p}^{S} + \boldsymbol{p}^{R} = \boldsymbol{L}^{E}\boldsymbol{C}^{E,S}\boldsymbol{r}^{E,S} + \boldsymbol{L}^{E}\boldsymbol{C}^{E,R}\boldsymbol{r}^{E,R} \tag{4.6}$$

[24] Hereafter, the superscript S refers to a measure of producing sectors and the superscript R refers to a measure of non-producing sectors

4.2 The primary-to-final energy input-output model

A direct energy coefficient matrix (see Section 3.2.3.2) is determined for producing non-energy sectors. This matrix represents the direct energy intensity of producing non-energy sectors, i.e. the amount of final energy carriers required to produce a unit of economic output.

$$\boldsymbol{T}^{E} = \hat{\boldsymbol{r}}^{E,S}(\hat{\boldsymbol{x}}^{S})^{-1} \tag{4.7}$$

where $\boldsymbol{x}^{S}$ is the output in monetary units of producing non-energy sectors.

The total output of producing non-energy sectors ($\boldsymbol{x}^{S}$) can be defined from the input-output model of the economy in Section 3.2.1, which connects the output of all producing sectors (including energy industries) with final demand (Equation (3.14)). However, the rows of the total requirements matrix that represent the transactions of energy industries should be removed to only account for the output of producing non-energy sectors[25] and to avoid double counting of energy transactions that are already accounted for in the input-output model of the energy sector (Section 4.1) (Strømman et al., 2009). Therefore, $\boldsymbol{x}^{S}$ is a function of the total energy requirements matrix of non-energy interindustry transactions ($\boldsymbol{L}^{M}$) and final demand ($\boldsymbol{f}$)[26]:

$$\boldsymbol{x}^{S} = \boldsymbol{L}^{M}\boldsymbol{f}^{M} \tag{4.8}$$

In addition, final demand can be decomposed in two factors, i.e. a demand composition matrix and demand scale vector ($\boldsymbol{f}^{M} = \boldsymbol{C}^{M}\boldsymbol{s}^{M}$) (see Section 3.3.3.3-Issue 6), so

$$\boldsymbol{x}^{S} = \boldsymbol{L}^{M}\boldsymbol{C}^{M}\boldsymbol{s}^{M} \tag{4.9}$$

$\boldsymbol{T}^{E}$ establishes a link between the energy and the non-energy components of the economy and closes the primary-to-final energy input-output model of primary energy use (PF model):

$$\boldsymbol{p} = \begin{cases} \boldsymbol{p}^{S} = \boldsymbol{L}^{E}\boldsymbol{C}^{E,S}\boldsymbol{T}^{E}\boldsymbol{L}^{M}\boldsymbol{C}^{M}\boldsymbol{s}^{M} \\ + \\ \boldsymbol{p}^{R} = \boldsymbol{L}^{E}\boldsymbol{C}^{E,R}\boldsymbol{r}^{E,R} \end{cases} \tag{4.10}$$

The present model is a hybrid-unit model: $\boldsymbol{L}^{E}$, $\boldsymbol{C}^{E}$ & $\boldsymbol{r}^{E,R}$ in physical units, $\boldsymbol{L}^{M}$, $\boldsymbol{C}^{M}$ & $\boldsymbol{s}^{M}$ in monetary units and $\boldsymbol{T}^{E}$ in mixed units. Also, it accounts for producing and non-producing energy use, separately. In the following section, the similarities with the two conventional energy input-output models are discussed (the hybrid-unit and the direct impact coefficient models, Section 3.2.3).

Furthermore, the model relies on the energy sector independence assumption (Section 4.1). This assumption is valid when: 1) the input structure of energy industries consists mostly of energy inputs, i.e. transactions from non-energy industries to energy industries (i.e. non-energy products that energy industries use in their operation) are much smaller than transactions between energy industries, see Appendix A.3 ; and 2) the effect of changes with time in non-energy input requirements by energy industries is not significant (only applicable

[25] The removal of the rows of energy sector transactions leads to an unbalanced technology matrix $\boldsymbol{L}^{M}$, which is a common issue of models in hybrid units (see Section 3.2.3.4-Issue 7).
[26] The superscript M is attached to $\boldsymbol{L}^{M}$ and $\boldsymbol{f}^{M}$ to indicate that these factors are in monetary terms.

to SDA studies, Section 4.3.2, Issue 1). Nevertheless, this assumptions is likely to be valid for most modern economies (CEEP, 2011; Stawinska, 2009; WEF, 2012). In Section 7.4.5.2, an example to check the validity of this assumption is shown.

4.2.1 Correspondences with conventional energy input-output models

The identity of energy flows (Equation (3.32)),

$$\boldsymbol{g} = \boldsymbol{E}\boldsymbol{i} + \boldsymbol{h} \tag{4.11}$$

can be built by the make and use framework of energy flows in Figure 4-1 as

$$\boldsymbol{q}^{E} = [\boldsymbol{U}^{E} \quad \boldsymbol{Y}^{E,S}] \begin{bmatrix} \boldsymbol{i} \\ \boldsymbol{i} \end{bmatrix} + \boldsymbol{Y}^{E,R}\boldsymbol{i} \tag{4.12}$$

where $\boldsymbol{q}^{E}$, $[\boldsymbol{U}^{E} \quad \boldsymbol{Y}^{E,S}]$ and $\boldsymbol{Y}^{E,R}\boldsymbol{i}$ are the product-by-industry forms (Section 3.2.2) of $\boldsymbol{g}$, $\boldsymbol{E}$ and $\boldsymbol{h}$, respectively. Therefore the Make-Use framework of energy flows can be used to develop the two conventional models (Section 3.2.3).

The hybrid-unit model

As seen in Section 3.2.3.3, the total energy requirements matrix of the hybrid unit model ($\boldsymbol{\alpha}$) is composed by two sub-matrices ($\boldsymbol{\theta}^{*}$ and $\boldsymbol{\tau}^{*}$) (Figure 3-5). Sub-matrix $\boldsymbol{\theta}^{*}$ describes the technology matrix of an energy sector that only serves final demand, while sub-matrix $\boldsymbol{\tau}^{*}$ describes the direct energy use by energy carrier type per unit of final demand. $\boldsymbol{\theta}^{*}$ and $\boldsymbol{\tau}^{*}$ also include indirectly non-energy interindustry transactions in the economy.

Under the assumption of energy sector independence, the proposed primary-to-final model in Equation (4.10) can replicate the information contained in $\boldsymbol{\theta}^{*}$ and $\boldsymbol{\tau}^{*}$ as:

$$\boldsymbol{p} = \begin{cases} \boldsymbol{p}^{S} = \overbrace{\boldsymbol{L}^{E}\boldsymbol{C}^{E,S}\hat{\boldsymbol{T}}^{E}\boldsymbol{L}^{M}}^{\text{Equivalent to } \boldsymbol{\tau}^{*}} \boldsymbol{C}^{M}\boldsymbol{s}^{M} \\ + \\ \boldsymbol{p}^{R} = \underbrace{\boldsymbol{L}^{E}}_{\text{Equivalent to } \boldsymbol{\theta}^{*}} \boldsymbol{C}^{E,R}\boldsymbol{r}^{E,R} \end{cases} \tag{4.13}$$

Appendix A.1 presents a numerical example that confirms the equivalence between the elements of the hybrid-unit and the PF models under the energy sector independence assumption. This equivalence implies that the information contained in the hybrid-unit model is not lost but organized in the PF model according to the processes of energy use and conversion. Additionally, Appendix A.2 and Appendix A.3 show that the energy sector independence assumption of the PF model can be considered valid for an economy with over 70% independence of its energy sector without involving significant differences from the hybrid-unit model.

The direct impact coefficient model

The primary-to-final model constitutes an extension of the direct impact coefficient model hence it can be adapted to the form of the conventional model by using the relationship $\boldsymbol{r}^{E,R} = \widetilde{\boldsymbol{Q}}^{E}\boldsymbol{f}$, where $\widetilde{\boldsymbol{Q}}^{E}$ is the matrix of inverse direct energy prices to final demand (Section 3.2.3.2).

For example, the economy-wide direct energy use ($\boldsymbol{e}$)

$$\boldsymbol{e} = \boldsymbol{e}^S + \boldsymbol{e}^R = \left(\boldsymbol{T}^E \boldsymbol{L}^M + \widetilde{\boldsymbol{Q}^E}\right)\boldsymbol{C}^M \boldsymbol{s}^M \tag{4.14}$$

or the total primary energy use

$$\boldsymbol{p} = \left(\boldsymbol{T}^P \boldsymbol{L}^M + \widetilde{\boldsymbol{Q}}^P\right)\boldsymbol{C}^M \boldsymbol{s}^M \tag{4.15}$$

where the matrix $\boldsymbol{T}^P = \boldsymbol{L}^E \boldsymbol{C}^{E,S} \boldsymbol{T}^E$ is the primary energy intensity of producing non-energy sectors, i.e. the primary energy use required to produce a unit of gross output, and $\widetilde{\boldsymbol{Q}}^P = \boldsymbol{L}^E \boldsymbol{C}^{E,R} \widetilde{\boldsymbol{Q}}^E$ represent the primary energy embodied in residential energy demand per residential energy expenditures.

Other models

Kagawa and Inamura (2001), extending the wok of Lin and Polenske (1995), developed a model that decomposes non-energy and energy transactions in the economy by applying to the conventional hybrid-unit model a hierarchical system with feedback loops from non-energy sectors. This model successfully accounts for non-energy and energy transactions, separately. However it cannot provide detail to energy transactions (e.g. levels of energy use, conversion efficiency or energy intensity).

Liang et al. (2010) proposed a model with the aim of improving the economy wide hybrid-unit model. Their model consists of an input-output model with direct energy demand of non-energy sectors as final demand. This model is equivalent to the input-output model of the energy sector in Section 4.1 hence it cannot be considered as an energy input-output model for the whole economy.

4.2.2 Advantages and issues

The primary-to-final model has the following advantages compared to conventional models:

- Energy (in physical units) and non-energy transactions (in monetary units) in the economy are accounted for separately (Section 3.2.3.4-Issue 4). Moreover, energy transactions are organized according to the processes of energy use and conversion.
- The energy sector can be represented in more detail, i.e. energy technologies and carriers with lower degree of aggregation. In addition, non-energy-use and non-marketable energy carriers can be included (Section 3.2.3.4-Issue 6).
- The model complies with the energy conservation principle (not always true for the direct impact coefficient model), i.e. primary-to-final energy conversion losses are accounted for in the energy technology matrix ($\boldsymbol{L}^E$) so direct energy intensities are always smaller than primary energy intensities ($T^E_{kj} < T^P_{kj}$). (Section 3.2.3.4-Issue 3), see also Schmidt (2008b).
- The primary and final levels of energy use are represented, which improves the understanding of energy use mechanisms in the economy. Moreover, the primary and the direct energy embodied in final demand can be estimated (Section 3.2.3.4-Issue 2).
- The model is able to isolate two indicators of energy performance and to account for them separately (Section 3.2.3.4-Issue 4): $\boldsymbol{L}^E$ and $\boldsymbol{T}^E$ give insight into primary-to-final efficiencies and the efficiency of production-related energy use, respectively.

However, the model cannot address the following issues:

- Constant returns to scale and linear production function are considered to build the energy and non-energy technology matrices, $\boldsymbol{L}^{E}$ and $\boldsymbol{L}^{M}$ (Section 3.2.3.4-Issue 1).
- The model assumes an independent energy sector. Even though in many cases this assumption is valid, this can lead to a distorted representation of the energy sector.
- The useful and service levels of energy use are not represented, i.e. they are aggregated in the direct energy intensity matrix ($\boldsymbol{T}^{E}$) and final energy demand vector ($\boldsymbol{r}^{E,R}$) (Section 3.2.3.4-Issue 2).
- The economic value of the services that energy industries provide is neglected in the proposed model due to the substitution of monetary by physical coefficients (Section 3.2.3.4-Issue 5).

4.3 Structural decomposition analysis with the PF model

The proposed model allows for a more detailed decomposition of the aggregate indicator $\boldsymbol{p}$ into static changes of constitutive factors. So from Equation (4.10) we obtain:

$$\Delta \boldsymbol{p} = \begin{cases} \Delta \boldsymbol{p}^{S} = \delta \boldsymbol{L}^{E} + \delta \boldsymbol{C}^{E,S} + \delta \boldsymbol{T}^{E} + \delta \boldsymbol{L}^{M} + \delta \boldsymbol{C}^{M} + \delta \boldsymbol{s}^{M} \\ + \\ \Delta \boldsymbol{p}^{R} = \delta \boldsymbol{L}^{E} + \delta \boldsymbol{C}^{E,R} + \delta \boldsymbol{r}^{E,R} \end{cases} \tag{4.16}$$

where the notation of decomposition coefficient in Section 3.3.1 is simplified so $D\boldsymbol{p}_{\boldsymbol{X}} = \delta \boldsymbol{X}$, i.e the contribution of changes in factor $\boldsymbol{X}$ to the observed variation in primary energy use. Each factor and its coefficient are discussed in detail in the following section.

4.3.1 Explanation of factors and decomposition coefficients

$\boldsymbol{L}^{E}$ Factor: Structure of the Energy Sector

The total primary energy requirements matrix connects the direct demand for energy carriers with the primary energy requirements to meet this demand (see Equation (4.2)). The element L_{ik}^{E} is the amount (in energy units) of primary energy carrier i which is required to produce a unit of final energy carrier k (e.g., the amount of natural gas required by thermoelectric power plants to produce a kWh of electricity).

The k^{th} column of $\boldsymbol{L}^{E}$ represents the energy input structure of total primary energy per unit of final energy carrier k. In addition, the summation of this k^{th} column, if not zero, is the total amount of primary energy required to produce a unit of energy carrier k for the use of non-energy sectors. This is defined as the inverse of the overall primary-to-final conversion efficiency of final energy carrier (ν_k).

$$\sum_{i} L_{ik}^{E} = \frac{1}{\nu_k} \tag{4.17}$$

Notice that ν_k is smaller than the conversion efficiency of the energy processes (e.g. oil refining or coal-fuelled power system) because it also accounts for the use of final energy carriers by the energy sector (e.g. the amount electricity used by coal refinery).

Therefore, the SDA coefficient $\delta \boldsymbol{L}^E$ accounts for changes in the structure and overall conversion efficiencies of the energy sector. Possible explanations for an effect $\delta \boldsymbol{L}^E < 0$

- Improvements in overall primary-to-final conversion efficiencies ($v_k{}'s$)
- Weather conditions that affect renewable energy production
- Entry of new conversion technologies with higher than average v_k (e.g. natural gas vs. coal thermoelectric generation)
- Discontinuation of conversion technologies with lower than average v_k

$\boldsymbol{C}^E$ ($\boldsymbol{C}^{E,S}$ and $\boldsymbol{C}^{E,R}$) Factor: Demand Composition of Direct (final or secondary) Energy Use

This factor describes the composition of direct energy use by non-energy sectors. The element c_{kj}^E is the fraction of the energy demand of the non-energy sector *j* which is provided by energy carrier k (e.g. the share of natural gas in the energy use of the chemical industry). The sum of the columns of this matrix is either one or zero.

The SDA coefficient $\delta \boldsymbol{C}^E$ accounts for changes in the shares of use of energy carriers by non-energy sectors. Possible explanations for an effect $\delta \boldsymbol{C}^E < 0$

- Decreasing share in demand for final energy carriers with larger associated primary energy use (e.g. thermoelectricity)

$\boldsymbol{T}^E$ Factor: Direct Energy Intensity

The direct energy intensity factor represents the total amount of energy use per unit of total output. The element T_{ij}^E is the direct energy consumption (in energy units) of industry i of final energy use ($r_i^{E,S}$) which is required to generate one unit of output (in monetary units) of a corresponding industry $\left(x_j^S\right)$.

Note: if the industrial classification of direct energy demand is equivalent to the classification of non-energy sectors of the rest of the economy, $\boldsymbol{T}^E$ is a diagonal matrix.

This factor accounts for several variables of the economic system hence it is highly aggregated. However it is possible to identify some of these variables. In Section 9.2, the direct energy intensity of an industry *j* is decomposed into the following variables: 1) the inverse final-to-useful efficiency $\left(\epsilon_j^{-1}\right)$; 2) the inverse useful-to service efficiency $\left(\mu_j^{-1}\right)$; 3) the aggregate price of products; and 4) the energy service (i.e. the intensity of productive useful energy per unit of output in physical units).

Since the energy service is constant for a given mix of product of industry j, the SDA coefficient $\delta \boldsymbol{T}^E$ mainly accounts for changes in ϵ_j, μ_j and the real price of products. Possible explanations for an effect $\delta \boldsymbol{T}^E < 0$

- Improvements in final-to-useful efficiencies when these efficiency gains are related with carriers with lower associated primary energy use.
- Improvements in useful-to-service efficiencies through updating passive system and human use of passive systems
- Real price increase of products due to market interactions
- Real price increase of products due to increases in input costs (e.g. labor, energy or materials costs)

$\boldsymbol{L}^M$ Factor: Structure of the Rest of the Economy

This factor represents interindustry transactions of the economy without the rows of transaction of the energy sector (Section 3.2.3.1). The element L_{ij} represents the amount of purchases from industry i that that industry j uses to provide a unit of product to final demand.

As seen in Figure 3-5 (see also Section 3.2.3.3), this matrix accounts for every non-energy interindustry transaction in the economy, i.e. including the non-energy transactions of the energy sector with non-energy industries. This issue is discussed below (Section 4.3.2-Issue 1).

Therefore, the SDA coefficient $\delta \boldsymbol{L}^M$ accounts for changes in non-energy interindustry transactions in the economy. Possible explanations for an effect $\delta \boldsymbol{L}^M < 0$

- Larger interindustry requirements for less energy intensive products (e.g. services)
- Substitution of domestic energy intensive products for imported equivalents
- Entrance of less energy intensive products or industries
- Improvements in the production function, i.e. Increases in the value added to output ratio
- Entrance of industries with higher than average value added to output ratio

$\boldsymbol{C}^M$ Factor: Final Demand Composition

The final demand composition factor describes the relative share of every product delivered to final demand. The element C_{ij}^M is the fraction of the final demand category j which is provided by industry i (e.g. the share of air transport in the total expenditures of residential consumers). The sum of the columns of this matrix is either one or zero.

The SDA coefficient $\delta \boldsymbol{C}^M$ accounts for changes in the composition of final demand by category. Possible explanations for an effect $\delta \boldsymbol{C}^M < 0$

- Decreasing share in final demand for products with larger associated primary energy use (e.g. water transport)

$\boldsymbol{s}^M$ Factor: Economic Scale or total final demand

This factor describes the total final demand by category (i.e. residential, government, etc.). It is related to the level of production in the economic system, hence to the size of the economy. The element s_j^M is the demand for products of category j (e.g. total expenditures of residential consumers or total amount of exports).

The SDA coefficient $\delta\boldsymbol{s}^M$ accounts for changes in final demand. Possible explanations for an effect $\delta\boldsymbol{s}^M < 0$

- Decrease in private or public expenditure
- Decrease in exports

Any positive change in the economic scale factor, i.e. economic growth, always leads to increases in primary energy use.

$\boldsymbol{r}^{E,R}$ Factor: Energy demand of non-producing non-energy sectors

This factor accounts for the direct energy use of the non-producing non-energy sectors (i.e. final demand of energy carriers). The element $r_j^{E,R}$ is the energy use by final demand category j (e.g. residential energy use).

The SDA coefficient $\delta\boldsymbol{r}^{E,R}$ accounts for changes in energy use by final demand categories. Possible explanations for an effect $\delta\boldsymbol{r}^{E,R} < 0$ are decreases in energy use.

4.3.2 Issues regarding SDA with the PF model

Issue 1: Non-energy and energy transactions of the energy sector

The factor $\boldsymbol{L}^E$ only accounts for energy transactions between energy industries while $\boldsymbol{L}^M$ accounts for the non-energy transactions from non-energy industries to energy industries (represented by the sub-matrix $\boldsymbol{\pi}$, Section 3.2.3.3). Consequently, changes in $\boldsymbol{\pi}$ are accounted for in $\delta\boldsymbol{L}^M$ when they should be accounted for by $\delta\boldsymbol{L}^E$. However these changes are likely to be insignificant (see Section 7.4.5.2) validating the energy sector independence assumption (Section 4.1).

Issue 2: Primary energy equivalent of renewables

The effect of changes in the structure of the energy sector ($\delta\boldsymbol{L}^E$) depends on the approach used to account for the primary energy equivalent of renewables sources (Section 2.1.1).

The partial substitution method (PSM) amplifies the amount of primary energy associated to renewables and magnifies the contribution to $\delta\boldsymbol{L}^E$ of the progress of thermoelectric primary-to-final conversion efficiencies. Any shift to renewables would have the same effect on primary energy use as an increase of output of a conventional thermal technology.

The physical content method I (PCM-I) put emphasis on a future ideal structure of the energy sector, i.e. an all renewable energy sector with 100% primary-to-final conversion efficiency. Any shift toward renewable energy represents an improvement of overall primary-to-final conversion efficiency and a reduction of primary energy use.

The physical content method II (PCM-II) accounts for the progress in renewable and non-renewable technology. However, since renewable technology has relatively low efficiency, any shift towards renewables represents a reduction of overall primary-to-final conversion efficiency and an increase of primary energy use. In addition, the aggregate primary energy indicator is not consistent because the energy content of energy carriers is measured according to different thermodynamic potentials.

A summary of the effect of using the different methods in SDA are summarized in Table 4-1.

Table 4-1 Comparison of different accounting methods on δL^E

$\delta \boldsymbol{L}^E$ Accounts for…	PSM	PCM	
		PCM-I	PCM-II
Progress in renewable technology	No	No	Yes
Transition to renewable energy	No	Yes	Yes[b]
Progress in non-renewable energy conversion technologies	Yes	Yes	Yes
Energy resources	Yes[a]	Yes[a]	No[c]

[a] The value of primary energy can be used for resource analysis
[b] PCM-II decreases the effect of renewable substitution for fossil fuels
[c] The value of primary energy make no sense for resource analysis

Therefore, I recommend the use of PCM-I for structural decomposition analysis since it is capable to build a consistent primary energy indicator for resource accounting while including renewable transitions in the energy sector (see Section 2.1.1).

Issue 3: Accounting for imports of final energy carriers

Depending on the purpose of the study, energy imports can be either neglected or accounted for by a domestic technology assumption, i.e. the primary energy equivalent of energy imports is calculated as if imports were domestically produced by conventional technology.

To account for primary energy equivalent of imports and renewables (see Issue 2) in the proposed model, the bridge matrix $\boldsymbol{K}^P$ in Equation (4.2) needs to be modified as:

$$\boldsymbol{K}^P = \widehat{\boldsymbol{a}}\left(\widehat{\boldsymbol{d}}^E + \widehat{\boldsymbol{m}}^E\right)\left(\widehat{\boldsymbol{q}}^E\right)^{-\mathbf{1}} \tag{4.18}$$

where $\boldsymbol{a}$ is a vector, whose element b_m is the transformation coefficients according to the chosen method for primary energy equivalent when m points to renewable or imported energy carriers.

Issue 4: Accounting for exports

Energy exports (contained in $\boldsymbol{r}^{E,R}$, Equation (4.6)) and the primary energy to produce them are usually excluded from the analysis of energy use within an economy. In addition, even if energy exports are excluded, the non-energy transactions associated to them can be included in the analysis by the primary-to-final energy input-output model (see Issue 1).

Issue 5: Direct energy intensity is a highly aggregated factor

As explained in Section 9.2, the direct energy intensity factor ($\boldsymbol{T}^E$) is a function of several components of the economic system. Consequently, the exact contribution of a certain component to $\delta\boldsymbol{T}^E$ is uncertain.

4.4 Summary

This chapter introduces a novel energy input-output model, which has a detailed description of the primary and final levels of energy use and of the energy conversion stage between these levels. The PF model combines characteristics of the two conventional energy input-output models in literature (Section 3.2.3) though it is able to evaluate energy and economic transactions separately. Additionally, the PF model can improve the analysis of economy-wide studies of energy use provided that the energy sector independence assumption is valid.

5 Two decomposition models of primary energy use: primary to final to useful

The objective of this chapter is to build two alternative models of primary energy use for IDA and SDA. These models are designed to include the useful level of energy use (undisclosed in conventional models).

5.1 A structural decomposition model of primary energy use: primary to final to useful

This section presents a primary-to-final-to-useful energy input-output model (PFU model), which is an extension of the primary-to-final model in Section 4. The PFU model is based on the primary-to-final model with the inclusion of an input-output model of an extended energy sector.

The extended energy sector is a theoretical energy sector that implements final-to-useful energy conversions in the economy (Santos et al., 2013). It includes all end-use devices that convert energy carriers into useful work flows (e.g. electric motors, light bulbs or boilers). These end-use devices are distributed in the infrastructure of non-energy sectors. Because of the different characteristics of the extended energy sector compared to the energy sector, the input-output model of this extended energy sector is constructed with a different procedure as those in Sections 3.2.3 and 4.1[27].

5.1.1 An input-output model of the extended energy sector

The extended energy sector uses n_E final energy carriers as inputs to deliver n_U flows of useful work to non-energy sectors. Conversion technologies of the extended energy sector are equal in number to the flows of useful work, hence one conversion technology produces one and only one useful work flow. Moreover, there are neither transactions of useful work flows between conversion technologies nor transactions from non-energy sectors to the extended energy sector.

[27] It is possible to build a model of the extended energy sector under the conventional input-output framework that leads to a simple square total requirements matrix of this sector. However, this option was dropped in this thesis because the direct sectoral use of secondary carriers obtained by this approach was significantly different from the actual data.

Useful work flows are defined by useful work category (e.g. lighting or hot temperature heat) and the type of final energy carrier (e.g. gasoline or electricity) that is used in the conversion process. Examples of useful work flows are: 1) lighting obtained from a kerosene lamp; 2) mechanical work obtained from an electric motor; or 3) low temperature heat obtained from a gas boiler.

Useful work flows and second-law final-to-useful efficiencies data are obtained from useful work accounting (Section 3.1) in the form shown in Figure 5-1.

The matrix $\boldsymbol{Y}^{U,W}$ of size $n_U \times n_F$ is the direct useful work demand by type of useful work flow and by demand category. There is a matrix of second law final-to-useful efficiency ($\boldsymbol{\epsilon}^{U,W}$) with the same characteristics.

The input-output model of the extended energy sector aims to construct a simple relationships as:

$$\boldsymbol{e} = \boldsymbol{L}^U \boldsymbol{Y}^{U,W} \boldsymbol{i} \tag{5.1}$$

where vector $\boldsymbol{e}$ of length n_E is the direct use of final energy carriers by the extended energy sector, matrix $\boldsymbol{L}^U$ of size $n_E \times n_U$ is the total final energy requirements matrix, and matrix $\boldsymbol{Y}^{U,W}$ of size $n_U \times n_F$ is the direct demand of useful work flows by non-energy sectors.

UW flows			**Direct useful work demand** (i.e. non-energy sectors)			
	UW category	Final energy carrier	**1**	**2**	⋯	$\boldsymbol{n_F}$
1	1	1	Y^U_{11}	Y^U_{21}	⋯	$Y^U_{1n_F}$
⋮		⋮	⋮	⋮	⋱	⋮
$\boldsymbol{n_E}$		n_E	$Y^U_{n_E1}$	$Y^U_{n_E2}$	⋯	$Y^U_{n_En_F}$
$\boldsymbol{n_E + 1}$	2	1	⋮	⋮	⋯	⋮
⋮		⋮	⋮	⋮	⋱	⋮
$\boldsymbol{2 \cdot n_E}$		n_E	⋮	⋮	⋯	⋮
⋮	⋮	⋮	⋮	⋮	⋱	⋮
⋮	n_W	1	⋮	⋮	⋯	⋮
⋮		⋮	⋮	⋮	⋱	⋮
$\boldsymbol{n_U = n_W \cdot n_E}$		n_E	$Y^U_{n_U1}$	$Y^U_{n_U2}$	⋯	$Y^U_{n_Un_F}$
					$\boldsymbol{Y}^{U,W}$	

Figure 5-1 Presentation of useful work accounting output data

By definition the extended energy sector is present in every non-energy sector. As a result, the direct use of final energy carriers by a non-energy sector coincides with the use of final energy carriers of the extended energy sector in that non-energy sector. So the vector $\boldsymbol{e}$ is equivalent to $\boldsymbol{Y}^E \boldsymbol{i}$ in Equation (4.1)**.**

The model consists therefore of connecting the direct demand of energy carriers with the direct demand of useful work by non-energy sectors.

$$\boldsymbol{Y}^{E}\boldsymbol{i} = \boldsymbol{L}^{U}\boldsymbol{Y}^{U,W}\boldsymbol{i} \tag{5.2}$$

According to the definition of useful work, direct exergy demand can be calculated from useful work flows by:

$$\text{Final exergy} = \frac{1}{\epsilon_{ij}} \cdot Y_{ij}^{U} \tag{5.3}$$

The relationships requires a Hadamard or element-wise product (⊗) of matrix $\boldsymbol{Y}^{U,W}$ by the inverse of matrix $\boldsymbol{\epsilon}^{U,W}$. The resulting matrix $\boldsymbol{Y}^{X,W}$ of size $n_U \times n_F$ is the direct exergy demand by non-energy sectors per type of useful work flow.

$$\boldsymbol{Y}^{X,W} = (\boldsymbol{\epsilon}^{U,W})^{-1} \otimes \boldsymbol{Y}^{U,W} \tag{5.4}$$

The matrices $(\boldsymbol{\epsilon}^{U,W})^{-1}$ and $\boldsymbol{Y}^{U,W}$ are rearranged into equivalent matrices $(\boldsymbol{\epsilon}^{U})^{-1}$ size $n_U \times (n_U \cdot n_F)$ and $\boldsymbol{Y}^{U}$ of size $(n_U \cdot n_F) \times n_F$, respectively, so as to substitute the Hadamard product by a normal matrix multiplication (as described in Appendix B).

$$\boldsymbol{Y}^{X,W} = (\boldsymbol{\epsilon}^{U})^{-1}\, \boldsymbol{Y}^{U} \tag{5.5}$$

The final exergy demand per type of useful work flow ($\boldsymbol{Y}^{X,W}$) is transformed into final exergy demand per type of final energy carrier ($\boldsymbol{Y}^{X,E}$) through a bridge matrix $\boldsymbol{G}^{EC}$, whose architecture is shown in Figure 5-2.

$$\boldsymbol{Y}^{X,E} = \boldsymbol{G}^{EC}\boldsymbol{Y}^{X,W} \tag{5.6}$$

	UW flows	**1**	**2**	⋯	$\boldsymbol{n_E}$	$\boldsymbol{n_E+1}$	$\boldsymbol{n_E+2}$	⋯	$\boldsymbol{2 \cdot n_E}$	⋯	⋯		$\boldsymbol{n_U}$
	UW category	1				2					n_U		
Final energy carrier		1	2	⋯	n_E	1	2	⋯	n_E	⋯	1	2	⋯	n_E
1		1	0	⋯	0	1	0	⋯	0		1	0	⋯	0
2		0	1	⋯	0	0	1	⋯	0		0	1	⋯	0
⋮		⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮		⋮	⋮	⋱	⋮
$\boldsymbol{n_E}$		0	0	⋯	1	0	0	⋯	1		0	0	⋯	1
								$\boldsymbol{G^{EC}}$						

Figure 5-2 Architecture of the bridge matrix G^{EC}

Furthermore, $\boldsymbol{Y}^{X,E}$ is transformed from exergy into energy values by pre-multiplying by the inverse of the exergy factor vector $\boldsymbol{\phi}^{E}$ whose element ϕ_k^E is the exergy factor of the final energy carrier k (see Section 2.2).

$$\boldsymbol{Y}^{E} = \left(\widehat{\boldsymbol{\phi}}^{E}\right)^{-1}\boldsymbol{Y}^{X,E} \tag{5.7}$$

Finally, Equations (5.6) and (5.7) are combined to define the total final energy requirements matrix of the extended energy sector ($\boldsymbol{L}^{U}$)

$$\boldsymbol{L}^{U} = \left(\widehat{\boldsymbol{\phi}}^{E}\right)^{-1}\boldsymbol{G}^{EC}(\boldsymbol{\epsilon}^{U})^{-1} \tag{5.8}$$

5.1.2 The primary-to–final-to-useful energy input-output model

The matrix of useful work demand by non-energy sectors ($\boldsymbol{y}^U$) can be also represented by a (dimensionless) composition matrix of useful work demand ($\boldsymbol{C}^U$) and a vector of total useful work demand ($\boldsymbol{r}^U$).

$$\boldsymbol{Y}^U\boldsymbol{i} = \boldsymbol{C}^U\boldsymbol{r}^U \tag{5.9}$$

Additionally, useful work demand can be decomposed in useful work demand of producing non-energy sectors ($\boldsymbol{Y}^{U,S}$) and of non-producing non-energy sectors ($\boldsymbol{Y}^{U,R}$), leading to:

$$\boldsymbol{Y}^U\boldsymbol{i} = \boldsymbol{C}^{U,S}\boldsymbol{r}^{U,S} + \boldsymbol{C}^{U,R}\boldsymbol{r}^{U,R} \tag{5.10}$$

A direct useful work coefficient matrix (see Section 4.1.2) is determined for producing non-energy sectors. This matrix represents the direct useful work intensity of producing non-energy sectors, i.e. the amount of useful work required to produce a unit of economic output.

$$\boldsymbol{T}^U = \hat{\boldsymbol{r}}^{U,S}(\hat{\boldsymbol{x}}^S)^{-1} \tag{5.11}$$

where $\boldsymbol{x}^S$ is the output in monetary units of producing non-energy sectors in Equation (4.9).

The inclusion of $\boldsymbol{T}^U$ and $\boldsymbol{L}^E$ establishes a link between the energy and the non-energy components of the economy and closes the primary-to-final-to-useful energy input-output model of primary energy use (PFU model).

$$\boldsymbol{p} = \begin{cases} \boldsymbol{p}^S = \boldsymbol{L}^E\boldsymbol{L}^U\boldsymbol{C}^{U,S}\boldsymbol{T}^U\boldsymbol{L}^M\boldsymbol{C}^M\boldsymbol{s}^M \\ + \\ \boldsymbol{p}^R = \boldsymbol{L}^E\boldsymbol{L}^U\boldsymbol{C}^{U,R}\boldsymbol{r}^{U,R} \end{cases} \tag{5.12}$$

The present model is a hybrid-unit model: $\boldsymbol{L}^E$, $\boldsymbol{L}^U$, $\boldsymbol{C}^U$ & $\boldsymbol{r}^{U,R}$ in physical units, $\boldsymbol{L}^M$, $\boldsymbol{C}^M$ & $\boldsymbol{s}^M$ in monetary units and $\boldsymbol{T}^U$ in mixed units. Also, it accounts for producing and non-producing energy use, separately. The inclusion of final-to-useful energy conversion processes causes the products $\boldsymbol{C}^{E,S}\boldsymbol{T}^E$ and $\boldsymbol{C}^{E,R}\boldsymbol{r}^{ER}$ in Equation (4.10) to be substituted by $\boldsymbol{L}^U\boldsymbol{C}^{U,S}\boldsymbol{T}^U$ and $\boldsymbol{L}^U\boldsymbol{C}^{U,R}\boldsymbol{r}^{U,R}$, respectively. Furthermore, the assumption of independence of the energy sector (Section 4.1) must be also valid for this model. Note: the extended energy sector, by definition, is independent from the rest of the economy, i.e. the extended energy sector does not use inputs from non-energy sectors.

5.1.2.1 Advantages and issues

The PFU model has the same advantages of the PF model compared to conventional models (Section 4.2.2) and surpasses the latter in the following:

- The useful level of energy use is represented, which improves the understanding of energy use mechanisms in the economy. Moreover, it is possible to estimate the primary, direct and useful energy embodied in final demand (Section 3.2.3.4-Issue 2).
- The model is able to isolate three indicators of energy performance and to account for them separately (Section 3.2.3.4-Issue 4): $\boldsymbol{L}^E$, $\boldsymbol{L}^U$ and $\boldsymbol{T}^U$ give insight into primary-to-final conversion efficiencies, final-to-useful conversion efficiencies and the efficiency of production-related useful work use, respectively.

Nevertheless, the model cannot address some of the issues of the PF model (Section 4.2.2) and the following:

- The input-output model relies on the same assumptions made for useful work accounting hence it involves the consequences of these assumptions (Section 3.1).
- The model assumes an independent extended energy sector.
- The service level of energy use is not represented, i.e. it is included in the useful work intensity matrix ($\boldsymbol{T}^{U}$) and final useful work demand vector ($\boldsymbol{r}^{U,R}$) (Section 3.2.3.4-Issue 2).

5.1.3 Structural decomposition analysis with the PFU model

The proposed model allows for a more detailed decomposition of the aggregate indicator $\boldsymbol{p}^{E}$ into static changes of constitutive factors. So from Equation (5.12) we obtain:

$$\Delta \boldsymbol{p} = \begin{cases} \Delta \boldsymbol{p}^{S} = \delta \boldsymbol{L}^{E} + \delta \boldsymbol{L}^{U} + \delta \boldsymbol{C}^{U,S} + \delta \boldsymbol{T}^{U} + \delta \boldsymbol{L}^{M} + \delta \boldsymbol{C}^{M} + \delta \boldsymbol{s}^{M} \\ + \\ \Delta \boldsymbol{p}^{R} = \delta \boldsymbol{L}^{E} + \delta \boldsymbol{L}^{U} + \delta \boldsymbol{C}^{U,R} + \delta \boldsymbol{r}^{U,R} \end{cases} \tag{5.13}$$

where the notation of decomposition coefficient in Section 3.3.1 is simplified so $D\boldsymbol{p}_{\boldsymbol{X}} = \delta \boldsymbol{X}$, i.e the contribution of changes in factor $\boldsymbol{X}$ to the observed variation in primary energy use. Each additional factor from those in Section 4.3.1 and its coefficient are discussed in detail in the following section.

5.1.3.1 Explanation of factors and decomposition coefficients

$\boldsymbol{L}^{U}$ Factor: Structure of the Extended Energy Sector

The total final-to-useful energy requirements matrix connects the demand for useful work with the final energy requirements to meet this demand. The element L_{ik}^{U} is the amount (in physical units) of final energy carrier i which is required to produce a unit of useful work flow k (e.g., the amount of natural gas required by industrial boiler to produce a TJ of high temperature heat).

The SDA coefficient $\delta \boldsymbol{L}^{U}$ accounts for changes in final-to-useful efficiencies and the structure of the extended energy sector (i.e. the type of final-to-useful conversion technologies available in the economy). Possible explanations for an effect $\delta \boldsymbol{L}^{U} < 0$

- Improvements in final-to-useful efficiencies ($\epsilon_k{}'s$) when these efficiency gains are related with carriers with lower associated primary energy use.
- Entrance of new conversion technologies with higher than average ϵ_k
- Discontinuation of conversion technologies with lower than average ϵ_k

$\boldsymbol{C}^{U}$ ($\boldsymbol{C}^{U,S}$ and $\boldsymbol{C}^{U,R}$) Factor: Demand Composition of useful work

This factor describes the composition of useful work by non-energy sectors. The element c_{kj}^{U} is the fraction of total useful work demand of the non-energy sector j which is provided by useful work k (e.g. the share of mechanical work from an electric motor in the useful work use by the chemical industry). The sum of the columns of this matrix is either one or zero.

The SDA coefficient $\delta \boldsymbol{C}^U$ accounts for changes in the shares of use of useful work flows by non-energy sectors. Possible explanations for an effect $\delta \boldsymbol{C}^{\boldsymbol{U}} < 0$

- Decreasing share in demand for useful work flows with larger associated primary energy use (e.g. low temperature heat from a gas boiler)
- Increasing share in demand for useful work flows with lower associated primary energy use (e.g. mechanical work by a high efficient diesel engine)

$\boldsymbol{T}^U$ Factor: Useful Work Intensity

The useful work intensity factor represents the total amount of useful work use per unit of total output. The element T_{ij}^U is the direct energy consumption (in physical units) of industry i of total useful work use ($r_i^{U,S}$) which is required to generate one unit of output (in monetary units) of a correspondent industry $\left(x_j^S\right)$.

Note: if the industrial classification of useful work demand is equivalent to the classification of non-energy sectors of the rest of the economy, $\boldsymbol{T}^U$ is a diagonal matrix.

In Section 9.2, the useful work intensity of an industry j is decomposed into the following variables: 1) the inverse useful-to service efficiency $\left(\mu_j^{-1}\right)$; 2) the aggregate price of products; and 4) the energy service (i.e. the intensity of productive useful energy per unit of output in physical units).

Since the energy service is constant for a given mix of product of industry j, the SDA coefficient $\delta \boldsymbol{T}^U$ mainly accounts for changes in μ_j and the real price of products. Possible explanations for an effect $\delta \boldsymbol{T}^U < 0$

- Improvements in useful-to-service efficiencies through updating passive systems and human use of passive systems
- Real price increase of products due to market interactions
- Real price increase of products due to increases in input costs (e.g. labor, energy or materials costs)

5.1.3.2 Issues regarding SDA with the PFU model

Issue 1: Useful intensity is a highly aggregated factor

As explained in Section 9.2, the useful work intensity factor ($\boldsymbol{T}^U$) is a function of several variables of the economic system though fewer than in the direct energy intensity factor $\boldsymbol{T}^E$. Consequently, the exact contribution of a certain variable to $\delta \boldsymbol{T}^U$ is uncertain.

Issue 2: Useful work accounting assumptions

The time series of useful work data for an economy are built under assumptions regarding the state of end-use conversion technologies and the structure of useful work use by non-energy sectors. The proximity to reality of these assumptions determines the validity of the conclusions drawn from $\delta \boldsymbol{L}^U$, $\delta \boldsymbol{C}^U$, $\delta \boldsymbol{T}^U$ and $\delta \boldsymbol{r}^{U,R}$.

5.1.4 Summary

This section introduces a novel energy input-output model, which expands the PF model in Chapter 4. The PFU model has a detailed description of the primary, final and useful levels of energy use and of the two energy conversion stage between these levels. Table 5-1 summarizes and compares the characteristics of the energy input-output models discussed in this thesis.

Table 5-1 Characteristics of different energy input-output models

Energy input-output model	Energy efficiency indicators	Levels of energy use[a]	Energy and economic transactions are accounted for by	Other features[b]				
				1	2	3	a	b
Conventional								
Hybrid-unit	-	P or F	$\boldsymbol{\alpha}$	Y	Y	-	-	X
Direct impact coefficient	$\boldsymbol{T}$	P or F	$\boldsymbol{T}$ and $\boldsymbol{L}$	-	-	-	X	-
Proposed								
PF (Chapter 4)	$\boldsymbol{L}^E$ and $\boldsymbol{T}^E$	P and F	$\boldsymbol{L}^E$, $\boldsymbol{C}^E$, $\boldsymbol{T}^E$ and $\boldsymbol{L}^M$	Y	Y	Y	X	X
PFU (Section 5.1)	$\boldsymbol{L}^E$, $\boldsymbol{L}^U$ and $\boldsymbol{T}^E$	P, F and U	$\boldsymbol{L}^E$, $\boldsymbol{L}^U$, $\boldsymbol{C}^U$, $\boldsymbol{T}^U$ and $\boldsymbol{L}^M$	Y	Y	Y	X	X

[a] P – Primary, F – Final and U – Useful

[b] Advantages

1. Hybrid units
2. Energy conservation
3. Energy sector described in detail

Disadvantages

a. Independent energy sector
b. Data intensive

The table shows that the PF and PFU models can significantly improve the analysis of economy-wide studies of energy use, compared to conventional models, because they provide detailed information about the processes of energy conversion and use in the economy. Their main disadvantage is that they depend on the validity of the energy sector independence assumption (see Appendix A.3).

5.2 An index decomposition model of primary energy use: primary-to-final-to-useful

This section presents the development of a primary-to-final-to-useful index decomposition model of primary energy use (PU model), which is an extension of the energy decomposition models in Section 3.3.2.2.

5.2.1 A primary energy intensity model

The primary energy intensity of producing sectors is defined as

$$\frac{P^S}{Q} \tag{5.14}$$

where P^S is the total primary energy use by producing sectors and Q is the gross output of the economy in monetary units.

If we consider an energy sector that converts n_d types of primary energy source (e.g. oil or biomass) to n_c secondary energy carriers for direct use (e.g. electricity), the conversion process within the energy sector follows

$$E^S = \sum_c^{n_c} \sum_d^{n_d} \nu_{cd} P_d^S = \bar{\nu} P^S \tag{5.15}$$

where the E^S is the total direct energy use by producing sectors, P_d^S is the amount of primary energy type d, ν_{cd} is the primary-to-final efficiency from the primary energy carrier type d to the secondary energy carrier of type c and $\bar{\nu}$ is the average primary-to-final conversion efficiency of the energy sector.

Furthermore, final energy carriers are transformed by an end-use device (e.g. electric motor of a machine) into n_b useful work / exergy flows (e.g. mechanical work or heat). Such transformation is characterized by:

$$U^S = \sum_b^{n_b} \sum_c^{n_c} \epsilon_{bc} \phi_c \, E_c^S = \overline{\epsilon\phi} E^S \tag{5.16}$$

where the U^S is the direct useful work consumption by producing sectors, E_c^S is the amount of secondary energy type c, ϕ_c is the exergy factor of secondary energy type c (Section 2.2), ϵ_{bc} is the final-to-useful efficiency from the secondary energy carrier type c to the useful work flow type b and $\overline{\epsilon\phi}$ is the average final energy to useful exergy conversion efficiency, i.e. technical efficiency of all end-use devices in producing sectors (i.e. the extended energy sector, Section 5.1.1).

Equations (5.15) and (5.16) are integrated into primary intensity, expressed for industry k:

$$\frac{P_k^S}{Q_k} = \bar{\nu}_k^{-1} (\overline{\epsilon\phi})_k^{-1} \frac{U_k^S}{Q_k} \tag{5.17}$$

Ultimately, the IDA decomposition model of primary energy intensity of producing sectors in Section 3.3.2.3 is extended to account for elements in Equation (5.17)

$$\frac{P^S}{Q} = \sum_{k=1}^{n_k} \bar{\nu}_k^{-1} (\overline{\epsilon\phi})_k^{-1} \frac{U_k^S}{Q_k} \frac{Q_k}{Q} = \sum_{k=1}^{n_k} \nu_k^{-1} \phi \epsilon_k^{-1} UI_k M_k \tag{5.18}$$

where ν_k^{-1}, $\phi\epsilon_k^{-1}$, UI_k and M_k are the primary-to-final conversion efficiency related, technical efficiency, sectoral useful work intensity and activity mix of sector k, respectively.

The model in Equation (5.18) only accounts for primary energy use in producing sectors. The model can be adapted for accounting for residential primary energy intensity as:

$$\frac{P^R}{A} = \sum_{h=1}^{n_h} \bar{v}_h{}^{-1} (\overline{\epsilon\phi})_h{}^{-1} \frac{U_h^R}{A} \tag{5.19}$$

where P^R is the total primary energy use by n_h households, A is the activity indicator for households (e.g. number of households or gross floor area, Xu and Ang (2014)). $\bar{v}_h$ is the average primary-to-final conversion efficiency associated to household h. $\overline{\epsilon\phi}_h$ is the average final energy to useful exergy conversion efficiency, i.e. technical efficiency of all end-use devices in household h. Finally, U_h^R is the useful work use by household h.

Nevertheless, the model of residential energy use must be developed further to include all the range of energy services that households use (each service normalized by a suitable activity indicator) (Haas, 1997; Haas et al., 2008).

5.2.2 The primary-to-final-to-useful index decomposition model

The models developed in the previous sections lead to a complete model of primary energy use in the economy, i.e. primary energy use of producing and non-producing sectors in the economy

$$P = \begin{cases} P^S = \sum_{k=1}^{n_k} \nu_k{}^{-1} \phi \epsilon_k{}^{-1} UI_k M_k Q \\ \qquad + \\ P^R = \sum_{h=1}^{n_h} \bar{v}_h{}^{-1} (\overline{\epsilon\phi})_h{}^{-1} U_h^R \end{cases} \tag{5.20}$$

Most of the factors of the IDA model are equivalent to those in the SDA model (5.12), i.e. $\nu_k{}^{-1} \cong \boldsymbol{L}^E$, $\phi\epsilon_k{}^{-1} \cong \boldsymbol{L}^U \boldsymbol{C}^U$, $UI_k \cong \boldsymbol{T}^U$ and $U_h^R \cong \boldsymbol{r}^{U,R}$, except the activity mix and the activity factors (M_k and Q). To address this issue, an alternative model for producing sectors is defined as

$$P^S = \sum_{k=1}^{n_k} \bar{\nu}_k{}^{-1} (\overline{\epsilon\phi})_k{}^{-1} \frac{U_k^S}{Q_k} \frac{Q_k}{f_k} \frac{f_k}{f} f = \sum_{k=1}^{n_k} \nu_k{}^{-1} \phi \epsilon_k{}^{-1} UI_k L_k F_k f \tag{5.21}$$

where L_k, F_k and f are the production technology of sector k (gross output per unit final demand, $\cong \boldsymbol{L}^M$), final demand mix of sector k ($\cong \mathrm{C}^{\mathrm{M}}$) and the total final demand ($\cong \boldsymbol{s}^M$) factors, respectively.

So

$$P = \begin{cases} P^S = \sum_{k=1}^{n_k} {\nu_k}^{-1} \phi {\epsilon_k}^{-1} U I_k L_k F_k f \\ + \\ P^R = \sum_{h=1}^{n_h} {\nu_h}^{-1} \phi {\epsilon_h}^{-1} U_h^R \end{cases} \quad (5.22)$$

The model represents the three levels of energy use and is able to isolate different self-contained energy performance indicators (analogous to the PFU model in Equation (5.12)).

Advantages and issues

The PU model has the following advantages compared to conventional models:

- The primary, final and useful levels of energy use are represented, which improves the understanding of energy use mechanisms in the economy (Section 3.3.2.3-Issue 3).
- The model is able to isolate three indicators of energy performance in the economy to account for them separately (Section 3.3.2.3-Issue 2): ν gives insight into primary-to-final conversion efficiencies of the energy sector, $\epsilon\phi$ provides information of final-to-useful conversion efficiencies of the extended energy sector, and I_k accounts for the efficiency of production-related useful work use.

Nevertheless, the model cannot address the following issues:

- The model assumes independence of the energy sector and the extended energy sector (Section 4.2.2).
- The service level of energy use is not isolated. It is included in the sectoral useful work intensity (Section 3.3.2.3-Issue 3).
- The level of data aggregation significantly affects the model and applications (Section 3.3.2.3-Issue 1).

5.2.3 Index decomposition analysis with the PU model

The model of primary energy use allows for a more detailed decomposition of the aggregate indicator P into static changes of constitutive factors. So from Equation (5.20) we obtain:

$$\Delta P = \begin{cases} \Delta P^S = DP_\nu^S + DP_\epsilon^S + DP_{UI}^S + DP_L^S + DP_F^S + DP_f^S \\ + \\ \Delta P^R = DP_\nu^R + DP_\epsilon^R + DP_U^R \end{cases} \quad (5.23)$$

Each factor and its coefficient are discussed in detail in the following section.

5.2.3.1 Explanation of factors and decomposition coefficients

ν Factor: Average primary to final conversion efficiency

This factor accounts for changes in the structure and the technology of the energy sector. Possible explanations for an effect $DP_{\nu} < 0$

- Improvements in average primary-to-final conversion efficiencies
- Weather conditions that affect renewable energy production
- Entrance of new conversion technologies with higher than average efficiencies
- Discontinuation of conversion technologies with lower than average efficiencies

$\epsilon\phi$ Factor: Average final energy to useful exergy conversion efficiency

This factor accounts for changes in the structure and the technology of the extended energy sector (Section 5.1.1). Possible explanations for an effect $DP_{\epsilon\phi} < 0$

- Improvements in average final-to-useful conversion efficiencies
- Entrance of new end-use technologies with higher than average efficiencies
- Discontinuation of end-use technologies with lower than average efficiencies

UI Factor: Sectoral useful work intensity

This factor accounts for changes in the direct use of useful work by producing sectors. Possible explanations for an effect $DP_{I} < 0$

- Reduction of dissipation losses through updates and better use of passive systems
- Entrance of new passive systems with higher than average non-dissipation efficiency
- Real price increase of products due to market interactions or increases in input costs

L Factor: The production technology

This factor accounts for changes in the production processes and technology. Possible explanations for an effect $DP_{L} < 0$

- Improvements in production processes
- Progress in production technology

F Factor: Final demand mix

This factor accounts for changes in the composition of final demand. Possible explanations for an effect $DP_{F} < 0$

- Decreasing share in final demand for products with larger associated primary energy use (e.g. water transport)

Factor: The economic scale or Total final demand

These factor accounts for changes in the total final demand for non-energy products. Possible explanations for an effect

- Decrease in private or public expenditure
- Decrease in exports

Factor: Residential useful work demand

This factor accounts for the direct useful work use of residential consumers. Possible explanations for an effect

- Decrease in total residential useful work demand

Note: Any positive change in and/or leads to increases in primary energy use.

5.2.3.2 Issues regarding IDA with the PU model

Issue 1: Data aggregation

See Section 3.3.2.3-Issue 1.

Issue 2: Primary energy equivalent of renewables

See Section 4.3.2-Issue 2.

Issue 3: Primary exergy vs. final exergy

The model establishes a transition to the exergy level of energy analysis at the final level of energy use (Figure 5-3). The reason is that there are less consistency issues in defining and measuring the energy content in final energy flows than in primary energy flows (Sections 2.1.1 and 2.1.2).

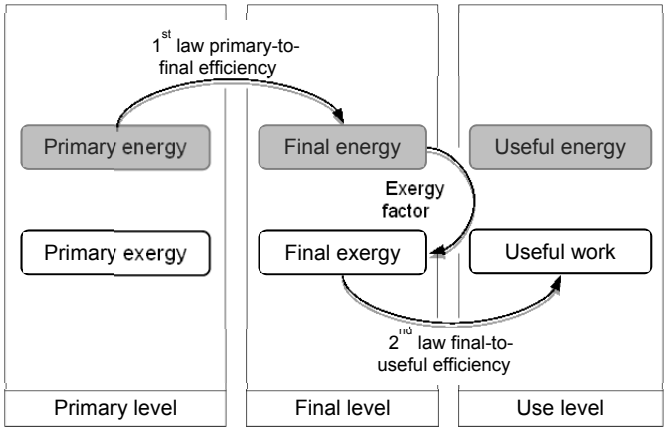


Figure 5-3 Primary-to-final analysis path of the PU model

Issue 4: Accounting for direct use of final energy carriers of the energy sector

In this work, the overall primary-to-final conversion stage includes the direct use of final energy carriers by the energy sector (i.e. contained in v). In addition, the final demand of the energy sector is accounted for by factor I and U^R rather than by factor f. Nevertheless, if the output of the energy sector is relatively small compared to other producing sectors, this issue is less relevant.

Issue 5: Useful work accounting assumptions

See Section 3.1.2-Issue 1.

6 The evaluation of energy efficiency trends: Mexico 1971-2009

Index decomposition has been extensively used to identify the driving factors for changes in energy aggregates. Traditionally, two factors are central for such analyses (see Section 3.3.2.2): the activity mix and the sectoral energy intensity. The latter is usually considered an indicator of energy efficiency. However sectoral energy intensity also represents other features of the economic system hence it is limited to accurately evaluate energy efficiency (Section 9.2). To improve the understanding of the effect of energy efficiency on changes in aggregate energy intensity, an approach that allows disentangling the technical energy efficiency and the intensity of useful work consumption from the sectoral energy intensity is proposed. The traditional and the proposed approaches are applied to analyze the technical energy efficiency trends in Mexican industry. Results from the traditional approach suggest that technical energy efficiency decreased because changes in sectoral energy intensity drove the aggregate final exergy intensity up while the useful work-based approach shows that technical energy efficiency actually increased and that the overall increase of aggregate final exergy intensity was caused by the introduction of useful work intensive, rather than less efficient, industries. The proposed approach gives the direction and absolute value of the effect of technical energy efficiency changes and therefore can help avoid misinterpretation of energy efficiency trends.

6.1 Introduction

The role of energy efficiency in the economy is fundamental for energy security, economic competitiveness and environmental sustainability (Ang et al., 2010; Lovins, 2004). Therefore the analysis of historical energy efficiency trends can provide insights on potential benefits, future evolution and policy intervention. Nonetheless, as noticed by Ang et al. (2010) and Giampietro and Sorman (2012), tracking of energy efficiency trends depends on detailed system information and a developed framework of data collection, which are not usually available. In addition, there is no consensus on the perspective of energy efficiency that should be tracked, i.e. energy intensity, energy conversion efficiency, output per energy-dollar, etc. (Eichhammer, 2004).

Bhattacharyya (2011) and Patterson (1996) among others defined energy efficiency as the ratio of useful output (i.e. any function, service, or value) provided by any process / system to the energy input converted to provide it. According to this definition, energy efficiency could

be represented by different types of indicators. Patterson (1996) classified energy efficiency indicators into four categories, presented in the following table:

Table 6-1 Categories of energy efficiency indicators, based on Patterson (1996)

Energy efficiency Indicators	Indicators/ Units	Advantages	Disadvantages
Thermodynamic (TEE)	1st and 2nd-law efficiencies / $[-], \left[\frac{TJ}{TJ}\right] \left[\frac{kToe}{kToe}\right]$	• Based on and limited by physical principles • Objectively measured hence convergent	• Of limited value for macro-level analysis • Unable to include end use services
Physical-Thermodynamic (PTEE)	Fuel efficiency, specific energy consumption / $\left[\frac{km}{TJ}\right], \left[\frac{m^2}{kToe}\right]$	• Adequately reflect end use services • Objectively measured hence convergent	• Too specific • Cannot be compared between end use services • Problems with multi-product aggregation • Unable to be generalize
Economic-Thermodynamic (ETEE)	Primary energy intensity / $\left[\frac{USD}{TJ}\right], \left[\frac{USD}{kToe}\right]$	• Applicable to the overall economy at different aggregation levels • Can be compared between sectors and countries (with no) • Simple, easily obtainable from current database frameworks	• Based on measures that presents quantification problems (GDP, primary energy equivalent) • Cannot accurately measure technical efficiency (product mix, sectoral mix, energy for labor substitution, energy input mix) • It is influenced by other variables of the economic system • Do not include the effect of energy prices
Economic (EEE)	Output per energy-dollar / $\left[\frac{USD}{Energy\ USD}\right]$	• Include the value of energy commodities, which reflect energy supply and demand forces • Could inform about energy cost savings	• Based on measures that presents quantification problems • Cannot accurately measure technical efficiency • Influenced by other variables of the economic system

As seen in Table 6-1, each category of energy efficiency indicators would be therefore best suited for different applications. For example, TEE indicators give better information at the process level while PTEE indicators provide a better understanding of the historical evolution of a single industry. In this respect, the ETEE indicators are the most used for monitoring economy-wide trends on energy efficiency, e.g. Goldemberg and Siqueira Prado (2011) and Voigt et al. (2014).

The index decomposition model of final energy intensity in Section 3.3.2.2 (hereby called the traditional approach) is widely used for tracking economy-wide and/or industrial trends in energy efficiency (Ang et al., 2010; Khatib, 1995; Liu and Ang, 2007), as well as, for evaluating changes in emissions (Ang and Xu, 2013). Because sectoral energy intensity is believed to be a better indicator of energy efficiency than aggregate energy intensity (Ang and Zhang, 2000). However sectoral energy intensity presents the same disadvantages as other ETEE indicators (Table 6-1). For example, if a product of a single-product industry doubles its value and there are no changes in its production process or in any of the process inputs, the energy intensity of that industry would decrease by half without any improvements in technical energy efficiency.

On the other hand, if that industry develops a technology to build the same product with the same value but with half of the energy input required before, its energy intensity would decrease by half only due to improvements on technical energy efficiency. The previous example shows that energy intensity inherently comprises technical energy efficiency though is unable to provide an accurate measure without detailed case-by-case information.

Liu and Ang (2007) analyzed the results of over 60 IDA studies of industrial final energy intensity in order to identify systematic features. They found that in most studies the sectoral final energy intensity factor was the main driver of changes in aggregate final energy intensity. Nevertheless, sectoral final energy intensity presents the same disadvantages as other economic-thermodynamic indicators as this factor aggregates the effect of several other variables of the economic system (ϵ, μ, p^{-1} and S, Section 9.2).

Furthermore, even though policy targets at the macro level focus on energy intensity or energy savings (see e.g. the European Union Energy Efficiency Directive), actual policy measures are mainly focused on TEE (i.e. technical energy efficiency) and PTEEindicators (see e.g. IEA (2013) or ADEME (2012a)). Therefore, the traditional approach to energy efficiency trends would be limited to evaluate the effectiveness of such policy measures.

The goal of the present chapter is to improve the understanding of efficiency trends by introducing the useful level of energy use to the traditional approach. This allows tracking technical energy efficiency and useful work intensity trends and also evaluating their effect on the aggregate final energy intensity.

Case study: Mexico 1971-2009

During 1971-2009, Mexico underwent a radical transformation of its economic system. From an import-substituting (protectionist) economy[28], it became an relatively open economy largely integrated with the U.S. (Kuntz, 2012). This transition is divided in four intervals, which are briefly described in the following paragraphs.

Interval 1971-1982: In the first half of the 1970's, the productivity of primary and secondary industries declined due to the tight government control over the economy and currency in the previous decades (Reynolds, 1978).The country faced economic slowdown in 1976, which did not continue because oil revenues compensated the effect of productivity losses. However oil revenues gave a sense of economic stability, motivating public overspending, and increasing the flow of foreign revenues to the country, which boosted the so-called *Dutch disease*[29]. In addition, a sudden drop of oil prices ultimately led to the crisis of 1982 (Colmenares, 2008; Kuntz, 2012; Looney, 1985).

[28] Import substitution industrialization (ISI) consisted of government protection of heavy industries. The aim of the program was to develop these industries within borders hence improving the country's productive structure and reducing its imports. It was recommended to developing nations after the Second World War by the main world development organizations, including the World Bank (Lin, 2009). In Mexico, import substitution started early in the 1950's and continued till the end of the 1970's (Aspra, 1977; The World Bank, 1979; UNAM, 2012).

[29] Sharp inflows of foreign income induce real exchange appreciation, which decreases the competitiveness of the main industrial sub-sectors compared with imports (Corden, 1984; Ebrahim-zadeh, 2003)

Interval 1982-1988: In this interval, the country underwent important structural changes to allow for a less protectionist state, e.g. requirements and taxes on imports were reduced. Even though the economic performance was poor as a result the 1982's crisis, these changes enabled the opening of the economy in the subsequent interval (1988-2001) (Cárdenas, 2009; Kuntz, 2012)

Interval 1988-2001: From 1988, the Mexican government put emphasis on liberalizing the economy. The main proposal to achieve this goal was a free-trade agreement with the U.S. and Canada (i.e. North American Free Trade Agreement, NAFTA). The government updated the institutions and regulation to enable the agreement and also privatized many state companies, e.g. telecommunications and banks (Hoshino, 1996). Foreign investment euphoria followed the announcement of the NAFTA, large amounts of foreign capital flowed into the country. The latter fact led to a second version of the *Dutch disease* (see Footnote 28) and to the 1994's economic crisis. However Mexico experienced a fast export-led recovery and by the end of 1995 the economy was again growing (Kuntz, 2012).

Interval 2001-2009: The main difference from the previous interval relies on the significant price surge of oil in 2001, which increased the share of oil exports compared to the 1990's and boosted public investment (Colmenares, 2008). In addition, in 2009, the country experienced an economic slowdown due to the world crisis of 2007-2009.

Furthermore, the present analysis is a contribution to the scarce and scattered specific research on Mexico's energy and efficiency transitions, which is described in the following paragraphs:

Sheinbaum et al. (1996) evaluated the trends of Mexican residential energy use between 1970 and 1990. They found that electricity was the fastest growing end-use though the share of electricity in this sector was much smaller than that of oil products. Rosas et al. (2010) analyzed the structure of household energy consumption between 1996 and 2006. They concluded that energy consumption for water heating and electric appliances significantly increased, while for cooking, it decreased; and that inequity in energy services among income groups grew.

Sheinbaum et al. (2010)and Sheinbaum and Ozawa (1998) studied the iron & steel industry in 1970-2006 and the cement industry in 1982-1994, respectively. They found that increases of energy efficiency and changes in the energy mix decreased the energy intensity in these industries. These improvements helped in reducing the gap in energy intensity with respect to best international practices. Moreover, Sheinbaum et al. (2012) decomposed the driving factors of primary energy consumption of all manufacturing industries of the country between 1970 and 2008 (an expansion and update of the analysis of Sheinbaum and Rodríguez V (1997)). They identified the structure of production and energy intensity as the main contributors to changes in energy use and CO_2 emissions in most industries.

Berndt and Botero (1985) in 1985 analyzed the energy demand of the transportation sector. Their main finding was that the effect of income on energy demand for transportation was larger than the effect of energy prices. In addition, Solís and Sheinbaum (2013) evaluated the trends of energy consumption and CO_2 emissions in the transportation sector in 1990-2010.

They found that the increase of private vehicles and light truck transport were the main factors driving up the energy demand and emissions of the sector. They also found no correlation between fuel prices and energy consumption for the transportation sector.

Cheng (1997) in 1997 applied the Granger causality test to Mexico's primary energy consumption and economic growth aggregate variables and found no causal linkages between those variables. Galindo (2005), through a cointegration approach, found that energy demand in Mexico over the period 1965-2001 was mainly driven by income and not by energy prices. Aguayo and Gallagher (2005) gave insights on primary energy intensity in Mexico between 1965 and 1999. They found that it increased before 1988 and declined thereafter. According to their analysis, the decline was mainly caused by compositional factors and technological progress in the most energy-intensive industries. Finally, Sheinbaum et al. (2011) examined the trends of energy demand and CO_2 of five Latin American countries (including Mexico) from 1990 to 2006. They concluded that even though energy intensity decreased, the reduction of CO_2 emissions was not significant due to an increased dependency on fossil fuels.

6.2 Methods

The useful work relationship in Equation (3.1) is introduced into the traditional form of index decomposition of final energy intensity in Equation (3.56) as

$$T = \sum_{k=1}^{m} T_k = \sum_{k=1}^{m} \frac{Q_k}{Q} \frac{1}{\epsilon_k} \frac{U_k}{Q_k} = \sum_{k=1}^{m} M_k \epsilon_k^{-1} UI_k \tag{6.1}$$

where T is the aggregate final exergy intensity and M_k, ϵ_k^{-1} & UI_k are the activity mix, technical efficiency and sectoral useful work intensity factors for sector k, respectively.

The change of aggregate final exergy intensity can be decomposed as:

$$\Delta T = DT_M + DT_\epsilon + DT_{UI} \tag{6.2}$$

where DT_M, DT_ϵ and DT_{UI} are the change of aggregate final exergy intensity due to changes in activity mix, technical efficiency and sectoral useful work intensity, respectively. The values of these coefficients are determined with the LMDI technique (Section 3.3.2.1) as follows:

$$DT_M = \sum_k \frac{{T_k}^{t_2} - {T_k}^{t_1}}{ln\,{T_k}^{t_2} - ln\,{T_k}^{t_1}} ln\left(\frac{{M_k}^{t_2}}{{M_k}^{t_1}}\right) \tag{6.3}$$

$$DT_\epsilon = \sum_k \frac{{T_k}^{t_2} - {T_k}^{t_1}}{ln\,{T_k}^{t_2} - ln\,{T_k}^{t_1}} ln\left(\frac{{\epsilon_k}^{t_2}}{{\epsilon_k}^{t_1}}\right) \tag{6.4}$$

$$DT_{UI} = \sum_k \frac{{T_k}^{t_2} - {T_k}^{t_1}}{ln\,{T_k}^{t_2} - ln\,{T_k}^{t_1}} ln\left(\frac{{UI_k}^{t_2}}{{UI_k}^{t_1}}\right) \tag{6.5}$$

This decomposition model is referred to as the UW-based IDA approach in this section.

6.3 Data

Useful work data for Mexico for the period 1971-2009 were estimated through useful work accounting (Section 3.1) as described.

Step 1 Conversion of existing final energy data to final exergy values

Collecting energy data

Final energy consumption data were collected from the International Energy Agency´s Energy Statistics and Balances (IEA, 2011a, b) and from the National Institute of Statistics and Geography (INEGI, for its Spanish acronym) (INEGI, 2010b, c, 2012). Consistency of data was evaluated by comparing IEA´s and INEGI's data with each other. There were little variations between the two databases with respect to total final energy values per sector per carrier. However INEGI's data of the industrial and transportation sectors was preferred over IEA's, since the latter presented inconsistencies in disaggregation. Moreover, the sectoral classification of the IEA's database was adopted for this work, which consists of 4 sectors (see Appendix C.1): Energy sector, industrial, transportation and others –including the residential, commercial, agricultural, forestry and public sub-sectors.

Final food supply per capita as metabolizable energy data[30] and as-is-weight[31] livestock feed supply[32] was collected from the United Nations - Food and Agriculture Organization databases (FAO, 2011). Additionally, other economic indicators and variables, e.g. GDP per capita, industrial value added and demographics were collected from IEA (2011a), INEGI (2012), OECD (2011) and The World Bank (2011).

Conversion of energy data to exergy values

Final exergy values, except for the food and feed carrier, were calculated by Equation (3.1) with final energy data, described above, and exergy factors from Table 3-1.

In the case of the food and feed carrier, the collected data was converted to final gross exergy values in the following way: 1) Final food supply per capita as metabolizable energy was first multiplied by a gross/metabolizable ratio (Table 6-2) to obtain total gross exergy supply and then by an eaten/supplied ratio, which accounts for the amount of food that is not consumed; and 2) As-is-weight feed supply[33] was converted to gross exergy with Wirsenius (2000)'s data for gross exergy of feed products. Finally, the eaten/supplied ratio in Table 6-2 was applied.

[30] Defined as energy available for the organism´s use, e.g. heat production and body gains (FAO, 2003)
[31] i.e. including embodied water (FAO, 2011).
[32] It includes the total livestock, i.e. draft and non-draft animals hence it was considered that the working animal share corresponds to a constant 10% of total livestock. This value was estimated by assuming Mexican working animal to total livestock ratio similar to that of Portugal in the 1960's. Data of total Mexican Livestock were obtained from INEGI (2010b) and USDA (2012). Data of Portuguese draft animals and total livestock were obtained from Henriques (2011) and USDA (2012).
[33] FAO's livestock feed data does not include pasture hence pasture consumption was obtained from Wirsenius (2000)'s figures of Latin-America and Caribbean countries' feed and feedstock.

Table 6-2. Food and feed conversion variables from Wirsenius (2000)

	Eaten/supplied ratio	Gross/metabolizable ratio
Food[a]	81% in 1970[b] 74% in 1992-2009[c]	1.197
Feed	63%	NA

[a] Latin-America and Caribbean countries' data
[b] Obtained by assuming Mexico's conditions in 1970 similar to those of South & Central Asia in 1992-1994
[c] Wirsenius's data is for 1992-1994 hence it was assumed constant through 1994-2009

Step 2 Allocation of final exergy consumption to useful work categories

The allocation of final exergy uses from IEA´s energy balances followed in general the assumptions for allocation by Serrenho et al. (2012). However a few modifications were applied to account for Mexico´s specific conditions and available data. The rationale for allocation by each energy carrier is described in the following sections and in Appendix C.1.

Coal and coal products

High temperature processes of the metallurgical industries have accounted for most of the final consumption of coal over the studied period (Wallace, 2009). On the other hand, low temperature uses in the residential sector have been negligible (IEA, 2011a) and uses for railroad transportation almost vanished due to the introduction of diesel technology before the 1970's (Hernández Lecanda, 2007).

Oil and oil products

Oil is fundamental for the economy and has had a significant impact on the economic performance in the last 40 years because it is the major contributor to government's revenue and has accounted for a significant share of all Mexican exports since 1974, though with a decreasing trend: 68%, 37%, 10% and 16% in 1985, 1990, 2000 and 2011 respectively (Colmenares, 2008; EIA, 2012; INEGI, 2012). In particular, between 1973-1982, Mexico's oil production notably increased from 150 to over 1000 million barrels a year (Alvarez de la Borda, 2006)[34].

The transportation sector accounts for the largest final demand for oil and its products. Automotive vehicles as well as major automobile manufacturers forayed into Mexico early in the 20th century (Carrillo and García, 1987; Fujigaki Cruz, 1997). Oil-fuelled motorization expanded and nowadays dominates freight and passenger transportation (Capasso, 2007; Solís and Sheinbaum, 2013).

Demand of oil products (kerosene and oil lubricants) for residential uses, such as lighting and heating, were still significant in the second half of 20th century due to the slow introduction of electricity. However nowadays lighting residential oil uses have practically vanished over the

[34] The oil boom in Mexico was caused by the Arab oil embargo of 1973, which induced the rise of oil prices (Barsky and Kilian, 2004) and hence boosted incentives to invest in the oil industry of non-OPEC countries.

studied period as the electric grid reached most households (INEGI, 2012; Merrill and Miroì, 1997).

Natural gas

Natural gas production has remained almost constant at about 14% of total energy production in the country during the entire studied period (IEA, 2011a). However production did not cover total internal consumption, which made Mexico a net importer of natural gas from the United States since before the 1970's (EIA, 2011b) [35].

Industrial heating, mainly for MTH and HTH processes, held most of natural gas consumption before 2000 (COLMEX, 2008). After that year, both industrial heating and electricity generation (non-final use) have led the demand of natural gas (IEA, 2011a). In addition, residential uses, which comprises low temperature heat for space, water and cooking, have been steadily rising (INEGI, 2012).

Combustible renewables

According to INEGI (2012), two combustible renewables were mainly used in the period 1965-2011: sugar cane bagasse and wood for industrial and residential uses, respectively. Other sources, such as biofuels, waste and biogas were also used but in smaller quantities. However, data with respect to the residential sector are likely to be underestimated due to lack of information about biomass consumption in rural areas, which had 40% to 22% of the total population during the studied period (INEGI, 2010b; McCaa, 1997).

Residential uses consist almost exclusively of LTH for cooking. On the other hand industrial uses mainly correspond to MTH for sugar production, since bagasse is fed into boilers at ~ 280ºC temperature (D'Angelo et al., 2006). In recent years, other combustibles renewables have been included, e.g. biofuels for transportation (i.e. mechanical drive) and waste for electricity generation (non-final use) though their shares remain negligible.

Electricity

Electricity gained relevance since the country completed electrification[36] over the studied period. In 1970, over 40% of the population remained without electricity. Further electricity generation/transmission projects were implemented boosting electricity access to 87% in 1990 and 98% in 2011 (Merrill and Miroì, 1997).(INEGI, 2012)

The allocation of final electric uses to useful work categories follows a sectoral analysis.

The residential sector uses electricity for lighting, electric appliances and electronic equipment. Usually TV´s, radios and fridges lead consumption (INEGI, 2010a), except in urban areas where electronic devices are widely used and in regions with extreme climates where air conditioning is needed. In the case of the industrial sector, electricity is used for lighting, machinery, refrigeration, electronic appliances and air-conditioning. Detailed data of residential and

[35] Valdez (2003) infers that the low natural gas production with respect to reserves in Mexico is responsible for distortion and increases of natural gas prices in North America.

[36] Electrification is measured by the percentage of total households in a country that have electricity (The World Bank, 2011)

industrial consumption are limited: only a few data points are available (CONAFOVI, 2006; CONUEE, 2010a, b; Maqueda and Sánchez, 2008; SENER and IEA, 2011). Therefore useful work shares were obtained by adjusting U.S. and U.K. estimates (Ayres et al., 2005; Fouquet and Pearson, 2006) according to available Mexican data points as described in Appendix C.2.

Finally, the transportation sector uses electricity mainly for subway transport systems, which started in the 1960´s, and has had since a significant participation in the three most important cities (SETRAVI, 2005) However electric transportation remains negligible in terms of total transportation energy use and total electric uses, i.e. <1% (INEGI, 2012).

Food and feed

The final exergy of this carrier is entirely allocated to muscle work useful work category provided to the economy by humans in the case of food and draft animals in the case of feed. Other uses by humans of food exergy such as cognitive activities are also allocated into this useful work category.

Other non-conventional

IEA´s databases include the contribution of solar thermal systems, which is used for low temperature water heating. In addition, other non-conventional carriers, such as wind flow to drive mechanical mills, are not accounted in databases since their contributions are negligible over the studied period.

Step 3 Estimation of second-law efficiencies for each final-to-useful transformation

In this section, the definition of parameters of second-law efficiencies for each category and sub-category is described.

Heat:

Second law efficiencies for this category are given by Equation (3.2), which depends onη, θ_0 and θ_2. The values for these variables were obtained as follows:

The evolution of first law efficiencies (η) for most heat processes was estimated based on a representative industry for each temperature range and efficiencies of generic heat conversion devices (Cullen and Allwood, 2010b). For the HTH range, estimates were obtained from studies of the iron and steel industry (De Beer et al., 1995, 1998; Worrell et al., 1997). In the case of the MTH range, the ammonia industry (Smil, 2001) and medium temperature processes of the iron industry (De Beer et al., 1995, 1998) were used. For the LTH range, efficiencies were obtained from specifications of space heating devices from Cullen and Allwood (2010b) and Serrenho et al. (2012)'s estimates.

Concerning the environment reference temperature (θ_0), Mexico has a wide variety of climates, yet it has three main industrial regions: Centro, Norte and Bajio, which are defined by the three most important cities in the country: Mexico City, Monterrey and Guadalajara. Therefore six different reference temperatures were taken into account (Table 6-3), i.e. average temperatures during cold months and yearly average temperature during the rest of the year for each one of the industrial regions (SMN, 2010). It is assumed that each region has

the same share of total heat uses since the three cities have similar output of primary and secondary industries (INEGI, 2011).

Table 6-3 Climate conditions of reference regions.
Note: Data from SMN (2010)

Region	θ_0		Fraction of the year
Centro	Average Temp. cold	14.32˚C	1/3
	Yearly Temp.	16.36˚C	2/3
Norte	Average Temp. cold	16.4˚C	1/3
	Yearly Temp.	22.48˚C	2/3
Bajio	Average Temp. cold	16.35˚C	1/3
	Yearly Temp.	19.48˚C	2/3

Finally the temperature at which heat transfer occurs (θ_2) is defined within the limits of each heat sub-category (Table 6-4).

Table 6-4. Characteristic process temperatures (θ_2)

Useful work sub-category	Temperature range	θ_2
High temperature heat (HTH)	>600˚C	600˚C
Medium temperature heat (MTH)	120-600˚C	360˚C
Low temperature heat (LTH)	<120˚C	80˚C

Mechanical drive:

The evolution of ϵ_{mech} for gasoline and diesel engines is built from Equations (3.3) and (3.4). The values of the α_i coefficients and the evolution of compression ratios were obtained from Ford et al. (1975) and Serrenho et al. (2012). ϵ_{mech} for electric motors and other mechanical equipment, were estimated from engine specific information (Cullen and Allwood, 2010b; IEA-ETSAP, 2010) and the evolution paths of the U.S. (Ayres et al., 2005; Serrenho et al., 2012; Warr et al., 2010) since most equipment was imported from or manufactured according to standards of the northern neighbor.

Lighting:

Second law efficiencies for lighting, as defined in Section 3.1.1.3, were obtained from U.S. estimated data (Ayres et al., 2005). To account for differences in economic development and infrastructure between of U.S. and Mexico, time-lags were applied to the data according to the characteristics of historical electric use in both countries, see Appendix C.2. Fouquet and Pearson (2006)'s and Nordhaus (1997)'s data were used for other energy carriers (i.e. kerosene) and for evaluating consistency of the results.

Other electric uses:

Similarly to lighting, other electric uses ϵ's were adjusted based on U.S. estimates by Ayres et al. (2005) as explained in Appendix C.2. In addition, estimates from Rosen and Bulucea (2009) were used for evaluating consistency of adjusted data.

Muscle work:

Humans and animals have an efficiency to convert metabolizable energy from food and feed into useful muscle work with an efficiency of 17% and 21%, respectively (Smil, 1994, 2008; Wilson et al., 2004). The difference relies on the assumption that work performed by humans is half anaerobic and half aerobic; and by animals, mainly aerobic. To obtain the second law final to useful efficiency, this metabolizable-to-useful efficiency should be divided by a Gross/metabolizable ratio (Table 6-2).

$$\epsilon_{muscle} = \frac{\left(\frac{\text{Useful work}}{\text{Metabolizable exergy}}\right)}{\left(\frac{\text{Gross}}{\text{Metabolizable}}\right)} = \frac{\text{Useful work}}{\text{Final gross exergy}} \quad (6.6)$$

Step 4 Calculation of aggregate useful work values

Aggregate useful work and a second law final-to-useful efficiency were calculated. In addition, GDP in USD at constant prices and PPP's data from IEA (2011b) and the distribution of value added at constant prices from INEGI (2012) were used to determine the economy-wide and industrial useful work intensities, respectively.

6.4 Results

This section presents the results of estimates of aggregate and sectoral technical efficiencies and the IDA of final exergy intensity in Mexico between 1971 and 2009, as well as an overview of total final exergy and useful work consumption.

6.4.1 Total final exergy use

Mexico experienced a fourfold growth in final exergy consumption from 1.8 EJ to over 6 EJ in 40 years (Figure 6-1). The country had an average annual growth rate (AAGR) of final exergy demand of 3.4% (1.42% p/c).

In the interval 1971-1982, both final exergy use and per capita values were characterized by a large growth rate (AAGR 6.74% & 3.97% p/c). This was caused by 1) structural changes and government investment in infrastructure brought by the oil industry boom (Colmenares, 2008); 2) the sharp increase in final exergy use in the transportation sector (Figure 6-2); 3) productivity loss in non-oil industries (Ebrahim-zadeh, 2003); and 4) the introduction / adaptation of heavy industries promoted by import substitution (Aspra, 1977; The World Bank, 1979).

During 1982-1988, the growth rate of final exergy consumption slowed down (AAGR 0.57%, -1.43% p/c). This was caused by the economic crisis of 1982, which also led to the stabilization of the oil industry, the deceleration of the growth rate of final energy use by the transportation sector and the end of heavy industrialization by import substitution.

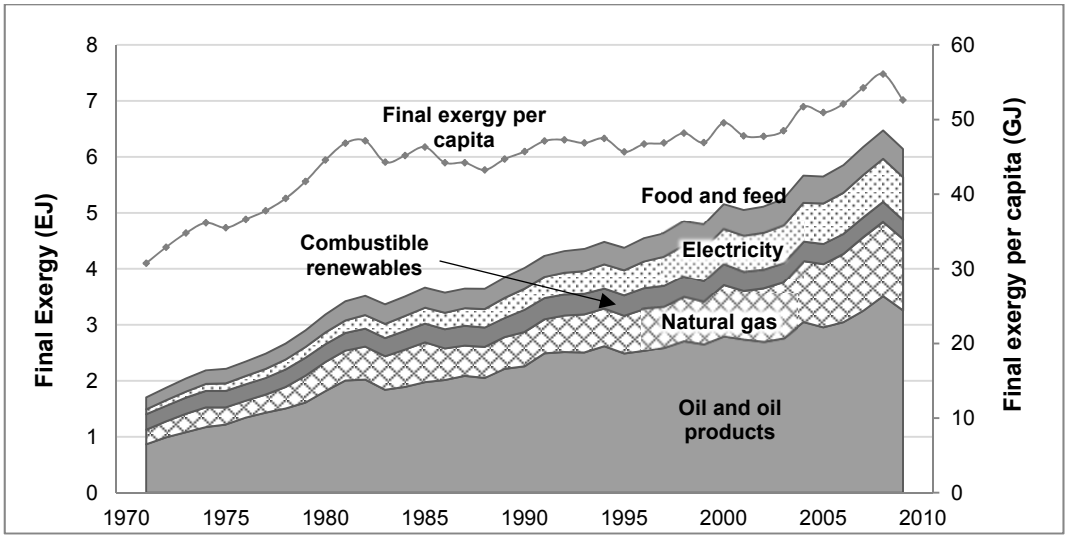


Figure 6-1 Final exergy use by energy carrier and per capita: Mexico 1971-2009

The interval 1988-2001 was characterized by a larger growth rate of the final exergy demand (AAGR 2.49%, 0.77% p/c). Major changes in the country drove final exergy demand such as 1) the abolition of import licensing (Cárdenas, 2009; The World Bank, 1979); 2) the North-American Free Trade Agreement (NAFTA) of 1994, which brought competition and productivity gains to previously protected industries; and 3) the privatization of many state-owned industries (including banks, rail, telecommunications, etc.) After the NAFTA came into force, Mexico's exports doubled and diversified (Kuntz, 2012).

In 2001-2009, aggregate final exergy consumption had a larger growth rate (AAGR 3.57%, 2.3% p/c) mainly driven by the increase in exports and the rise of final exergy use by the transportation sector (Figure 6-2). Finally, the drop of aggregate final exergy consumption in 2009 was caused by the 2008's world economic crisis that severely hit the U.S., the major commercial partner of Mexico.

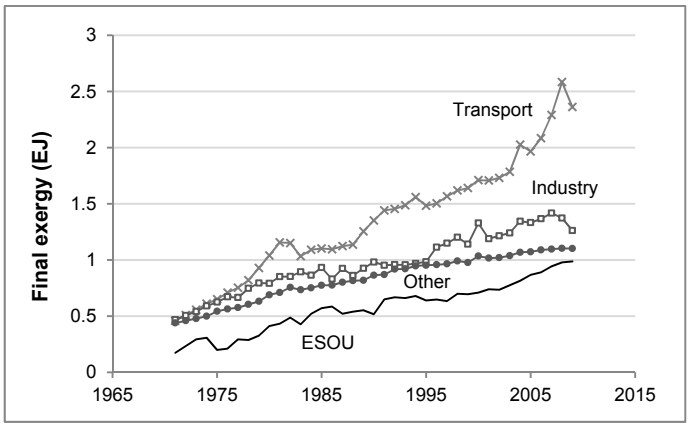


Figure 6-2 Final exergy use by sector: Mexico 1971-2009
Note: ESOU stands for Energy Sector Own Uses.

The trend of total final exergy use is largely influenced by the demand of final exergy by the transportation sector, which is the largest demand by sector. Road transportation accounted for over 90% of this demand. On the other hand, final exergy use by the industrial and other sectors steadily increased. Additionally, the energy sector own use reflects the status of

Mexico as an oil exporter, i.e. oil extraction and refining accounted for more than 95% of the final exergy use of the energy sector.

The final exergy mix shows a strong dependency of the economy on oil and natural gas. Oil and oil products accounted for half of total final exergy consumption while the natural gas share increased from 15% to 21%. Moreover, combustible renewables reduced their share by a half (15% to 7%) while electricity gained relevance from a 5% share in 1971 to 12% in 2000 as the country reached full electrification.

6.4.2 Total useful work consumption

Useful work reflects the evolution of exergy uses, which are influenced by structural changes of the economy. As seen in Figure 6-3, useful work had a sixfold growth from 0.2 EJ to 1.2 EJ over the studied period. The country had an AAGR of useful work demand of 4.49% (2.48% p/c).

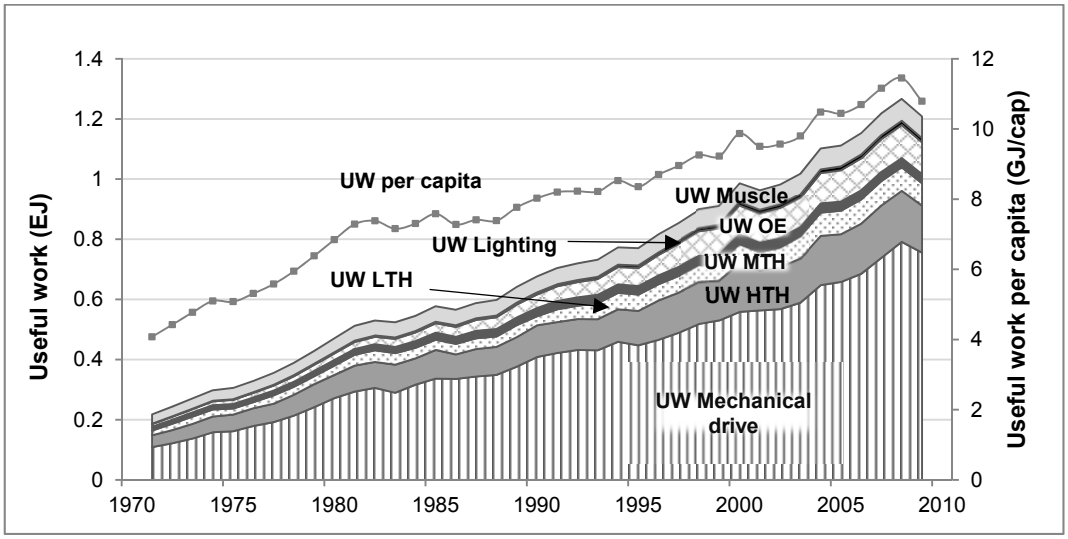


Figure 6-3 Useful work by category and per capita: Mexico 1971-2009
Note: HTH, MTH and LTH stand for high, medium and low temperature heat, respectively. In addition, OE stands for other electric uses.

The first interval (1971-1982) was characterized by a sharper rise (AAGR 8.22%, 5.35% p/c). As discussed before, this trend was caused by the development of the industrial structure, especially the oil industry, infrastructure projects and by the increase in transportation final exergy use. In 1982-1988, useful work slowed down (AAGR 1.99%, -0.04% p/c) while the country was struggling with the effects of the 1982's economic crisis. The intervals 1988-2001 and 2001-2008, which are almost mutually indistinguishable, had a stable growth rate (AAGR 3.66% and 3.83%, respectively) associated to the transition towards an export-led economy.

The trend of useful work was highly influenced by the industrial sector, which held the largest share of useful work over the studied period (Figure 6-4); and, to a less extent, by the transportation sector, especially during the interval 1971-1982.

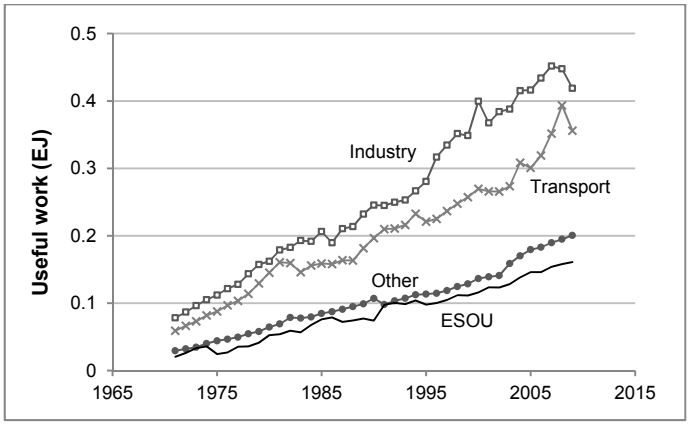


Figure 6-4 Useful work by sector: Mexico 1971-2009

In the industrial sector, the trend in useful work experienced a stable growth, as shown in Figure 6-5. In the transportation sector, the trend in useful work is similar to the trend in final exergy (Figure 6-2). The energy and the other sectors had stable but lower growth rates than the industrial and transportation sectors.

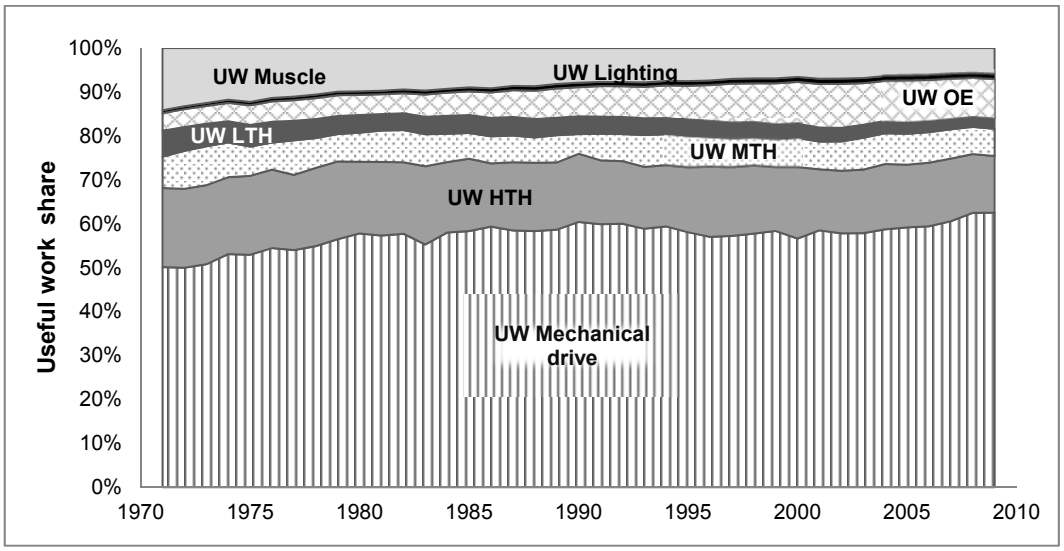


Figure 6-5 Useful work shares by category: Mexico 1971-2009

The shares of each useful work category are depicted in Figure 6-5. The role of mechanical work on the economy progressively increased in opposition to a decrease of the high temperature heat share. This was caused by growing energy needs for transportation (pure mechanical drive) and an expansion of mechanical drive uses compared to high temperature heat uses in the industrial sector[37]. The shares of medium temperature heat, low temperature heat and lighting uses remained almost constant. Moreover, the share of other electric uses also increased because of electricity availability and the deployment of electronic devices, especially in urban areas. Finally the share of muscle work was reduced by 50% though it seems to have stabilized around 6% since 2005, which differs from the case of developed countries, e.g. 2% in Portugal (Serrenho et al., 2012). The latter is because of the lower degree of automation of Mexican industries, i.e. Mexico is still more labor-intensive than developed economies.

[37] Mechanical drive uses in the industry increased 6 times by 2009 vis-a-vis its 1971's value, while high temperature heat increased less than 4 times (INEGI, 2012).

6.4.3 Energy efficiency trends

The aggregate technical efficiency ϵ_T in Figure 6-6 represents the improvements that the final-to-useful conversion stage of the Mexican economy went through during the studied period. It accounts for the larger increase of useful work (sixfold growth) compared to final exergy demand (fourfold growth).

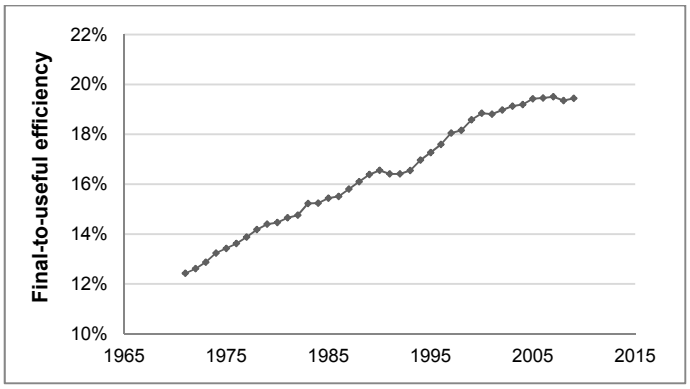


Figure 6-6 Aggregate final-to-useful efficiency: Mexico 1971-2009

Progress based on technological transfer from more developed countries, mainly U.S., brought more energy-efficient end-use devices and processes and partially led to an increasing trend of ϵ_T (13% to 19%). Two fluctuations from the trend are pointed out: 1) In (1982-1983), ϵ_{agg} increased despite the economic crisis, which might be due to the closure of inefficient industries that could not endure the crisis. 2) In (1988-1994), ϵ_{agg} declined due to the structural changes that the government undertook during those years. Later on, it increased again due to the productivity gains of an open economy.

The progress of ϵ_{agg} was mainly driven by the industrial sector, which had the highest improvement on final-to-useful efficiency, i.e. 17% to 33% (Figure 6-7). On the other hand, the energy, transportation and other sectors also had improvements in efficiency though much lower than the industrial sector. In addition, the small increase in the efficiency of the transportation sector (13% to 15%) explains the fact that this sector had a lower amount of useful work use compared to the industrial sector (Figure 6-4) even though it had the largest demand of final exergy (Figure 6-2).

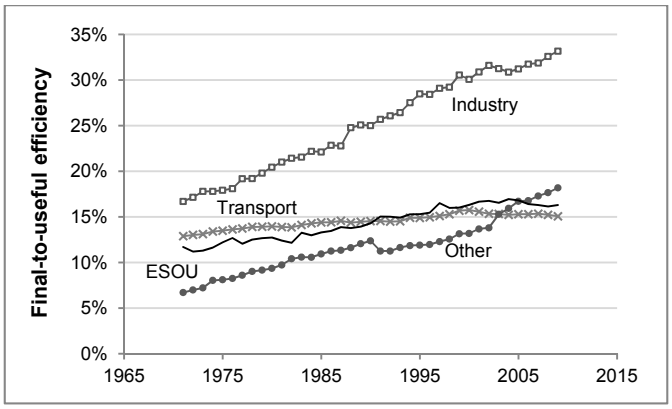


Figure 6-7 Final-to-useful efficiencies by sector: Mexico 1971-2009

Furthermore the evolution of the technical efficiencies by energy carrier in Figure 6-8 shows that energy carriers were in general more efficiently used either by improvements in processes or carrier allocation to more efficient uses. Even though oil and oil products had a modest improvement in technical efficiency (9% to 13%), this carrier accounted for a third of the increase in the aggregate technical efficiency. Coal and coal product uses experienced the largest improvement in technical efficiency (20% to 32%, mainly due to the development of high temperature processes), though their impact was limited since this carrier accounted for less than 4% of total final exergy consumption. Moreover, the technical efficiency of natural gas shows an upward slope before 2000. After this year it stabilized because improvements in natural gas use by the industry were offset by the increase of low temperature heat residential uses, which have low efficiency (INEGI, 2012). Finally, electricity, which has the highest technical efficiency, shows a very moderate improvement. However, this carrier whose share in the final energy mix increased from 5 to 12% was fundamental for the increase of the aggregate second-law final-to-useful efficiency.

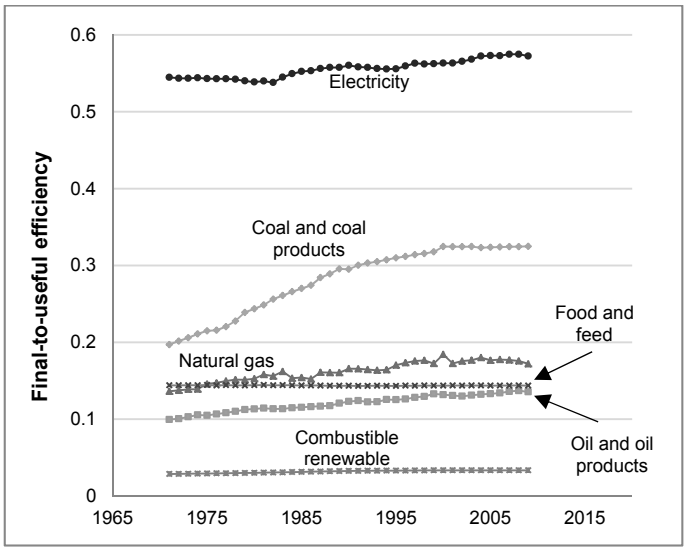


Figure 6-8 Final-to-useful efficiencies by energy carrier: Mexico 1971-2009

The useful work intensity of the economy had an increasing trend (Figure 6-9), which implies that the Mexican economy grew its minimum energy requirements to produce one unit of GDP. In other words, the economy became less productive per unit of useful work.

On the one hand, the upward trend of useful work intensity in a period in which Mexico was industrializing is congruent with what other economies experienced during industrialization such as U.S., Japan, U.K., Austria and Portugal (Serrenho et al., 2012; Warr et al., 2010). In 1970-1988, the country unlocked the protectionist scheme in favor of a more opened economy, which increased useful work intensity by an AAGR of 1.78%. After 1988, most sectors of the economy opened, which induced a decline of the growth rate of useful growth intensity, i.e. AAGR 0.58%. This fact suggests that useful work intensity will eventually stop growing and even decline as it has happened in some of the countries mentioned above.

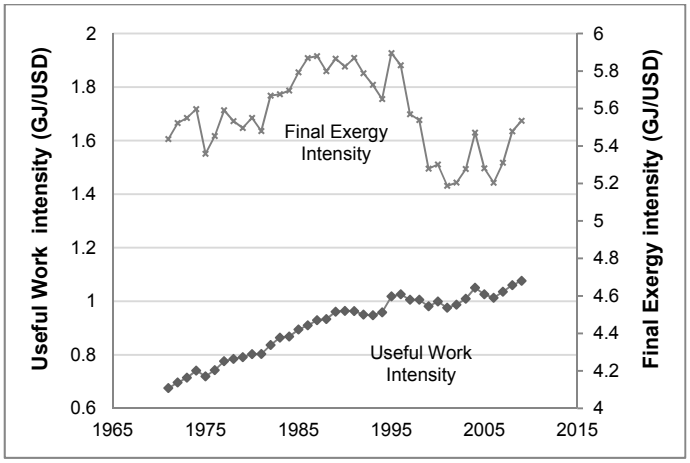


Figure 6-9 Economic final exergy and useful work intensities: Mexico 1971-2009
Note: GDP data at constant prices of 2008 from IEA (2011b)

On the other hand, final exergy intensity (Figure 6-9) had a rather different trend, i.e. it varied ±10% from its 40-year average. In 1971-1982, it remained almost constant with a sharp decrease in 1975 as a prelude of the 1976's economic deceleration. After 1982, final exergy intensity rose under the economic stagnation before 1988. In most of the interval 1988-2001, the final exergy intensity decreased, except between 1994 and 1995, as a consequence of the 1994's crisis. The decline of final exergy intensity during this interval mainly reflect the efficiency gains and changes of composition of the industrial sector as concluded by Aguayo and Gallagher (2005). Finally, in 2001-2009, final exergy intensity experienced significant fluctuations, though with a slightly increasing trend (AAGR 0.78%).

The differences of final exergy and useful work intensities show that useful work intensity was more influenced by structural changes while final exergy intensity was more influenced by the economic fluctuations. Moreover these differences also show that improvements of the aggregate final-to-useful efficiency had a positive effect on stabilizing final exergy intensity despite the rise of useful work intensity. These results confirm what Warr et al. (2010) and Serrenho et al. (2012) found: the trends in useful work and final exergy intensities can be radically different.

6.4.4 The effect of efficiency on final exergy intensity (producing sectors)

The results of the traditional and UW-based IDA approaches are summarized in Table 6-5 and shown in detail in Figure 6-10. These were calculated with the values of useful work, final exergy intensity and technical efficiency of producing sectors, i.e. including industry, transport and services, extracted form the economy-wide figures of the previous section. In addition, the studied period has been reduced to 1980-2009 to focus from the beginning of the structural transition of the country (Section 0).

Table 6-5: IDA coefficients by the traditional and UW-based approaches: Mexican industry 1980-2009

Approach	Year	IDA effects				
		ΔT	DT_M	DT_{EI}	DT_{UI}	DT_ϵ
Traditional	1980-2009	0.2334	0.0586	0.1747		
UW-base	1980-2009	0.2334	0.0586		1.0469	-0.8722

Units MJ/USD

On the one hand, results from the traditional approach show that the effect of sectoral exergy intensity changes (DT_{EI}) surpassed the effect of activity mix changes (DT_M) and hence was the main driver of T transitions, which coincides to the findings of most studies (Liu and Ang, 2007). Changes in sectoral exergy intensity led to an increase in aggregate final exergy intensity, which suggests that the evolution of energy efficiency in Mexican producing sectors deteriorated.

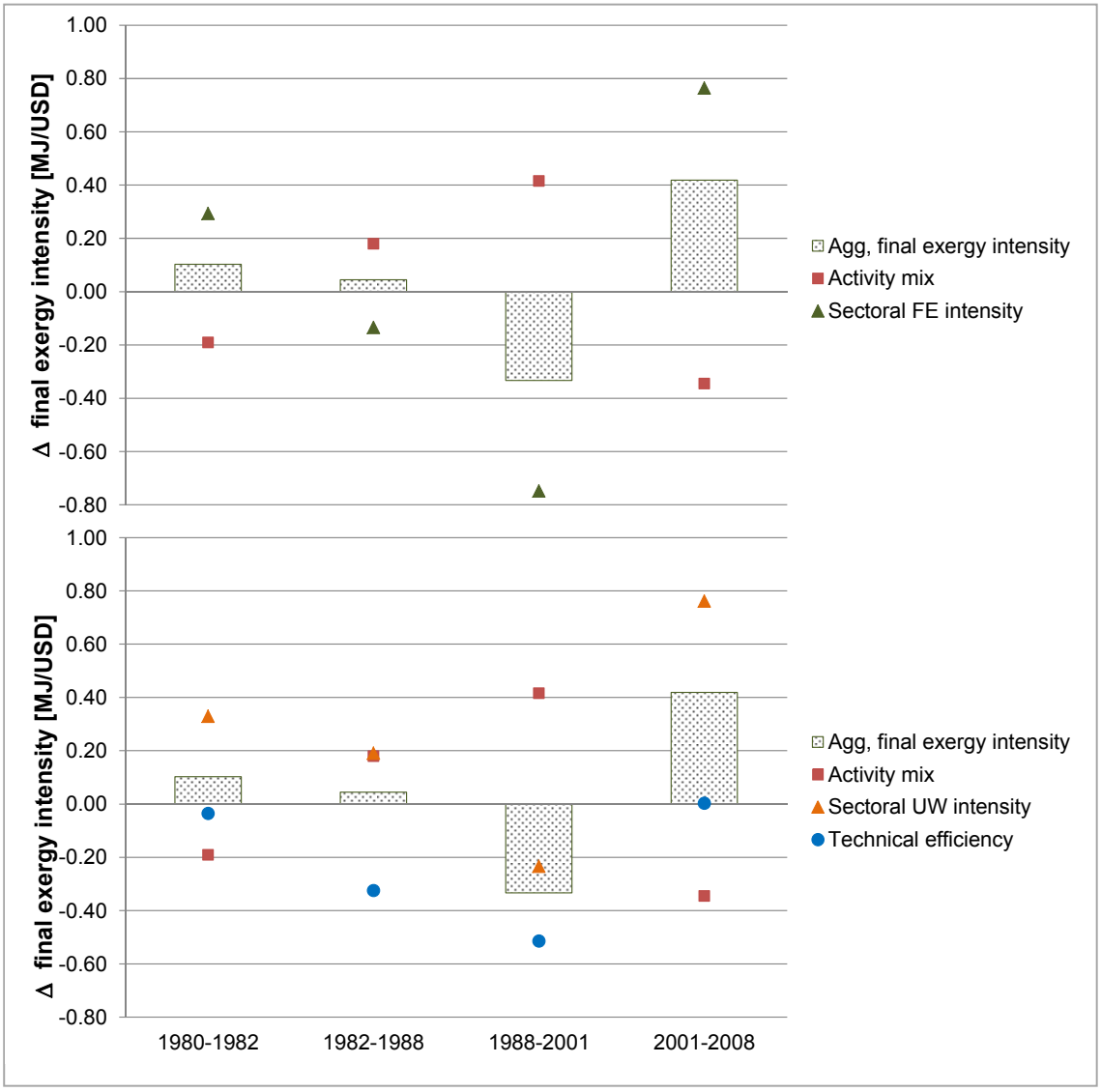


Figure 6-10 Evolution of IDA coefficients by the traditional (above) and UW-based (below) approaches: Mexican industry 1980-2009

On the other hand, the useful work-based approach shows that the changes in the technical efficiency (i.e. improvements in final-to-useful conversion processes and technology) actually contributed to reduce the aggregate final exergy intensity in the period 1980-2009. All other things held constant, technical efficiency would have significantly reduced T. Contrarily, changes in sectoral useful work intensity counteracted the positive effect of technical efficiency changes. This implies that the overall increase of energy intensity was caused by the development of useful work intensive, rather than less technically efficient, sectors.

Finally from the historical perspective, the useful-work approach can provide better insights on energy transitions. Between 1982 and 2001, as most reforms to open the economy were carried out, advanced technologies and energy intensive industries rushed into the country, which explains the large effect of technical efficiency changes to decrease T, especially during the interval 1988-2001. However after 2001, technical improvements reduced their pace and useful work intensive producing sectors increased their impact.

The contrast in the results between these approaches shows a limitation of the traditional IDA approach to evaluate energy efficiency trends. The view that sectoral energy intensity is an adequate indicator for energy efficiency in the traditional IDA approach is only approximately correct when the effects of DT_{UI} and DT_{ϵ} (interval 1988-2001) are in the same direction or when the $|DT_{UI}| < |DT_{\epsilon}|$ (interval 1982-1988), which are not always the case as it can be seen in Figure 6-10. Therefore these studies might have misread the effect of technical energy efficiency changes. Alternatively, the UW-based approach gives the direction and value of the effect of technical efficiency changes and therefore can help avoid misinterpretation of energy efficiency trends.

6.5 Conclusions

In this section, an approach for a better evaluation of energy efficiency trends (UW-based IDA) is described. The approach consists of including the useful level of energy use in the traditional IDA approach to energy intensity (Section 3.3.2.2). By doing so, the absolute values and the effect of technical energy efficiency and useful work intensity trends on aggregate energy performance can be evaluated.

Aggregate technical energy efficiency was accounted for Mexico 1971-2009. Technological progress and the transition to energy carriers with more quality, i.e. electricity, led to a steady improvement in the aggregate technical efficiency of the economy. This improvement was mainly influenced by the Industrial sector, which had the highest growth in technical efficiency compared to the energy, transportation and other sectors. Even though the transportation sector had a largest demand of final exergy, it experienced the lowest increase in sectoral technical efficiency. This was caused by small improvements in technical efficiency of gasoline and diesel engines (2% points) and by the small share of electricity use for transportation.

Furthermore, the upward trend of useful work intensity reflects that the economy became more dependent on useful work per unit of economic output over the studied period. However, the results also show that this increasing trend slowed down after 1990, which suggests that useful work intensity will eventually stop growing. On the other hand, final exergy intensity varied by ±10% from its 40-year average while useful work intensity increased. The differences of the evolution path of final exergy and useful work intensities show, on the one hand, that useful work intensity was more influenced by the structural transition from a generally protectionist to an export-led open economy and, on the other hand, that final exergy intensity was more influenced by economic fluctuations, e.g. recession.

Furthermore, the final exergy intensity of Mexican producing sectors between 1980 and 1982 was evaluated with the UW-based and the traditional IDA approaches. The results show that the traditional IDA approach could lead to misinterpretation of energy efficiency trends as it

does not distinguish between the effect of changes in the Technical Efficiency and changes in the intensity of useful work use. On the other hand, the UW-based IDA approach is able to determine the effect of the Technical Efficiency and to identify that the overall increase of energy intensity in the Mexican producing sectors was caused by the introduction of useful work intensive, rather than less technically efficient, industries. In addition, it was found that results of the proposed approach are better aligned with the historical structural transitions that the country underwent. Nevertheless, the availability of data is the principal drawback for the UW-based approach since there are few countries for which sectoral useful work data are available.

Finally, it can be concluded that the proposed approach is more suitable to evaluate the effectiveness of energy saving policies, most of which focus on technical energy efficiency improvements. It also emphasizes the need of additional policy measures that target reductions of useful work intensity. To do so, the components of useful work intensity should be included in the analysis (see Section 9.2).

7 The effect of energy and economic transitions on primary energy: Portugal 1995-2010

The Portuguese energy sector changed dramatically in the last two decades, with the adoption of natural gas and an increase in renewable power generation. During the same period, the Portuguese economy continued a transition into a service economy (that started in the 1980's) and joined the euro in 1999. The combination of these two phenomena led to a decline in primary energy intensity. The goal of this analysis is to identify the main factors driving the changes in primary energy use (PEU) in Portugal over the period 1995-2010 by performing a Structural Decomposition Analysis (SDA) with the PF model (Section 4.2). Within this setting, the relative contributions of the economic and energy transitions to the observed PEU change can be determined. The results show that the main drivers were the final demand of non-energy products (leading to an increase in PEU) and improvements in the direct energy intensity of non-energy sectors (leading to a decrease in PEU). Furthermore, the drastic structural changes that occurred both in the energy sector and in the rest of the economy also led to a decrease in PEU, although smaller than the improvements in direct energy intensity.

7.1 Introduction

The European Union (EU) is currently committed to increase the share of energy consumption produced from renewable resources to 20% by the year 2020 (Amorim et al., 2010; Brown, 2013; EU, 2009; Haas et al., 2011). In this respect, Portugal has achieved an outstanding progress, passing from a renewable share of 15% in 1995 to 24% in 2010 (DGEG, 2012). Because of this fact, Portugal has become a role model for many countries, including major economies such as China and USA (Heer and Langniß, 2007; Rosenthal, 2010).

The electricity sector in particular underwent an impressive transition. In 1995 most electricity was generated from fossil fuels (40% coal and 31% oil) and hydropower. However, by 2010, renewables reached 11 GW of installed capacity and 54% of total electricity generation while coal and oil accounted for only 18% of total generation (DGEG, 2014a, b; IEA, 2011a).

The introduction of natural gas imports from Algeria in 1997 was also fundamental for this energy transition. By 2010, natural gas accounted for 28% of total electricity generation (DGEG, 2014a, b; IEA, 2011a). In addition, natural gas for final consumption reached 16% of final energy use in the industrial sector and of 10% in the residential and service sectors

(DGEG, 2012). Even though natural gas use is still relatively low in comparison to other European countries (Amador, 2010), it has helped diversify the primary energy mix and reduce the growth rate of CO_2 emissions (Arto et al., 2009; Diakoulaki and Mandaraka, 2007; Robaina Alves and Moutinho, 2013).

Nevertheless, the energy performance of the country has been poor (Henriques, 2011). Total primary energy intensity did not experience a significant reduction during most of the period under study (DGEG, 2012). Technological improvements were limited: e.g., the evolution of energy use efficiency slowed down since around 1990 (Serrenho et al., 2012); and were offset by growing energy needs of private transportation and comfort in the service sector (Henriques, 2011; Serrenho et al., 2013). Moreover, high and volatile energy prices, mainly of crude oil and natural gas (EIA, 2014; EUROSTAT, 2014b; IEA, 2012b), represented a threat to growth prospects but also an incentive for renewable energy development (Amador, 2010).

During the same period, Portugal also experienced a significant economic transition: The country continued the structural shift from manufacturing into services, which started since the 1980's (BdP, 2009; EUROSTAT, 2014a; Henriques, 2011). The integration to the European Economic and Monetary Union, which bound the economy into a single EU currency, promoted further economic and structural changes such as a the avoidance of internal monetary policy, increases in wages and a larger focus in sectors with mainly undifferentiated products (Aguiar-Confraria et al., 2012; BdP, 2009; Leite, 2010). Finally, in the late 2000's the country suffered the financial crisis of 2007-2009 (Farto and Morais, 2011; French et al., 2009; Gros, 2012; Lourtie, 2012) and entered a macroeconomic adjustment process (Claessens et al., 2010; Costa, 2012; Rodrigues and Reis, 2012).

The fact that the outstanding development of the energy sector between 1995 and 2010 did not result in a better energy performance might be explained by the economic transition. However, there is currently little understanding of the relative contributions of the energy and economic transitions to overall energy performance.

The goal of the present chapter is to identify the main drivers of change in total Primary Energy Use (PEU) in Portugal during the period of 1995-2010 through Structural Decomposition Analysis (SDA).

The analysis carried out represents the first SDA of PEU in Portugal. Existing decomposition studies with the IDA approach that included Portugal in 1995-2007 (Alcántara and Duarte, 2004; Henriques, 2011; Mendiluce et al., 2010; Voigt et al., 2014) found that the structural effect (i.e. changes in the productions structure of the economy) led to an increase in the intensity of final energy use while the intensity effect (i.e. technological changes) led to a reduction. Nevertheless, these studies were not able to account for the contribution of the energy transitions.

7.2 Methods

The primary-to-final energy input-output model, developed in Section 4.2, is used because it allows accounting for changes in the structure of the energy sector and the rest of the economy, separately:

$$\boldsymbol{p} = \begin{cases} \boldsymbol{p}^S = \boldsymbol{L}^E \boldsymbol{C}^{E,S} \boldsymbol{T}^E \boldsymbol{L}^M \boldsymbol{C}^M \boldsymbol{s}^M \\ + \\ \boldsymbol{p}^R = \boldsymbol{L}^E \boldsymbol{C}^{E,R} \boldsymbol{r}^{E,R} \end{cases} \tag{7.1}$$

The scope of the present section is concerned with the accounting of the PEU associated with final demand for domestic products of Portugal. Hence, PEU associated with the energy consumed within Portugal to generate exports of non-energy products is taken into account. However, the PEU associated with exports of final energy carriers and the PEU that occurs abroad to generate Portuguese imports are not taken into account. Therefore, the primary energy use by non-producing non-energy sectors ($\boldsymbol{p}^R$) is limited to the accounting for household / residential primary energy use. In addition, the model of $\boldsymbol{p}^R$ is further extended as:

$$\boldsymbol{p}^R = \boldsymbol{L}^E \boldsymbol{c}^{E,R} b^H c^H s^H \tag{7.2}$$

where there are the following new terms:

- Vector $\boldsymbol{c}^E$ of length n_C is the *household energy demand composition* factor. c_i^E corresponds to the fraction of total household energy demand which is provided by energy carrier i. This vector is an analogous of matrix $\boldsymbol{C}^{E,R}$ in Equation (4.10).
- Scalar b^R is the *aggregate energy price* faced by households, i.e., total household energy demand (in energy units) per energy expenditure (in monetary units).
- Scalar c^H is the (dimensionless) *share of energy expenditure in total household expenditure*.
- Scalar s^H is the *household expenditure* in monetary terms.

The SDA explains the variation in PEU in the time frame $t_1 - t_2$ as the sum of n distinct decomposition coefficients (Section 3.3.1):

$$\Delta\boldsymbol{p} = \begin{cases} \Delta\boldsymbol{p}^S = \delta\boldsymbol{L}^{E,S} + \delta\boldsymbol{C}^{E,S} + \delta\boldsymbol{T}^E + \delta\boldsymbol{L}^M + \delta\boldsymbol{C}^M + \delta\boldsymbol{s}^M \\ + \\ \Delta\boldsymbol{p}^R = \delta\boldsymbol{L}^{E,R} + \delta\boldsymbol{c}^{E,R} + \delta b^R + \delta c^H + \delta s^H \end{cases} \tag{7.3}$$

The total effects of the structure of the energy sector $\delta\boldsymbol{L}^E$ and the composition of direct energy demand $\delta\boldsymbol{C}^E$ have a component related to production ($\delta\boldsymbol{L}^{E,S}$ & $\delta\boldsymbol{C}^{E,S}$) and another to residential energy demand ($\delta\boldsymbol{L}^{E,R}$ & $\delta\boldsymbol{c}^{E,R}$). In the case of the decomposition coefficients pairs $\delta\boldsymbol{C}^M$ & δc^H and $\delta\boldsymbol{s}^M$ & δs^H, there is a certain degree of correspondence though not perfect hence they are not grouped together.

Finally, to estimate the value of these coefficients, the D&L technique (Section 3.3.3.1) is selected because of its characteristics of complete decomposition (i.e. no residual term) and robustness to zero and negative values.

7.3 Data

The source data and the data processing required to perform the SDA are described in this section.

7.3.1 Economic data

The main data source for the economic factors were the EUROSTAT Portuguese Make-Use tables for the period 1995-2010 (EUROSTAT, 2014a).

EUROSTAT tables for the period 1995-2006 follow the CPA2002/NACE1.1 classification (respectively for m products and n industries) with $n = m = 59$ elements, whereas the tables for the period 2006-2010 follow the CPA2008/NACE2 classification, with $m = n = 65$ elements. Therefore, a harmonized time-series (Wood, 2011) was constructed in a common classification with $m = n = 49$ elements based on EUROSTAT (2008a) and EUROSTAT (2009). The equivalence between the different classifications is reported in Appendix D.1.

The harmonization of the two classification systems (NACE1 from 1995 to 2005 and NACE2.2 from 2006 to 2010) was performed mostly through aggregations. The only instance of disaggregation was sector C33 (Repair and installation of machinery and equipment) of the NACE2 classification, which does not exist as an independent sector in classification NACE1.1, but is instead reported as a component of nine different types of machinery. Hence, in the 2006-2010 data NACE2 sector 33 was disaggregated among different machinery types in proportion to that machinery sector's share of total output.

Furthermore, to perform the SDA it was necessary to convert the data from current to constant prices (Dietzenbacher and Temurshoev, 2012; Miller and Blair, 2009). Because the EUROSTAT source data are reported both in current and in previous year prices, a time series in constant prices of 2002 was obtained by deflating/inflating the entire dataset with the appropriate chain indices (Dietzenbacher and Hoen, 1998; Jackson and Murray, 2004). Note: Some entries reported a zero value in the tables in previous year prices while the value in the tables in current prices was different from zero. When such a situation occurred, the deflator used was the average deflator (across industries) for that commodity class as in the double deflation method (Miller and Blair, 2009; UN, 1993).

Finally, in accordance with the System of National Accounts (UN, 1999, 2009), the EUROSTAT tables report make data in basic prices and use data in purchaser prices (with additional information on total imports, trade and transport margins and taxes less subsidies on products). Because of this, the use data was converted from total flows in purchaser prices to domestic flows in basic prices and the industry technology assumption was used to obtain an industry-by-product total requirements matrix (Section 3.2.2.2).

7.3.2 Energy data

The energy sector model is based on Portuguese energy balances (DGEG, 2012). These balances were arranged to conform to a Make-Use framework, as in Figure 4-1. The energy Make-Use tables in physical units have a classification of $n_F = 26$ sectors of final energy demand, $n_T = 34$ energy technologies, and $n_E = 38$ energy carriers, of which $n_P = 14$ are

primary energy carriers, are final energy carriers and non-energy carriers (Appendix D.2).

The set of final energy demand sectors in the energy model differs from the set of sectors in the economic model since the classifications belong to different sources. In the description of economic data there are sectors whereas in the demand for final energy there are only (not including residential energy demand and energy exports). Hence, the final energy intensity matrix, , has dimensions and performs the necessary aggregations and disaggregations to ensure that Equation (4.7) is valid for every pair ( ) .

Finally, the energy technology matrix ( ) was obtained as a product-by-product matrix using the industry technology assumption (Section 3.2.2.2). This matrix accounts for the primary energy equivalent of energy imports and renewables, see Section 4.3.2-Issue 2.

7.4 Results

This section presents the results of the SDA of PEU in Portugal between 1995 and 2010, as well as an overview of total PEU and energy performance.

7.4.1 Total primary energy use

Portugal increased the use of primary energy from 847 PJ in 1995 to 993 PJ in 2010 (an increase of 17%). This growth in PEU was marked by an initial upward trend, with a peak of 1179 PJ in 2005, followed by a clear decline (Figure 7-1).

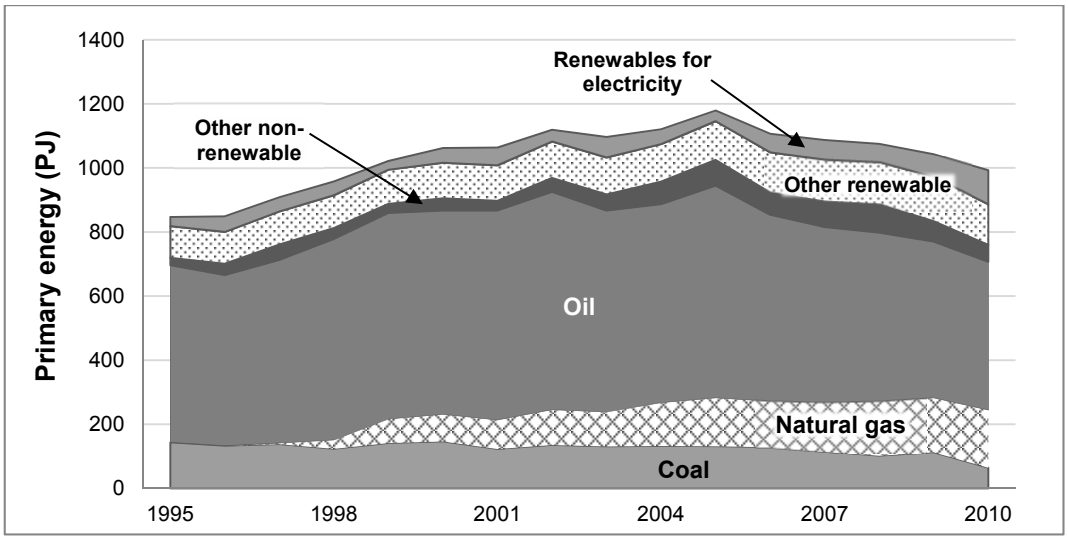


Figure 7-1 Total primary energy use: Portugal 1995-2010.
Note: Data from DGEG (2012)

The Portuguese primary energy mix started changing with the introduction of natural gas in 1997. This energy carrier represented a cleaner substitute to crude oil for power generation as well as to some oil products (e.g. fueloil and LPG) for final use. Furthermore, there was a significant increase in renewable energy production. Particularly, from 2005 to 2010, renewable energy production increased by a half (153 to 232 PJ), reaching a 23% share of total primary energy use. These occurrences, together with the decrease in overall energy demand and the decline in coal use, resulted in a different primary energy mix.

As shown in Figure 7-2, primary energy intensity (PEU per unit of GDP) exhibited no significant variation from 1995 to 2005 with a value of 8.18 MJ/Euro $\pm$ 5%. However, in the lustrum 2005-2010 this value fell by 20.6%.

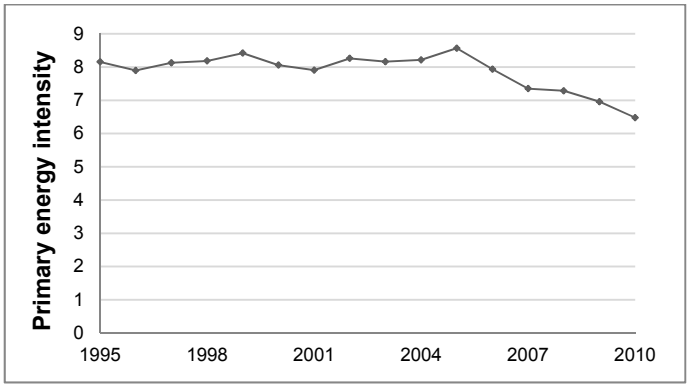


Figure 7-2 Overall primary energy intensity: Portugal 1995-2010.
Units MJ/Euro

The drastic changes that occurred after 2005 can be related to variations in the prices of crude oil and natural gas. World crude oil prices witnessed a sharp increase after 2001 (they were over 4 times higher in 2010 than in 2000) (EIA, 2014). Before 2005 Portugal coped with this surge by replacing crude oil with natural gas for power generation. However, natural gas prices almost doubled between 2004 and 2010 with a large price shock in 2008 (EUROSTAT, 2014b; IEA, 2012b). This price surge led in turn to a major development of renewables in order to reduce the dependency on fossil energy carriers (Amador, 2010).

7.4.2 Production structure and energy use

In the period 1995-2010, the Portuguese economy continued a transition that had begun in the 1980's (Henriques, 2011; Serrenho et al., 2012), with a shift in the composition of output, value added and energy use into the service sector.

To illustrate the structural changes that the country underwent, Figure 7-3 depicts the distribution of Portuguese gross value added by industry. Following Weber (2009), the figure shows manufacturing industries divided into energy intensive (pulp and paper, basic chemical and nonmetallic mineral industries) and non-energy intensive industries (all the rest). In addition, the primary industry consists of agriculture, fishing, forestry and related activities.

In 1995 the service industry already had the largest share of value added (63%), which continued to grow until reaching 75% in 2010. The trade & transport and construction industries more than doubled their value added although their share remained almost constant (around 2.8% and 7.5%, respectively). Meanwhile, the non-energy intensive industries, energy intensive industries and primary activities all saw their share in value added reduced, being the most significant reduction in non-energy intensive industries (a fall from a share of 16.2% to 11.1%).

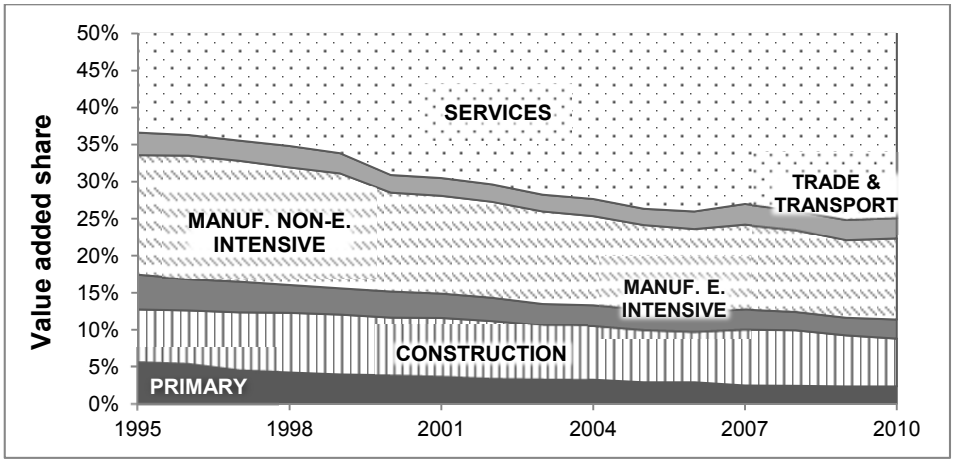


Figure 7-3 Value added share by industry: Portugal 1995-2010.
Note: Data from EUROSTAT (2014a). Notice that the y-axis shows up to 50% of value added share.

PEU associated with production increased from 519 to 570 PJ between 1995 and 2010, although it peaked at 716 PJ in 2005 (a similar pattern to total primary energy use, see Figure 7-1). Additionally, between 2005 and 2010, the renewable energy share of total energy use in production (e.g. 27% in 2010) was higher than for the whole economy (23% in 2010), i.e. including residential energy demand.

Table 7-1 presents the direct energy intensity (direct energy use by output) of different industries. This metric gives insights on the relative energy performance, which decreases when the increase in an industry's output outpaces the growth in its energy use.

Table 7-1 Industrial direct energy intensity in selected years: Portugal 1995-2010

Sector	1995	1998	2001	2004	2007	2010
Primary	2.72	1.83	1.94	1.55	1.65	1.56
Construction	1.57	1.54	1.45	1.34	0.95	0.97
Energy int. manufacturing	8.82	8.51	7.05	6.78	6.11	5.48
Non-en. int. manufacturing	0.90	0.83	0.72	0.72	0.61	0.61
Trade & Transport	11.17	12.91	11.60	11.41	9.31	6.87
Services	0.52	0.66	0.73	0.84	0.67	0.55

Units MJ/Euro

The service industry performed poorly with an increase in direct energy intensity of 7%. This pattern is explained by an increase in comfort-related energy use (e.g., heating and cooling) as pointed out by Henriques (2011). However, in 2004, the energy intensity of services peaked and started to decline as oil and natural gas prices soared (EIA, 2014; IEA, 2012b). on the other hand, the rest of the industries, i.e. non-energy intensive industries, trade & transport, construction, energy intensive industries and primary industry, had significant reductions in their energy intensities (of -32%, -38%, -38%, -37% and -42%, respectively).

Since the service industry accounts for 63-75% share of value and about a quarter (20-25%) of production-related PEU, its poor energy performance diminished the effect of improvements that occurred in other industries.

7.4.3 The total change in primary energy use

Table 7-2 and Table 7-3 present the results of the SDA of PEU change associated with the final demand for non-energy products and the household consumption of energy carriers in the period 1995-2010. In the case of production-related PEU, the SDA coefficients of each category of final demand are presented separately.

Table 7-2 SDA coefficients of production-related PEU: Portugal 1995-2010

Final demand category	$\Delta \boldsymbol{p}^{S}$	$\delta \boldsymbol{L}^{E,S}$	$\delta \boldsymbol{C}^{E,S}$	$\delta \boldsymbol{T}^{E}$	$\delta \boldsymbol{L}^{M}$	$\delta \boldsymbol{C}^{M}$	$\delta \boldsymbol{s}^{M}$
Total	51.1	-79.6	29.0	-172.4	-67.7	1.9	339.9
Households	11.9	-31.7	12.2	-44.7	-17.7	-31.5	125.2
Non-profits	1.5	-1.1	0.5	-1.4	0.0	-0.6	4.1
Government	10.6	-9.4	4.1	-10.2	3.6	4.0	18.4
Capital formation	-29.8	-13.2	5.3	-37.3	-9.8	-13.2	38.4
Exports	56.9	-24.1	6.8	-78.8	-43.8	43.1	153.8

Units PJ

Table 7-3 SDA coefficients of PEU associated with household energy demand: Portugal 1995-2010

	$\Delta \boldsymbol{p}^{R}$	$\delta \boldsymbol{L}^{E,R}$	$\delta \boldsymbol{c}^{E,R}$	δb^{R}	δc^{H}	δs^{H}
Total	94.5	-37.5	20.8	-61.8	-26.8	199.7

Units PJ

There was a total increase of 145.5 PJ in PEU in the period under study ($\Delta \boldsymbol{p}^{S} + \Delta \boldsymbol{p}^{R}$). Household demand for energy carriers and exports of non-energy products had the largest impact on PEU (94.5 and 56.9 PJ, respectively). These were mainly driven by the increase of household expenditure per capita (δs^{H}) and a larger demand for exports ($\delta \boldsymbol{s}^{M}$), respectively. Conversely, capital formation contributed to decrease PEU since it was more and more concentrated in industries with improvements in energy intensity ($\delta \boldsymbol{T}^{E}$).

Changes in the final demand ($\delta \boldsymbol{s}^{M}$ and δs^{H}) had the largest effect on overall PEU growth. However this effect was mainly offset, but not entirely, by improvements in direct energy intensity ($\delta \boldsymbol{T}^{E}$), structural changes in the energy sector and the rest of the economy ($\delta \boldsymbol{L}^{E}$ & $\delta \boldsymbol{L}^{M}$), and increases of aggregate energy prices to households (δb^{R}).

The effect of decreasing PEU of $\boldsymbol{T}^{E}$ was caused by: 1) improvements in technical efficiency of final energy use (though limited according to (Serrenho et al., 2012); 2) price increases of non-energy products due to high prices of energy inputs or other market interactions; 3) and reductions in useful work intensity (see Section 6.4.4).

There was a large effect of decreasing PEU brought about by drastic changes in the energy sector ($\delta \boldsymbol{L}^{E}$): a larger share of renewable power generation and improvements in primary-to-final conversion efficiencies. On the other hand, the structural changes of the rest of the economy ($\delta \boldsymbol{L}^{M}$), i.e. the transition into a service economy, also had the effect of decreasing PEU since the service sector has a much lower energy intensity (see Table 7-1). However, the effect of decreasing PEU of improvements of direct energy intensity was the most significant.

Increases in household energy prices (δb^{R}) also contributed to significantly decrease PEU associated with residential energy demand. Moreover, even though aggregate energy prices rose, the share of energy expenditure in total household expenditure decreased, which implies

that households not only demanded less energy carriers but also increased the consumption of non-energy products with respect to energy carriers (i.e. $\delta c^H < 0$).

Furthermore, shifts in the composition of direct demand for energy carriers ($\delta \boldsymbol{C}^{E,S}$ and $\delta \boldsymbol{c}^{E,R}$) and non-energy products ($\delta \boldsymbol{C}^{M}$) contributed to increase PEU. The value of $\delta \boldsymbol{C}^{E}$ suggests that the share of energy carriers with large related PEU in total energy demand increased, e.g. larger use of thermoelectricity. On the other hand, the overall value of $\delta \boldsymbol{C}^{M}$ is negligible although the demand composition of non-energy products by households and exports had counteracting effects: non-energy exports consisted of increasing shares of products with large related PEU (see also Amador (2012)) while the opposite holds true for household demand composition of non-energy products.

7.4.4 Evolution of primary energy use

For a historical analysis of the effect of energy and economic transitions on PEU, Figure 7-4 depicts the SDA results of the evolution of the PEU associated with the final consumption of non-energy products, i.e., not including household demand for energy carriers.

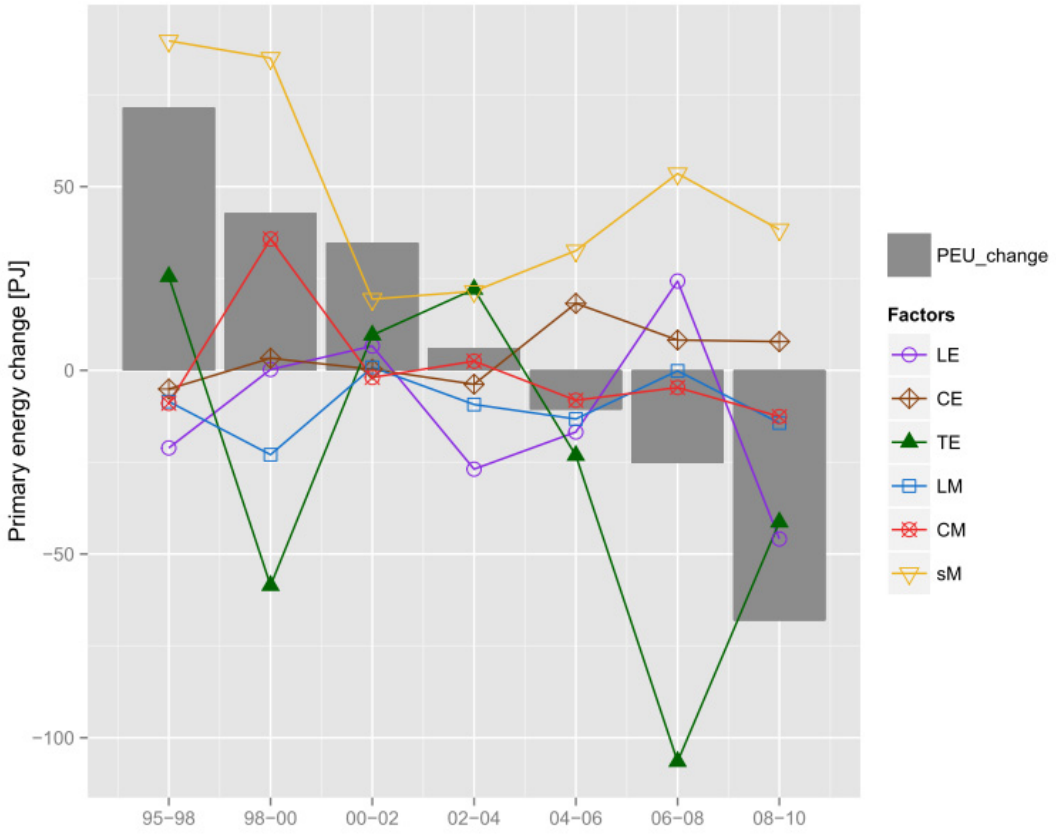


Figure 7-4 Primary-to-final SDA of production-related PEU: Portugal 1995-2010
Note: LE – Structure and efficiency of the energy sector, CE – Composition of direct energy demand, TE – Direct energy intensity, LM – Structure of the economy, CM – composition of non-energy final demand and sM – final demand of non-energy products, see Section 4.3.1.

The intervals 1995-1998 and 1998-2000 were characterized by a sharp rise in PEU, mainly driven by final demand of non-energy products $\delta \boldsymbol{s}^{M}$). This was caused by a good economic performance of the country that boosted private consumption (due to real per capita income improvements) and eventually led to the integration to the EU single currency scheme in 1999

(Aguiar-Confraria et al., 2012; BdP, 2009; Mata and Valério, 2003). Although between 1995 and 1998 other factors had only relatively minor effects, in the interval 1998-2000: 1) the composition of final demand of non-energy products ($\delta \boldsymbol{C}^{M}$) contributed to increase PEU due to a shift of demand towards non-energy products with larger related PEU (e.g. land transport); 2) structural changes ($\delta \boldsymbol{L}^{M}$) had the effect of decreasing PEU, which reflects a relatively large rise in the value added of the services industry (Figure 7-3); and 3) there was an improvement in direct energy intensity ($\delta \boldsymbol{T}^{E}$) caused by a productivity increase and the use of more efficient technology (mostly explained by the introduction of natural gas for final use).

After Portugal joined the euro, the economic performance weakened and suffered a contraction in 2003 (Aguiar-Confraria et al., 2012; BdP, 2009). Between 2000 and 2004, this poor economic performance derived in a smaller effect of $\boldsymbol{s}^{M}$ and a change in direction of the effect of the direct energy intensity ($\delta \boldsymbol{T}^{E} > 0$). The increase in $\boldsymbol{T}^{E}$ (see Table 7-1) reflects a loss in productivity and non-price competitiveness experienced during this interval (BdP, 2009; Farto and Morais, 2011). Despite the latter fact PEU growth slowed down in 2002-2004 due to the effect of changes in the energy sector($\delta \boldsymbol{L}^{E,S}$), i.e., increases of renewable power generation and improvements in conversion efficiencies for thermoelectricity generation due to increasing imports of natural gas.

In the interval 2004-2006, PEU decreased slightly. Changes in final demand ($\delta \boldsymbol{s}^{M}$) had the effect of increasing PEU, as did the composition of demand for energy products ($\delta \boldsymbol{C}^{E,S}$). However, these effects of increasing PEU were offset by improvements in direct energy intensity, advances of the energy sector and structural changes. The effect of $\boldsymbol{T}^{E}$ can be explained by the rise of oil and natural gas prices (EIA, 2014; EUROSTAT, 2014b) which forced the rest of the economy to increase prices (thus leading to a reduction in direct energy intensity) and to pursue improvements in productivity and energy efficiency (though relatively small, see Table 7-1 and (Serrenho et al., 2012).

The interval 2006-2008 was characterized by a reduction of PEU. The combination of the 2007 financial crisis, high and rising energy prices (with a big oil and natural gas price shocks in 2008) and the launch of regulations on industrial energy efficiency (such as the SGCIE, see MEI (2008)) forced the rest of the economy to increase prices even further and to improve productivity and energy efficiency ($\delta \boldsymbol{T}^{E} \ll 0$). Shifts in the composition of final demand for energy carriers ($\delta \boldsymbol{C}^{E,S}$) led to an increase in PEU through shifts in final demand towards final energy carriers with larger associated PEU. Furthermore, $\delta \boldsymbol{s}^{M}$ had a large effect of increasing PEU, which implies an increase in final demand despite the financial crisis. This puzzling result might be explained by rising private consumption due to a sense of partial recovery from the economic recession of 2003, and increased government spending, which reinforced the image of economic recovery (BdP, 2009; Leite, 2010). Moreover, changes in the energy sector had the effect of increasing PEU in this interval, which was caused by the deceleration of the rate of substitution of oil by natural gas for power generation, stagnant primary-to-final conversion efficiencies and a reduction of renewable electricity generation (2008 was a particularly bad year for hydroelectric production, (DGEG, 2014b)).

Finally, in the interval 2008-2010, the country was severely hit by the international crisis and experienced a contraction in 2009, which led to a significant reduction of PEU. Changes in final

demand of non-energy products ($\delta \boldsymbol{s}^M$) contributed to increase PEU, though to a lesser extent than in the previous interval due to the reduction of private consumption and government austerity measures (Claessens et al., 2010; Costa, 2012). Also the demand of energy products with larger associated PEU increased ($\delta \boldsymbol{C}^{E,S} > 0$). Conversely, changes in the economic structure and in the demand composition of non-energy products ($\delta \boldsymbol{C}^M$ and $\delta \boldsymbol{L}^M$) contributed to a slightly decrease in PEU. $\boldsymbol{T}^E$ had a significant effect of decreasing PEU though not as large as in the previous interval. In addition, transitions in the energy sector $\delta \boldsymbol{L}^{E,S}$) had a large effect of decreasing PEU since renewable power generation almost doubled (DGEG, 2014b).

7.4.5 Additional results

7.4.5.1 The accounting of primary energy equivalent of renewables

According to Section 4.3.2, the calculation of $\delta \boldsymbol{L}^E$ depends on the approach taken to account for primary renewable energy. The present analysis is based on the PCM-I (Section 2.1.1), which assumes a 100% efficiency of conversion primary renewable energy to final electricity. Therefore, using this method any shift toward renewable energy represents an improvement of overall conversion efficiency ($\delta \boldsymbol{L}^E < 0$).

Table 7-4 shows the results of SDA of production-related PEU in Portugal 1995-2010, using the PCM-I and, alternatively, the PSM (IEA, 2014) described in Section 2.1.1.

SDA coefficients of PEU for final demand $\boldsymbol{s}^M$: Portugal 1995-2010. Comparison between methods to account for primary equivalent energy of renewables

Table 7-4 Comparison between methods to account for primary energy equivalent of renewables

Method	$\Delta \boldsymbol{p}^S$	$\delta \boldsymbol{L}^{E,S}$	$\delta \boldsymbol{C}^{E,S}$	$\delta \boldsymbol{T}^E$	$\delta \boldsymbol{L}^M$	$\delta \boldsymbol{C}^M$	$\delta \boldsymbol{s}^M$
PCM-I	51.1	-79.6	29.0	-172.4	-67.7	1.9	339.9
PSM	146.0	-11.9	41.2	-183.3	-72.8	1.5	371.2

Units PJ

The results show that the impact of using the partial substitution method does not considerably affect the coefficient of most factors except $\delta \boldsymbol{L}^{E,S}$. This happens because this method amplifies the amount of primary renewable energy use and magnifies the contribution of the slow progress of conventional thermoelectric primary-to-final conversion efficiencies. Therefore, the PCM-I is more appropriate to evaluate the effects of energy sector transitions on PEU with SDA since it emphasizes a future ideal structure of the energy sector, i.e. an all renewable energy sector with 100% conversion efficiency.

7.4.5.2 Non-energy transactions of the energy sector

As discussed in Section 4.3.1, the factor $\boldsymbol{L}^M$ also accounts for the non-energy transactions from non-energy industries to the energy sector. Moreover, the suitability of the primary-to-final energy input-output model for SDA studies depends on the validity of the assumption of independence of the energy sector from the rest of the economy, i.e. transactions from non-energy industries to energy industries are much smaller than transactions between energy industries (Section 4.3.1 and Section 4.3.2-Issue 1).

To confirm the suitability of the model for this particular SDA, complete total requirement matrices (including energy sector) from 1995 to 2010 were built from the Eurostat Make-Use table (EUROSTAT, 2014a) to compare the non-energy and energy transactions of the energy sector. It was found that energy transactions in the Portuguese energy sector represented more than 80% of total inputs per unit of final demand. Therefore, non-energy transactions are four times smaller than energy transactions of the energy sector.

Furthermore, the effects of the non-energy transactions of the energy sector ($\delta\boldsymbol{\pi}^M$) can be compared to the effect of energy sector structure ($\delta\boldsymbol{L}^E$) and the effect of transactions between non-energy industries ($\delta\boldsymbol{\psi}^M$). Note: $\delta\boldsymbol{\psi}^M$ and $\delta\boldsymbol{\pi}^M$ are extracted from $\delta\boldsymbol{L}^M$ through the sub-matrices $\boldsymbol{\pi}^M$ and $\boldsymbol{\psi}^M$ (in monetary units) (see Section 3.2.3.3).

Table 7-5 Effect of changes in non-energy transactions of the energy sector

	$\delta\boldsymbol{L}^M$		$\delta\boldsymbol{L}^E$
	$\delta\boldsymbol{\pi}^M$	$\delta\boldsymbol{\psi}^M$	
Total effect	-0.32	-67.38	-117.1

Units PJ

Table 7-5 shows that $\delta\boldsymbol{\pi}^M$ is much smaller than the effect of the energy sector (0.27% of $\delta\boldsymbol{L}^E$), which confirms that, for the specific case of Portugal 1995-2010, changes in energy transactions of the energy sector have a much larger impact than changes in non-energy transactions. Additionally, the $\delta\boldsymbol{\pi}^M$ is also insignificant with respect to effect of interindustry transactions of non-energy industries (0.47% of $\delta\boldsymbol{\psi}^M$) and hence changes in non-energy transactions of the energy sector do not significantly affect the estimates of $\delta\boldsymbol{L}^E$ and $\delta\boldsymbol{L}^M$.

7.5 Conclusions

This chapter presents a structural decomposition analysis (SDA) of primary energy use (PEU) in Portugal between 1995 and 2010 in order to identify the main driving forces of the trend in PEU. In particular, the focus was to understand the relative contribution of the significant energy and economic transitions that the country underwent during this period. For this purpose the primary-to-final energy input-output model in Section 4.2 was selected.

In the period under study there was an overall increase of 17% in PEU (relative to 1995), with an increase of 35% from 1995 to 2003 and a decrease of 18% from 2003 to 2010.

The SDA showed that the major driving factor leading to an increase in PEU was final demand. This factor was especially important before the year 2000, a period during which the country enjoyed thriving economic growth. After that year (and the adoption of the common currency) the country witnessed weak economic growth and final demand had a lesser impact on PEU.

The main driving force leading to a reduction in PEU were improvements in direct energy intensity (final energy use per output of non-energy sectors of the rest of the economy). These improvements were motivated mostly by the international crisis of 2007-2009 and high prices of oil and natural gas, to which the rest of the economy responded with productivity gains, technological improvements and increases in the price of outputs (e.g. land transport).

Besides examining the impact of the production of non-energy products on PEU, the impact of household demand for energy carriers was also studied. Overall, household demand for energy carriers led to an increase in PEU, being total household expenditure the dominant factor (leading to an increase in PEU). This effect was partially offset by other factors, with increases in the price of energy carriers faced by households being the most important one.

The main goal of the present study was the assessment of the relative contribution of energy and economic transitions to PEU. It was found that both transitions led to a decrease in PEU, but they were overall less important in reducing PEU than the improvements in direct energy intensity.

The economic transition toward a service economy had the effect of reducing PEU in the whole period under study, due to the relative expansion of industries with lower-than-average energy requirements per unit of output.

The effect of the energy transition had a more oscillatory nature. Technology change in the energy sector had the overall effect of reducing PEU in the period under study, which is explained by the expansion of renewables and the adoption of natural gas. However, in 2000-2002 and 2006-2008 the effect of technology change in the energy sector had the effect of increasing PEU. These were years of lower-than-average rainfall in which the full potential of hydropower installed capacity could not be used.

It is also worth noting that technological change in the energy sector exhibited an overall larger contribution to PEU, in absolute terms, than technological change in the rest of the economy. It can be inferred that the energy transition had a higher impact in primary energy use than did the economic transition.

8 Three-level energy decoupling: Portugal 1995-2010

This chapter presents the analysis of energy decoupling in Portugal 1995-2010, which complements and extends the results and conclusions of Chapter 7. The analysis was carried out with the PFU model (Section 5.1) that allows accounting for the final-to-useful conversion stage in the economy. Portugal experienced a relative decoupling driven by three main decoupling forces: the energy sector transition, economic structural changes and improvements of the useful work intensity. Moreover, these forces also caused an absolute reduction in the use of crude oil and coal hence reducing energy-related environmental impact. The results indicates that the primary-to-final conversion and useful-to-service transfer of energy flows significantly contributed to energy decoupling while the final-to-useful energy conversion had a counteracting effect. The latter fact suggests that policies targeted to increase technical efficiency in industries were ineffective with respect to energy decoupling. Finally, it is concluded that the analysis of energy decoupling is improved by the inclusion of three levels of energy use, i.e. primary, final and useful.

8.1 Introduction

Primary energy intensity of Portugal decreased by 20% while the change in primary energy use (PEU) was positive in 1995-2010 (DGEG, 2012). This fact shows that the Portuguese economy experienced relative energy decoupling (Chapter 1) with a de-carbonization of primary energy supply, caused by the increase in the renewable energy generation.

The SDA analysis in Chapter 7 identified the relative contributions to PEU of the substantial economic and energy transitions that the country underwent. It was found that both transitions had the effect of decreasing PEU. However, the effects of reducing PEU of these transitions were relatively smaller than the effect of the direct energy intensity factor, which as a result was the main force to decrease PEU. On the other hand, increases of the energy and non-energy final demand had the effect of increasing PEU. These results give insight into forces of decoupling though they are unable to distinguish between relative or absolute decoupling.

Therefore, the objective of this chapter is to further evaluate the energy decoupling forces in PEU in Portugal 1995-2010. To do so, the decoupling index, proposed by UNEP (2011) is used. Additionally, this evaluation also builds on the results and conclusions of the analysis in Chapter 7 and extends the scope of the previous analysis to include the useful level of energy

use. Finally, the SDA approach is compared to the IDA approach so to determine the most suitable approach for energy decoupling analysis.

8.2 Methods

This section describes the selected decomposition models and the decoupling index (UNEP, 2011), which are used for the evaluation of coupling and decoupling forces.

8.2.1 SDA model

The primary-to-final-to useful energy input-output model of producing sectors, developed in Section 5.1, is used.

$$\boldsymbol{p} = \begin{cases} \boldsymbol{p}^S = \boldsymbol{L}^E \boldsymbol{L}^U \boldsymbol{C}^{U,S} \boldsymbol{T}^U \boldsymbol{L}^M \boldsymbol{C}^M \boldsymbol{s}^M \\ + \\ \boldsymbol{p}^R = \boldsymbol{L}^E \boldsymbol{L}^U \boldsymbol{C}^{U,R} \boldsymbol{r}^{U,R} \end{cases} \tag{8.1}$$

The scope of the present study is concerned with the accounting of the PEU associated with associated with final demand for domestic products of Portugal, as in Section 7.3. Nevertheless, the extended model of residential energy use in Section 7.3 is not used due to the issue of using an aggregate useful work price (analogous to the aggregate energy price b^R) which cannot be assumed as being directly faced by residential consumers (in contrast to b^R).

The SDA explains the variation in PEU in the time frame $t_1 - t_2$ as the sum of n distinct decomposition coefficients:

$$\Delta\boldsymbol{p} = \begin{cases} \Delta\boldsymbol{p}^S = \delta\boldsymbol{L}^{E,S} + \delta\boldsymbol{L}^{U,S} + \delta\boldsymbol{C}^{U,S} + \delta\boldsymbol{T}^U + \delta\boldsymbol{L}^M + \delta\boldsymbol{C}^M + \delta\boldsymbol{s}^M \\ + \\ \Delta\boldsymbol{p}^R = \delta\boldsymbol{L}^{E,R} + \delta\boldsymbol{L}^{U,R} + \delta\boldsymbol{C}^{U,R} + \delta\boldsymbol{r}^{U,R} \end{cases} \tag{8.2}$$

Finally, the D&L technique (Section 3.3.3.1) is used to estimate the value of these coefficients. The superscripts S and R have been added to the $\delta\boldsymbol{L}^E$ and $\delta\boldsymbol{L}^U$ to distinguish the effect of these factors on production-related and residential PEU, respectively.

8.2.2 IDA model

The PU model for producing sectors, developed in Section 5.2.2, is extended to account for sub-sectorial disaggregation.

$$P^S = \sum_{k=1}^{m_{kj}} P_k = \sum_{k=1}^{m_{kj}} \bar{\nu}_k{}^{-1} (\overline{\epsilon\phi})_k{}^{-1} \frac{U_{kj}}{Q_{kj}} \frac{Q_{kj}}{f_{kj}} \frac{f_{kj}}{f_j} f_j = \sum_{k=1}^{m_{kj}} \nu_k{}^{-1} \phi\epsilon_k{}^{-1} I_{kj} L_{kj} F_{kj} f_j \tag{8.3}$$

where ν_k^{-1}, $\phi\epsilon_k^{-1}$, I_{kj}, L_{kj} and F_{kj} are the primary-to-final conversion efficiency, technical efficiency, sectoral useful work intensity, the production technology and final demand mix factors of sub-sector k of sector j, respectively. In addition, f_j is the final demand of sector j.

Analogously, the change of PEU can be decomposed in the following decomposition coefficients:

$$\Delta P^S = DP_\nu^S + DP_\epsilon^S + DP_I^S + DP_L^S + DP_F^S + DP_f^S \tag{8.4}$$

which are determined with the LMDI technique (Section 3.3.2.1).

8.2.3 Decoupling index

The decoupling index was proposed by (UNEP, 2011) as an indicator of energy decoupling. It is defined between the time t_1 and t_2, as the ratio of the change in the rate of consumption of primary energy (P) and the change in the rate of economic growth (measured by GDP).

$$d = \frac{\Delta P / P(t_1)}{\Delta GDP / GDP(t_1)} \tag{8.5}$$

This indicator is dimensionless and can have positive and negative values. UNEP (2011) gives the following interpretation of this index.

- $d > 1$, there is no decoupling (coupling), i.e. energy grows at a higher rate than the economy
- $d = 1$, a special case of coupling, i.e. energy use and the economy grow at the same rate
- $0 < d < 1$, there is relative decoupling, i.e. energy grows at a lower rate than the economy
- $d = 0$, a special case of relative decoupling when energy use remains constant while the economy grows
- $d < 0$, there is absolute energy decoupling, i.e. energy uses decreases while the economy grows

It is worth mentioning that the interpretation of this index changes when the economy contracts ($\Delta GDP < 0$), see Wang (2011). However, this issue is not relevant for the present analysis.

8.3 Data

The source data (additional to those in Section 7.3) and the data processing required to perform the SDA are described in this following paragraphs.

Useful work data were estimated with the final energy information of the Portuguese energy balances (DGEG, 2012) and the assumptions to account for useful work in Portugal by Serrenho et al. (2012) and Serrenho et al. (2013). Useful work tables in physical units in the form of Figure 5-1 have a classification of $n_F = 25$ sectors of useful work demand, $n_E = 38$ energy carriers (as in Section 7.3), $n_W = 8$ useful work categories and $n_U = n_W \cdot n_E = 304$ useful work flows (Appendix D.2 and Appendix E.1).

Note: The useful exergy of non-energy-use carriers is included in the demand of useful work so as to be consistent with the input-output model of the energy sector in Section 7.2. Including these carriers, which are not originally included in useful work accounting (Section 3.1.1.1) does not significantly affect the results of the present analysis (see Section 8.4.5.1)

The set of useful work demand sectors in the energy model differs from the set of sectors in the economic model. In the description of economic data there are $n = 49$ sectors whereas in the demand for useful work there are only $n_F^S = 24$ producing sectors. Hence, the useful work intensity matrix, $\boldsymbol{T}^U$, has dimensions 24×49 and performs the necessary aggregations

and disaggregations to ensure that Equation (4.7) is valid for every pair $(r_i^{U,S}, x_j^S)$ (as in Section 7.3.2). Finally, the useful work technology matrix of the extended energy sector ($\boldsymbol{L}^U$) was obtained as described in Section 5.1.1.

Furthermore, time-series for index decomposition analysis were built from sectoral primary energy and economic data in Section 7.3 and useful work data (described above). IDA data consists of $m_{kj} = 19$ sub-sectors distributed in $m_j = 7$ producing sectors (Appendix E.2).

8.4 Results

This section presents the results of the decomposition and decoupling analysis of PEU in Portugal between 1995 and 2010 with the inclusion of the final-to-useful energy conversion stage. In addition, a comparison of the SDA and IDA of production-related PEU is included.

8.4.1 The total change in primary energy use

Table 8-1 and Table 8-2 present the results of the SDA of PEU change associated with the final demand for non-energy products and with residential energy demand, respectively. Note: the SDA results of Section 7.4.1 are included for comparison.

Table 8-1 SDA coefficients of production-related PEU: Portugal 1995-2010

Model	$\Delta \boldsymbol{p}^S$	$\delta \boldsymbol{L}^{E,S}$	$\delta \boldsymbol{L}^{U,S}$	$\delta \boldsymbol{C}^{U,S}$	$\delta \boldsymbol{T}^U$	$\delta \boldsymbol{L}^M$	$\delta \boldsymbol{C}^M$	$\delta \boldsymbol{s}^M$
PFU model	51.1	-80.1	16.7	-21.6	-138.2	-67.6	1.9	340.0
	$\Delta \boldsymbol{p}^S$	$\delta \boldsymbol{L}^{E,S}$	$\delta \boldsymbol{C}^{E,S}$		$\delta \boldsymbol{T}^E$	$\delta \boldsymbol{L}^M$	$\delta \boldsymbol{C}^M$	$\delta \boldsymbol{s}^M$
PF model (Section 7.4)	51.1	-79.6	29.0		-172.4	-67.7	1.9	339.9

Units PJ

Table 8-2 SDA coefficients of PEU associated with household energy demand: Portugal 1995-2010

	$\Delta \boldsymbol{p}^R$	$\delta \boldsymbol{L}^{E,R}$	$\delta \boldsymbol{L}^{U,R}$	$\delta \boldsymbol{c}^{U,R}$	$\delta \boldsymbol{r}^{U,R}$
PFU model	94.5	-37.5	-10.7	4.8	137.9
	$\Delta \boldsymbol{p}^R$	$\delta \boldsymbol{L}^{E,R}$	$\delta \boldsymbol{c}^{E,R}$	$\delta \boldsymbol{r}^{E,R}$	
PF model (Section 7.4)	94.5	-37.5	20.8	111.1[a]	

Units PJ

[a] Aggregate of factor coefficients δb^R, δc^H and δs^H (Section 7.2)

As explained in Section 4.2, the PFU model allows to decompose the effect of the factors $\boldsymbol{C}^{E,S}$ and $\boldsymbol{T}^E$ of the PF model into three factors $\boldsymbol{T}^U$, $\boldsymbol{C}^{U,S}$ and $\boldsymbol{L}^{U,S}$ (for residential energy use, $\boldsymbol{c}^{E,R}$ and $\boldsymbol{r}^{E,R}$ into $\boldsymbol{c}^{U,R}$,$\boldsymbol{L}^{U,R}$and $\boldsymbol{r}^{U,R}$). The effects of the rest of factors that the PF model and the PFU share are approximately equal (i.e. they differ because of the approximation nature of the D&L technique, Section 3.3.3.1).

Changes in the useful work intensity has the largest effect of decreasing PEU ($\delta \boldsymbol{T}^U \ll 0$) followed by the primary-to-final energy sector structure and efficiency, economic structure and composition of useful work demand factors ($\delta \boldsymbol{L}^{E,S}$, $\delta \boldsymbol{L}^M$ and $\delta \boldsymbol{C}^{U,S}$). This large effect of $\boldsymbol{T}^U$ might have been caused by 1) price increases of non-energy products due to high prices of

energy inputs or other market interactions; and 2) increases in the aggregate non-dissipation efficiency of passive systems (see Section 5.1.3.1).

The structure and efficiency of the extended energy sector has the effect of increasing production-related PEU ($\delta \boldsymbol{L}^{U,S} > 0$) despite the improvements in the aggregate technical efficiency (22.6% in 1995 to 25.9% in 2010). This was caused by the fact that efficiency improvements were achieved in conversion technologies that use energy carriers with a larger associated PEU (e.g. thermoelectricity). The latter suggests that measures to improve the technical energy efficiency in producing sectors were unsuccessful in reducing the overall PEU in the country. On the other hand, improvements in the final-to-useful energy conversion in households ($L^{U,R}$) actually contributed to decrease PEU.

8.4.2 Evolution of production-related primary energy use

For a historical analysis, Figure 8-1 depicts the SDA results of the evolution of the PEU by producing sectors. Note: The evolution of the effects of factors $\boldsymbol{L}^{E,S}$, $\boldsymbol{L}^{M}$, $\boldsymbol{C}^{M}$ and $\boldsymbol{s}^{M}$ has been explained in Section 7.4.4.

The evolution of the effect of changes in direct useful work intensity is similar in shape and value to the evolution of $\delta \boldsymbol{T}^{E}$ along most of the studied period (see Figure 7-4) except in the interval 1995-1998, where $\delta \boldsymbol{T}^{U} > \delta \boldsymbol{T}^{E}$. The latter suggest that during this interval producing sectors became more useful work intensive due to an increase in non-productive uses of useful work (e.g. comfort, see Section 7.4.2) caused by the good economic performance of the country in those years (Aguiar-Confraria et al., 2012; BdP, 2009).

The structure and efficiency of the final-to-useful conversion stage ($\boldsymbol{L}^{U,S}$) had a small effect to increase PEU at every interval. However, it was relatively larger in the interval 2004-2010 despite the launch of regulations on industrial energy efficiency (such as the SGCIE, see MEI (2008)). Even though the aggregate final-to-useful conversion efficiency increased, the direction of this effect was caused by intervals of decline in final-to-useful efficiencies in producing sectors, especially in the transport & trade, services and energy-intensive industries.

Additionally, changes in demand composition of useful work flows ($\boldsymbol{C}^{U,S}$) had a relatively minor effect from 1998 to 2010. In the interval 1995-1998, this factor contributed to decrease PEU caused by a reduction in demand of useful work flows with a larger associated PEU.

Finally, the figure allows analyzing general trends of effects of the different factors of PEU in Portugal 1995-2010. There are only three decomposition coefficients that did not change direction ($\delta \boldsymbol{L}^{U,S} > 0$, $\delta \boldsymbol{L}^{M} < 0$ and $\delta \boldsymbol{s}^{M} > 0$) while the rest had negative and positive values over the studied period. Nevertheless, the decomposition coefficients in Table 8-1 and Figure 8-1 correspond to the average of all possible decomposition forms according to the D&L technique (Section 3.3.3.1). Therefore, to identify general trends of factor effects the minimum and maximum limits of the decomposition coefficients are evaluated (Figure 8-2).

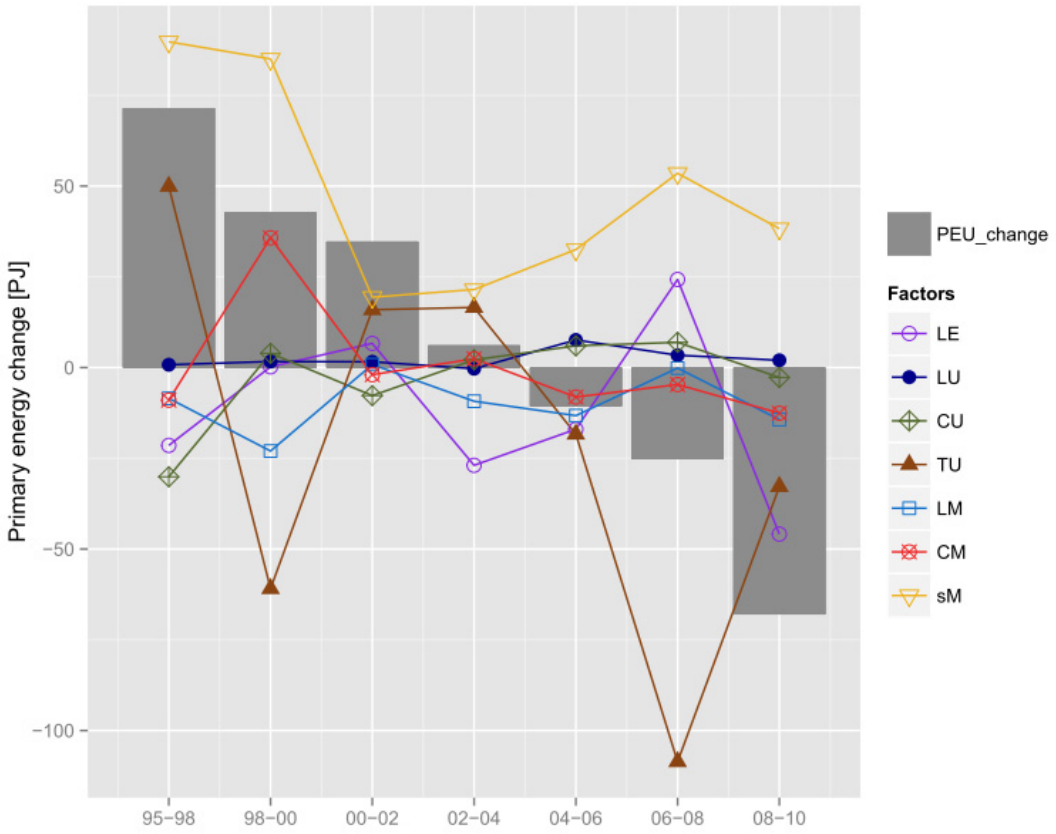
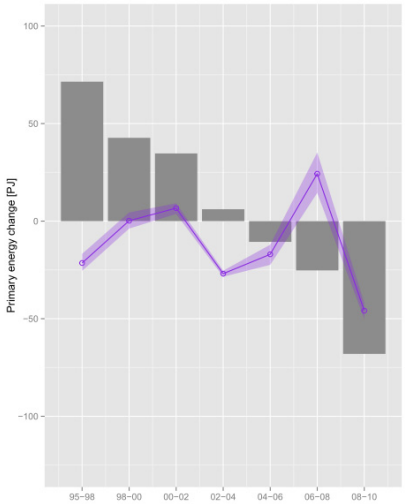


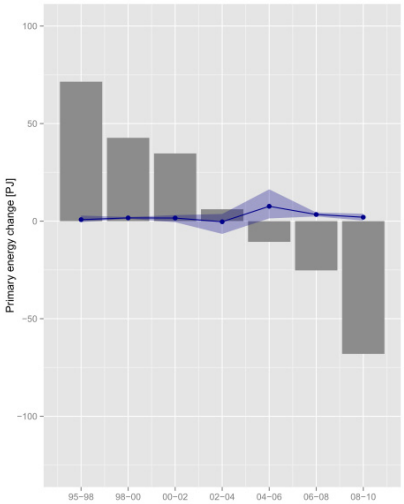
Figure 8-1 Primary-to-final-to-useful SDA of production-related PEU: Portugal 1995-2010
Note: LE – Structure and efficiency of the energy sector, LU – Structure and efficiency of the final-to-useful conversion stage, CU – Composition of direct useful work demand, TU – Direct useful work intensity, LM – Structure of the economy, CM – Composition of non-energy final demand and sM – Final demand of non-energy products, see Section 4.3.1.

As mentioned in Section 4.3.1, the economic scale is related to economic growth; hence if the economy grows, the effect of this factor should have a positive value. The decomposition results confirm this as $\delta \boldsymbol{s}^{M}$ had always a positive value (Figure 8-2-g). The distribution of $\delta \boldsymbol{s}^{M}$ values is precise in between 1998-2008, where the absolute change in PEU is relatively small while in the intervals 1995-1998 and 2008-2010 the range of values is larger.

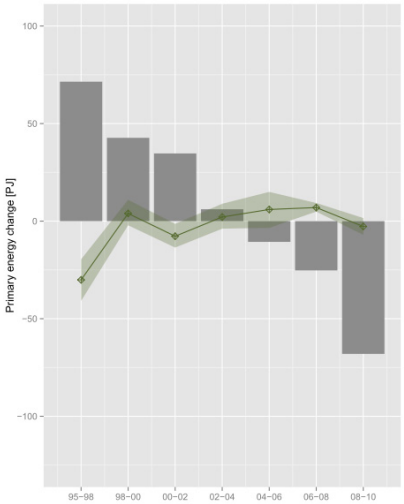
The structure of the primary-to-final energy sector and the direct useful work intensity were the two factors that contributed the most to overall energy decoupling though with large fluctuations (Figure 8-2-a,d). On the one hand, positive values of $\delta \boldsymbol{T}^{U}$ (2000-2004) were probably caused by the loss of productivity and competitiveness (BdP, 2009; Farto and Morais, 2011) and by the increasing demand of useful work for energy uses not directly related to production (e.g. space comfort and lighting of non-occupied spaces). On the other hand, the value of $\delta \boldsymbol{L}^{E,S}$ for Portugal depends on the intermittence of renewable energy sources. As pointed in Section 7.4.4, rainy and dry years were responsible for the fluctuation of $\delta \boldsymbol{L}^{E,S}$. In addition, the ranges of effect values of these two factors are relatively small.



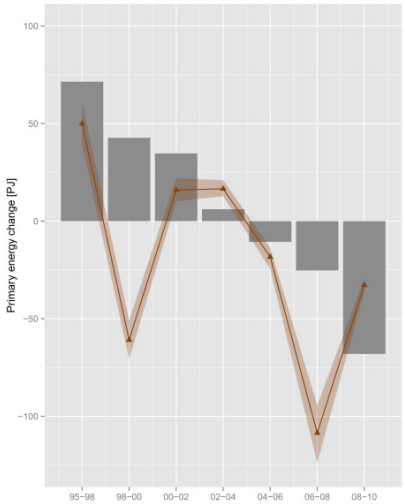
(a) $\boldsymbol{L}^{E,S}$ Structure and efficiency of the energy sector



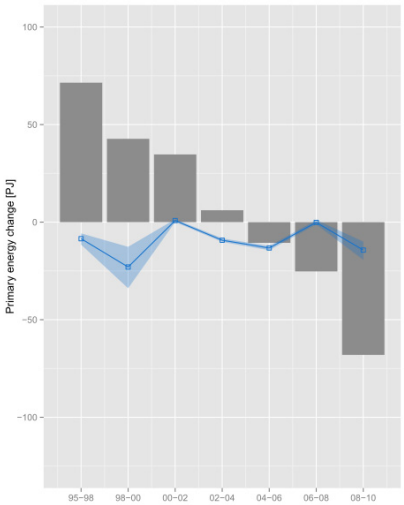
(b) $\delta\boldsymbol{L}^{U,S}$ Structure and efficiency of the final-to-useful conversion



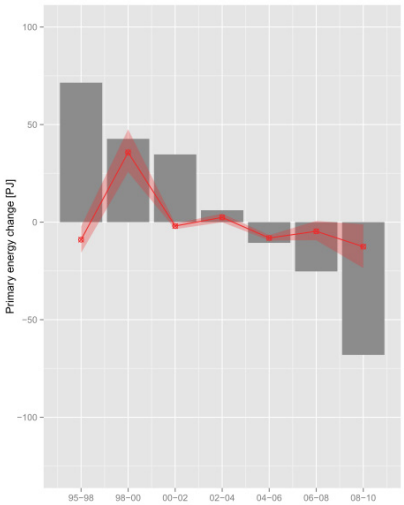
(c) $\delta\boldsymbol{C}^{U,S}$ Composition of direct useful work demand



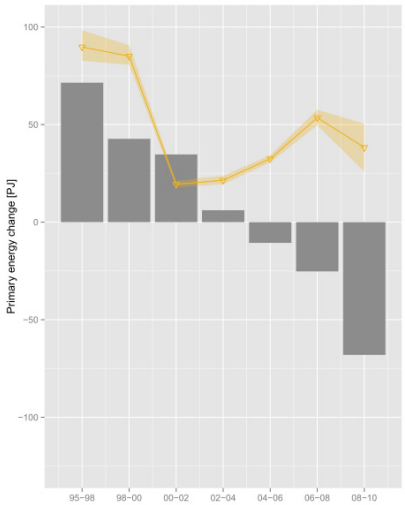
(d) $\delta\boldsymbol{T}^{U}$ Direct useful work intensity



(e) $\delta\boldsymbol{L}^{M}$ Structure of the economy



(f) $\delta\boldsymbol{C}^{M}$ Composition of non-energy final demand



(g) $\delta\boldsymbol{s}^{M}$ Final demand of non-energy products

Figure 8-2 Range of decomposition coefficients: Portugal 1995-2010
Note: The grey bar corresponds to the total change in production-related PEU

Changes in the structure of the economy had the effect of reducing PEU along the period under study (Including its maximum and minimum limits, Figure 8-2-e). This result shows that the transition towards services helps reduce PEU in the economy. Even though the values of this factor are consistent, they are relatively modest, see also Henriques and Kander (2010).

The case of the final-to-useful conversion stage is disappointing. The analysis shows that, only between 2002 and 2004, $\delta \boldsymbol{L}^{U,S}$ might have contributed to reduce PEU ($\min \delta \boldsymbol{L}^{U,S} < 0$). Additionally, the range of $\delta \boldsymbol{L}^{U,S}$ values seems to be larger for smallest absolute changes in PEU (2002-2004 and 2004-2006).

In the case of $\delta \boldsymbol{C}^{U,S}$, the range of values is relatively large, which makes difficult to determine if there is an actual contribution to reduce PEU in some intervals (1998-2000, 2002-2004 and 2004-2006). Finally, the demand composition of non-energy products ($\boldsymbol{C}^{M}$) contributed to decrease PEU during most of the studied period (except in 1998-2000).

8.4.3 Renewable vs. non-renewable energy sources

As mentioned in Chapter 1, energy decoupling is important to reduce environmental impact due to energy use by an economic system. To do so, the rate of use of non-renewable energy sources should be reduced. Moreover, the reduction of non-renewable energy use can help increase energy security through reducing energy imports, which is a serious issue in Portugal since all non-renewable sources are imported (Amador, 2010; DGEG, 2012). Therefore, in this section, the effect of changes in PEU factors is evaluated with respect to the type of primary energy source (Table 8-3).

Table 8-3 SDA of changes in total PEU by type of carrier: Portugal 1995-2010

	$\Delta \boldsymbol{p}$	$\delta \boldsymbol{L}^{E}$	$\delta \boldsymbol{L}^{U}$	$\delta \boldsymbol{C}^{U}$	$\delta \boldsymbol{T}^{U}$	$\delta \boldsymbol{L}^{M}$	$\delta \boldsymbol{C}^{M}$	$(\delta \boldsymbol{s}^{M} + \delta \boldsymbol{r}^{U,R})$[b]
Primary fossil sources (PFES)								
Coal	-78.8	-119.2	7.1	-10.2	-14.8	-10.8	3.0	66.1
Crude oil	-74.4	-137.2	-9.0	-62.1	-53.3	-21.8	6.8	202.4
Natural gas	179.7	91.9	3.9	75.4	-19.2	-8.2	-4.4	40.3
Total PFES	**26.5**	**-164.5**	**2.0**	**3.0**	**-87.3**	**-40.8**	**5.4**	**308.7**
Imports of secondary carriers (ISEC)[a]								
Electricity	34.2	6.2	4.2	12.7	-11.2	-4.0	-1.0	27.2
Oil derivatives	-16.1	-30.1	-3.0	-12.8	-28.4	-11.1	0.9	68.5
Total ISEC	**18.1**	**-23.9**	**1.2**	**-0.1**	**-39.6**	**-15.1**	**-0.1**	**95.7**
Total								
Non-renewable (PFES+ISEC)	**44.6**	**-188.4**	**3.1**	**2.9**	**-126.8**	**-55.9**	**5.3**	**404.4**
Renewable	**101.0**	**70.8**	**2.9**	**-19.7**	**-11.4**	**-11.7**	**-3.4**	**73.5**

Units PJ

[a] As in Section 7.3.2, the primary energy equivalent of ISEC was calculated with the PSM under the domestic technology assumption (Section 2.1.1).

[b] $\boldsymbol{s}^{M}$ and $\boldsymbol{r}^{U,R}$ are aggregated together because they represent the final demand for energy services both indirect (embodied in non-energy products) and direct (energy use by households) (Section 2.1.4)

Changes in the structure of the energy sector had the largest effect of reducing fossil PEU ($\delta \boldsymbol{L}^E \ll 0$). The introduction of natural gas and improvements in the primary-to-final conversion efficiencies led to an overall reduction of coal and crude oil use (-78.8 PJ and -74.4 PJ, respectively). However, the increase in natural gas use offset these reductions (PFES' $\Delta \boldsymbol{p} > 0$). The latter fact was significant for the reduction of environmental impact associated to non-renewable PEU because natural gas produces much less CO_2 emissions per PJ than coal and crude oil (EIA, 2013)

Direct useful work intensity ($\boldsymbol{T}^U$) contributed to reduce PEU from every type of energy source, having the largest effect on PFES and ISEC and a relatively small effect on renewables. Moreover, the structure of the economy ($\boldsymbol{L}^M$) also contributed to reduce PEU from every energy source. In addition, changes in the structure and efficiency of the final-to-useful conversion stage ($\boldsymbol{L}^U$) had the effect of increasing PEU, except from crude oil and use (improvements in final-to-useful conversion led to a relatively small reduction in PEU).

Finally, Portugal increased the use of non-renewable sources to a lesser extent than renewable sources, which led to a relative de-carbonization of the energy supply. This is reflected by a positive value of $\delta \boldsymbol{L}^E$ for renewable sources, in contrast to $\delta \boldsymbol{L}^E$ for non-renewable sources. Notice that in the case of renewables, the factor $\boldsymbol{L}^E$ only accounts for the structure of the energy sector since renewable primary-to-final conversion efficiencies are considered constant (according to the accounting method for primary energy of renewable sources, Section 2.1.1).

8.4.4 Energy decoupling

Decoupling indices ($d's$) of the different factors were calculated with GDP data and SDA decomposition results of previous sections.

The Portuguese GDP grew from 103.87 to 153.3 billion euros (constant prices 2002, Section 7.3.1) from 1995 to 2010 (EUROSTAT, 2014a) (Table 8-4).

Table 8-4 Values and growth rate of Portuguese GDP 1995-2010 (EUROSTAT, 2014a)

Year	GDP (Billion Euros)	Interval ($t_1 - t_2$)	$\Delta GDP / GDP(t_1)$ (%)
1995	103.87	-	-
1998	117.0	1995-1998	12.6
2000	131.8	1998-2000	12.6
2002	135.5	2000-2002	2.8
2004	136.4	2002-2004	0.7
2006	139.5	2004-2006	2.2
2008	147.5	2006-2008	5.8
2010	153.2	2008-2010	3.9

Since the GDP growth rate was positive in every interval of the studied period, a negative value of a decomposition coefficient, i.e. a decrease of PEU, represents an absolute decoupling force (i.e. the change in the rate of use of PEU is negative), while a positive decomposition coefficient can represent either a coupling or a relative decoupling force. Table 8-5 presents the value of the decoupling index for each factor of PEU in selected time intervals.

The value of the decoupling index of factor $\boldsymbol{X}$ was calculated as:

$$d = \frac{\delta \boldsymbol{X} / \boldsymbol{p}(t_1)}{\Delta GDP / GDP(t_1)} \tag{8.6}$$

which represents the decoupling index that factor $\boldsymbol{X}$ would have caused if the other factors would have remained constant in the period $t_1 - t_2$ (see Section 3.3.1). Note: the sum of decoupling indices of all factors equals the decoupling index of the indicator PEU.

Table 8-5 Evolution of decoupling index of PEU factors: Portugal 1995-2010

Interval	Decoupling index (d)							
	$\boldsymbol{p}$	$\boldsymbol{L}^E$	$\boldsymbol{L}^U$	$\boldsymbol{C}^U$	$\boldsymbol{T}^U$	$\boldsymbol{L}^M$	$\boldsymbol{C}^M$	$(\boldsymbol{s}^M + \boldsymbol{r}^{U,R})$
1995-1998	1	-0.3	0	-0.3	0.5	-0.1	-0.1	1.3
1998-2000	0.9	0.1	0	0	-0.5	-0.2	0.3	1.2
2000-2002	1.9	0.2	0	0	0.5	0	-0.1	1.3
2002-2004	0.2	-4.4	-0.2	0.5	2.0	-1.1	0.3	3.2
2004-2006	-0.6	-0.8	0.3	0.4	-0.7	-0.5	-0.3	1.2
2006-2008	-0.5	0.4	0	0.3	-1.7	0	-0.1	0.6
2008-2010	-2	-1.5	0	-0.5	-0.8	-0.3	-0.3	1.5

Units –
Colors red, blue and green indicate absolute, relative and no decoupling, respectively

Changes in total final demand for products (energy and non-energy) contributed to couple PEU to economic growth (except in 2006-2008). Changes in other factors had an index of either relative or absolute decoupling (except $\boldsymbol{T}^U$ in 2002-2004). However, the effect of factors with an index of relative decoupling ($0 < d < 1$) contributed to increase the coupling effect of final demand instead of the opposite. Therefore, a factor represents a decoupling force when its decoupling index is in the range of absolute decoupling ($d < 0$), i.e. when the value of a decomposition coefficient is negative.

Before 2004, Portugal experienced two intervals of relative decoupling and two of energy coupling ($d \leq 1$). The major decoupling forces were the structure of the energy sector and the structure of the economy. The decoupling index of $\boldsymbol{L}^E$ (-4.4) in 2002-2004 shows the beginning of the outstanding renewable energy transition for the following years (Section 7.1). Moreover, the direct useful work intensity contributed to further couple the PEU to the economy, which was caused by the increase of non-productive useful work uses (Section 7.4.4). After, 2004 the economy experienced absolute decoupling triggered by four decoupling forces $\boldsymbol{L}^E$, $\boldsymbol{T}^U$, $\boldsymbol{L}^M$ and $\boldsymbol{C}^M$.

Table 8-6 presents the decoupling index over 1995-2010 by type of source, by sector and for the whole economy.

Table 8-6 Total decoupling index of PEU factors, by carrier and economic sector: Portugal 1995-2010

Type	Decoupling index (d)							
	$\boldsymbol{p}$	$\boldsymbol{L}^{E}$	$\boldsymbol{L}^{U}$	$\boldsymbol{C}^{U}$	$\boldsymbol{T}^{U}$	$\boldsymbol{L}^{M}$	$\boldsymbol{C}^{M}$	$(\boldsymbol{s}^{M}+\boldsymbol{r}^{U,R})$
By type of source								
Non-renewable	0.13	-0.55	0.01	0.01	-0.37	-0.16	0.02	1.18
Renewable	1.71	1.20	0.05	-0.33	-0.19	-0.20	-0.06	1.24
By sector								
Industries	0.21	-0.32	0.07	-0.09	-0.56	-0.27	0.01	1.38
Residential	0.61	-0.24	-0.07	0.03	-	-	-	0.88
Total								
	0.36	-0.29	0.02	-0.04	-0.34	-0.17	0	1.19

Units –
Colors red, blue and green indicate absolute, relative and no decoupling, respectively

Portugal had a relative decoupling of non-renewable PEU while coupling the economy to the use of renewable energy source, which helped reduce environmental impacts and energy dependency. This was mainly caused by the transition in the energy sector ($\boldsymbol{L}^{E}$). The major decoupling forces with respect to the type of source were the improvements in direct useful work intensity ($\boldsymbol{T}^{U}$) and production technology in producing sectors ($\boldsymbol{L}^{M}$).

Furthermore, PEU related to production and to residential-energy use experienced relative decoupling. The structure of the energy sector was a common decoupling force while changes in final-to-useful conversion efficiencies had opposite effects. Finally, the country had an overall relative decoupling ($d = 0.36$) due to four decoupling forces $\boldsymbol{L}^{E}$, $\boldsymbol{T}^{U}$, $\boldsymbol{L}^{M}$ and $\boldsymbol{C}^{U}$.

8.4.5 Additional results

8.4.5.1 The inclusion of useful exergy of non-energy carriers

As mentioned in Section 7.3.2, the energy input-output data includes energy carriers for non-energy uses, which are no included in useful work accounting. The inclusion of these carriers has a small impact on the results of the present SDA as shown in Table 8-7.

Table 8-7 SDA of changes in PEU associated to energy carriers for non-energy uses: Portugal 1995-2010

	$\Delta\boldsymbol{p}^{S}$	$\delta\boldsymbol{L}^{E,S}$	$\delta\boldsymbol{L}^{U,S}$	$\delta\boldsymbol{C}^{U,S}$	$\delta\boldsymbol{T}^{U}$	$\delta\boldsymbol{L}^{M}$	$\delta\boldsymbol{C}^{M}$	$\delta\boldsymbol{s}^{M}$
PEU related to carriers for non-energy uses	-3.6	3.1	-0.5	-6.2	-6.4	0.1	-0.9	7.3

Units PJ

8.4.5.2 IDA vs SDA approach

Table 8-8 presents the results of the IDA of PEU change associated with the final demand for non-energy products. In addition, the SDA results of the previous section are included for comparison.

Table 8-8 IDA vs. SDA coefficients of production-related PEU: Portugal 1995-2010

Approach	ΔP^S	DP_v^S	DP_ϵ^S		DP_I^S	DP_L^S	DP_F^S	DP_f^S
IDA	51.1	-54.0	-34.8		-132.8	-90.1	-43.1	405.8
	$\Delta \boldsymbol{p}^S$	$\delta \boldsymbol{L}^{E,S}$	$\delta \boldsymbol{L}^{U,S}$	$\delta \boldsymbol{C}^{U,S}$	$\delta \boldsymbol{T}^U$	$\delta \boldsymbol{L}^M$	$\delta \boldsymbol{C}^M$	$\delta \boldsymbol{s}^M$
SDA	51.1	-80.1	16.7	-21.6	-138.2	-67.6	1.9	340.0

Units PJ

The two major driving forces (coupling and decoupling) of production-related PEU changes identified by the IDA approach coincides with those of the SDA approach: The economic scale ($DP_f^S > 0$) and the direct useful work intensity ($DP_f^S > 0$). However, the effect of the economic scale in the IDA is about 20% larger than that of the SDA.

Furthermore, the effects of the rest of factors present significant differences. The primary-to-final conversion efficiency (ν^{-1}) and the production technology (L) contributed to energy decoupling, though DP_L^S is the second largest decoupling force in the case of IDA, i.e. $DP_\nu^S < DP_L^S$ (opposite to SDA results). Moreover, the IDA assigns a large decoupling effect to the final demand mix factor (DP_F^S) while, in the SDA, the analogous factor had a negligible effect. Finally, the IDA estimated that final-to-useful conversion efficiencies contributed to energy decoupling.

The differences between the IDA and SDA are caused by the level of data aggregation of time series data (Section 3.3.2.3-Issue 1). The aggregation of data makes some decomposition coefficients of specific factors account for changes in other factors (Weber, 2009). Nevertheless, the summation of decomposition coefficients of the energy sector side (ν^{-1} and $\epsilon\phi^{-1}$; $\boldsymbol{L}^{E,S}$, $\boldsymbol{L}^{U,S}$ and $\boldsymbol{C}^{U,S}$) and the economic side (L, F and f; $\boldsymbol{L}^M$, $\boldsymbol{C}^M$ and $\boldsymbol{s}^M$) are approximately equal in the IDA as in the SDA, i.e.

$$DP_I^S \approx \delta \boldsymbol{T}^U$$

$$DP_\nu^S + DP_\epsilon^S \approx \delta \boldsymbol{L}^{E,S} + \delta \boldsymbol{L}^{U,S} + \delta \boldsymbol{C}^{U,S} \text{ (Energy side)}$$

$$DP_L^S + DP_F^S + DP_f^S \approx \delta \boldsymbol{L}^M + \delta \boldsymbol{C}^M + \delta \boldsymbol{s}^M \text{ (Economic side)}$$

The present discussion suggests that the SDA approach is more suitable for the analysis of energy decoupling forces. However, as the availability of input-output data is limited for long term historical analysis, the IDA can be used to identify the main decoupling forces considering that the absolute value of these forces need to be taken with caution.

8.5 Conclusions

This chapter extended the analysis of PEU in Portugal 1995-2010 of Chapter 7 to evaluate energy decoupling and its characteristics. For this purpose the primary-to-final-to-useful energy input-output model in Section 5.1 was used.

Portugal experienced an overall relative decoupling caused by the outstanding renewable transition of the energy sector, the structural changes in the economy and the direct useful work intensity of producing sectors. Moreover, the economy increased its dependency on renewable energy sources while decreasing dependency on crude oil and coal (partially substituted by renewables and natural gas), which had a positive impact on reducing energy-related environmental impact.

The main progress with respect to energy decoupling was obtained after the year 2004. The country achieved absolute decoupling between 2006 and 2010 due to two main decoupling forces: improvements in the direct useful work intensity and increases in renewable generation by the energy sector.

The results indicates that primary-to-final conversion and useful-to-service transfer of energy flows significantly contributed to energy decoupling while the effect of the structure and conversion efficiency of the extended energy sector (final-to-useful conversion stage, Section 5.1.1) is disappointing. Despite the improvements in the aggregate final-to-useful conversion efficiency in producing sectors, this factor contributed to couple PEU to economic growth, i.e. had the effect of increasing production-related PEU. This fact suggests that policies targeted to increase technical efficiency in producing sectors did not contribute to energy decoupling.

Finally, it can be concluded that the analysis of energy decoupling is improved by the inclusion of three levels of energy use, i.e. primary, final and useful. This approach allows estimating the effect on energy decoupling and PEU of several energy efficiency indicators and the structural energy conversion stages in the economy.

9 The extension to the service level of energy use

The objective of this chapter is to describe areas for future research. First, it presents a detailed theoretical discussion of how to extend the primary-to-final-to-useful models in Chapters 5 to the service level of energy use. Then, it describes a general framework for energy efficiency indicators that is derived from the proposed models. Finally, it concludes with other areas for future research.

9.1 Primary-to-final-to-useful-to-service model

This section builds on the model of primary energy use in Section 5.2, which is extended to include the service level of energy use.

9.1.1 A primary energy intensity model

The model starts by the primary energy intensity model in Section 5.2.1, which only represents the primary, final and useful level of energy use.

The useful-to-service energy transition, as mentioned in Section 2.1.4, is carried out by passive systems. These systems consume useful work to perform energy services (e.g. the deformation of metal). A share of useful work is dissipated while the rest is left to do energy services (i.e. productive useful work). The share of productive useful work depends on the characteristics of passive systems (e.g. the physical structure of a bending machine and the infrastructure of a building) to consume useful work. For example, the bending machine needs to overcome friction losses of the mechanism and mass inertia. This energy use stage is complex since passive systems are complex too (Section 2.1.4). However, it could be represented by a simple relationship

$$W^S = \sum_a^{n_a} \sum_b^{n_b} \mu_{ab}\, U_b^S = \bar{\mu} U^S \tag{9.1}$$

where the W^S is the productive useful work consumed in a producing sector, U_b^S is the amount of useful work flow b (see Equation (5.16)), μ_{ab} is the non-dissipation efficiency[38] of the

[38] The non-dissipation efficiency μ of passive systems also accounts for the dissipation that is caused by the direct human participation with the passive systems (see Section 2.1.4).

passive system a fed by the useful work flow b and $\bar{\mu}$ is the average non-dissipation efficiency of all passive systems in producing sectors.

Equations (9.1) and (5.17) are integrated into primary intensity, expressed for industry k:

$$\frac{P_k^S}{Q_k} = \bar{v}_k{}^{-1}(\overline{\epsilon\phi})_k{}^{-1}\bar{\mu}_k{}^{-1}\frac{W_k^S}{Q_k} \tag{9.2}$$

On the other hand, the gross output of industry k, considering that this industry produces a single product, is defined as:

$$Q_k = b_k Y_k \tag{9.3}$$

where b_k is the average unit price of product k in monetary per physical units (e.g. $/kg)and Y_k is the total physical units of product k produced (e.g. kg). Therefore, the productive useful work intensity can be expressed as

$$\frac{W_k^S}{Q_k} = b_k^{-1}\frac{W_k^S}{Y_k} \tag{9.4}$$

where the ratio of productive useful work used in industry k (W_k^S) and the total physical units of product k produced by industry k (Y_k) is defined as the energy service requirements (S_k^S) (see Section 9.1.2.2). Note: the inverse of the average unit product price (b_k^{-1}) is defined as the dematerialization factor by Ang and Xu (2013).

The primary energy intensity (normalized by the gross output) can be expressed as:

$$\frac{P^S}{Q} = \sum_k^{n_k} \bar{v}_k{}^{-1}(\overline{\epsilon\phi})_k{}^{-1}\bar{\mu}_k{}^{-1}b_k^{-1}S_k^S \tag{9.5}$$

The previous equation can be adapted for the residential primary energy intensity as:

$$\frac{P^R}{A} = \sum_h^{n_h} \bar{v}_h{}^{-1}(\overline{\epsilon\phi})_h{}^{-1}\bar{\mu}_h{}^{-1}S_h^R \tag{9.6}$$

which differs from Equation (5.19) by the terms: $\bar{\mu}_h$ is the average non-dissipation efficiency of all passive systems in household h and S_h^R is the energy service requirements for household h, i.e. the ratio of productive useful work (W_h^R) and the activity level (A) of household h.

9.1.2 The primary-to-final-to-useful-to-service energy use model (PFUS model)

The models developed in the previous sections lead to a complete model of primary energy use in the economy, i.e. primary energy use of producing and non-producing sectors in the economy.

$$P = \begin{cases} P^S = \sum_{k}^{n_k} \bar{v}_k{}^{-1} (\overline{\epsilon\phi})_k{}^{-1} \bar{\mu}_k{}^{-1} S_k^S Y_k \\ \qquad + \\ P^R = \sum_{h}^{n_h} \bar{v}_h{}^{-1} (\overline{\epsilon\phi})_h{}^{-1} \bar{\mu}_h{}^{-1} S_h^R A \end{cases} \tag{9.7}$$

The model represents the four levels of energy use and is able to isolate different energy performance indicators. It shows that production-related and residential energy use have the same number of analogous factors. In addition, the model resembles the simple model, proposed by Wirl (1995), where primary energy use (P) is a function of aggregate technology efficiency $\eta(t)$ (including conversion technologies and infrastructure) and energy services (S), i.e. $P = S\,\eta^{-1}(t)$.

9.1.2.1 Advantages and issues

The PFU model has the same advantages of the PU model compared to conventional models (Section 0) though it surpasses the PU model in the following:

- The service level of energy use is represented, which improves the understanding of energy use mechanisms in the economy (Section 3.3.2.3-Issue 3).
- The model is able to isolate one additional indicator of energy performance in the economy to account for it separately (Section 3.3.2.3-Issue 2): μ gives insight into the efficiency of passive systems. Note: the case of S is discussed in Section 9.1.2.2.
- The energy use of producing and non-producing sectors can be accounted by analogous factors (Section 3.3.2.3-Issue 4).
- The model can be built with economic factors either in terms of gross output, value added or physical output to build IDA models similar to those in Section 3.3.2.2 (Section 3.3.2.3-Issue 5).

Nevertheless, the model cannot address some of the issues of the PU model (Section 0) and the following:

- There is no consistent approach to estimate the value of energy service requirements (S_k^S and S_h^R) (see Section 9.1.2.2).
- The level of data aggregation significantly affects the model and applications (Section 3.3.2.3-Issue 1).

9.1.2.2 An alternative estimation of energy services

The definition of the energy service requirements (S), the amount of productive useful work that is required to perform an energy service, is fundamental for the PFUS model. In this section, the concept of S is discussed based on the concept of passive systems introduced by

Cullen and Allwood (2010a) and the insights on energy services by Nakićenović and Grübler (1993) (Section 2.1.4). The advantage of S in defining energy services is that it allows having a measure of energy services that is linked to its consuming unit, see Gouveia et al. (2012).

As mentioned in Section 2.1.4, only direct energy services are considered part of the service level of energy use. These services are relatively easy to define for producing sectors. Since the ultimate purpose of these sectors is to make products, the energy service is the production of a certain product hence the energy service requirements (S) can be measured with respect to a product unit. In the case of non-producing sectors, energy service requirements can be classified according to the consumption units of the different types of uses and benefits achieved by the user, for example, number of showers, square meters cleaned with a vacuum machine, hours of television, etc., see Jonsson et al. (2011), Gouveia et al. (2012), Cullen et al. (2011), Sovacool (2011) and Nakićenović et al. (1996).

The energy service requirements are estimated by the minimum amount of useful exergy that would be required by an ideal passive system, with a specific input structure, to provide a unit of service. An ideal passive system is defined as an abstraction of the actual passive system that is only allowed to dissipate energy through certain mechanisms. For example:

1. A transportation service of an object of one kilogram of mass along 100 km with a speed of 1 km/min (60 km/hr). The dissipation mechanisms of the passive system (car without the engine, and the road) are the friction losses due to air resistance, i.e. friction losses in the mechanical moving parts and the road are not considered[39]. The energy service requirements would be the minimum work needed to overcome air friction resistance untill the destiny of the object is reached. The energy service requirements for this specific service are constant (though different if the service speed is set at 80 km/hr or along 50 km). Therefore, the transport of this object along 200 km at 60 km/hr needs the consumption of 2 units of this type energy service.
2. A service to produce a ton of steel to form a specific input structure (the characteristics of input materials are fixed, e.g. natural iron ore). The energy service requirements correspond to the minimum energy that is needed to modify the physical and chemical properties of input materials into the desired characteristics of one ton steel. This energy service requirements corresponds to the contained exergy per ton of steel (see Cullen et al. (2011)), which is constant if the characteristics of input materials do not change.
3. A five-minute shower at 40ºC with a flow rate 8 lt/min. The dissipation mechanism of the passive system (pipe from the boiler, mixer, shower head, drain pipe and shower enclosure) correspond to the energy contained in the water that flows through the drain pipe. The energy service requirements can be calculated as the minimum amount of heat needed to increase the temperature of 40 liters of water from ambient temperature to 40ºC. Therefore a 10-minute shower at 40ºC with a flow rate 8 lt/min needs the consumption of two units of this type of service.

[39] Friction losses between the car wheels and the road can be assumed negligible if the road and wheel has a large friction coefficient.

The estimation of the value of different energy service requirements in the examples above has a bottom-up approach, as proposed by Nakićenović and Grübler (1993). Depending on the detail of energy services classification and on the service itself the bottom-up estimation can be complex. An alternative approach is a top-down approach from the delivery of useful energy, as mainly done by Cullen et al. (2011).

The advantage of the introduction of the energy service requirements is that it is always possible to define a passive system for a specific energy service, for which energy service requirements are constant[40] (regardless of the arbitrariness in the definitions of the passive system or of the energy service). This advantage is especially significant for the decomposition analysis of the PFUS model presented below (Section 9.1.3.2). Nonetheless, this advantage of the proposed estimation of energy service requirements depend on the detailed stratification of energy services in the economy.

9.1.3 Index decomposition analysis with the PFUS model

The model of primary energy use allows for a more detailed decomposition of the aggregate indicator P into static changes of constitutive factors. So from Equation (5.20) we obtain:

$$\Delta P = \begin{cases} \Delta P^S = DP_\nu^S + DP_{\epsilon\phi}^S + DP_\mu^S + DP_S^S + DP_Y^S \\ + \\ \Delta P^R = DP_\nu^R + DP_{\epsilon\phi}^R + DP_\mu^R + DP_S^R + DP_A^R \end{cases} \tag{9.8}$$

Each additional factor from those in Section 5.2.3.1 and its coefficient are discussed in detail in the following section.

9.1.3.1 Explanation of factors and decomposition coefficients

μ Factor: Average non-dissipation efficiency

This factor accounts for changes in the structure and technology of passive systems. Possible explanations for an effect $DP_\mu < 0$

- Reduction of dissipation losses through updates of current passive systems
- Entry of new passive systems with higher than average non-dissipation efficiency
- Discontinuation of passive systems with lower than average non-dissipation efficiency

S Factor: The energy service unit

By definition for a given product (Section 9.1.2.2), energy service units (S_j^S and S_j^R) are constant hence $DP_S = 0$.

[40] The energy service requirements can be seen as a transformation constant between energy units and the units of measurement of products and services actually delivered.

Y Factor: The gross output

These factor accounts for changes in the activity level of producing sectors (i.e. the gross output in physical units). Possible explanations for an effect $DP_Y < 0$

- Decrease in total gross output
- Decrease in total final demand

A Factor: The activity level of households

These factor accounts for changes in the activity level of households. Possible explanations for an effect $DP_A < 0$

- Decrease in total activity level
- Decrease in variables that reduce total activity level

Note: Any positive change in activity level factors (Y and A) leads to increases in primary energy use.

9.1.3.2 The effect of changes in the average non-dissipation efficiency (DP_μ)

The estimation of the average non-dissipation efficiency of all passive systems in the economy is for the current state of information close to impossible. Not even the boundaries of every passive system have been defined, see Cullen and Allwood (2010a). To address this issue, the non-dissipation efficiency factor and the energy service factor are aggregated together into the useful work physical intensity (N^U):

$$N_i^U = \bar{\mu}_i^{-1} S_i = \frac{U_i}{Y_i} \tag{9.9}$$

In decomposition analysis with the LMDI technique (Section 3.3.2.1), the decomposition coefficient of a product of two factors with respect to an aggregate variable is equal to:

$$\mathrm{D}P_N = DP_\mu + DP_S \tag{9.10}$$

As mentioned in the previous section, $S_j = constant$ and $DP_S \approx 0$ hence the decomposition coefficient of the useful work physical intensity accounts for changes in the structure and technology of passive systems, i.e.

$$\mathrm{D}P_N \approx DP_\mu \tag{9.11}$$

Equation (9.11) shows the major advantage of the proposed decomposition model: I.e. the difficulties to define the boundaries of the passive system and the specifications of the energy services (Section 9.1.2.2) can be avoided when there are sufficiently disaggregated data of useful work (U) and physical activity indicators (Y_j for producing sectors and A_k for residential consumers) (see Section 9.1.3.3-Issue 1).

9.1.3.3 Issues of the PFUS model applied to IDA

Issue 1: Data aggregation

See Section 3.3.2.3-Issue 1. In addition to affecting other factors, this issue affects the capacity of the model to estimate DP_{μ} (Section 9.1.3.2) since, with highly aggregated data, the S factor cannot be assumed as constant (i.e. it will vary with changes in the mix of goods and services in the economy).

Issue 2: Primary energy equivalent of renewables

See Section 4.3.2-Issue 2.

Issue 3: Primary exergy vs. final exergy

See Section 5.2.3.2-Issue 3.

Issue 4: Accounting for direct and indirect human participation at the service level of energy use

The direct human participation (i.e. human operation of passive systems, Section 2.1.4) is included in the non-dissipation efficiency factor (μ). On the other hand, indirect human participation (consumption behavior) is included in the activity factors (Y and A). However, the coefficients DP_Y^S and DP_A^R account for changes in total consumption (including the changes created by different consumption behaviors). Therefore, it is not possible to isolate the effect of changing consumption behavior on primary energy use. For example, these coefficients cannot distinguish an increase of energy use by increases in demand for energy services (more population, more households, more income, etc.) from an increase in energy use by non-conservative behavior (families leaving the heating system on while they are not at home).

Issue 5: Accounting for direct use of final energy carriers of the energy sector

See Section 5.2.3.2-Issue 4.

Issue 6: Useful work accounting assumptions

See Section 3.1.2-Issue 1

9.2 A generic model of energy efficiency indicators

Equations (9.5) and (9.6) show that the most aggregated economic-thermodynamic energy efficiency indicator (Table 6-1), i.e. the primary energy intensity, is composed by several economic and energy efficiency factors: Two thermodynamic efficiency indicators of energy conversion processes ($\bar{v}_k$ and $\overline{\epsilon\phi}_k$), one thermodynamic efficiency indicator of energy use ($\bar{\mu}_k$), an economic variable (b, prices) and a physical-thermodynamic constant (S_k^S).

Therefore the developments of Sections 5.2 and 9.1 can allow for a generalized representation of economic, physical-thermodynamic and economic-thermodynamic energy efficiency indicators (Table 6-1) as a function of thermodynamic energy efficiency indicators, economic variables and energy service requirements (constant). For example:

- Direct economic energy efficiency of industry k (economic energy efficiency indicator)

$$\frac{Q_k}{E^S\ (US\$)} = \ (b^E)_k^{-1}(\overline{\epsilon\phi})_k{}^{-1}\bar{\mu}_k{}^{-1}b_k^{-1}S_k^S \tag{9.12}$$

  where b^E is the average energy price to industry k
- Direct primary, final and useful work intensities of industry k (economic-thermodynamic efficiency indicators)

$$\frac{P_k^S}{Q_k} = \bar{v}_k{}^{-1}\underbrace{(\overline{\epsilon\phi})_k{}^{-1}\underbrace{\bar{\mu}_k{}^{-1}b_k^{-1}S_k^S}_{useful\ level}}_{Final\ level} \tag{9.13}$$

- Specific energy consumption, i.e. physical direct energy efficiency, of industry k (physical-thermodynamic indicator)

$$\frac{E_k^S}{Y_k} = (\overline{\epsilon\phi})_k{}^{-1}\bar{\mu}_k{}^{-1}S_k^S \tag{9.14}$$

- Economy-wide primary energy intensity (normalized by gross output Q)

$$\frac{P}{Q} = \begin{cases} \dfrac{P^S}{Q} = \displaystyle\sum_k^{n_k} \bar{v}_k{}^{-1}(\overline{\epsilon\phi})_k{}^{-1}\bar{\mu}_k{}^{-1}b_k^{-1}S_k^S\frac{Q_k}{Q} \\ + \\ \dfrac{P^R}{Q} = \displaystyle\sum_h^{n_h} \bar{v}_h{}^{-1}(\overline{\epsilon\phi})_h{}^{-1}\bar{\mu}_h{}^{-1}S_h^R\frac{A}{Q} \end{cases} \tag{9.15}$$

These examples show that most energy efficiency indicators at different levels of energy use can be constructed by a combination of up to three energy efficiency indicators ($\bar{v}$, $\overline{\epsilon\phi}$ and $\bar{\mu}$), economic variables (Y, A, b and b^E) and physical–thermodynamic energy constants (i.e. energy service requirements).

Further research on the inclusion of the levels of energy use in energy efficiency studies can help: 1) achieve a better understanding of energy efficiency trends (e.g. as in Chapter 6); 2) identify the causes of differences between energy efficiency indicators instead of comparing them directly, as done by e.g. Worrell et al. (1997); and 3) provide a more detailed comparison between energy efficiency trends between countries and industries.

9.3 Other areas for future research

This section presents a brief description of other areas of future research that are derived from the present thesis.

9.3.1 Evaluation of emissions

The evaluation of energy-related GHG emissions is one of the most important applications of energy use models. As shown in Table 3-3, SDA studies of emissions have significantly outnumbered the studies of energy use and intensity. The proposed models in this thesis (PF,

PFU, PU and PFUS) can serve as tools to improve the evaluation of driving factors of energy-related emissions.

9.3.2 Energy use responsibility

Energy decoupling of an economy can also be achieved by externalizing the energy burden to other economies, i.e. if an economy can reduce the internal production and increase imports of energy intensive products, the energy intensity of this economy will decrease while the intensity of exporting economies will increase (Schütz et al., 2004; UNEP, 2011; Weisz et al., 2006). In this thesis, the production-based responsibility approach was used. This accounts for the energy use in the production process within national borders (UNFCCC, 2008) though it does not account for the externalities issue. In this respect, there are two other approaches that can be applied to the proposed models in this thesis to evaluate the effect of these externalities: consumption-based responsibility, which accounts for the energy used to produce all products consumed in an economy (imported and domestic), see (Bastianoni et al., 2004) and (Peters, 2008); and income-based responsibility, which accounts for the energy required to generate a country's income (Marques et al., 2012; Rodrigues et al., 2010). Note: these approaches were originally developed for carbon responsibility analysis.

9.3.3 Energy sources scarcity constraints

As mentioned in Chapter 1, energy decupling is fundamental to increase energy security and to decrease the pressure on limited global reserves of fossil energy sources. In addition, the input-output model assumes that resources are not constrained (Section 3.2.1). Therefore, the proposed models in this thesis should be complemented with the analysis of variables that account for the scarcity of energy sources, see e.g. Neumayer (2000), Smith (2012), Stern (1999) and Uri (1995)

9.3.4 Redefinition of energy factors in the PFU energy input-output model

The Equation (5.8):

$$\boldsymbol{L}^{U} = \left(\widehat{\boldsymbol{\phi}}^{E}\right)^{-1}\boldsymbol{G}^{EC}(\boldsymbol{\epsilon}^{U})^{-1} \tag{9.16}$$

shows that the total requirements matrix of the extended energy sector can be deconstructed into a factor of structure ($\left(\widehat{\boldsymbol{\phi}}^{E}\right)^{-1}\boldsymbol{G}^{EC}$) and other of final-to-useful efficiency ($(\boldsymbol{\epsilon}^{U})^{-1}$). Based on this, the technology matrix of the primary-to-final energy sector ($\boldsymbol{L}^{E}$) can also be deconstructed into a structure and a primary-to-final conversion matrices. The column sums of the structure matrices of the energy and extended energy sectors are either 1 or 0. A shift from 1 to 0 means that a certain energy technology (i.e. wind farm generation or an oil refinery) stopped being used, while a shift from 0 to 1 means that an energy technology was introduced. This deconstruction of $\boldsymbol{L}^{E}$ and $\boldsymbol{L}^{U}$ was used with data of Chapter 8 to perform SDA of primary energy use of Portugal 1995-2010. The results of this exercise show that the proposed deconstruction of $\boldsymbol{L}^{E}$ and $\boldsymbol{L}^{U}$ has a negligible effect at the level of data aggregation. Nevertheless, if the data is more disaggregated, the deconstruction of these factors could provide more insights into energy use and decoupling driving forces.

10 Conclusions

The present thesis contributes to the literature of energy decoupling, energy input-output analysis and energy-related decomposition studies. It shows that the inclusion of a detailed description of energy flows can significantly improve the analysis of energy use and decoupling in economic systems. To do so, three novel models of energy use were developed and combined with decomposition techniques, which allow identifying the driving forces of energy use and decoupling. This thesis also shows that the detailed description of energy flows can improve the understanding of economy-wide and industrial energy efficiency trends.

The major contribution to input-output analysis is the primary-to-final energy input-output model (PF model). This model is introduced as an alternative to the two conventional energy models in input-output analysis, i.e. the hybrid-unit and direct impact coefficient models, which have been extensively used in the last 40 years without significant improvements. The PF model combines characteristics of these conventional models, namely the use of hybrid units (physical for energy flows and monetary for economic transitions) and the use of a direct impact coefficients variable. Under specific conditions, the proposed model can be reduced to replicate the form of conventional models. Nevertheless, it includes a detailed description of the primary and final levels of energy use and of the primary-to-final conversion stage in the economy, which is absent in conventional models.

The usefulness of the PF model depends on the validity of the assumption of an independent energy sector. This assumption establishes that the energy inputs account for the largest share of the input structure of energy industries. It was found that if energy inputs (in monetary units) have a greater than 70% share of total inputs to energy industries, the energy sector can be considered independent. Because of this, the energy sector independence assumption would be valid for most economies, which implies that the PF model can be used in most applications of the conventional energy input-output models. In this respect, this model is especially suitable for energy-related structural decomposition analysis (SDA) because it is able to separately account for energy and economic transactions according to the actual physical energy conversion processes carried out in the economy. Moreover, the PF model, in contrast to conventional models, can distinguish the effect of two energy efficiency indicators on economy-wide or industrial energy use, i.e. direct energy intensity and primary-to-final energy conversion efficiency.

Furthermore, the PF model enables the inclusion of other levels of energy use and energy transition stages in the economy. This led to the development of the primary-to-final-to-useful energy input-output model (PFU model), which is the first ever energy input-output model to include the useful level of energy use and the final-to-useful energy conversion stage. The construction of the PFU model relied on the concept of the extended energy sector, i.e. a theoretical sector that includes all final-to-useful energy conversion processes in the economy. In this work, the PFU model is applied to SDA studies of energy use while other applications are left for further research. The main advantage of the PFU model in energy-related SDA is that it can distinguish the effect of three energy efficiency indicators on economy-wide or industrial energy use, i.e. direct useful work intensity, final-to-useful conversion efficiency and primary-to-final conversion efficiency. Also, the PFU model enables the inclusion of the service level of energy use though further research is needed to do so.

In addition to the PF and PFU models, this thesis also introduces a primary-to-useful model (PU model) for energy-related index decomposition analysis (IDA). The PU model is analogous to the PFU model though it provides less detailed results. This model can complement the analysis of energy decoupling at the three levels of energy use in the long term due to its lower data requirements compared to the SDA. Consequently, the usefulness of the PU model relies on long term data availability (not the case of input-output data) and the level of data aggregation. Moreover, it is possible to extend the PU model to account for the service level of energy use and develop a generic framework for energy efficiency indicators.

The PF, PFU and PU models allow analyzing the effect on energy decoupling of the transformation and use of energy flows in an economy. These models successfully deconstruct primary energy use into several components: 1) Structure and efficiency of primary-to-final conversion; 3) structure and efficiency of final-to-useful conversion; 3) useful exergy demand composition and intensity; 4) economic structure; and 5) final demand of non-energy goods and services. Also, they allow the estimation of the effect of each factor on the evolution of primary energy use and energy decoupling, which was not possible with existing models in literature. To show this, the models were applied to evaluate energy decoupling and the trends of primary energy use (PEU) in Portugal 1995-2010.

This case study represents the first analysis of the significant energy and economic transitions that Portugal underwent in the last two decades. On the one hand, natural gas was introduced to the country in 1997 and renewable power generation had a remarkable increase. On the other hand, the country continued a transition into a service economy (that started in the 1980's), joined the euro in 1999 and endured the world economic crisis of 2007-2009.

Portugal experienced relative energy decoupling along the period under study. The main progress was obtained after the year 2004, after which the country achieved absolute decoupling. Moreover, the Portuguese economy increased its dependency on renewable energy sources while decreasing dependency on crude oil and coal, which had a positive impact on reducing energy-related environmental impact.

The SDA with the PF and PFU models showed that the coupling effect of the economic scale factor (total final demand) was offset by three energy decoupling forces: 1) the structure and efficiency of the primary-to-final conversion stage in the economy (energy transition); 2) the

structure of the economy (economic transition); and 3) the direct useful work intensity of producing sectors (energy demand at the useful level of energy use).

Improvements in direct useful work intensity had the main decoupling effect, especially after 2004. These improvements were motivated mostly by the international crisis of 2007-2009 and high prices of oil and natural gas in the 2000's, to which producing sectors responded with productivity gains, technological improvements in passive systems and increases in the price of outputs (e.g. land transport).

The energy transition had the second largest decoupling effect. However, it had a more oscillatory nature, compared to the economic transition. This was caused by changing weather conditions that affected renewable power generation (wind- and hydropower). In the meantime, the economic transition toward a service economy had a consistent decoupling effect over the whole period under study, due to the relative expansion of industries with lower-than-average useful work requirements per unit of output.

A relevant result is that improvements in the aggregate efficiency of final-to-useful energy conversion processes had the effect of increasing production-related PEU. This result suggests that policies targeted to increase technical efficiency in producing sectors did not contribute to energy decoupling. This fact defies the common belief that increasing the technical efficiency is effective to achieve energy decoupling.

Additionally, this thesis also introduces a better approach to evaluate energy efficiency trends, which shows that a better characterization of energy flows can also help improve the analysis of energy efficiency trends. The proposed approach extends the traditional IDA approach to evaluate the economy-wide and industrial final energy intensity (one of the most used approaches in literature) by including the useful level of energy use. The traditional and the proposed approaches were applied to evaluate the final energy intensity of Mexican producing sectors between 1980 and 2009. Results from the traditional approach suggest that technical energy efficiency decreased because changes in sectoral energy intensity drove the aggregate final exergy intensity up while the proposed approach shows that the overall increase of aggregate final exergy intensity was caused by the introduction of useful work intensive, rather than less technically efficient, industries. Therefore, the traditional IDA approach could lead to misinterpretation of energy efficiency trends as it does not distinguish between the effect of technical efficiency and useful work intensity.

References

ADEME, 2012a. Energy efficiency policies in the European Union. Environment and Energy Management Agency, London.

ADEME, 2012b. Energy efficiency trends in the European Union. Environment and Energy Management Agency, London.

Aguayo, F., Gallagher, K.P., 2005. Economic reform, energy, and development: The case of Mexican manufacturing. Energy Policy, 33, 829-837.

Aguiar-Confraria, L., Alexandre, F., Pinho, M.C., 2012. O euro e o crescimento da economia portuguesa: Uma análise contrafactual. Análise Social, 298-321.

Akpan, U.S., Green, O.A., Bhattacharyya, S., Isihak, S., 2014. Effect of technology change on CO_2 emissions in Japan's industrial sectors in the period 1995–2005: An input–output structural decomposition analysis. Environmental and Resource Economics, 1-25.

Alam, M.S., 2009. Bringing energy back into the economy. Review of Radical Political Economics, 41, 170-185.

Alcántara, V., Duarte, R., 2004. Comparison of energy intensities in European Union countries: Results of a structural decomposition analysis. Energy Policy, 32, 177-189.

Alvarez de la Borda, J., 2006. Crónica del Petróleo en México de 1863 a Nuestros Días. Petróleos Mexicanos, México D.F.

Amador, J., 2010. Energy Production and Consumption in Portugal: Stylized Facts, Economic Bulletin. Banco de Portugal, Lisbon.

Amador, J., 2012. Energy content in manufacturing exports: A cross-country analysis. Energy Economics, 34, 1074-1081.

Amorim, F., Martins, M.V.M., Pereira da Silva, P., 2010. A new perspective to account for renewables impacts in Portugal, 7th International Conference on the European Energy Market Madrid, pp. 1-6.

Ang, B.W., 1999. Decomposition methodolody in energy demand and environmental analysis, in: Van den Bergh, J.C.J.J. (Ed.), Handbook of environmental and resource economics. Edward Elgar Publishing, Cheltenham.

Ang, B.W., 2004. Decomposition analysis for policymaking in energy: Which is the preferred method? Energy Policy, 32, 1131-1139.

Ang, B.W., 2005. The LMDI approach to decomposition analysis: A practical guide. Energy Policy, 33, 867-871.

Ang, B.W., Huang, H.C., Mu, A.R., 2009. Properties and linkages of some index decomposition analysis methods. Energy Policy, 37, 4624-4632.

Ang, B.W., Lee, S.Y., 1994. Decomposition of industrial energy consumption: Some methodological and application issues. Energy Economics, 16, 83-92.

Ang, B.W., Liu, F.L., 2001. A new energy decomposition method: Perfect in decomposition and consistent in aggregation. Energy, 26, 537-548.

Ang, B.W., Liu, F.L., Chew, E.P., 2003. Perfect decomposition techniques in energy and environmental analysis. Energy Policy, 31, 1561-1566.

Ang, B.W., Liu, N., 2007a. Handling zero values in the logarithmic mean Divisia index decomposition approach. Energy Policy, 35, 238-246.

Ang, B.W., Liu, N., 2007b. Negative-value problems of the logarithmic mean Divisia index decomposition approach. Energy Policy, 35, 739-742.

Ang, B.W., Mu, A.R., Zhou, P., 2010. Accounting frameworks for tracking energy efficiency trends. Energy Economics, 32, 1209-1219.

Ang, B.W., Xu, X.Y., 2013. Tracking industrial energy efficiency trends using index decomposition analysis. Energy Economics, 40, 1014-1021.

Ang, B.W., Zhang, F.Q., 2000. A survey of index decomposition analysis in energy and environmental studies. Energy, 25, 1149-1176.

Ang, B.W., Zhang, F.Q., Choi, K.-H., 1998. Factorizing changes in energy and environmental indicators through decomposition. Energy, 23, 489-495.

Apergis, N., Payne, J.E., 2010. Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. Energy Policy, 38, 656-660.

Ardent, F., Beccali, M., Cellura, M., 2009. Chapter 22: Application of the IO methodology to the energy and environmental analysis of a regional context, in: Suh, S. (Ed.), Handbook of Input-Output Analysis Economics in Industrial Ecology. Springer, Dordrecht, pp. 435-458.

Arto, I., Gallastegui, C., Ansuategi, A., 2009. Accounting for early action in the European Union Emission Trading Scheme. Energy Policy, 37, 3914-3924.

Aspra, L.A., 1977. Import substitution in Mexico: Past and present. World Development, 5, 111-123.

Ayres, R.U., 1998. Eco-thermodynamics: economics and the second law. Ecological Economics, 26, 189-209.

Ayres, R.U., 2008. Sustainability economics: Where do we stand? Ecological Economics, 67, 281-310.

Ayres, R.U., Ayres, L.W., Pokrovsky, V., 2005. On the efficiency of US electricity usage since 1900. Energy, 30, 1092-1145.

Ayres, R.U., Ayres, L.W., Warr, B., 2003. Exergy, power and work in the US economy, 1900-1998. Energy, 28, 219-273.

Ayres, R.U., Masini, A., 2004. Exergy: Reference states and balance conditions, in: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Volume 2. Elsevier, New York, NY, pp. 633-640.

Ayres, R.U., Warr, B., 2005. Accounting for growth: the role of physical work. Structural Change and Economic Dynamics, 16, 181-209.

Ayres, R.U., Warr, B., 2009. The Economic Growth Engine. How Energy and Growth Drive Material Prospertity. Edward Elgar, Cheltenham.

Baiocchi, G., Minx, J.C., 2010. Understanding changes in the UK's CO_2 emissions: a global perspective. Environmental Science & Technology, 44, 1177-1184.

Bandi, V., 2010. Decentralized energy services delivery in developing countries, Case study; India. M.Sc. Dissertation. Aalto University, Helsinki.

Barsky, R.B., Kilian, L., 2004. Oil and the macroeconomy since the 1970s. Journal of Economic Perspectives, 18, 115-134.

Bastianoni, S., Pulselli, F.M., Tiezzi, E., 2004. The problem of assigning responsibility for greenhouse gas emissions. Ecological Economics, 49, 253-257.

BdP, 2009. A Economia Portuguesa no Contexto da Integração Económica, Financeira e Monetária. Banco de Portugal, Lisboa.

Ben Hammamia, A., Dakhlaoui, A., Abbassi, A., 2014. Analysis of the decomposition of energy intensity in Tunisia. International Journal of Energy Economics and Policy, 4, 420-426.

Berndt, E.R., Botero, G., 1985. Energy demand in the transportation sector of Mexico. Journal of Development Economics, 17, 219-238.

Bhattacharyya, S.C., 2011. Energy Economics: Concepts, Issues, Markets and Governance. Springer, Dundee.

Bithas, K., Kalimeris, P., 2013. Re-estimating the decoupling effect: Is there an actual transition towards a less energy-intensive economy? Energy, 51, 78-84.

Brizga, J., Feng, K., Hubacek, K., 2014. Drivers of greenhouse gas emissions in the Baltic States: A structural decomposition analysis. Ecological Economics, 98, 22-28.

Brockway, P.E., Barrett, J.R., Foxon, T.J., Steinberger, J.K., 2014. Divergence of trends in US and UK aggregate exergy efficiencies 1960–2010. Environmental Science & Technology, 48, 9874-9881.

Brown, P., 2013. European Union Wind and Solar Electricity Policies: Overview and Considerations. Congressional Research Service Washington, DC.

Bullard, C.W., Herendeen, R.A., 1975a. The energy cost of goods and services. Energy Policy, 3, 268-278.

Bullard, C.W., Herendeen, R.A., 1975b. Energy impact of consumption decisions. Proceedings of the IEEE, 63, 484-493.

Bullard, C.W., Penner, P.S., Pilati, D.A., 1978. Net energy analysis: Handbook for combining process and input-output analysis. Resources and Energy, 1, 267-313.

Butnar, I., Llop, M., 2011. Structural decomposition analysis and input–output subsystems: Changes in CO_2 emissions of Spanish service sectors (2000–2005). Ecological Economics, 70, 2012-2019.

Cahill, C.J., Bazilian, M., Ó Gallachóir, B.P., 2010. Comparing ODEX with LMDI to measure energy efficiency trends. Energy Efficiency, 3, 317-329.

Cao, S., Xie, G., Zhen, L., 2010. Total embodied energy requirements and its decomposition in China's agricultural sector. Ecological Economics, 69, 1396-1404.

Capasso, A.G., 2007. Situacion actual del ferrocarril en México. B.Sc. Dissertation. Universidad de las Américas, Cholula.

Cárdenas, E., 2009. La reestructuración económica de 1982 a 1994, Latin American Economies: History and Globalization Conference. UCLA Center for Economic History, Los Angeles, CA.

Carmody, J.M., 1939. Rural Electrification in the United States. Annals of the American Academy of Political and Social Science, 201, 82-88.

Carrillo, J., García, P., 1987. Etapas industriales y conflictos laborales: La industria automotriz en México. Estudios Sociológicos, V, 303-340.

Casler, S., Blair, P.D., 1997. Economic structure, fuel combustion, and pollution emissions. Ecological Economics, 22, 19-27.

Casler, S., Rose, A., 1998. Carbon dioxide emissions in the U.S. economy: A structural decomposition analysis. Environmental and Resource Economics, 11, 349-363.

Casler, S., Wilbur, S., 1984. Energy input-output analysis: A simple guide. Resources and Energy, 6, 187-201.

CEEP, 2011. Analysis of central Europe's energy sector: The Prague report. Central Europe Energy Partners, Brussels.

Cegonho, N., Delgado Domingos, J., Domingos, T., 2012. Um novo método de cálculo de energia primária e a sua aplicação a Portugal, in: MEFTE (Ed.), IV Conferência Nacional em Mecânica dos Fluidos, Termodinâmica e Energia, Lisboa.

Cellura, M., Longo, S., Mistretta, M., 2012. Application of the structural decomposition analysis to assess the indirect energy consumption and air emission changes related to Italian households consumption. Renewable and Sustainable Energy Reviews, 16, 1135-1145.

Chai, J., Guo, J.-E., Wang, S.-Y., Lai, K.K., 2009. Why does energy intensity fluctuate in China? Energy Policy, 37, 5717-5731.

Chang, Y.F., Lewis, C., Lin, S.J., 2008. Comprehensive evaluation of industrial CO_2 emission (1989–2004) in Taiwan by input–output structural decomposition. Energy Policy, 36, 2471-2480.

Chang, Y.F., Lin, S.J., 1998. Structural decomposition of industrial CO_2 emission in Taiwan: An input-output approach. Energy Policy, 26, 5-12.

Cheng, B.S., 1997. Energy consumption and economic growth in Brazil, Mexico and Venezuela: A time series analysis. Applied Economics Letters, 4, 671-674.

Choi, K.-H., Ang, B.W., 2012. Attribution of changes in Divisia real energy intensity index: An extension to index decomposition analysis. Energy Economics, 34, 171-176.

Chontanawat, J., Hunt, L.C., Pierse, R., 2008. Does energy consumption cause economic growth?: Evidence from a systematic study of over 100 countries. Journal of Policy Modeling, 30, 209-220.

Christ, C.F., 1955. A review of input-output analysis, in: National Bureau of Economic Research (Ed.), Input-Output Analysis: An Appraisal. Princeton University Press, Princeton, pp. 137-182.

Chung, H.-S., Rhee, H.-C., 2001. A residual-free decomposition of the sources of carbon dioxide emissions: a case of the Korean industries. Energy, 26, 15-30.

Claessens, S., Dell'Ariccia, G., Igan, D., Laeven, L., 2010. Cross-country experiences and policy implications from the global financial crisis. Economic Policy, 25, 267-293.

Cleveland, C.J., Kaufmann, R.K., Stern, D.I., 2000. Aggregation and the role of energy in the economy. Ecological Economics, 32, 301-317.

Coccia, M., 2010. Energy metrics for driving competitiveness of countries: Energy weakness magnitude, GDP per barrel and barrels per capita. Energy Policy, 38, 1330-1339.

Cohen, C., Lenzen, M., Schaeffer, R., 2005. Energy requirements of households in Brazil. Energy Policy, 33, 555-562.

Colmenares, F., 2008. Petróleo y crecimiento económico en México 1938-2006. EconomíaUNAM, 5, 53-65.

COLMEX, 2008. Fuentes para la historia del petróleo en México: Estadísticas [Online database], Colegio México. Available: http://petroleo.colmex.mx/index.php/estadisticas/86 [Accessed Nov 2012]

CONAFOVI, 2006. Guia para el uso eficiente e la energía en la vivienda. Comisión Nacional de Fomento a la Vivienda, Mexico D.F.

CONUEE, 2010a. Proyecto nacional de eficiencia energética en alumbrado público municipal. Comisión Nacional para el Uso Eficiente de la Energía, Mexico D.F.

CONUEE. 2010b. Publicación de la norma oficial mexicana de eficiencia energética de lámparas para uso general [Online], Comunicados. Available: http://www.conuee.gob.mx/wb/CONAE/comunicado112010

Corden, W.M., 1984. Booming sector and Dutch disease economics: Survey and consolidation. Oxford Economic Papers, 36, 359-380.

Costa, H.A., 2012. From Europe as a model to Europe as austerity: the impact of the crisis on Portuguese trade unions. European Review of Labour and Research, 18, 397-410.

Costantini, V., Martini, C., 2010. The causality between energy consumption and economic growth: A multi-sectoral analysis using non-stationary cointegrated panel data. Energy Economics, 32, 591-603.

Cruz, L.M., 2002. Energy-environment-economy interactions: An input-output approach applied to the Portuguese case in: ISEE (Ed.), 7th Biennial Conference of the International Society for Ecological Economics. ISEE, Tunisia.

Cruz, L.M., Dias, J., 2014. Assessing the evolution of energy and CO_2 intensities in the EU, 22nd International Input–Output Conference. IIOA, Lisbon.

Cullen, J.M., Allwood, J.M., 2010a. The efficient use of energy: Tracing the global flow of energy from fuel to service. Energy Policy, 38, 75-81.

Cullen, J.M., Allwood, J.M., 2010b. Theoretical efficiency limits for energy conversion devices. Energy, 35, 2059-2069.

Cullen, J.M., Allwood, J.M., Borgstein, E.H., 2011. Reducing energy demand: What are the practical limits? Environmental Science & Technology, 45, 1711-1718.

D'Angelo, J., Paz, D., Cardenas, G., 2006. Posibilidades del secado de bagazo en la industria azucarera de México. Ingenieria Mecánica Tecnología y Desarrollo, 2, 41-46.

Das, A., Paul, S.K., 2014. CO_2 emissions from household consumption in India between 1993–94 and 2006–07: A decomposition analysis. Energy Economics, 41, 90-105.

De Beer, G., Blok, K., Worrell, E., 1995. Long term energy efficiency improvements in the iron and steel industry in: ECEEE (Ed.), Summer Study. European Council for an Energy Efficient Economy, Stockholm.

De Beer, G., Blok, K., Worrell, E., 1998. Future technologies for energy-efficient iron and steel making. Annual Review of Energy and the Environment, 23, 123-205.

De Haan, M., 2001. A structural decomposition analysis of pollution in the Netherlands. Economic Systems Research, 13, 181-196.

De Meester, B., Dewulf, J., Janssens, A., Van Langenhove, H., 2006. An improved calculation of the exergy of natural resources for Exergetic Life Cycle Assessment (ELCA). Environmental Science & Technology, 40, 6844-6851.

de Nooij, M., van der Kruk, R., van Soest, D.P., 2003. International comparisons of domestic energy consumption. Energy Economics, 25, 359-373.

DGEG, 2012. Balanços energéticos [Online database], Direcção-Geral de Energia e Geologia, Lisboa. Available: http://www.dgeg.pt/ [Accessed Dec 2013]

DGEG, 2014a. Potência instalada nas centrais produtoras de energia elétrica (2008-2012) [Online database], Direcção-Geral de Energia e Geologia. Available: http://www.dgeg.pt/ [Accessed Apr 2014]

DGEG, 2014b. Produção bruta de energia elétrica [Online database], Direcção-Geral de Energia e Geologia. Available: http://www.dgeg.pt/ [Accessed Apr 2014]

Diakoulaki, D., Mandaraka, M., 2007. Decomposition analysis for assessing the progress in decoupling industrial growth from CO_2 emissions in the EU manufacturing sector. Energy Economics, 29, 636-664.

Dietzenbacher, E., Hoen, A.R., 1998. Deflation of input-output tables from the user's point of view: A heuristic approach. Review of Income and Wealth, 44, 111-122.

Dietzenbacher, E., Lenzen, M., Los, B., Guan, D., Lahr, M.L., Sancho, F., Suh, S., Yang, C., 2013. Input-output analysis: The next 25 years. Economic Systems Research, 25, 369-389.

Dietzenbacher, E., Los, B., 1998. Structural decomposition techniques: Sense and sensitivity. Economic Systems Research, 10, 307-324.

Dietzenbacher, E., Stage, J., 2006. Mixing oil and water? Using hybrid input-output tables in a structural decomposition analysis. Economic Systems Research, 18, 85-95.

Dietzenbacher, E., Temurshoev, U., 2012. Input-output impact analysis in current or constant prices: does it matter? Journal of Economic Structures, 1, 1-18.

Dincer, I., 2002. The role of exergy in energy policy making. Energy Policy, 30, 137-149.

Dincer, I., Rosen, M.A., 2005. Thermodynamic aspects of renewables and sustainable development. Renewable and Sustainable Energy Reviews, 9, 169-189.

Dincer, I., Rosen, M.A., 2012. Exergy: Energy, Environment and Sustainable Development. Newnes, Oshawa.

Dong, Y., Ishikawa, M., Liu, X., Wang, C., 2010. An analysis of the driving forces of CO_2 emissions embodied in Japan–China trade. Energy Policy, 38, 6784-6792.

Duchin, F., Steenge, A.E., 1999. Input-output analysis, technology and the environment, in: Van den Bergh, J.C.J.J. (Ed.), Handbook of environmental and resource economics. Edward Elgar Publishing, Cheltenham.

Ebrahim-zadeh, C., 2003. Dutch Disease: Too much wealth managed unwisely. Finance & Development, 40, 50-51.

EIA, 2010. Consumption & efficiency [Online database], U.S. Energy Information Administration. Available: http://www.eia.gov/consumption/ [Accessed Nov 2012]

EIA, 2011a. Annual Energy Outlook 2011 with Projections to 2035. Energy Information Administration, Washington, DC.

EIA, 2011b. Natural Gas Prices [Online database], U.S. Energy Information Administration. Available: http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm [Accessed Nov 2012]

EIA, 2012. Analysis Briefs: Mexico [Online database], U.S. Energy Information Administration. Available: http://www.eia.gov/countries/cab.cfm?fips=MX [Accessed Nov 2012]

EIA. 2013. Carbon dioxide emissions coefficients [Web Page], U.S. Energy Information Administration, Washington, DC. Available: http://www.eia.gov/environment/emissions/co2_vol_mass.cfm [Accessed 9 June 2014]

EIA, 2014. Crude oil prices: Europe Brent Spot Price FOB (Dollars per Barrel) [Online database], U.S. Energy Information Administration. Available: http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=A [Accessed Nov 2012]

Eichhammer, W., 2004. Industrial energy efficiency, in: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Volumen 3. Elsevier, New York, NY, pp. 383-393.

Ertesvåg, I.S., 2005. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy, 30, 649-675.

Ertesvåg, I.S., Mielnik, M., 2000. Exergy analysis of the Norwegian society. Energy, 25, 957-973.

EU, 2006. Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Official Journal of the European Union, 114, 64-85.

EU, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union, 140, 16–62.

EUROSTAT, 2008a. Correspondence table NACE Rev. 2 - NACE Rev. 1.1. European Comission, Luxembourg.

EUROSTAT, 2008b. Manual of supply, use and input-output tables. European Comission, Luxembourg.

EUROSTAT, 2009. Correspondence table CPA 2002 - CPA 2008. European Comission, Luxembourg.

EUROSTAT, 2014a. ESA 95: Supply, use and input-output tables [Online database], European Comission, Luxembourg. Available: http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks [Accessed Feb 2014]

EUROSTAT, 2014b. Gas prices for industrial consumers [Online database], European Comission. Available: http://epp.eurostat.ec.europa.eu/tgm/graph.do?tab=graph&plugin=0&pcode=ten00112&language=en&toolbox=data [Accessed May 2014]

FAO, 2003. Calculation of the energy content of foods: Energy conversion factors, in: FAO (Ed.), Food Energy: Methods of Analysis and Conversion Factors. Food and Agriculture Organization, Rome.

FAO, 2011. FAOSTAT [Online database], Food and Agriculture Organization. Available: http://faostat.fao.org/ [Accessed Nov 2012]

Farto, M., Morais, H., 2011. A crise portuguesa, o resgate internacional e o crescimento económico: Notas e reflexões. JANUS.NET e-journal of International Relations, 2, 124-132.

Ferreira Neto, A.B., Perobelli, F.S., Bastos, S.Q.A., 2014. Comparing energy use structures: An input–output decomposition analysis of large economies. Energy Economics, 43, 102-113.

Fiorito, G., 2013. Can we use the energy intensity indicator to study “decoupling” in modern economies? Journal of Cleaner Production, 47, 465-473.

Fisher, I., 1922. The Making of Index Numbers: A Study of Their Varieties, Tests and Reliability. Houghton Mifflin Company, New York, NY.

Ford, K.W., Rochlin, G.I., Socolow, R.H., Hartley, D.L., Hardesty, D.R., Lapp, M., Dooher, J., Dryer, F., Berman, S.M., Silverstein, S.D., Ross, M., 1975. Efficient Use of Energy. American Institute of Physics, New York, NY.

Fouquet, R., Pearson, P.J.G., 2006. Seven centuries of energy services: The price and use of light in the United Kingdom (1300-2000). Energy Journal, 27, 139-177.

French, S., Leyshon, A., Thrift, N., 2009. A very geographical crisis: the making and breaking of the 2007–2008 financial crisis. Cambridge Journal of Regions, Economy and Society, 2, 287-302.

Fujigaki Cruz, E., 1997. Periplo industrial 1940 -1960: Una ojeada al surgimiento de algunas ramas, in: Jáuregui, L., Romero Sotelo, M.E. (Eds.), La Industria Mexicana y su Historia: Siglos XVIII, XIX y XX. Facultad de Economía - UNAM, México D.F.

Galindo, L.M., 2005. Short- and long-run demand for energy in Mexico: A cointegration approach. Energy Policy, 33, 1179-1185.

Garbaccio, R.F., Ho, M.S., Jorgenson, D.W., 1999. Why has the energy-output ratio fallen in China? The Energy Journal, 20, 63-91.

Gaudreau, K., Fraser, R.A., Murphy, S., 2009. The tenuous use of exergy as a measure of resource value or waste impact. Sustainability, 1, 1444-1463.

Gerilla, G.P., Teknomo, K., Hokao, K., 2005. An evaluation of carbon emission changes in the Japanese housing sector from 1980-1995. Journal of Asian Architecture and Building Engineering, 4, 509-515.

Giampietro, M., Sorman, A.H., 2012. Are energy statistics useful for making energy scenarios? Energy, 37, 5-17.

Goldemberg, J., Siqueira Prado, L.T., 2011. The decline of the world's energy intensity. Energy Policy, 39, 1802-1805.

Gong, M., Wall, G., 2001. On exergy and sustainable development—Part 2: Indicators and methods. Exergy, an International Journal, 1, 217-233.

Gould, B.W., Kulshreshtha, S.N., 1986. An interindustry analysis of structural change and energy use linkages in the Saskatchewan economy. Energy Economics, 8, 186-196.

Gouveia, J.P., Fortes, P., Seixas, J., 2012. Projections of energy services demand for residential buildings: Insights from a bottom-up methodology. Energy, 47, 430-442.

Griffin, J.M., 1976. Energy input-output modelling: Problems and prospects. General Electric Co., Washington, DC.

Gros, D., 2012. Macroeconomic Imbalances in the Euro Area: Symptom or cause of the crisis? CEPS Policy Brief, April, 1-11.

Grubler, A., 2012. Energy transitions research: Insights and cautionary tales. Energy Policy, 50, 8-16.

Guan, D., Hubacek, K., Weber, C.L., Peters, G.P., Reiner, D.M., 2008. The drivers of Chinese CO_2 emissions from 1980 to 2030. Global Environmental Change, 18, 626-634.

Guan, D., Peters, G.P., Weber, C.L., Hubacek, K., 2009. Journey to world top emitter: An analysis of the driving forces of China's recent CO_2 emissions surge. Geophysical Research Letters, 36, L04709.

Guo, J., Lawson, A.M., Planting, M.A., 2009. From make-use to symmetric input-output tables: An assessment of alternative technology assumptions 14th International Conference on Input-Output Techniques. IIOA, Montreal.

Haas, R., 1997. Energy efficiency indicators in the residential sector: What do we know and what has to be ensured? Energy Policy, 25, 789-802.

Haas, R., C., P., G., R., M., R., G., R., A., H., 2011. A historical review of promotion strategies for electricity from renewable energy sources in EU countries. Renewable and Sustainable Energy Reviews, 15, 1003-1034.

Haas, R., Nakicenovic, N., Ajanovic, A., Faber, T., Kranzl, L., Müller, A., Resch, G., 2008. Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies. Energy Policy, 36, 4012-4021.

Haberl, H., 2001a. The energetic metabolism of societies: Part I: Accounting concepts. Journal of Industrial Ecology, 5, 11-33.

Haberl, H., 2001b. The energetic metabolism of societies: Part II: Empirical examples. Journal of Industrial Ecology, 5, 71-88.

Haberl, H., 2006. The global socioeconomic energetic metabolism as a sustainability problem. Energy, 31, 87-99.

Hannon, B., 2010. The role of input–output analysis of energy and ecologic systems. Annals of the New York Academy of Sciences, 1185, 30-38.

Hannon, B., Blazeck, T., Kennedy, D., Illyes, R., 1983. A comparison of energy intensities: 1963, 1967 and 1972. Resources and Energy, 5, 83-102.

Harvey, L.D., 2010. Energy and the New Reality 1: Energy efficiency and the demand for energy services. Earthscan, London.

Hasegawa, R., 2006. Regional comparisons and decomposition analyses of CO_2 emissions in Japan. ENVIRONMENTAL SCIENCE, 19, 277-289.

Hawdon, D., Pearson, P., 1995. Input-output simulations of energy, environment, economy interactions in the UK. Energy Economics, 17, 73-86.

Heer, K., Langniß, O., 2007. Promoting renewable energy sources in Portugal: Possible implications for China Centre for Solar Energy and Hydrogen Research, Stuttgart.

Henriques, S.T., 2011. Energy Transitions, Economic Growth and Structural Change: Portugal in a Long-Run Comparative Perspective. Lund University, Lund.

Henriques, S.T., Kander, A., 2010. The modest environmental relief resulting from the transition to a service economy. Ecological Economics, 70, 271-282.

Hernández Lecanda, R.F., 2007. El futuro de la fuerza motriz en los Ferrocarriles Mexicanos, Mirada ferroviaria. Museo Nacional de los Ferrocarriles Mexicanos, Puebla, pp. 9-13.

Hoekstra, R., 2005. Economic Growth, Material Flows and the Environment: New Applications of Structural Decomposition Analysis and Physical Input-Output Tables. Edward Elgar Publishing, Northampton, MA.

Hoekstra, R., van den Bergh, J.C.J.M., 2002. Structural decomposition analysis of physical flows in the economy. Environmental and Resource Economics, 23, 357-378.

Hoekstra, R., van den Bergh, J.C.J.M., 2003. Comparing structural decomposition analysis and index decomposition analysis. Energy Economics, 25, 39-64.

Hoen, A., Mulder, M., 2003. Explaining Dutch emissions of CO_2: A decomposition analysis. CPB Netherlands Bureau for Economic Policy Analysis, The Hague.

Hoshino, T., 1996. Privatization of Mexico's public enterprises and the restructuring of the private sector. The Developing Economies, 34, 28-60.

IEA-ETSAP, 2010. Automotive LPG and natural gas engines, in: ETSAP (Ed.), Technology Brief Energy Technology Systems Analysis Program, Paris.

IEA, 2010. World energy outlook. International Energy Agency, Paris.

IEA, 2011a. Energy balances of OECD countries: Documentation for beyond 2020 files [Dataset], International Energy Agency, Paris.

IEA, 2011b. Energy statistics of OECD countries: Documentation for beyond 2020 files [Dataset], International Energy Agency, Paris.

IEA, 2012a. Key world energy statistics. International Energy Agency, Paris.

IEA, 2012b. Natural Gas Information. OECD Publishing, Paris.

IEA, 2013. Policies and measures: Energy efficiency [Online database], International Energy Agency. Available: http://www.iea.org/policiesandmeasures/energyefficiency/ [Accessed Feb 2014]

IEA. 2014. What are the methods of calculation of primary energy equivalent? [Web Page], International Energy Agency, Paris. Available: http://www.iea.org/statistics/ [Accessed 7 May 2014]

Imran, K., Siddiqui, M.M., 2010. Energy consumption and economic growth: A case study of three SAARC countries. European Journal of Social Sciences, 16, 206-213.

INEGI, 2010a. Censo de población y vivienda [Online database], Instituto Nacional de Estadística y Geografía. Available: http://www.inegi.org.mx/est/contenidos/proyectos/ccpv/cpv2010/Default.aspx [Accessed Jan 2013]

INEGI, 2010b. Estadísticas Históricas de México 2009. Instituto Nacional de Estadística y Geografía, Aguascalientes.

INEGI, 2010c. Sistema para la consulta de las estadísticas históricas de México 2009 [Online database], Instituto Nacional de Estadística y Geografía. Available: http://dgcnesyp.inegi.org.mx/cgi-win/ehm.exe/I [Accessed Nov 2012 - Feb 2013]

INEGI, 2011. Mexico en cifras [Online database], Instituto Nacional de Estadística y Geografía. Available: http://www3.inegi.org.mx/sistemas/mexicocifras/ [Accessed Nov 2012]

INEGI, 2012. Banco de información estadística [Online database], Instituto Nacional de Estadística y Geografía. Available: http://www.inegi.org.mx/sistemas/bie/ [Accessed Nov 2012-Feb 2013]

IPCC, 2007. Climate Change 2007: Mitigation of Climate Change. Cambridge University Press, Cambridge.

Jackson, R., Murray, A., 2004. Alternative input-output matrix updating formulations. Economic Systems Research, 16, 135-148.

Jacobsen, H.K., 2000. Energy demand, strctural change and trade: A decomposition analysis of the Danish manufacturing industry. Economic Systems Research, 12, 319-343.

Jansen, P.K., Ten Raa, T., 1990. The choice of model in the construction of input-output coefficients matrices. International Economic Review, 31, 213-227.

Jiang, Z., Lin, B., 2012. China's energy demand and its characteristics in the industrialization and urbanization process. Energy Policy, 49, 608-615.

Jonsson, D., Gustafsson, S., Wangel, J., Höjer, M., Lundqvist, P., Svane, Ö., 2011. Energy at your service: Highlighting energy usage systems in the context of energy efficiency analysis. Energy Efficiency, 4, 355-369.

Kagawa, S., Inamura, H., 2001. A structural decomposition of energy consumption based ona a hybrid rectangular input-output framework: Japan's case. Economic Systems Research, 13, 339-363.

Kagawa, S., Inamura, H., 2004. A spatial structural decomposition analysis of Chinese and Japanese energy demand: 1985–1990. Economic Systems Research, 16, 279-299.

Kahrl, F., Roland-Holst, D., 2008. Energy and exports in China. China Economic Review, 19, 649-658.

Kahrl, F., Roland-Holst, D., 2009. Growth and structural change in China's energy economy. Energy, 34, 894-903.

Khatib, H., 1995. Energy intensity: A new look. Energy Policy, 23, 727-729.

Krenz, J.H., 1974. Energy per dollar value of consumer goods and services. IEEE Transactions on Systems, Man and Cybernetics, SMC-4, 386-388.

Kuntz, S., 2012. Historia Mínima de la Economía Mexicana, 1519-2010. Colegio México, Mexico D.F.

Lee, C.F., Lin, S.J., 2001. Structural decomposition of CO_2 emissions from Taiwan's petrochemical industries. Energy Policy, 29, 237-244.

Leite, A.N., 2010. A internacionalização da economia portuguesa. Relações Internacionais, 119-132.

Leontief, W., 1955. Some basic problems of empirical input-output analysis, in: National Bureau of Economic Research (Ed.), Input-Output Analysis: An Appraisal. Princeton University Press, Princeton, pp. 137-182.

Leontief, W., 1986. Input-Output Economics. Oxford University Press, Oxford.

Leontief, W.W., 1936. Quantitative input and output relations in the economic systems of the United States. Review of Economics and Statistics, 18, 105-125.

Liang, S., Wang, C., Zhang, T., 2010. An improved input–output model for energy analysis: A case study of Suzhou. Ecological Economics, 69, 1805-1813.

Liao, H., Wang, C., Zhu, Z., Ma, X., 2013. Structural decomposition analysis on energy intensity changes at regional level. Transactions of Tianjin University, 19, 287-292.

Liddle, B., 2010. Revisiting world energy intensity convergence for regional differences. Applied Energy, 87, 3218-3225.

Lightfoot, H.D., 2007. Understand the three different scales for measuring primary energy and avoid errors. Energy, 32, 1478-1483.

Lim, H.-J., Yoo, S.-H., Kwak, S.-J., 2009. Industrial CO_2 emissions from energy use in Korea: A structural decomposition analysis. Energy Policy, 37, 686-698.

Limmeechokchai, B., Suksuntornsiri, P., 2007. Embedded energy and total greenhouse gas emissions in final consumptions within Thailand. Renewable and Sustainable Energy Reviews, 11, 259-281.

Lin, J.Y., 2009. Economic Development and Transition: Thought, Strategy, and Viability. Cambridge University Press, Cambridge, MA.

Lin, X., Polenske, K.R., 1995. Input–output anatomy of China's energy use changes in the 1980's. Economic Systems Research, 7, 67-84.

Lindner, S., Li, X., Guan, D., Hubacek, K., 2011. Embodied energy of Chinese Provinces, 19th International Input–Output Conference. IIOA, Alexandria.

Liu, H., Xi, Y., Guo, J.e., Li, X., 2010. Energy embodied in the international trade of China: An energy input–output analysis. Energy Policy, 38, 3957-3964.

Liu, N., Ang, B.W., 2007. Factors shaping aggregate energy intensity trend for industry: Energy intensity versus product mix. Energy Economics, 29, 609-635.

Liu, X.Q., Ang, B.W., Ong, H.L., 1992. The application of the Divisia index to the decomposition of changes in industrial energy consumption. The Energy Journal, 13, 161-177.

Llop, M., 2007. Economic structure and pollution intensity within the environmental input–output framework. Energy Policy, 35, 3410-3417.

Looney, R.E., 1985. Economic Policymaking in Mexico: Factors Underlying the 1982 Crisis. Duke University Press, Durham.

Lourtie, P., 2012. Understanding Portugal in the context of the Euro crisis, in: Cline, W.R., Wolff, G. (Eds.), Resolving the European Debt Crisis: Special Report 21. Peterson Institute for International Economics, Brussels.

Lovins, A.B., 2004. Energy efficiency: Taxonomic overview, in: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Volumen 2. Elsevier, New York, NY, pp. 383-401.

Ma, L., Allwood, J.M., Cullen, J.M., Li, Z., 2012. The use of energy in China: Tracing the flow of energy from primary source to demand drivers. Energy, 40, 174-188.

Machado, G., Schaeffer, R., Worrell, E., 2001. Energy and carbon embodied in the international trade of Brazil: an input–output approach. Ecological Economics, 39, 409-424.

Machado, G.V., 2000. Energy use, CO_2 emissions and foreign trade: an IO approach applied to the Brazilian case, 13th International Conference on Input–Output Techniques. IIOA, Macerata.

MacKay, D.J.C., 2008. Sustainable energy without the hot air. Cambridge University Press, Cambridge, MA.

Maital, S., 1972. The Tableau Economique as a simple Leontief model: An amendment. The Quarterly Journal of Economics, 86, 504-507.

Maqueda, M.R., Sánchez, L.A., 2008. Curvas de demanada de energía eléctrica en el sector doméstico de dos regiones de México, Smart metering West Coast conference. Metering International Magazine, Seattle, WA.

Markandya, A., Pedroso-Galinato, S., Streimikiene, D., 2006. Energy intensity in transition economies: Is there convergence towards the EU average? Energy Economics, 28, 121-145.

Marques, A., Rodrigues, J.F.D., Lenzen, M., Domingos, T., 2012. Income-based environmental responsibility. Ecological Economics, 84, 57-65.

Martin, J.-C., Becuwe, S., 2014. Regionalising the results of a national structural decompositon anlysis of greenhouse gas emissions: An application to Aquitaine region. Environmental Modeling & Assessment, 19, 257-269.

Mata, E., Valério, N., 2003. História Económica de Portugal: Uma Perspectiva Global, 2nd Ed. ed. Editorial Presença, Lisboa.

McCaa, R., 1997. The peopling of Mexico from origins to revolution in: Haines, M.R., Steckel, R.H. (Eds.), A Population History of North America. Cambridge University Press, Cambridge, pp. 241-304.

MEI, 2008. Decreto-Lei n.º 71/2008. Diário da República, 1, 2222-2226.

Mendiluce, M., Pérez-Arriaga, I., Ocaña, C., 2010. Comparison of the evolution of energy intensity in Spain and in the EU15. Why is Spain different? Energy Policy, 38, 639-645.

Merrill, T.L., Miroì, R., 1997. Mexico: Social indicators, in: Library of Congress (Ed.), Country Studies, Washington, DC.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions, 2nd ed. Cambridge University Press, Cambridge.

Moran, M.J., Shapiro, H.N., Boettner, D.D., Bailey, M., 2006. Fundamentals of Engineering Thermodynamics. John Wiley & Sons, Sussex.

Mukhopadhyay, K., 2002. A structural decomposition analysis of air pollution from fossil fuel combustion in India. International Journal of Environment and Pollution, 18, 486-497.

Mukhopadhyay, K., Chakraborty, D., 1999. India's energy consumption changes during 1973/74 to 1991/92. Economic Systems Research, 11, 423-438.

Mukhopadhyay, K., Forssell, O., 2005. An empirical investigation of air pollution from fossil fuel combustion and its impact on health in India during 1973–1974 to 1996–1997. Ecological Economics, 55, 235-250.

Mulder, P., de Groot, H.L.F., 2004. Decoupling Economic Growth and Energy Use: An Empirical Cross-Country Analysis for 10 Manufacturing Sectors. Tinbergen Institute, Amsterdam.

Munksgaard, J., Pedersen, K.A., Wien, M., 2000. Impact of household consumption on CO_2 emissions. Energy Economics, 22, 423-440.

Nakićenović, N., Gilli, P.V., Kurz, R., 1996. Regional and global exergy and energy efficiencies. Energy, 21, 223-237.

Nakićenović, N., Grübler, A., 1993. Energy conversion, conservation, and efficiency. Energy, 18, 421-435.

Nakićenović, N., Grübler, A., Inaba, A., Messner, S., Nilsson, S., Nishimura, Y., Rogner, H.-H., Schäfer, A., Schrattenholzer, L., Strubegger, M., Swisher, J., Victor, D., Wilson, D., 1993. Long-term strategies for mitigating global warming. Energy, 18, 401.

Neumayer, E., 2000. Scarce or Abundant? The Economics of Natural Resource Availability. Journal of Economic Surveys, 14, 307-335.

Nie, H.-g., Zhang, S.-j., 2013. Decomposition analysis on changes of energy efficiency in China, International Conference on Management Science and Engineering, Harbin.

Nie, H., Kemp, R., 2013. Why did energy intensity fluctuate during 2000–2009?: A combination of index decomposition analysis and structural decomposition analysis. Energy for Sustainable Development, 17.

Nordhaus, W.D., 1997. Do real output and real wage measures capture reality? The history of lighting suggests not, in: Bresnahan, T.F., Gordon, R.J. (Eds.), The Economics of New Goods. University of Chicago Press, Chicago, IL, pp. 29-66.

Ockwell, D.G., 2008. Energy and economic growth: Grounding our understanding in physical reality. Energy Policy, 36, 4600-4604.

OECD, 2011. OECD.Stat [Online database], Organisation for Economic Co-operation and Development. Available: http://stats.oecd.org/ [Accessed Nov 2012]

Okushima, S., Tamura, M., 2007. Multiple calibration decomposition analysis: Energy use and carbon dioxide emissions in the Japanese economy, 1970–1995. Energy Policy, 35, 5156-5170.

Okushima, S., Tamura, M., 2010. What causes the change in energy demand in the economy?: The role of technological change. Energy Economics, 32, Supplement 1, S41-S46.

Okushima, S., Tamura, M., 2011. Identifying the sources of energy use change: Multiple calibration decomposition analysis and structural decomposition analysis. Structural Change and Economic Dynamics, 22, 313-326.

Orecchini, F., 2006. The era of energy vectors. International Journal of Hydrogen Energy, 31, 1951-1954.

Orecchini, F., Naso, V., 2012. Energy Systems in the Era of Energy Vectors. Springer, London.

Östblom, G., 1982. Energy use and structural changes: Factors behind the fall in Sweden's energy output ratio. Energy Economics, 4, 21-28.

Pachauri, S., Spreng, D., 2004. Energy use and energy access in relation to poverty. Economic and Political weekly, 39, 271-278.

Palma, M., 2014. Improvements on useful work accounting. M.Sc. Dissertation. University of Lisbon, Lisbon.

Park, H.-C., Heo, E., 2007. The direct and indirect household energy requirements in the Republic of Korea from 1980 to 2000: An input–output analysis. Energy Policy, 35, 2839-2851.

Park, S.-H., 1982. An input-output framework for analysing energy consumption. Energy Economics, 4, 105-110.

Patterson, M.G., 1993. An accounting framework for decomposing the energy-to-GDP ratio into its structural components of change. Energy, 18, 741-761.

Patterson, M.G., 1996. What is energy efficiency?: Concepts, indicators and methodological issues. Energy Policy, 24, 377-390.

Peng, Y., Shi, C., 2011. Determinants of carbon emissions growth in China: A structural decomposition analysis. Energy Procedia, 5, 169-175.

Percebois, J., 1979. Is the concept of energy intensity meaningful? Energy Economics, 1, 148-155.

Peters, G.P., 2008. From production-based to consumption-based national emission inventories. Ecological Economics, 65, 13-23.

Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2007. China's growing CO_2 Emissions: A race between increasing consumption and efficiency gains. Environmental Science & Technology, 41, 5939-5944.

Phillips, A., 1955. The Tableau Economique as a simple Leontief model. The Quarterly Journal of Economics, 69, 137-144.

Piantanakulchai, M., Inamura, H., 1999. The decomposition for the sources of changes in carbon emission intensities: A case study of arbon emission from road construction work in Japan during 1975-1990. Journal of the Eastern Asia Society for Transportation Studies, 3, 9-18.

Proops, J.L.R., 1977. Input-output analysis and energy intensities: A comparison of some methodologies. Applied Mathematical Modelling, 1, 181-186.

Proops, J.L.R., 1984. Modelling the energy-output ratio. Energy Economics, 6, 47-51.

Recalde, M., Ramos-Martin, J., 2012. Going beyond energy intensity to understand the energy metabolism of nations: The case of Argentina. Energy, 37, 122-132.

Reinders, A.H.M.E., Vringer, K., Blok, K., 2003. The direct and indirect energy requirement of households in the European Union. Energy Policy, 31, 139-153.

Reynolds, C.W., 1978. Why Mexico's 'stabilizing development' was actually destabilizing (with some implications for the future). World Development, 6, 1005-1018.

Rhee, H.-C., Chung, H.-S., 2006. Change in CO_2 emission and its transmissions between Korea and Japan using international input–output analysis. Ecological Economics, 58, 788-800.

Robaina Alves, M., Moutinho, V., 2013. Decomposition analysis and Innovative Accounting Approach for energy-related CO_2 (carbon dioxide) emissions intensity over 1996–2009 in Portugal. Energy, 57, 775-787.

Roca, J., Serrano, M., 2007. Income growth and atmospheric pollution in Spain: An input–output approach. Ecological Economics, 63, 230-242.

Rodrigues, J., Reis, J., 2012. The asymmetries of European integration and the crisis of capitalism in Portugal. Competition & Change, 16, 188-205.

Rodrigues, J.F.D., Domingos, T., Marques, A., 2010. Carbon Responsibility and Embodied Emissions: Theory and Measurement. Routledge, Taylor & Francis, London.

Rodrigues, J.F.D., Rueda-Cantuche, J.M., 2013. A two-stage econometric method for the estimation of carbon multipliers with rectangular supply and use tables. Ecological Economics, 95, 206-212.

Rosas, J., Sheinbaum, C., Morillon, D., 2010. The structure of household energy consumption and related CO_2 emissions by income group in Mexico. Energy for Sustainable Development, 14, 127-133.

Rose, A., 1999. Input-output structural decomposition analysis of energy and the environment, in: Van den Bergh, J.C.J.J. (Ed.), Handbook of environmental and resource economics. Edward Elgar Publishing, Cheltenham.

Rose, A., Casler, S., 1996. Input–output structural decomposition analysis: A critical appraisal. Economic Systems Research, 8, 33-62.

Rose, A., Miernyk, W., 1989. Input–output analysis: The first fifty years. Economic Systems Research, 1, 229-272.

Rosen, M.A., 2004. Exergy analysis of energy systems, in: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Volume 2. Elsevier, New York, NY, pp. 607-621.

Rosen, M.A., Bulucea, C.A., 2009. Using exergy to understand and improve the efficiency of electrical power technologies. Entropy, 11, 820-835.

Rosenthal, E., 2010. Portugal gives itself a clean-energy makeover, The New York Times, New York, NY.

Rubio, M.d.M., Folchi, M., 2012. Will small energy consumers be faster in transition? Evidence from the early shift from coal to oil in Latin America. Energy Policy, 50, 50-61.

Santos, G.F., Haddad, E.A., Guilhoto, J.J., Imori, D., 2009. Spatial interactions between energy and energy-intensive sectors in the Brazilian economy: A field of influence approach, 17th International Input–Output Conference. IIOA, São Paulo.

Santos, J., 2013. The role of energy in economic growth: A two-sector model with useful work. M.Sc. Dissertation. University of Lisbon, Lisbon.

Santos, J., Domingos, T., Sousa, T., Serrenho, A., 2013. National accounts with a broader energy sector. University of Lisbon, Lisbon.

Schmidt, M., 2008a. The Sankey diagram in energy and material flow management: Part I: History. Journal of Industrial Ecology, 12, 82-94.

Schmidt, M., 2008b. The Sankey diagram in energy and material flow management: Part II: Methodology and current applications. Journal of Industrial Ecology, 12, 173-185.

Schütz, H., Bringezu, S., Moll, S., 2004. Globalisation and the shifting environmental burden: Material trade flows of the European Union. Wuppertal Institute, Wuppertal.

Seibel, S., 2003. Decomposition analysis of carbon dioxide emission changes in Germany: Conceptual framework and empirical results, in: Eurostat (Ed.), Working Papers and Studies, Luxemburg.

SENER, 2013. Sistema de información energética [Online database], Secretaría de Energía, Mexico D.F. Available: http://sie.energia.gob.mx/ [Accessed Oct 2013]

SENER, IEA, 2011. Indicadores de Eficiencia energética en Mexico: 5 sectores, 5 retos. Secretaría de Energía, Mexico D.F.

Serrenho, A., 2013. Useful work as and energy end-use accounting method: Historical and economic transitions and european patterns. Ph.D. Dissertation. University of Lisbon, Lisboa.

Serrenho, A., Warr, B., Sousa, T., Ayres, R.U., Domingos, T., 2012. Useful work accounting in Portugal, 1856 - 2009, 5th Annual International ESP Conference, Portland, OR.

Serrenho, A., Warr, B., Sousa, T., Ayres, R.U., Domingos, T., 2013. Useful work transitions for Portugal from 1856 to 2009: Intensities and European patterns., International Conference on Energy & Environment. University of Porto, Porto.

Serrenho, A.C., Sousa, T., Warr, B., Ayres, R.U., Domingos, T., 2014. Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009. Energy (In Press).

SETRAVI. 2005. Cronología del Transporte en la Ciudad de México [Online]. Available: http://www.setravi.df.gob.mx/wb/stv/cronologia_del_transporte_en_la_ciudad_de_mexico_

Sheinbaum, C., Martínez, M., Rodríguez, L., 1996. Trends and prospects in Mexican residential energy use. Energy, 21, 493-504.

Sheinbaum, C., Mora, S., Robles, G., 2012. Decomposition of energy consumption and CO_2 emissions in Mexican manufacturing industries: Trends between 1990 and 2008. Energy for Sustainable Development, 16, 57-67.

Sheinbaum, C., Ozawa, L., 1998. Energy use and CO_2 emissions for Mexico's cement industry. Energy, 23, 725-732.

Sheinbaum, C., Ozawa, L., Castillo, D., 2010. Using logarithmic mean Divisia index to analyze changes in energy use and carbon dioxide emissions in Mexico's iron and steel industry. Energy Economics, 32, 1337-1344.

Sheinbaum, C., Rodríguez V, L., 1997. Recent trends in Mexican industrial energy use and their impact on carbon dioxide emissions. Energy Policy, 25, 825-831.

Sheinbaum, C., Ruíz, B.J., Ozawa, L., 2011. Energy consumption and related CO_2 emissions in five Latin American countries: Changes from 1990 to 2006 and perspectives. Energy, 36, 3629-3638.

Shirvani-Mahdavi, A., 1999. Energy-intensity factors for Shanxi Province and China: Shift-share and interregional structural decomposition analysis. M.Sc. Dissertation. Massachusetts Institute of Technology, Massachusetts

Smil, V., 1994. Energy in World History. Westview Press, Boulder.

Smil, V., 2000. Energy in the twentieth century: Resources, conversions, costs, uses, and consequences. Annual Review of Energy and the Environment, 25, 21-51.

Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. MIT Press, Cambridge, MA.

Smil, V., 2003. Energy at the Crossroads: Global Perspectives and Uncertainties. MIT Press, Cambridge, MA.

Smil, V., 2008. Energy in Nature and Society: General Energetics of Complex Systems. MIT Press, Cambridge, MA.

Smith, J.L., 2012. On the portents of peak oil (and other indicators of resource scarcity). Energy Policy, 44, 68-78.

SMN, 2010. Normales meteorológicas 1951-2000 [Online database], Servicio Meteorológico Nacional. Available:

http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=42&Itemid=75 [Accessed Nov 2012]

Solís, J.C., Sheinbaum, C., 2013. Energy consumption and greenhouse gas emission trends in Mexican road transport. Energy for Sustainable Development, 17, 280-287.

Sorman, A.H., Giampietro, M., 2011. Generating better energy indicators: Addressing the existence of multiple scales and multiple dimensions. Ecological Modelling, 223, 41-53.

Sovacool, B.K., 2011. Conceptualizing urban household energy use: Climbing the "Energy Services Ladder". Energy Policy, 39, 1659-1668.

Stawinska, A., 2009. Energy sector in Europe EUROSTAT, Paris.

Stern, D.I., 1999. Use value, exchange value, and resource scarcity. Energy Policy, 27, 469-476.

Stern, D.I., 2010. Energy quality. Ecological Economics, 69, 1471-1478.

Stern, D.I., 2011. The role of energy in economic growth. Annals of the New York Academy of Sciences, 1219, 26-51.

Strømman, A.H., Peters, G.P., Hertwich, E.G., 2009. Approaches to correct for double counting in tiered hybrid life cycle inventories. Journal of Cleaner Production, 17, 248-254.

Su, B., Ang, B.W., 2012a. Structural decomposition analysis applied to energy and emissions: Aggregation issues. Economic Systems Research, 24, 299-317.

Su, B., Ang, B.W., 2012b. Structural decomposition analysis applied to energy and emissions: Some methodological developments. Energy Economics, 34, 177-188.

Su, B., Ang, B.W., 2013. Input–output analysis of CO2 emissions embodied in trade: Competitive versus non-competitive imports. Energy Policy, 56, 83-87.

Su, B., Ang, B.W., 2014. Input–output analysis of CO_2 emissions embodied in trade: A multi-region model for China. Applied Energy, 114, 377-384.

Suh, S., 2009. Handbook of Input-Output Analysis Economics in Industrial Ecology. Springer, Dordrecht.

Summers, C.M., 1971. The conversion of energy. Scientific American, 224, 148-160.

Ten Raa, T., Rueda-Cantuche, J.M., 2003. The construction of input–output coefficients matrices in an axiomatic context: Some further considerations. Economic Systems Research, 15, 439-455.

The World Bank, 1979. Mexico - Manufacturing Sector: Situation, Prospect and Policies. The World Bank, Washington, DC.

The World Bank, 2011. Data by country [Online database], The World Bank. Available: http://data.worldbank.org/ [Accessed Nov 2012]

Thi Anh Tuyet, N., Ishihara, K.N., 2006. Analysis of changing hidden energy flow in Vietnam. Energy Policy, 34, 1883-1888.

Tian, X., Chang, M., Tanikawa, H., Shi, F., Imura, H., 2013. Structural decomposition analysis of the carbonization process in Beijing: A regional explanation of rapid increasing carbon dioxide emission in China. Energy Policy, 53, 279-286.

Treloar, G.J., 1997. Extracting embodied enegy paths from input-output tables: Towards an input-output-based hybrid energy analysis method. Economic Systems Research, 9, 375-391.

U.S. Census Bureau, 1995. Population of United States [Online database], U.S. Census Bureau. Available: http://www.census.gov/population/censusdata/urpop0090.txt [Accessed Nov 2012]

U.S. Census Bureau, 2010. Computer and internet use [Online database], U.S. Census Bureau. Available: http://www.census.gov/hhes/computer/publications/2010.html [Accessed Nov 2012]

UN, 1982. Concepts and methods in energy statistics with special reference to energy accounts and balances: A technical report. United Nations, New York, NY.

UN, 1993. System of National Accounts 1993. United Nations, New York, NY.

UN, 1999. Handbook of Input-Output Table Compilation and Analysis. United Nations, New York, NY.

UN, 2009. System of National Accounts 2008. United Nations, New York, NY.

UNAM. 2012. Historia económica de México [Web Page]. Available: http://www.economia.unam.mx/sua/site/materia/sem5/histecmexico2/presentacion.html [Accessed 23 Oct 2012]

UNDP, 2000. World Energy Assessment: Energy and the Challenge of Sustainability. United Nations Development Programme, New York, NY.

UNDP, 2004. World Energy Assessment: Overview: 2004 Update. United Nations Development Programme, New York, NY.

UNEP 2011. Decoupling natural resource use and environmental impacts from economic growth [ebook]. United Nations Environment Programme, Paris. Available: http://www.unep.org/resourcepanel/decoupling/files/pdf/decoupling_report_english.pdf

UNFCCC, 2008. Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount. United Nations Framework Convention on Climate Change, Bonn.

Uri, N.D., 1995. A reconsideration of effect of energy scarcity on economic growth. Energy, 20, 1-12.

USDA, 2012. Production, Supply and Distribution [Online database], U.S. Department of Agriculture. Available: http://www.fas.usda.gov/psdonline/ [Accessed Nov 2012]

Valdez, J., 2003. Perspectives of natural gas in Mexico, IAEE North American conference. The International Association for Energy Economics, Mexico D.F.

Valero, A., 2006. Exergy accounting: Capabilities and drawbacks. Energy, 31, 164-180.

Voigt, S., De Cian, E., Schymura, M., Verdolini, E., 2014. Energy intensity developments in 40 major economies: Structural change or technology improvement? Energy Economics, 41, 47-62.

Wachsmann, U., Wood, R., Lenzen, M., Schaeffer, R., 2009. Structural decomposition of energy use in Brazil from 1970 to 1996. Applied Energy, 86, 578-587.

Wall, G., 2004. Exergy, in: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Volume 2. Elsevier, New York, NY, pp. 593-606.

Wall, G., 2009. Exergetics. Exergy, Ecology, Democracy, Bucaramanga.

Wall, G., Gong, M., 2001. On exergy and sustainable development—Part 1: Conditions and concepts. Exergy, an International Journal, 1, 128-145.

Wallace, R.-B., 2009. Coal in Mexico. Economia Informa, 359.

Wang, H., 2011. Decoupling Measure between Economic Growth and Energy Consumption of China. Energy Procedia, 5, 2363-2367.

Wang, Y., Zhao, H., Li, L., Liu, Z., Liang, S., 2013. Carbon dioxide emission drivers for a typical metropolis using input–output structural decomposition analysis. Energy Policy, 58, 312-318.

Wang, Z., Liu, W., Yin, J., 2014a. Driving forces of indirect carbon emissions from household consumption in China: An input–output decomposition analysis. Natural Hazards, 1-16.

Wang, Z., Yuming, S., Yueyun, Z., 2014b. Increased CO_2 emissions from energy consumption based on three-level nested IO structural decomposition analysis for Beijing. Journal of Resources and Ecology, 5, 115-122.

Warr, B., Ayres, R.U., 2010. Evidence of causality between the quantity and quality of energy consumption and economic growth. Energy, 35, 1688-1693.

Warr, B., Ayres, R.U., 2012. Useful work and information as drivers of economic growth. Ecological Economics, 73, 93-102.

Warr, B., Ayres, R.U., Eisenmenger, N., Krausmann, F., Schandl, H., 2010. Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. Ecological Economics, 69, 1904-1917.

Warr, B., Schandl, H., Ayres, R.U., 2008. Long term trends in resource exergy consumption and useful work supplies in the UK, 1900 to 2000. Ecological Economics, 68, 126-140.

Weber, C.L., 2009. Measuring structural change and energy use: Decomposition of the US economy from 1997 to 2002. Energy Policy, 37, 1561-1570.

WEF, 2012. Energy for economic growth. World Economic Forum, Cambridge.

Weisz, H., Krausmann, F., Amann, C., Eisenmenger, N., Erb, K.-H., Hubacek, K., Fischer-Kowalski, M., 2006. The physical economy of the European Union: Cross-country comparison and determinants of material consumption. Ecological Economics, 58, 676-698.

Wier, M., 1998. Sources of changes in emissions from energy: A strutural decomposition analysis. Economic Systems Research, 10, 99-112.

Wier, M., Hasler, B., 1999. Accounting for nitrogen in Denmark: A structural decomposition analysis. Ecological Economics, 30, 317-331.

Wilson, D.G., Whitt, F.R., Papadopoulos, J., 2004. Bicycling Science. MIT Press, Cambridge, MA.

Wirl, F., 1995. Impact of regulation on demand side conservation programs. Journal of Regulatory Economics, 7, 43-62.

Wirsenius, S., 2000. Human use of land and organic materials: Modeling the turnover of biomass in the global food system. Ph.D. Dissertation. Chalmers University of Technology, Goteborg.

Wolde-Rufael, Y., 2005. Energy demand and economic growth: The African experience. Journal of Policy Modeling, 27, 891-903.

Wood, R., 2009. Structural decomposition analysis of Australia's greenhouse gas emissions. Energy Policy, 37, 4943-4948.

Wood, R., 2011. Construction, stability and predictability of an input-output time-series for Australia. Economic Systems Research, 23, 175-211.

Wood, R., Lenzen, M., 2009. Structural path decomposition. Energy Economics, 31, 335-341.

Worrell, E., Price, L., Martin, N., Farla, J., Schaeffer, R., 1997. Energy intensity in the iron and steel industry: A comparison of physical and economic indicators. Energy Policy, 25, 727-744.

Wright, D.J., 1974. Good and services: An input-output analysis. Energy Policy, 2, 307-315.

Wright, D.J., 1975. The natural resource requirements of commodities. Applied Economics, 7, 31-39.

Wu, J.-H., Chen, Y.-Y., Huang, Y.-H., 2007. Trade pattern change impact on industrial CO_2 emissions in Taiwan. Energy Policy, 35, 5436-5446.

Wu, R.-H., Chen, C.-Y., 1990. On the application of input-output analysis to energy issues. Energy Economics, 12, 71-76.

Xie, S.-C., 2014. The driving forces of China's energy use from 1992 to 2010: An empirical study of input–output and structural decomposition analysis. Energy Policy, 73, 401-415.

Xu, M., Li, R., Crittenden, J.C., Chen, Y., 2011. CO_2 emissions embodied in China's exports from 2002 to 2008: A structural decomposition analysis. Energy Policy, 39, 7381-7388.

Xu, X., 2013. Index decomposition analysis of energy consumption and carbon emissions: Some methodological issues. Ph.D. Dissertation. National University of Singapore, Singapore.

Xu, X.Y., Ang, B.W., 2013. Index decomposition analysis applied to CO_2 emission studies. Ecological Economics, 93, 313-329.

Xu, X.Y., Ang, B.W., 2014. Analysing residential energy consumption using index decomposition analysis. Applied Energy, 113, 342-351.

Xu, Y., Dietzenbacher, E., 2014. A structural decomposition analysis of the emissions embodied in trade. Ecological Economics, 101, 10-20.

Yabe, N., 2004. An analysis of CO_2 emissions of Japanese industries during the period between 1985 and 1995. Energy Policy, 32, 595-610.

Yamakawa, A., Peters, G.P., 2011. Structural decomposition analysis of greenhouse gas emissions in Norway 1990–2002. Economic Systems Research, 23, 303-318.

Yuan, L.B., 2012. A structural decomposition analysis of CO_2 emission in China. Advanced Materials Research, 361, 1756-1760.

Yun, Z., Xiuzhen, L., 2011. Structural decomposition analysis of domestic CO_2 emissions from export products of industrial sectors in China, International Conference on Management and Service Science, Wuhan.

Zeng, L., Xu, M., Liang, S., Zeng, S., Zhang, T., 2014. Revisiting drivers of energy intensity in China during 1997–2007: A structural decomposition analysis. Energy Policy, 67, 640-647.

Zhang, H., Lahr, M.L., 2014a. Can the carbonizing dragon be domesticated? Insigths from a decomposition of energy consumption and intensity in China 1987–2007. Economic Systems Research, 26, 119-140.

Zhang, H., Lahr, M.L., 2014b. China's energy consumption change from 1987 to 2007: A multi-regional structural decomposition analysis. Energy Policy, 67, 682-693.

Zhang, Y., 2009. Structural decomposition analysis of sources of decarbonizing economic development in China; 1992–2006. Ecological Economics, 68, 2399-2405.

Zhang, Y., 2010. Supply-side structural effect on carbon emissions in China. Energy Economics, 32, 186-193.

A. Appendix to Chapter 4

This appendix presents a comparison of the hybrid-unit and the primary-to-final energy input-output models applied to a simple economy. The comparison focuses on the effect of the level of independence of the energy sector in the correspondences between the elements of these models (i.e. $\boldsymbol{\alpha}$, $\boldsymbol{L}^E$, $\boldsymbol{C}^E$, $\boldsymbol{T}^E$ and $\boldsymbol{L}^M$), based in Equation (4.13).

A.1 An economy with an independent energy sector

The economy consists of six producing sectors and on one category of final demand. Table A-1 show the interindustry transactions in monetary units and Table A-2 presents the energy flows in physical units. Energy industries are completely independent from the rest of the economy, i.e. energy inputs accounts for 100% share of all inputs to the energy sector.

Table A-1 Monetary interindustry transactions of an economy with an independent energy sector

	Oil	Gas	Electricity	Manufacturing	Services	Materials	Final demand	Total output
Oil	0	0	12.5	6	3.5	2.4	10.5	34.9
Gas	0	0	6	3.15	0.75	0.45	2	12.35
Electricity	1.5	0.7	0.5	3.75	6.3	1.5	9.9	24.15
Manufacturing	-	-	-	50	100	30	200	380
Services	-	-	-	130	50	20	150	410
Materials	-	-	-	80	5	0	5	130

Units MUSD

Table A-2 Energy flows

	Oil	Gas	Electricity	Manufacturing	Services	Materials	Final demand	Total output
Oil	0	0	250	100	50	40	150	590
Gas	0	0	150	70	15	10	40	285
Electricity	10	5	5	25	35	10	55	145

Units TJ

Interindustry transactions and energy flows data are used to build the hybrid-unit and the primary-to-final energy input-output models. The models, as explained theoretically in Section 4.2.1, are equivalent to each other.

The example shows that the sub-matrix $\boldsymbol{\theta}^*$ of the hybrid-unit total requirements matrix ($\boldsymbol{\alpha}$) is equal to $\boldsymbol{L}^E$:

$$\boldsymbol{\theta}^* = \boldsymbol{L}^E = \begin{bmatrix} 1.031 & 0.033 & 1.878 \\ 0.019 & 1.020 & 1.127 \\ 0.018 & 0.019 & 1.089 \end{bmatrix} \text{ MJ/MJ}$$

and the sub-matrix $\boldsymbol{\tau}^*$ of $\boldsymbol{\alpha}$ is equal to the columns of non-energy producing sectors of the matrix product $\boldsymbol{L}^E\boldsymbol{C}^E\boldsymbol{T}^E\boldsymbol{L}^M$:

$$\boldsymbol{\tau}^* = \begin{bmatrix} 1.051 & 0.763 & 1.191 \\ 0.590 & 0.391 & 0.531 \\ 0.240 & 0.215 & 0.259 \end{bmatrix} \text{ MJ/MUSD}$$

$$\boldsymbol{L}^E\boldsymbol{C}^E\boldsymbol{T}^E\boldsymbol{L}^M = \begin{bmatrix} 0 & 0 & 0 & 1.051 & 0.763 & 1.191 \\ 0 & 0 & 0 & 0.590 & 0.391 & 0.531 \\ 0 & 0 & 0 & \underbrace{0.240 \quad 0.215 \quad 0.259}_{\text{Non-energy industries}} \end{bmatrix} \text{ MJ/MUSD}$$

If the energy sector is 100% independent from the rest of the economy, the primary-to-final model can be reduced to the conventional hybrid-unit model. Therefore, the advantage of the PF model is that it organizes the energy transactions according to the energy conversion processes in the economy.

A.2 An economy with a relatively independent energy sector

The economy of the previous example is modified so the energy sector becomes relatively independent (i.e. 70% of all inputs to this sector are energy inputs).

Table A-3 Monetary interindustry transactions of an economy with a relatively independent energy sector (70% independence)

	Oil	Gas	Electricity	Manufacturing	Services	Materials	Final demand	Total output
Oil	0	0	12.5	6	3.5	2.4	10.5	34.9
Gas	0	0	6	3.15	0.75	0.45	2	12.35
Electricity	1.5	0.7	0.5	3.75	6.3	1.5	9.9	24.15
Manufacturing	0.5	0.3	2	50	100	30	200	382.8
Services	0.8	1	2	130	50	20	150	413.8
Materials	0.7	0.2	1	80	5	0	5	131.9

Units MUSD

Analogously to the previous section, a hybrid-unit and primary-to-final energy input-output-models are built for this economy and compared. In this case, $\boldsymbol{\theta}^*$ is not equal to $\boldsymbol{L}^E$:

$$\boldsymbol{\theta}^* = \begin{bmatrix} 1.036 & 0.038 & 1.925 \\ 0.021 & 1.023 & 1.151 \\ 0.019 & 0.020 & 1.101 \end{bmatrix} \qquad \boldsymbol{L}^E = \begin{bmatrix} 1.032 & 0.033 & 1.878 \\ 0.019 & 1.020 & 1.127 \\ 0.018 & 0.019 & 1.089 \end{bmatrix} \text{ MJ/MJ}$$

though the error between entries of these matrices is small, i.e. $\left(\theta^*_{kl} - L^E_{kl}\right)/\theta^*_{kl} < 14\%$

On the other hand, $\boldsymbol{\tau}^*$ is approximately equal to the columns of non-energy producing sectors of $\boldsymbol{L}^E\boldsymbol{C}^E\boldsymbol{T}^E\boldsymbol{L}^M$:

$$\boldsymbol{\tau}^* = \begin{bmatrix} 1.039 & 0.755 & 1.168 \\ 0.584 & 0.387 & 0.521 \\ 0.237 & 0.213 & 0.254 \end{bmatrix} \text{MJ/MUSD}$$

$$\boldsymbol{L}^E\boldsymbol{C}^E\boldsymbol{T}^E\boldsymbol{L}^M = \begin{bmatrix} 0.07 & 0.12 & 0.27 & 1.039 & 0.756 & 1.168 \\ 0.03 & 0.06 & 0.14 & 0.584 & 0.387 & 0.521 \\ \underbrace{0.02 \quad 0.03 \quad 0.07}_{\text{Error from } \boldsymbol{\theta}^* \text{ and } \boldsymbol{L}^E \text{ differences}} & & & \underbrace{0.237 \quad 0.213 \quad 0.254}_{\text{Non-energy industries}} & & \end{bmatrix} \text{MJ/MUSD}$$

If the energy sector is 70% independent from the rest of the economy, there are differences between the primary-to-final and the conventional hybrid-unit models. However the differences are small, especially for $\boldsymbol{\tau}^*$ and $\boldsymbol{L}^E\boldsymbol{C}^E\boldsymbol{T}^E\boldsymbol{L}^M$.

A.3 Validity of the energy sector independence assumption

This section evaluates the effect of the level of independence of the energy sector on the error between elements of the PF and hybrid-unit and on the estimates of embodied energy in final demand. The results of this evaluation are shown in Table A-4.

Table A-4 Errors between the PF and hybrid-unit models at different energy sector independence levels

Energy sector independence	Error between entries		Error in estimates of energy embodied in final demand	
	$\tau^*_{kj} - (L^E C^E T^E L^M)_{kj}$	$\theta^*_{kl} - L^E_{kl}$	Non-energy products	Energy products
100%	0%	0%	0%	0%
80%	<1%	<10%	<1%	<1%
70%	<1%	<14%	<1%	<2%
60%	<1%	<30%	<1%	<3%
50%	<1%	<46%	<1%	<4%
40%	<1%	<47%	<1%	<6%
30%	<1%	<60%	<1%	<9%

The results show that the equivalence between $\boldsymbol{\tau}^*$ and the columns of non-energy producing sectors of $\boldsymbol{L}^E\boldsymbol{C}^E\boldsymbol{T}^E\boldsymbol{L}^M$ and the estimates of primary embodied energy of non-energy products are not significantly affected at any level of energy sector independence. Moreover, the effect of the energy sector independence on primary embodied energy estimates of energy products is relatively small ($< 9\%$), especially over 50% independence. Finally, the error between entries of $\boldsymbol{\theta}^*$ and $\boldsymbol{L}^E$ is largely affected by the independence level of the energy sector.

Nevertheless, over 70% of energy sector independence, the error between entries and between embodied energy estimates are relatively small. Because of this, the energy sector independence assumption can be considered to be valid in this range of independence level.

B. Appendix to Chapter 5

This appendix describes the technique to substitute the Hadamard matrix product (⊗) by a normal matrix product.

Suppose that there are two matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ of size $n \times m$. The columns of these matrices can be represented as a horizontal arrangement of m vectors of length n ($\boldsymbol{a}_j$ and $\boldsymbol{b}_j$, respectively), as follows:

$$\boldsymbol{A} = [\boldsymbol{a}_1 \quad \boldsymbol{a}_2 \quad \cdots \quad \boldsymbol{a}_m] \qquad\qquad \boldsymbol{B} = [\boldsymbol{b}_1 \quad \boldsymbol{b}_2 \quad \cdots \quad \boldsymbol{b}_m]$$

It is possible to define the equivalent matrices $\boldsymbol{A}^{\circ}$ and $\boldsymbol{B}^{\circ}$, whose matrix product is equal to the Hadamard product of the matrices $\boldsymbol{A}$ and $\boldsymbol{B}$, i.e.

$$\boldsymbol{A} \otimes \boldsymbol{B} = \boldsymbol{A}^{\circ}\boldsymbol{B}^{\circ}$$

The matrices $\boldsymbol{A}^{\circ}$ and $\boldsymbol{B}^{\circ}$, which are equivalent to $\boldsymbol{A}$ and $\boldsymbol{B}$, are obtained by rearranging the vector elements of $\boldsymbol{A}$ and $\boldsymbol{B}$ as

$$\boldsymbol{A}^{\circ} = [\widehat{\boldsymbol{a}_1} \quad \widehat{\boldsymbol{a}_2} \quad \cdots \quad \widehat{\boldsymbol{a}_m}] \qquad\qquad \boldsymbol{B}^{\circ} = \begin{bmatrix} \boldsymbol{b}_1 & \boldsymbol{o} & \cdots & \boldsymbol{o} \\ \boldsymbol{o} & \boldsymbol{b}_2 & \cdots & \boldsymbol{o} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{o} & \boldsymbol{o} & \cdots & \boldsymbol{b}_m \end{bmatrix}$$

where $\widehat{\boldsymbol{a}_j}$ is the diagonal matrix of vector $\boldsymbol{a}_j$ and $\boldsymbol{o}$ is a vector of zeros of length n. The resulting matrices $\boldsymbol{A}^{\circ}$ and $\boldsymbol{B}^{\circ}$ are of sizes $n \times (n \cdot m)$ and $(n \cdot m) \times m$, respectively.

C. Appendix to Chapter 6

C.1 Final exergy allocation assumptions

The following tables show the assumptions for allocation to useful work categories of each energy carrier by sector. These assumptions were mainly estimated by Serrenho et al. (2012) based on the sectoral information about processes, technology and efficiency from Harvey (2010). However Serrenho *et al.*'s assumptions were complemented with the works of Ayres and Warr (2009), De Beer et al. (1998) , D'Angelo et al. (2006), MacKay (2008), Serrenho et al. (2014) and Warr et al. (2010)

Table C-1 Energy sector own use: Final exergy allocation assumptions

Sub-sector	Energy carrier		Useful work category
Coal mines	Coal and coal products		MTH[a]
Oil and gas extraction	Oil and oil products	Crude oil	MTH
	Natural gas		Mechanical drive
	Electricity		According to Appendix C.2
Coke ovens	Coal and coal products		HTH[a]
Refineries	Oil and oil products	Refinery gas	MTH
		LPG	MTH
		Gasoline	Mechanical drive
		Diesel	Mechanical drive
		Fuel oil	MTH
		Bitumen	MTH
		Petro coke	MTH
		Non-specified	MTH
	Natural gas		MTH
	Electricity		According to Appendix C.2
Power producer plants	Electricity		According to Appendix C.2
CHP and heat plants	Electricity		According to Appendix C.2
Non-specified energy	Oil and oil products	Kerosene	MTH
	Electricity		According to Appendix C.2

[a] HTH and MTH stand for high and medium temperature heat, respectively

Table C-2 Industrial sector: Final exergy allocation assumptions

Sub-sector	Energy carrier		Useful work category
Iron and steel	Coal and coal products		HTH[a]
	Oil and oil products	LPG	HTH
		Kerosene	HTH
		Gas diesel	Mechanical drive
		Fuel oil	HTH
		Petro coke	HTH
	Natural gas		HTH
	Electricity		According to Appendix C.2
Chemical/petrochemical	Oil and oil products	LPG	50% HTH / 50% MTH[a]
		Gas diesel	Mechanical drive
		Fuel oil	50% HTH / 50% MTH
		Petro coke	50% HTH / 50% MTH
	Natural gas		50% HTH / 50% MTH
	Electricity		According to Appendix C.2
Non-ferrous metals	Oil and oil products	LPG	50% HTH / 50% MTH
		Gas diesel	Mechanical drive
	Natural gas		50% HTH / 50% MTH
	Electricity		According to Appendix C.2
Non-metallic minerals	Coal and coal products		50% HTH / 50% MTH
	Oil and oil products	Gas diesel	Mechanical drive
		Fuel oil	50% HTH / 50% MTH
		Petro coke	50% HTH / 50% MTH
	Natural gas		50% HTH / 50% MTH
	Electricity		According to Appendix C.2
Transport equipment	Oil and oil products	Gas diesel	Mechanical drive
		Fuel oil	50% HTH / 50% MTH
	Natural gas		50% HTH / 50% MTH
	Electricity		According to Appendix C.2
Machinery	Oil and oil products	LPG	50% HTH / 50% MTH
		Gas diesel	Mechanical drive
		Fuel oil	50% HTH / 50% MTH
		Petro coke	50% HTH / 50% MTH
Mining and quarrying	Coal and coal products		50% HTH / 50% MTH
	Oil and oil products	LPG	50% HTH / 50% MTH
		Gas diesel	Mechanical drive
		Fuel oil	50% HTH / 50% MTH
	Natural gas		50% HTH / 50% MTH
	Electricity		According to Appendix C.2
Food and tobacco	Oil and oil products	LPG	LTH[a]
		Gas diesel	Mechanical drive
		Fuel oil	LTH
	Combustible renewables		LTH
	Natural gas		LTH
	Electricity		According to Appendix C.2
Paper, pulp and printing	Oil and oil products	LPG	LTH
		Gas diesel	Mechanical drive
		Fuel oil	LTH
	Combustible renewables		LTH
	Natural gas		LTH
	Electricity		According to Appendix C.2
Construction	Oil and oil products	Gas diesel	Mechanical drive
	Electricity		According to Appendix C.2

Textile and leather	Electricity		According to Appendix C.2
Non-specified	Coal and coal products		50% HTH / 50% MTH
	Oil and oil products	LPG	50% HTH / 50% MTH
		Kerosene	50% HTH / 50% MTH
		Gas diesel	Mechanical drive
		Fuel oil	50% HTH / 50% MTH
		Petro coke	50% HTH / 50% MTH
	Other non-conventional	Solar/wind	LTH
	Combustible renewables		LTH
	Natural gas		50% HTH / 50% MTH
	Electricity		According to Appendix C.2

[a] HTH, MTH and LTH stand for high, medium and low temperature heat, respectively

Table C-3 Others sector: Final exergy allocation assumptions

Sub-sector	Energy carrier		Useful work category
Residential	Oil and oil products	LPG	LTH[a]
		Kerosene	70% Lighting /30% LTH before 1985 and 100% Lighting after
	Natural gas		LTH
	Other non-conventional	Solar/wind	LTH
	Combustible renewables		LTH
	Electricity		According to Appendix C.2
Commerce/public services	Oil and oil products	LPG	LTH
		Diesel	Mechanical drive
		Fuel oil	LTH
	Natural gas		LTH
	Other non-conventional	Solar/wind	LTH
	Electricity		According to Appendix C.2
Agriculture/forestry	Oil and oil products	LPG	LTH
		Kerosene	LTH
		Diesel	Mechanical drive
	Electricity		According to Appendix C.2
Non-specified (e.g. public lighting)	Electricity		According to Appendix C.2

[a] LTH stands for low temperature heat

Table C-4 Transportation sector: Final exergy allocation assumptions

Sub-sector	Energy carrier		Useful work category
Road	Oil and oil products	LPG	Mechanical drive
		Gasoline	Mechanical drive
		Diesel	Mechanical drive
	Natural gas		Mechanical drive
Rail	Oil and oil products	Diesel	Mechanical drive
	Electricity		Mechanical drive
Domestic navigation	Oil and oil products	Diesel	Mechanical drive
		Fuel Oil	Mechanical drive
Domestic aviation	Oil and oil products	Diesel	Mechanical drive
		Fuel Oil	Mechanical drive
Non specified	Oil and oil products	Diesel	Mechanical drive

C.2 Allocation of electric uses

Disaggregate information about electric use in Mexico for the studied period is scarce and lacks detail. There are few data points available from reliable sources (CONAFOVI, 2006; CONUEE, 2010a, b; Maqueda and Sánchez, 2008; SENER and IEA, 2011) hence studies focused on U.S. electric use (Ayres et al., 2005; EIA, 2010) were used to estimate the allocation of electric use per economic sector.

Large differences exist between the productive structures, energy intensity and wealth of Mexico and the United States. However, due to their geographical proximity, technology, resources and capital have been flowing faster from the U.S. to Mexico in the past century than to other developing nations. Therefore we assumed that the share of electricity use as well as the final-to-useful efficiencies of the industrial, energy and other (except the residential) sectors [41] have a 30-year lag when compared with those of the U.S. This value was defined by the years after 1970 that Mexico took to reach the level of full electrification (Merrill and Miroì, 1997). The time lag was applied to Ayres et al. (2005)´s data of U.S. shares and efficiencies of functional electric uses for the abovementioned sectors.

For the residential sector, we took a different approach, related to three variables: rural-to-urban population ratio, electricity access and ownership of household appliances. Based on these variables, data from U.S. were compared to Mexico´s (Carmody, 1939; INEGI, 2010b; Merrill and Miroì; U.S. Census Bureau, 1995): Mexico lagged behind the U.S. in electricity access for about 40 years in 1960, though by 2010 it had caught up. In addition, the share of rural population in Mexico was 40% in 1970, which was the same as in the U.S. in 1940, yet by 2010 both countries had the same share of rural population (20% of total population). Finally, regarding household indicators such as internet and computers penetration, a large difference remains, e.g. 76% compared with 25% in computer penetration in 2010 though this difference is exponentially decreasing (INEGI, 2010a; U.S. Census Bureau, 2010). Therefore for the period 1940-2010, we assumed an initial time lag of 40 years in 1970 but decreasing linearly to 10 years by 2010 for residential electric uses. This 10-year lag accounts for the difference in

[41] INEGI (2012) provides data for electricity consumption by the transportation sector. However the use of electricity for transportation is negligible compared to the total electricity consumption of the country (<1%) as well as to the total final exergy use by this sector (also <1%).

household indicators. The time lag was applied to Ayres et al. (2005)´s data of U.S. shares and efficiencies of functional electric uses for the residential sector.

Figure C-1 shows the final estimates of functional electric use shares of total electric use for Mexico, which were built as done by Ayres et al. (2005).

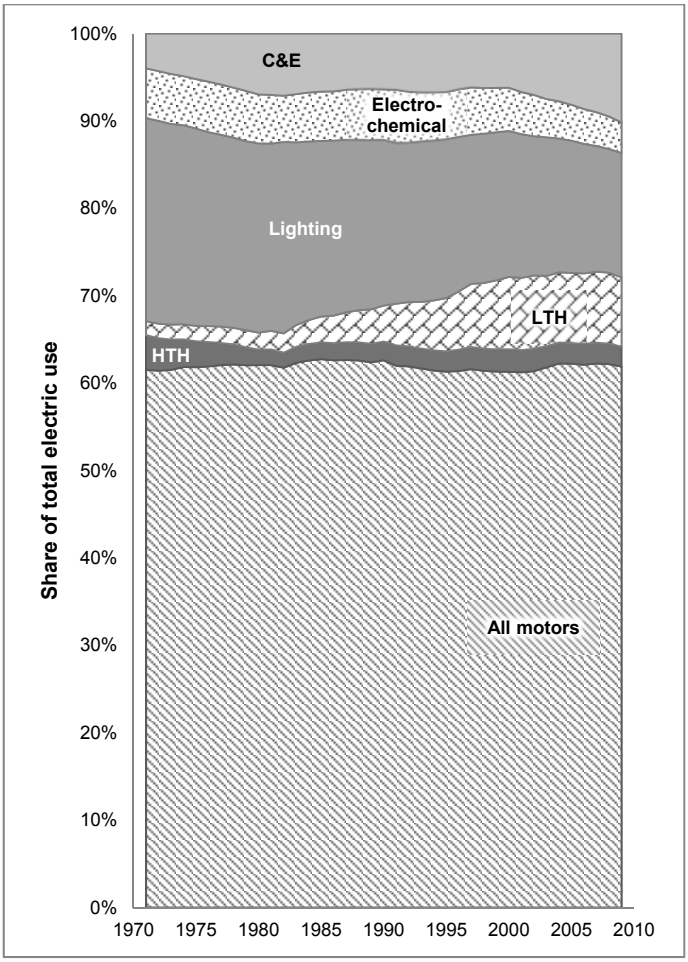


Figure C-1 Functional electric uses: Mexico 1971-2009
Note: HTH and LTH stand for high and low temperature heat, respectively. In addition, C&E stands for Communication and electronics.

The allocation of functional electric use into useful work categories is as follows: LTH, HTH and lighting electric uses are allocated to their homologous useful work categories. C&E and electrochemical electrical uses are allocated to *Other electric uses*. Finally, All Motors belong to *Mechanical drive*. Figure C-2 shows the useful work share of total electric uses by useful work category.

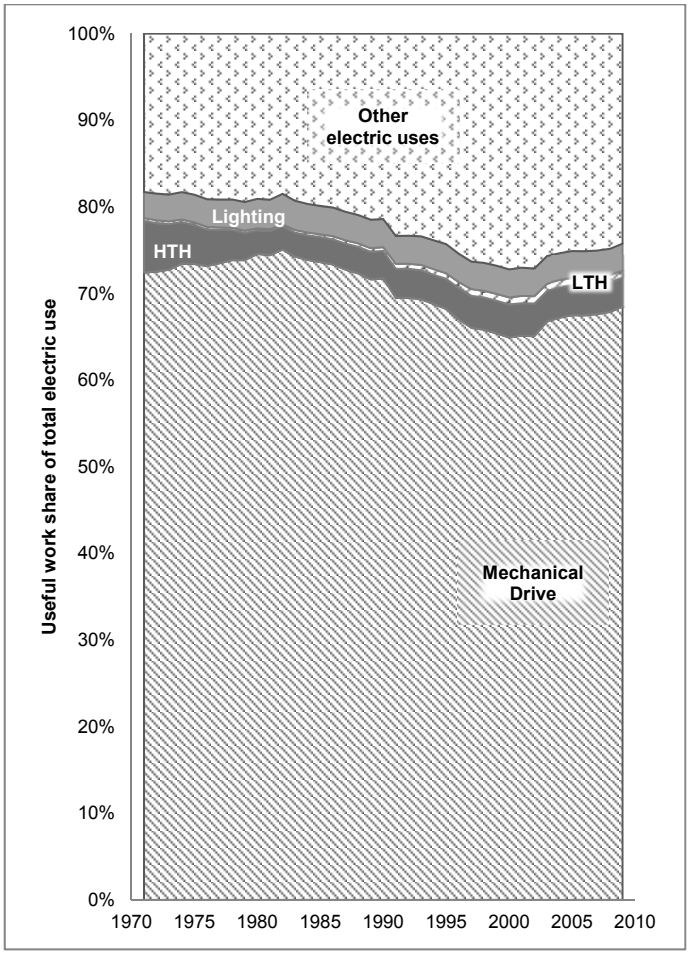


Figure C-2 Useful work of total electric use by useful work category: Mexico 1971-2009

D. Appendix to Chapter 7

D.1 Product and industry classification

Table D-1 shows the equivalence between the NACE1.1, NACE2 and the common classification used in Chapter 7. There is one-to-one correspondence between the classification of economic activities (NACE1.1 and NACE2) and the classification of products (CPA 2002 and CPA2008) systems from the SNA.

Table D-1 Equivalence between the NACE1.1 (59 sectors), NACE2 (65 sectors) and common classifications (49 sectors).}

NACE1.1	NACE2	Description
1	A01	Agriculture, hunting and related service activities
2	A02	Forestry, logging and related service activities
5	A03	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing
10-14	B	Mining and quarrying
15-16	C10-12	Manufacture of food products, beverages and tobacco products
17-19	C13-15	Manufacture of textiles, wearing apparel and leather products
20	C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
21	C17	Manufacture of pulp, paper and paper products
22	C18	Publishing, printing and reproduction of recorded media
23	C19	Manufacture of coke, refined petroleum products and nuclear fuels
24	C20-21	Manufacture of chemicals and chemical products
25	C22	Manufacture of rubber and plastic products
26	C23	Manufacture of other non-metallic mineral products
27	C24	Manufacture of basic metals
28	C25	Manufacture of fabricated metal products, except machinery and equipment
29	C28	Manufacture of machinery and equipment n.e.c.
30, 32-33	C26, 33	Manufacture of computer, electronic and optical products
31	C27, 33	Manufacture of electrical machinery and apparatus n.e.c.
34	C29, 33	Manufacture of motor vehicles, trailers and semi-trailers
35	C30, 33	Manufacture of other transport equipment
36	C31-32	Manufacture of furniture; manufacturing n.e.c.
40	D35	Electricity, gas, steam and hot water supply
41	E36	Collection, purification and distribution of water
45	F	Construction
50	G45	Sale, maintenance and repair of motor vehicles and motorcycles; retail sale

NACE1.1	NACE2	Description
		services of automotive fuel
51	G46	Wholesale trade and commission trade, except of motor vehicles and motorcycles
52	G47-S95	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods
55	I	Hotels and restaurants
60	H49	Land transport; transport via pipelines
61	H50	Water transport
62	H51	Air transport
63	H52, N79	Supporting and auxiliary transport activities; activities of travel agencies
64	H53, J61	Post and telecommunications
65	K64	Financial intermediation, except insurance and pension funding
66	K65	Insurance and pension funding, except compulsory social security
67	K66	Activities auxiliary to financial intermediation
70	L68-68A	Real estate activities
71	N77	Renting of machinery and equipment without operator and of personal and household goods
72	J58, J62-63	Computer and related activities
73	M72	Research and development
74	M69-71, M73-75, N78, N80-82	Other business activities
75	O84	Public administration and defense; compulsory social security
80	P85	Education
85	Q86-88	Health and social work
90-37	E37-39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
91	S94	Activities of membership organization n.e.c.
92	J59-60, R90-93	Recreational, cultural and sporting activities
93	S96	Other service activities
95	T, U	Private households with employed persons

D.2 Energy carriers and technologies classification

Table D-2, Table D-3 and Table D-4 show the classification of products, technologies and sectors of final demand of the energy model.

Table D-2 List of energy carriers (P = Primary, S = Secondary and NE = Non-Energy)

	Description	Type		Description	Type
1	Black coal and anthracite	P	20	Diesel	F
2	Anthracite national	P	21	Fueloil	F
3	Crude oil	P	22	Naphtha	F
4	Waste oil	P	23	Petroleum coke	F
5	Industrial waste	P	24	Natural gas final	F
6	Solar thermal	P	25	City gas	F
7	Wood and wood residuals	P	26	Coke gas	F
8	MUW	P	27	Furnance gas	F
9	Sulfite liquors	P	28	Tar	F

	Description	Type		Description	Type
10	Other renewables	P	29	Non condensate gas	S
11	Biogas	P	30	Hydrogen	S
12	Biodiesel raw	P	31	Electricity final	S
13	Natural gas raw	P	32	Heat	S
14	Electricity raw	P	33	Biodiesel final	S
15	Coke	S	34	Lubricant	NE
16	LPG	S	35	Asphalt	NE
17	Gasoline	S	36	Paraffin	NE
18	Petroleum	S	37	Solvents	NE
19	Jetfuel	S	38	Propene	NE

Table D-3 List of energy technologies (CG = cogeneration)

	Description		Description
1	Coal refinery	18	CG Metallurgic
2	Oil refinery	19	CG Iron and steel
3	Petrochemical	20	CG Clothing
4	Natural gas	21	CG Wood and cork
5	Thermoelectric sector	22	CG Rubber
6	Electric grid	23	CG Machinery
7	CG Thermoelectric	24	CG Other
8	CG Refineries	25	CG Mining
9	CG City gas	26	CG Services
10	CG Agriculture	27	Hydro power
11	CG Food and tobacco	28	Wind power
12	CG Textiles	29	Solar power
13	CG Pulp and paper	30	Geothermal power
14	CG Chemical	31	Biomass power
15	CG Ceramics	32	Waste to power
16	CG Glass	33	Biogas power
17	CG Cement	34	Biodiesel production

Table D-4 List of sectors of final energy demand

	Description		Description
1	Agriculture	13	Clothing
2	Fishing	14	Wood and cork
3	Mining and quarrying	15	Rubber
4	Food and tobacco	16	Machinery
5	Textiles	17	Other
6	Pulp and paper	18	Construction
7	Chemicals	19	Transp. Aviation
8	Ceramics	20	Transp. Navigation
9	Glass	21	Transp. Rail
10	Cement	22	Transp. Road
11	Metallurgic	23	Households
12	Iron and steel	24	Services

E. Appendix to Chapter 8

E.1 Useful work categories

Table E-1 List of useful work categories

	Description		Description
1	Stationary Mechanical drive	5	Hot temperature heat
2	Mechanical drive for transport	6	Other electric uses
3	Low temperature heat	7	Lighting
4	Medium temperature heat	8	Useful exergy of non-energy carriers[a]

[a] Not a useful work category but included to build the input-output model of the extended energy sector

E.2 Classification of producing sectors and sub-sectors

Table E-2 Sectoral classification for index decomposition analysis of PEU

	Sector		Sub-sector
1	Primary	1	Agriculture
		2	Fishing
2	High useful-work-intensive	3	Non-metallic minerals
		4	Basic metals
3	Medium useful-work-intensive	5	Mining and quarrying
		6	Pulp and paper
		7	Chemical industries
4	Low useful-work-intensive	8	Food and tobacco
		9	Textiles
		10	Wood
		11	Rubber
		12	Metallurgic
		13	Machinery
		14	Other manufacturing
5	Construction	15	Construction
6	Transport	16	Road transport
		17	Water transport
		18	Air transport
7	Services	19	Services