TÉCNICO LISBOA

Mexico 2030: Energy Efficiency & Economic Growth

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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October 2018

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

Acknowledgements

I would like to start thanking Tiago Domingos for letting me work on this topic in which I found a profound interest, Ricardo Vieira for his guidance, support and advice on the whole process of elaborating this thesis, and João Santos and Tiago Ribeiro for guiding me with the development of the economic model and helped me understand what I know so far on the topic.

I would also like to thank the Mexican Consejo Nacional de Ciencia y Tecnología (CONACyT) for trusting me and financing my master studies.

Finally I would like to thank my family and my girlfriend for their unconditional patience and support while I've been abroad

Abstract

Two scenarios for the economic growth of Mexico are presented based on different developments of the aggregate efficiency of the productive sectors of the country. One of this scenarios takes the assumption that improvements in efficiency, energy usage and energy carriers will keep the same trend that they have followed over the last ten years, while the second one proposes measures to improve the efficiency of three different sectors (energy, transportation and residential) based on the analysis of the end uses given to the energy and the efficiency of the carriers involved. The neoclassical economic theory is used in order to estimate the growth in GDP while employing a relationship between the efficiency of the country to exploit its energetic resources and the Total Factor Productivity. Although this approach has prove a strong correlation between energy efficiency and TFP in developed countries, results suggest that this trend does not apply to Mexico, and might as well not apply for other developing economies, a possible explanation to this can be the low TFP growth that this countries have presented since the economic crisis of 1984 and might be associated to high levels of informal employment and low levels of higher education and qualified labor.

Keywords

Exergy; Economic growth; Useful work; Energy efficiency.

Resumo

Dois cenários do crescimento econômico do México são apresentados com base em diferentes desenvolvimentos da eficiência agregada dos setores produtivos do país. Um dos cenários parte do pressuposto de que melhorias na eficiência, uso e as fontes de energia continuarão na mesma tendência que eles seguiram nos últimos dez anos, enquanto o segundo propõe medidas para melhorar a eficiência de três setores diferentes (energia, transporte e residencial) com base na análise dos usos finais dados à energia e à eficiência das fontes envolvidas. A teoria econômica neoclássica é usada para estimar o crescimento do PIB, enquanto se emprega uma relação entre a eficiência do país para explorar seus recursos energéticos e a Produtividade Total dos Fatores. Embora essa abordagem tenha provado uma forte correlação entre a eficiência energética e a PTF nos países desenvolvidos, os resultados sugerem que essa tendência não se aplica ao México e pode não se aplicar a outras economias em desenvolvimento, uma possível explicação para isso pode ser o baixo crescimento da PTF que esses países apresentaram desde a crise econômica de 1984 e podem estar associados a altos níveis de emprego informal e baixos níveis de educação superior e mão-de-obra qualificada.

Palavras-chave

Exergia; Crescimento económico; Trabalho útil; Eficiencia energética.

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List of Acronyms and Symbols

CFE	Comisión Federal de Electricidad
CNP	Consejo Nacional de la Población
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
GHG	Green House Gas
IEA	International Energy Agency
ILO	International Labor Organization
INEC	Instituto Nacional de Ecología y Cambio Climático
INEGI	Instituto Nacional de Estadística y Geografía
NAFTA	North America Free Trade Agreement
OECD	Organization for Economic Co-operation and Development
PEMEX	Petróleos Mexicanos
SEMARNAT	Secretaría de Medio Ambiente y Recursos Naturales
TFP	Total Factor Productivity
UEAM	Useful Exergy Accounting Methodology
USDA	United States Department of Agriculture

A_t	Total Factor Productivity
B	Exergy
E	Energy
h	Number of hours worked per employed individual
i_t	Interest rate
K_t	Capital
L_t	Labor
Pop_{15-64}	Population aged between 15-64
r	Compression ratio
T_0	Ambient temperature
T_2	Temperature of heat transfer process
td	Unemployment rate
TP	Labor force participation rate
U	Useful work
Y_t	Gross Domestic Product

α_i	Deviation from ideal process coefficient
a_k	Capital share
a_L	Labor share
ε	Second law efficiency
η	First law efficiency
Φ	Exergy factors
δ_t	Depreciation rate

Chapter 1

Introduction

This is the introductory chapter of this thesis, and it gives a brief overview of the work. An overview of the current research on exergy and economics is presented and the motivation for choosing this topic is explained, finally the scope of this work is described, and the structure of the thesis is provided.

1.1 Overview

Energy is something that we experience on a daily basis, from the food that we eat that nourishes our bodies with a certain calorific intake, to the electricity and gas that allow us to live comfortable at our homes, and the way we displace from one place to another either with private or public transportation. We can relate this to the first law of thermodynamics that establishes that energy is not created nor destroyed but transformed. We can think about how food is transformed into our physical and mental energy, how electricity is transformed into the lights and sounds emitted by our televisions and fuels are burned to take us from one point to another.

An often less popular term is exergy, which is related to the second law of thermodynamics: the availability of energy to perform work is reduced by every transformation process that it undergoes, producing useful and non-useful components in the process, this last one, that is in constant increase is known as entropy, while the useful component of energy is known as exergy.

From the previous examples we can think about exergy as the energy content in food, that degrades through the process of digestion and produces human waste, which means that there will be a share of the calorific content of food that won't be available to perform useful work. The same process happens with electricity, as heat is dissipated trough the wires and electronic components and with gasoline or diesel, as heat and noise are produced by the mechanical components of the car, while the amount of energy contained in the fuel is the same as the amount of work to produce displacement plus the lost energy, the amount of exergy contained by the fuel is not the same as the available exergy to produce work.

Economic growth is measured through GDP, this has been the way of accounting economic activity since the mid 40's, it has however been the source of debate on whether it is an accurate indicator, as some of its critics have argue its lack of capacity to measure sustainable growth, disregarding the consumption of fossil fuel resources as time-depreciated capital, and specially that it fails to quantify the wealth distribution among the population and does not take into account any kind of informal economic activity, which in turn can be misleading, specially when dealing with developing economies where it plays a significant role (Ayres and Warr 2009).

In order to explain how GDP grows, the standard neoclassical model, also known as the Solow-Sawn model has been widely employed, it was developed by Robert Solow and Trevor Swan during the decade of 1950 and it describes the logarithmic derivative of the GDP growth rate as the sum of the output elasticities of the production factors, capital and labor with respect to time multiplied by their corresponding growth rates, this methodology is described in detail in Chapter 2. This method however is not enough to explain the economic growth over time, as there is a residual between the measured progress and that estimated by the Solow-Swan model, this residual has been called Total Factor Productivity (TFP) and it is thought to have an exogenous root, it is often explained as technological progress as it represents an increase in output to the economy per worker or hour laboured (Ayres and Warr 2009).

While there have been previous attempts on finding a link between energy and economic growth in the past, Ayres and Warr (2009) have argued that an exergy approach to economics would bring better results to the matter, given that exergy measures the quality of energy, and it takes into account the resources since their raw state and all the degradation processes that they undergo within the economy up until their end use (Ayres and Voudouris 2014).

A link between the useful work produced within economies and TFP have been demonstrated in countries as the US, the UK and Japan (Warr and Ayres 2012), while studies have proven a relationship between the exergy efficiency and TFP developments in Portugal (Alvarenga et al. 2018). The Useful Exergy Accounting Methodology (UEAM) was developed by Serrenho et al. (2014) to measure the useful work performed by a country based on their trends of primary and secondary energy consumptions. These approaches together enable to replicate the results for any given country with the available energy and economic data.

Guevara et al. (2017) has performed a study regarding Mexico's final exergy and useful work trends following the UEAM and it is on the basis of his work that this thesis is being developed.

1.2 Motivation and Contents

Mexico is the second largest economy in Latin America, just after Brazil. It has the fifteenth-largest nominal GDP and the eleventh-largest by purchasing power parity, it was the first Latin American country to join the Organization for Economic Co-operation and Development (IEA 2017). Its proximity to the United States and the liberalisation of its market has made of exports one of the main contributors to economic development, as it went from representing 7.7% of the national GDP in 1970 to 37.88% in 2017 (World Bank 2018).

The country presented a significant economic development on the decade of the 70's, with an average annual growth of 6.9%, it was strongly affected by the economic crisis of the 80's and only managed to average a yearly increase of 1.88% during that period, it then manage to recover from 1990 to 2000 by growing 3.54% on average and has been keeping an average rate of around 2.1% since the beginning of the 2000's (Instituto Nacional de Estadística y Geografía 2018a).

This slowdown in economic growth has not been enough for the rapidly increasing population of the nation and has led to major social issues regarding economic inequality and a high share of informal labor, which might cause a potential feedback loop to slow the economic development of Mexico (Peralta 2010).

The objective of this thesis is to find a link between the growth of the second law efficiency of the processes involved in the energy sector and the Total Factor Productivity and propose potential policies that could lead to efficiency gains on the aggregate final to useful exergy efficiency, with the belief that this gain could in turn enhance a faster economic growth for the country.

In order to propose these potential polices, an analysis of the trends in the Mexican energy sector is performed based on the previous work of Guevara et al. (2016) and energy outlooks and reports of the International Energy Agency. To analyse the effect of these policies, two scenarios are performed, one assuming that the actual trends in the final exergy demand will remain over the following years and a second one where the adoption of the proposed policies will incentive the use of some technologies that will shift the useful work performed to be done by more efficient energy carriers. To develop these different scenarios the UEAM is followed and some corrections are made on the previous estimations of transport that take into consideration what is thought to be a more realistic approach for the case of Mexico.

An analysis on different approaches and interpretations to TFP is presented in the discussion as well as a comparison on the trends of this variable in diverse countries with different levels of development and distinct geographical locations

This thesis is structured as follows:

- Chapter 2 – Literature review: The general concepts to understand this thesis are described, these concepts are mainly related to thermodynamics and economic growth theory. Previous work on exergy and economy are presented and the Useful Work Accounting Methodology is described in detail.
- Chapter 3 – Mexico: Energy and Economy: Presents the historical situation of the last four decades of the Mexican energy sector and its economic growth. Some suggestions on improvements to the energy sector are discussed from each energy consuming sector perspective.
- Chapter 4 – Methodology: The proposed methodology to analyse two different scenarios for the development of the energy sector in Mexico up to the year 2030 is presented, as well as some modifications on previous works estimations specifically regarding the transportation sector. The methodology followed to link economic growth and final to useful exergy efficiency is also presented in this section together with all the assumptions that were made regarding energy and economy.
- Chapter 5 – Two scenarios for Mexico 2030: The results of analyzing the two different energy scenarios are presented and the relationship between exergy efficiency and Total Factor Productivity is established to further show the impact these scenarios produce in the future economic growth of Mexico.
- Chapter 6 – Discussion: This section includes a discussion on TFP analysis due to the different trend that it has shown for Mexico and other developing economies in Latin America that does not correlate with the results shown for developed countries. Possible causes of the poor performance of the Mexican TFP are presented and discussed, with recommendations to address this issue from an economic and social perspective and independently from the results obtained from the energy sector.

- Chapter 7 – Conclusion: The main findings of this work are presented in this section together with recommendations based on these results and suggestion for future works on this topic and its importance to understand the particular case of Mexico and how could be applied to help understand the Latin American region.

Chapter 2

Literature Review

The objective of this chapter is to give a clear definition of the concepts of: exergy from a thermodynamic approach and the method to estimate the useful work produced in an economy from it; economic growth from the neoclassical perspective and the production factors that play a role in a country's development; the relationship between exergy efficiency and economic growth and how efficiency has been used to explain growth; explain a forecasting model that has been used for economic growth bases on the neoclassic factors of production and exergy efficiency.

2.1 Exergy

The second law of thermodynamics establishes that the available energy to perform useful work is reduced through every transformation process that it undergoes, meaning that every production process is dissipative. This energy is then divided into available and non-available, the first one is known as exergy, while the last one is called entropy, and it is constantly increasing (Ayres and Warr 2009).

Exergy in its rawest form is found as natural resources which can be either renewable such as food, wood, wind and solar radiation, or non-renewable as minerals, coal, crude oil, natural gas, etc. In order to take advantage of these resources they go through transformation processes that depending on the source has to be harvested or extracted, processed or manufactured and used, the output of these processes or the end use that is given to these products is known as useful work (Ayres and Warr 2009).

In order to estimate the useful work demand of an economy, data on the primary and secondary energy consumption is needed and the efficiency of each conversion process is taken into account depending on the industry and the end use given, this useful exergy accounting methodology (UEAM) was developed by Serrenho et al. (2016) to study the useful work consumption of specific sector of Portugal and was later employed by Guevara et al. (2016) to produce results of Mexico for the period of 1971-2009.

Guevara et al. (2016) used data for the primary and secondary energy consumption of Mexico from the Instituto Nacional de Estadística y Geografía (2018a) and the IEA (2011) databases. To complete this information with the food and feed supply, information of supply per capita and Mexican livestock and draft animals was obtained from the Food and Agriculture Organization (2003a) and U.S. Department of Agriculture (2012) databases.

The classification defined by the IEA was used in this methodology, consisting of 4 energy consuming sectors defined as: 1) Energy sector own uses: includes the consumption of the fuels and energy producing industries such as coal mining, oil and gas extraction and oil refining; 2) Industry: consumption of each industry specified by subsectors, excluding energy used for transportation; 3) Transportation: covers all transport independently of the economic sector to which they contribute; and 4) Others includes the consumption of residential, commercial and public users, as well as the agriculture and forestry sector, does not include consumption of personal transportation (IEA 2016b)

The first step defined in the UEAM is to convert the above-mentioned primary and secondary energy (E) data to final exergy (B) values is by Equation 2.1, by multiplying the energy according to its carrier by the corresponding exergy factors (Φ) given in Table 2.1.

$$B = E * \Phi \tag{2.1}$$

Table 2.1 Exergy factors by energy carrier from Serrenho et al. (2016)

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

For the case of food and feed carriers a different approach was employed, in which the final food supply per capita is multiplied by a gross/metabolize ratio (Table 2.2) to obtain the total gross exergy supply and then by an eaten/supply ratio to disregard the food that is not being consumed. Feed supply is converted with Wirsenius (2000) data for gross exergy of feed products.

Table 2.2 Food and feed conversion variables from Wirsenius (2000)

Type	Eaten/Supplied Ratio	Gross/Metabolize Ratio
Food[a]	81% in 1970[b] 74% in 1992 – 2009[b]	1.197
Feed	63%	NA

[a] Latin-America and Caribbean countries data; [b]Obtained assuming Mexico's conditions in 1970 similar to those of South and Central Asia in 1992-1994; [c] Wirsenu's data is for 1991-1994, assumed constant through 1994-2009

After classifying the final exergy by carrier, the next step is to further allocate this exergy by its useful work category, there are five different categories and they are described by Guevara et al. (2016) as:

- Heat: Includes all the heat employed in the economy by transformation processes and devices, it is further subdivided in three different categories: (1) High temperature heat (HTH)(>600°C), typically employed in heat intensive industries such as iron, steel, cement, glass and oil refining; (2) Medium temperature heat (MTH) (120-600°C), mostly used in metallurgic and chemical industries as well as in oil refining processes of the energy industry; (3) Low temperature heat (LTH) (<120°C) most commonly used for water and space heating and cooking at a residential level and by low temperature processes such as those in the food, paper pulp and printing industries.
- Mechanical drive: This category comprises mechanical work obtained from any conversion to drive and movement by a mechanical device, independently of its energy carrier, for instance internal combustion engines, electric motors, and household motors as those employed for HVAC, refrigeration, water pumping.

- Light: This category consists of lighting for industrial and residential use from any given energy carrier, nowadays it is mostly produced by electricity, however it used to be provided by oil products before electrification became common.
- Other electric uses: This category is divided in two subcategories: (1) Communication, electric and electronic devices and (2) electrochemical processes.
- Muscle Work: Includes all useful exergy derived from the consumption of food by humans or feed by animals.

Once the energy carriers and useful work categories were properly disaggregated, useful exergy values were obtained from the second law of thermodynamics, or final-to-useful efficiency law (Equation 2.2).

$$U = \varepsilon * B \tag{2.2}$$

Final exergy to useful work efficiencies are dependent on the energy carrier as well as on the end use or useful work category and tend to improve over time, these efficiencies were estimated as follow:

- Heat: Equation 2.3 was employed to obtain the heat efficiency for the different processes as done by Ford et al. (1975):

$$\varepsilon = \eta\left(1 - \frac{T_0}{T_2}\right) \tag{2.3}$$

  With η being the first law efficiency of generic heat conversion devices, estimated for each process from a representative industry as done by Cullen and Allwood (2010). The industries used as reference were iron and steel; ammonia and iron; and space heating devices for HTH, MTH and LTH respectively, Guevara et al. (2016). T_0 represents the ambient reference temperature, which in the case of Mexico the estimated yearly average $T_0 = 18.2°C$, while T_2 represents the temperature at which the heat transfer process occurs, and is defined as follows (Table 2.3)

Table 2.3 Characteristic process temperatures T_2 from Guevara et al. (2016)

Useful Exergy Sub-Category	**Temperature Range**	$\boldsymbol{T_2}$
High Temperature Heat (HTH)	>600°C	600°C
Medium Temperature Heat (MTH)	120-600°C	360°C
Low Temperature Heat	<120°C	80°C

- Mechanical Drive: In the case of internal combustion engines the efficiency is obtained from the Otto thermodynamic cycle (Ford et al. 1975), as described in (2.4).

$$\varepsilon \approx \eta_{max} \prod_{i=1}^{6} \alpha_i \tag{2.4}$$

  With $\eta_{max} = 1 - (1/r)^{r-1}$, being the maximum theoretical efficiency of the engine and depending on the compression ratio (r) and α_i is a coefficient between 0 and 1 accounting for the deviations from the ideal process and were obtained from Ford et al. (1975) and Serrenho et al. (2016). The efficiency for electric motors was estimated from the literature, Ayres et al. (2005).

The following coefficients α_i were assumed by Guevara et al. (2016) to obtain the efficiency of internal combustions engines:

Table 2.4 Assumptions of α_i coefficients from Guevara et al. (2016)

Coefficient i	**Value**	**Notes**
1) Stoichiometry deviations	0.75	
2) Combustion and cylinder losses	0.75	
3) Friction losses	0.855-0.9	Evolution from 1971-2000
4) Partial load	0.47-0.5	Evolution from 1971-2000
5) Accessories losses	0.9	
6) Transmission losses	0.9	Manual transmission

- Light: In order to estimate the final to useful efficiency of lighting the assumptions of Ayres et al. (2005) are used, taking as a reference value of the lumens per watt for 100% lighting efficiency 400 ln/W, (2.5) was employed in order to calculate this efficiency:

$$\varepsilon = \frac{Generated\ light\ by\ a\ lighting\ technology\ \left[\frac{lm}{W}\right]}{Reference\ light\ generated\ by\ an\ ideal\ light\ source\ \left[\frac{lm}{W}\right]} \tag{2.5}$$

- Other electric Uses: This efficiency is calculated by means of equation 2.6 (Ford et al. 1975)

$$\varepsilon = \frac{Minimum\ amount\ of\ work\ required\ to\ produce\ the\ desire\ energy\ transfer}{Maximum\ amount\ of\ work\ that\ could\ be\ produced\ from\ the\ relevant\ energy\ input} \tag{2.6}$$

It mainly considers the heat losses within electric and electronic devices, it is computed from available data and studies of second law efficiency (Ayres et al. 2005).

- Muscle work: Efficiency of food conversion of humans and animals into useful work considers the absorption and digestion for growing and other body energy uses (Food and Agriculture Organization 2003b). To calculate the final to useful efficiency of this conversion process, the metabolize-to-useful efficiency is divided by a gross/metabolize ratio (Table 2.2) as seen in equation 2.7:

$$\varepsilon = \frac{\left(\frac{Useful\ exergy}{Metabolizable\ exergy}\right)}{\left(\frac{Gross}{Metabolizable}\right)} = \frac{Useful\ exergy}{Final\ gross\ exergy} \tag{2.7}$$

After computing the useful work for each category, the aggregated second law final-to-useful efficiency is calculated with equation 2.8

$$\varepsilon = \frac{Useful\ exergy\ by\ category\ i}{Total\ final\ exergy\ by\ useful\ work\ category\ i} \quad (2.8)$$

2.2 Economic Growth

Before the decade of the 50's economic growth lacked an empirical base and was measured mostly in a qualitative way. It was until the system of national accounts was developed that it became possible to construct historical series for some decades of Gross Domestic Product (GDP) for the United States and some other countries. Prior to that it was assumed that growth was a consequence of the accumulation of capital stock per worker, which is measured in terms of money and usually estimated through the perpetual inventory method (PIM). It was by that time that Robert Solow and Trevor Swan developed an aggregate production function of capital and labor services that allowed to measure the relative impact of these two factors of production as sources of economic growth (Ayres and Warr 2009).

Both capital and labor are known in the Solow-Swan theory as primary factors of production, as they enable economic value to be created, and their contribution to GDP is taken proportionally to what each of them receive from it. It has been shown that on a worldwide average a third of the GDP are bound to capital, for instance as interests, rents and dividends, while two thirds are going to labor in the form of wages to the labor force, (Alvarenga et al. 2018).

Coming back to the 50's decade, after using the PIM to try to explain the US economic growth for the first half of the twentieth century, economist came to realize that neither the accumulation of capital, nor the increase on capital stock per worker were able to explain growth, while Solow discovered that the capital/labor ratio could not account for almost 90 percent of the US GDP growth. This unexplained residual is known as the Solow residual and it was explained by him as measure of technological progress, which was thought to be exogenously driven and it is commonly known today as Total Factor Productivity (TFP) (Ayres and Warr 2009).

TFP is considered by some to be driven by technological progress, for example a development of new technologies that lead to the improvement of processes, either by cutting costs or increasing productivity. In microeconomics theory the law of supply and demand establishes that an excess in demand for goods will lead to an increase of prices and profits, which in turn will increases competition for labor and wages with it, pushing the excess in demand further. However, in order for this higher wages to come, an increase in efficiency is required, that increase will often come with the investment in new equipment that will likely use new technology (Ayres and Warr 2009).

As mentioned before, GDP (Y) is the standard measure of economic growth and it uses monetary units. A mathematical way of representing the Solow-Sawn theory is through the Cobb-Douglas production function (Equation 2.9), where labor (L) and capital (K) are considered to contribute by their respective shares, a_L and a_K, which is complementary to the labor ($a_K = 1 - a_L$), while the TFP (A) is represented by a third variable, Santos et al. (2009).

$$Y_t = A_t\, K_t^{a_k}\, L_t^{a_L} \tag{2.9}$$

Labor is normally measured by the population growth rate, although must recent models have taken more factors in account such as the average worked hours per individual within the working age group, unemployment rate and the human capital index, which is based on the years of schooling and returns to education that makes contributes to increase the efficiency of the labor force (Ayres and Warr 2009).

Considering that GDP, capital and labor are factors that can be measured, equation 2.9 can be solved to estimate the TFP growth, yielding:

$$A_t = \frac{Y_t}{K_t^{a_k}\, L_t^{a_L}} \tag{2.10}$$

Following the before mentioned statement of the shares of capital and labor being constant over time, and assuming constant returns to scale, the logarithmic derivative of this equation leads to:

$$\frac{\dot{A}_t}{A_t} = \frac{\dot{Y}_t}{Y_t} - a_k \frac{\dot{K}_t}{K_t} - a_L \frac{\dot{L}_t}{L_t} \tag{2.11}$$

If output per capita and capital per capita are defined as y=Y/L and k=K/L as done by García-Verdú (2005), TFP is defined as:

$$\frac{\dot{A}_t}{A_t} = \frac{\dot{y}_t}{y_t} - a_k \frac{\dot{k}_t}{k_t} \tag{2.12}$$

Which means that the growth rate of TFP equals the growth rate of GDP per capita minus the growth rate of capital per capita multiplied by its respective share.

2.3 Relation Between Exergy Efficiency and TFP

Every economic activity needs energy in order to develop, industrialization and economic development have been defined over the last century by an increasing adoption of energy consuming technologies and therefore an increasing demand of energy, it can also be said that developed countries have shifted from energy intensive industries, to non-intensive energy services, Warr and Ayres (2010).

Warr and Ayres (2010) found that there is both a short-run and long-run causality from exergy consumption to GDP growth, while for the lung-run, there is a causality from useful work to economic growth. These results make sense if we think that on the short term, an increase in exergy consumption implies that there is an increase in production of goods and services that translate to wealth creation, while on the long term, economic growth can be maintained by increasing the amount of useful work per unit of exergy employed, which in turns means increasing the final to useful exergy efficiency, given that different approaches as keeping a constant increase on primary exergy could have negative impacts, specially if the energy carriers available are fossil fuel based, such as an increase of green house gases emissions.

A methodology is defined in (*Alvarenga et al. 2018),* in which a relationship between the relative growth of TFP and exergy efficiency over the studied period is described by the constant C, obtained through equation 2.13.

$$C = \frac{\ln\left(\frac{TFP_t}{TFP_0}\right)}{\ln\left(\frac{EFF_t}{EFF_0}\right)} \tag{2.13}$$

This constant is employed to estimate the TFP growth as a function of the growth in final to useful efficiency exergy efficiency by means of equation 2.14. As shown by (Alvarenga et al. 2018), by estimating the GDP growth of Portugal using this energy efficiency based TFP, a good approximation of the country's economic development can be obtained for the observed period 1960-2010.

$$TFP_t = \left(\frac{EFF_t}{EFF_0}\right)^C * TFP_0 \tag{2.14}$$

2.4 Forecasting Economic Growth

After testing the results for the exergy efficiency based TFP to explain the historical GDP growth of Portugal, (Alvarenga et al. 2018), made use of the model developed, combined with participatory scenario building techniques, to define two scenarios for 2030 with the corresponding projections of GDP growth.

Since the forecasted GDP was estimated through the Cobb-Douglas production function, projections of capital, labor and exergy efficiency development were obtained.

To estimate the capital stock for the upcoming years, the PIM method was employed (Alvarenga et al. 2018). In this case the estimation of the capital for a certain year (K_t) is dependent on the previous period capital assets (K_{t-1}) , the investment capacity of the present year ($i_{t-1}GDP_{t-2}$) is being added to this value, while at the same time the capital that is not available anymore due to depreciation is being subtracted ($\delta_{t-1}K_{t-1}$). This methodology is described by equation 2.15, where i represents the investment capacity as a percentage of the GDP and δ is the depreciation rate of capital, which were estimated to be constant over time at an average value of the historical data.

$$K_t = K_{t-1} + i_{t-1}GDP_{t-2} - \delta_{t-1}K_{t-1} \tag{2.15}$$

Alvarenga et al. (2018) take labor as measured by the total number of hours worked by the engaged population of Portugal over each year and this value is corrected by multiplying the number of hours by the human capital index. In order to calculate the total number of hours labored in the economy (*L*), the hours worked per engaged individual is considered (*h*), as well as the engaged population within the working age limits (15-64 years), the unemployment rate (*td*), and the labor force participation rate (*TP*), (Alvarenga et al. 2018).

$$L = h * (1 - td) * Pop_{15-64} * TP \tag{2.16}$$

Some factors that were considered to make the projections of labor on this work were the impact of automation and digitalisation on employment, historical unemployment rates and the capacity of Portugal to retain talented workforce.

In order to estimate the final to useful exergy efficiencies up until 2030. In the MEET 2030 project, two workshops were performed with representatives of the largest companies in Portugal (around 40 companies were represented that account for about 20% of the country's GDP) and together with specialised reports and scientific papers developed two different scenarios of technological improvement. With the projection of this efficiency growth, it was possible to make projections of the TFP behaviour for the following years by means of equation 2.14.

Once these three ingredients were obtained, (Alvarenga et al. 2018) was able to perform an optimistic and a business as usual scenario of GDP growth for Portugal based on different efficiency improvement developments through equation 2.9.

Chapter 3

Mexico: Energy and Economy

This chapter describes the current status of the energy sector in Mexico, exploring the trends of final exergy and useful work consumption by sector and pointing out specific useful work categories in which major improvements in efficiency could be exploited. A brief explanation of the recent macroeconomic trends is presented as well of a discussion on different perspectives of the behavior of the Total Factor Productivity indicator. At the end of the chapter some energy policies that have been applied in other countries are explored as possible enhancers to increase the aggregate exergy efficiency by tackling specific sectors.

3.1 Energy Sector

Up until the year 2014 the Mexican energy sector was mostly controlled by the state. Exploitation of energy resources was performed by the national oil company Petróleos Mexicanos (PEMEX) while power generation was managed mostly by Comisión Federal de Electricidad (CFE), with some exemptions for large industrial consumers who were able to sign power purchase agreements trough a self-supply scheme. The energy reform approved this decade represents the most significant change for the regulation of this sector since the oil expropriation in 1938, with the creation of ten new articles in the constitution and the update of another twelve, the transformation of both PEMEX and CFE to state productive enterprises, is expected to be business driven and make them compete with the private sector (IEA 2017). As state productive enterprises, both companies will be operating as private, with legal, technical, and budgetary management independence and the autonomy to make their own business decisions at a national and international level, while remaining state owned (Miranda Olivo 2015).

The long-term impacts of this reform are a source of debate, with the government expecting a raise on renewable energy generation, an increase in exports, an increase in productivity and economic growth from the maximization of oil revenues, and the liberalization of the electricity markets. While on the other hand, some critics argue that complex market regulations, together with irregularities and lack of transparency could damage the national oil reserves, they also believe that a possible transfer of wealth to the outside could happen as it did in Brazil, some concerns are also raised from the lack of measures to ensure social and environmental sustainability that could lead to abuse of power against vulnerable groups and a disincentive for renewable energy generation (Guevara et al. 2017).

Significant changes expected to come from this reform are the reiteration of the constitutional principle of the state to own the subsoil resources, guarantee a free competition for economic actors within the sector, give independence and strengthen the regulatory agencies, ensure transparency in new contracts and enhance clean energy deployment and environmental protection (IEA 2017).

The energy policies coming from this reform are said to put Mexico in line with the IEA Shared Goals, which seek for the member countries to work on their energy sectors in a way to maximize their contribution to sustainable economic development, population well-being and environment. This means that the energy policy framework is consistent with the objectives of (IEA 2017):

1. Making the energy sector diverse, efficient and flexible.
2. The capability of properly responding in energy emergency cases.
3. The minimisation of adverse environmental impacts derived from energy activities.
4. The development and encouragement of cleaner energy sources.
5. The improvement of energy efficiency.
6. Research, development and promotion of new energy technologies.
7. Reflecting environmental cost of energy production in prices and not distorting them artificially to accomplish social or industrial goals.
8. A secure framework for investment and open trade.

9. Cooperation of all energy market participants.

However, even though the reform has been well received by international energy institutions and investment funds, according to the IEA (2017), Mexico's historical measures have been focusing on the supply side, leaving aside demand side actions that in energy efficiency and transportation are important and cost effective, specially with trends like the ones showed by Mexico on demography, transport patterns and urban sprawl. Recommendations have been made from the IEA regarding this issue on recalibrating policy and program balance between supply side and demand side considerations.

Another point against the reform from the IEA objectives perspective is that contrary to the goal of not distorting electricity prices artificially, Mexico has been subsidizing up to 60 and 70% of electricity bills in some of the residential tariffs. These subsidies are likely to disincentive increase in efficiency and it is suggested that they are replaced by specific social policies for vulnerable groups. Gradually removing subsidies can help to reduce the waste of energy at residential and agriculture levels, increase awareness among the society and incentives to invest in more energy efficient devices.

In order to detect the major areas where efficiency could be potentially improved, the final exergy and useful work consumption trends are analysed by sector, according to the classification of the IEA defined in section 2.1

3.1.1 Energy Industry Own Uses

Mexico has been known to be one of the largest oil producers and exporters worldwide, however the output of oil has decreased about 33% from 2004 to 2016, while 50% of the natural gas consumed in the country is being imported. This negative trends have been associated with a reduction on PEMEX funds and the lack of technology to perform extraction from deep water wells and refining heavy oil (IEA 2017).

As mentioned in the previous chapter, the processes of this sector have been almost entirely performed by PEMEX, the lack of competition in this field has led to an increase of aggregate final to useful efficiency of only 4% over the last four decades (Guevara et al. 2016).

The main contributors for the consumption of final exergy on this sector are the oil and gas extracting and oil refining industries, adding up a share of 98% in 1971 and being almost constant by reaching 96% in the year 2009 (Guevara et al. 2016).

Oil production is expected to rise to 3.4mb/d for the year 2040 from the actual 2.5mb/d produced today, while gas demand is projected to grow fast until 2029 according to the Energy Department (SENER for its Spanish acronym) (IEA 2017). These projections suggest that a growing demand of useful work will come for this sector and therefore improvements in efficiency could be welcome in order to make the best of the primary energy resources available.

Given that the mechanical power and medium heat temperature processes represent the highest useful work category shares, with 55% and 32% respectively in 2009, and that these are fuelled mostly by natural gas and oil (Guevara et al. 2016), a potential improvement in efficiency could be derived from the shifting of both mechanical work and heating from fossil fuels to electric power, which has a significantly higher conversion efficiency.

Although the share of electricity for these purposes has already been increasing over the last decade (Guevara et al. 2016), limitations to this effort in the extraction industry could be presented when considering the increasing share of oil and gas coming from offshore wells over time (Sistema de Información de Hidrocarburos 2018), and the expectation of this trend to continue due to the immersion on deep water wells coming from the reform. On the other hand, technologies as immersion electric heaters have proven to be a reliable alternative in the oil refining industry, especially in processes such as pipeline heating, storage heating, freeze protection and sterilization, presenting significant technological and efficiency advantages (EXHEAT 2018).

Other areas of opportunity have been addressed by the country in the Biennial Update Report to the United Nations Framework Convention on Climate Change (INEC and SEMARNAT 2015) in order to reduce GHG emissions such as: prioritising projects for increased operational and energy efficiency in PEMEX; reducing fugitive emissions by adopting best international practices; ensuring operational practices through competition and transparency; and increasing the supply of natural gas to displace fuels with higher carbon intensities.

The summary of the final exergy and useful work consumption by end uses and energy carrier trends of this sector can be observed in figure 3.1

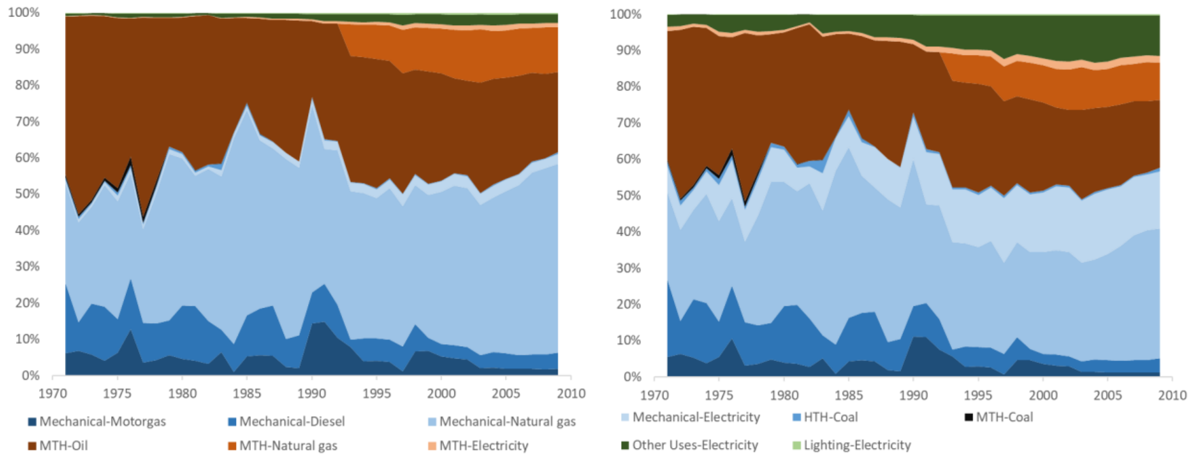


Figure 3.1 Shares of end use and energy carriers used in the energy sector. Left: Final exergy. Right: Useful work (Guevara et al. 2016)

3.1.2 Industry

The industrial sector is the second largest consumer of energy in Mexico, accounting for 33.6% of the total final consumption, its consumption has grown 11.6% from 2005 to 2015 (IEA 2017)

The main energy carriers employed in the industry are natural gas with a 31.8% share, electricity 30.8%, and oil products 28.5%, while coal and biofuels account for only about a 9% share together. The consumption of electricity and natural gas have increased 35.2% and 19.2% respectively since 2004, while oil consumption has fallen 9.3% in the same period (IEA 2017).

The final to useful efficiency in this sector has shown the best performance over all, it grew from 17% to 33% over a period of forty years mainly driven by electrification and the need of increasing productivity to be able to compete against international firms since the signing of the NAFTA in 1994 (Guevara et al. 2016)

Over the last ten years, about 40% of the final exergy demand has come from non-specified industries, which makes it hard to follow up technological efficiency improvements. Other industries like steel and iron, chemical and petrochemical, and the non-metallic minerals, accounted for another 40% of the energy consumption, these industries are known to be high energy intensive and this is reflected on the end uses of the sector, where mechanical work and high temperature heat processes accounted for 70% of the useful work performed, while the other electric uses category have been increasing significantly over the last years (Guevara et al. 2016)

Steel and chemical industries have improved significantly, declining their energy intensities between 20 and 50% since the year 2000, mostly due to efficiency gains derived by improving motor-driven systems, as well as the efficiency standards defined by the government, progress in this areas is expected to continue thanks to the next generation of motors harmonising with US standards, and the fact that motors consume almost 70% of the electricity of the sector (IEA 2017).

Areas of opportunities have been stated by the government in order to reduce the carbon footprint of the Mexican industry such as: increasing efficiency and supporting best practices also in small industries: standards to regulate energy consumption including energy services market; certification of products generated from efficient technologies (INEC and SEMARNAT 2015).

Recommendations from the IEA to the government of Mexico regarding the improvement of industrial energy efficiency include the implementation of financial incentives, as tax credits for heavy industrial consumers in order to enhance the implementation of energy management systems and energy audits; strengthening financial incentives to small and medium enterprises that can lead to a cost-benefit situation; and updating and extending the coverage of energy efficiency standards for motors (IEA 2017).

The trends of final exergy demand of the industry sector as well as the useful work performed by it disaggregated by useful work category and energy carrier can be observed in Figure 3.2

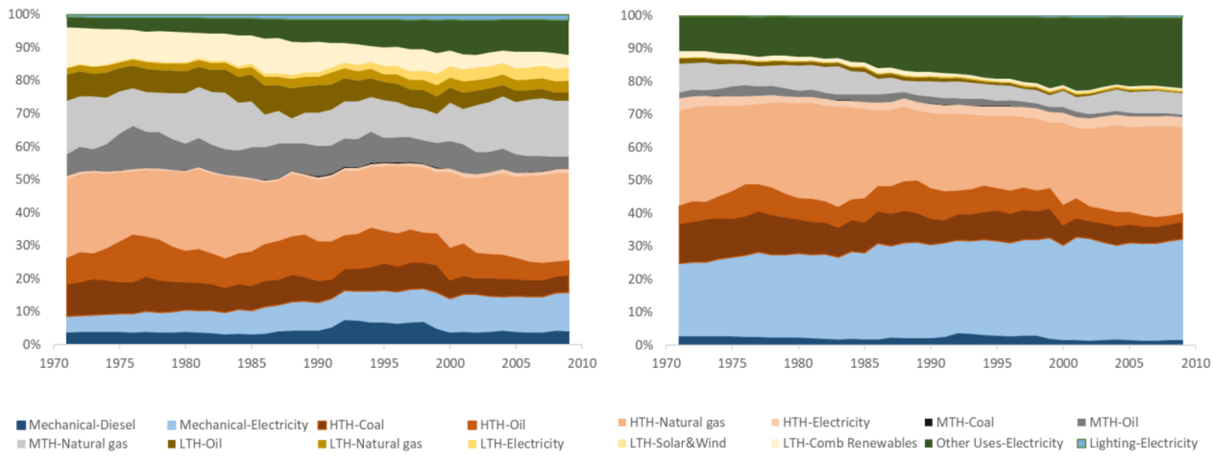


Figure 3.2 Shares of end use and energy carriers used in the industrial sector. Left: Final exergy. Right: Useful work (Guevara et al. 2016)

3.1.3 Transportation

Transport is the largest energy consuming sector in Mexico, with a share of 43.4% of total final consumption, the demand has increased 22.7% from 2005 to 2015, which is a faster rate than the average total consumption, this is the result of a historical low fuel cost and relatively easy access to car ownership due to crossborder flow of used vehicles from the US (IEA 2017).

Oil products are the main fuel of the transport sector, with a share of 99.8% of the energy demand, leaving only a negligible 0.2% of the sector powered by electricity (Guevara et al. 2016), mainly used by public transportation within the largest cities of the country. With oil production projected to grow from 3.4mb/d in 2029 compared to the actual 2.5mb/d (IEA 2017), the situation of the sector doesn't seem likely to change during the following years.

The second law efficiency of this sector is not only the lowest but is also the one with the most mediocre growth, going from 12 to 15% over the last forty years (Guevara et al. 2016). This could be attributed to the high average age of the vehicle fleet in Mexico, which for light duty vehicles was of 13 years in 2014 (Asociación Mexicana de la Industria Automotriz 2016), this has been mainly a consequence of the law for used imported vehicles included in the NAFTA that gradually reduces the minimum age of cars that can be imported (Lacayo Ojeda and Juárez G. 2016). According to the report “Used Vehicles: A Global Overview” (United Nations Economic Commission for Europe 2016), Mexico is the largest importer of used vehicles from the US, such that in the period of 2005-2014, 44% of the added country's vehicle fleet was composed by used imported vehicles (Secretaría de Economía 2014).

The high share of transport in the total final consumption of Mexico together with the inefficiencies of the sector gives to it an important weight for producing an impact on the overall country's energy consumption (IEA 2017).

While developed countries like Norway and the Netherlands have move fast on the integration of electric vehicles, a low adoption rate is expected from Mexico due to some obstacles such as the high upfront costs and scarce supporting infrastructure. These barriers are extended by other social factors, such as the already slow modernization of the national fleet and the uncertain cost of electricity. These problems lead to expect transport electrification as a long-term process. Social policies are not helping either, an example is Mexico City, where vehicles priced under $350,000 MXN (around $18,000 USD) are exempt to pay ownership taxes, incentivizing the use of cheap, less efficient vehicles (Marchán and Viscidi 2015).

The Government of Mexico has identified areas of opportunities in this sector such as: expanding and improving infrastructure for public transportation systems, supporting massive modal transportation; increasing energy efficiency of the national vehicle fleet and regulating emission levels; optimising mobility management by introducing electronic road tolls, restricting movement in congested areas, and encouraging non-motorised transportation; promoting the development of a climate culture and planning urban centres to reduce demand of transportation; producing biofuel at a national level (INEC and SEMARNAT 2015)

A strengthening of sectoral policies especially in transport is urgently required as given the energy consumption trends in Mexico it is expected that even by achieving a 71% share of clean electricity by the year 2046, GHG emissions might increase due to the consumption of fossil fuels from this sector (IEA 2017).

Given the mobility trends of Mexico, a potential policy that could be applied in order to reduce the average age of the vehicle fleet and therefore contribute to a significant increase in the overall efficiency of the sector is what was applied in Portugal as “Renove carro”, which consisted on three main policy instruments: including a CO_2 component in the annual circulation tax; including a second CO_2 component in the vehicle purchase tax; and giving a fixed economic incentive to replace vehicles (2008-2010) through a subsidy (Domingos et al. 2014).

The objective of these instruments was to promote the introduction of more efficient vehicles with low CO_2 emissions, as they promoted for instance a 50% reduction of the circulation tax for hybrid vehicles, while at the same time reduce the emissions of old vehicles, providing a subsidy of $1000 EUR and $1349 EUR if the cars were older than ten and fifteen years respectively. This led to the replacement of 37,326 old vehicles in 2010 and the abatement of 37,476 tons of CO_2 in the same period (Domingos et al. 2014).

The consumption of final and useful exergy by the transportation sector are shown in Figure 3.3, in this particular sector all the end uses correspond to mechanical work as everything correspond to engines used for the displacement of people and goods.

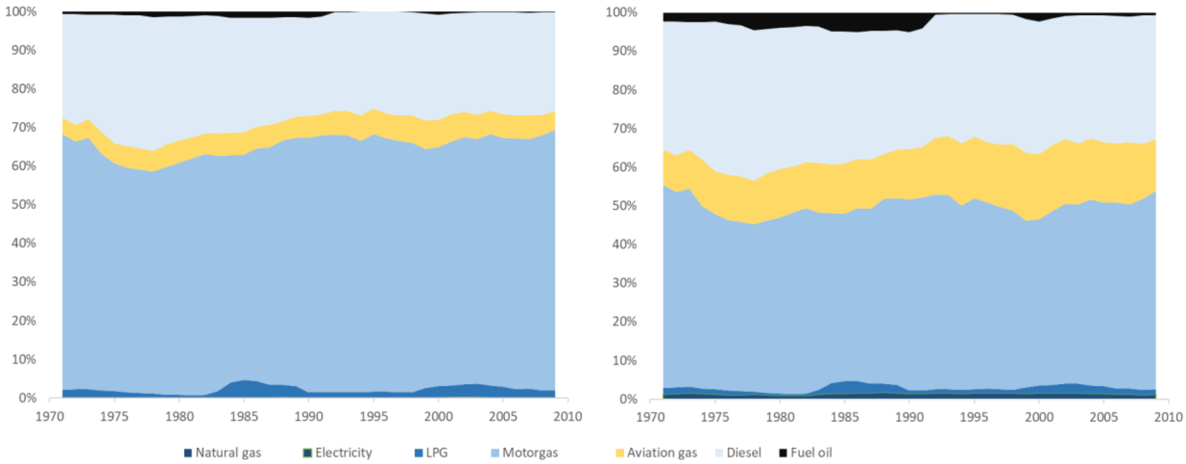


Figure 3.3 Shares of energy carriers used in the transportation sector. Left: Final exergy. Right: Useful work (Guevara et al. 2016)

3.1.4 Other Energy Uses

As mentioned in the previous chapter, this sector includes consumption of residential, commercial, and public users, as well as the energy consumed by the agriculture, fishing and forestry sectors. Residential consumers account for 15% of the total energy demand, this trend has kept relatively unchanged over the last decade, while the services sector, including public services and agriculture, has grown 35.5% during the same period and has come to represent 8.1% of the total demand in 2014 from 6.9% in 2004 (IEA 2017).

Regarding the energy carriers used in this sector, the consumption of oil, electricity, and combustible renewables are the more significant representing 38.8%, 34.3% and 22.2% respectively, the last one having still a significant share due to the economic situation of most of the population that still use wood for cooking and water heating. Even though the demand of oil remains the highest, it has been decreasing together with the combustible renewables as electrification has been reaching more rural areas. Natural gas and solar thermal have a share of 4% and 0.7% respectively, as liquified petroleum gas has a higher availability than natural gas and infrastructure for its residential distribution is still lacking in most parts of the country (Guevara et al. 2016).

Even though most of the energy consumed in mexican homes is used for low temperature heat purposes, it is not employed in space heating, as showed by Franco and Velazquez (2014), 65% of the residential consumption is used for water heating, while cooking is the next end use in the list with a share of 17.2%, this lefts the door open to a significant efficiency improvement by shifting the energy carrier to solar thermal heating, considering Mexico's solar power potential (with an average daily irradiation of 5.5kWh/m^2) and its above average amount of sun hours per year across the whole country (IEA 2016a).

Buildings in the country consume 25% its final energy and the urbanization process and the growth in the service sector is likely to increase this share. Although air condition can represent up to 50% of the energy consumption in buildings, and the forthcoming climate conditions are likely to increase the need for it (IEA 2017), as of 2014 less than 15% of the population counted with one (Cruz González and Durán Saldivar 2015)

Currently there are replacement programs going on in order to decrease the use of low efficient refrigerators, air conditioning systems and fluorescent lights. The Efficient lighting program saved 9.6TWh of electricity in the period of 2010-2015 being applied in 11.3 million households (IEA 2017).

While Mexico has managed to apply successful energy efficiency programs at the residential level, some measures have been discussed with the objective of reducing emissions such as: removing electricity subsidies that discourages investment to adopt more efficient technologies; promoting distributed generation of solar photovoltaics and solar thermal heating; increasing the adoption of efficient wood stoves; regulating for energy efficient appliances and making it mandatory for new constructions; strengthening incentives to purchase efficient electric appliances (INEC and SEMARNAT 2015).

As of today, almost 60% of the household electricity price in Mexico is still subsidized by the government (IEA 2017). Although removing this subsidy is a repeatedly discussed measure, some critics have emerged, arguing that due to the income inequality present in Mexico, an increase in the electricity prices could lead to a deterioration of the poverty level of the most vulnerable people, given that there is a low elasticity of demand in this sector of the population, compared to a higher elasticity among the wealthiest (Cruz González and Durán Saldivar 2015).

Countries like Portugal have successfully applied programs like “Renováveis na Hora” which was based on three policy instruments: compulsory installation of solar heating systems in new buildings; subsidies for the installation of solar thermal in existing houses; and feed in tariffs for residential generation of electricity. The first two instruments led to an avoidance of 7,980 tons of oil equivalent of energy, while the government subsidized 30% of the investment of the solar system by income tax deduction for existing buildings (Domingos et al. 2014).

The trends of the final exergy demand and useful work of the residential, commercial, governmental and agriculture sectors are shown in Figure 3.4

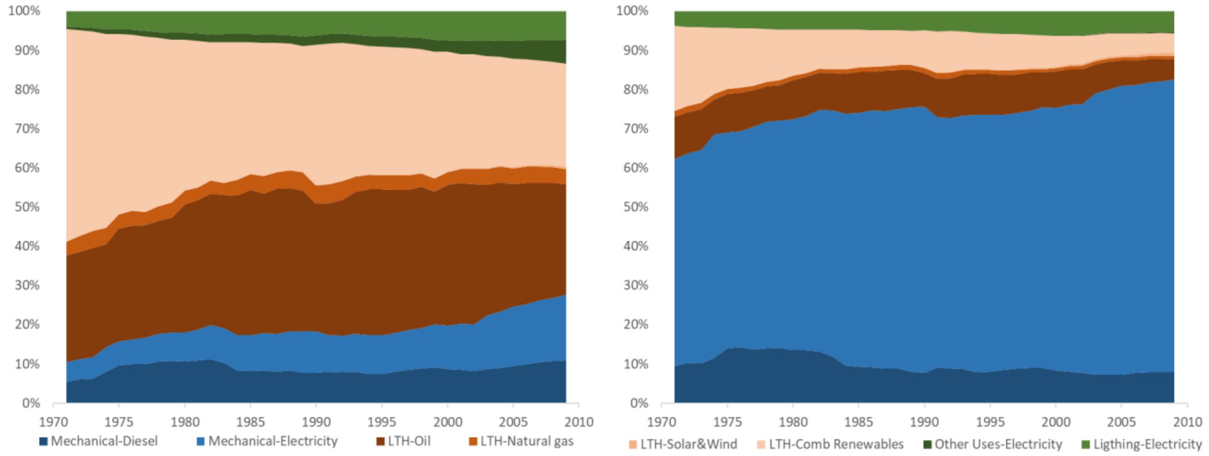


Figure 3.4 Shares of end use and energy carriers used in the other energy uses sector. Left: Final exergy. Right: Useful work (Guevara et al. 2016)

3.2 Economy

Mexico is the second-largest economy in Latin America just after Brazil and has the fifteenth-largest GDP globally. It is generally described as an upper-middle income country, and it was the first Latin American country to join the OECD, belonging to the G20 as well. The average growth of the country during the last decade has been modest, with a 2.5% increase between 2005 and 2015, at the same time the gross national income per capita raised by 44%, although the GDP per capita ($13,608 USD) remains quite below the IEA average ($32,621 USD) (IEA 2016a).

Mexico's economy has had a deep reorganization after the 80's, that transformed the country from a local manufacture and substituting imports focus to a liberalised economy open to foreign trade, investment and private sector participation, this was mainly achieved through the abolition of import licensing, the privatization of state owned industries, and NAFTA, which lead exports to double and diversify (Guevara et al. 2016).

Due to NAFTA, manufacturing exports accounted for more than 90% of the export revenue and Mexico position itself as the second largest consumer of US exports ad third largest exporter to the same country. The country's export success has been mainly attributed to the automobile manufacturing, which has grown around 12% yearly since 2004, making Mexico the seventh largest car manufacturer worldwide and the fourth largest exporter, making this industry more important than energy when it comes to export revenue (IEA 2016a).

The massive foreign investment coming into the country after NAFTA led to an economic crisis in 1994 that the nation was able to overcome easily by the end of 1995 and keep a stable but slow growth until today, keeping an annual average of 2.6% over the last 20 years. This insufficient growth was worsened during the 2009 crisis, leading to a negative growth in GDP of -6%, although the economy recovered rapidly, reaching an average yearly growth of 4.4% during the next three years. Expectations for growth of the economy are estimated to be between 1.2 and 3.5% for the upcoming years (International Labour Organization 2014).

Even with the slow growth in the economy during the mentioned period, the labor market in Mexico has kept a low unemployment rate and has manage to keep the growth of employed population above the proportion of the total population increase. Following the definition of labor as the total number of hours worked within an economy by the engaged population, Mexico presents a higher labor growth rate than developed countries such as the US, UK, Japan and Germany and also high compared to Latin American countries under similar economic conditions as Brazil, Colombia and Chile (University of Groningen 2017).

This labor conditions have been however co-existing with a high level of informal employment. It was reported by INEGI that informal employment in the country accounted for around 60% of the total employment during the period of 2011-2014 (International Labour Organization 2014).

Informal employment in Mexico has usually decreased in years of economic growth, while it has raised at times of crisis, however after the 2009 crisis it was kept relatively high compared to the total employment. This high rate of informal labor occurred during a time of low unemployment rate, meaning that for a large share of the population who lost their jobs, informality was the way to generating income, mainly due to the slow job creation and absence of mechanisms to support unemployed people looking for jobs (International Labour Organization 2014).

Data from INEGI has shown that informal unemployment differs by state, states like Oaxaca that remains one of the least developed regions in Mexico has informal employment rates of 81.2%, more than 30% above the national average, while states with a better developed labor market like Nuevo León have shares of informal unemployment of 39.5% (Instituto Nacional de Estadística y Geografía 2018a).

On the other hand, the capital stock accumulation in Mexico has managed to keep a stable growth and has sixfold over the period of 1970 to 2014, the investment capacity and the depreciation rates have been kept more or less constant around 22.3% and 3.9% respectively (University of Groningen 2017).

Shares of capital and labor in the economy are important for the determination of the GDP, as described by the Solow-Swan model and the Cobb-Douglas Production function, García-Verdú (2005) has shown that the estimation of this shares plays a significant role on the calculation of the TFP and has proven that informal unemployment can lead to obtain misleading values of capital and labor contribution. While data from the Penn World Table (University of Groningen 2017) suggest that the share of capital is around 52% and the labor one is complementary, the estimations made by García-Verdú through a household survey show that the actual shares are 34% and 66% respectively, which coincide with the 1/3, 2/3 rule of thumb of economic theory (Alvarenga et al. 2018). These methods have been tested in other developing countries with similar levels of informal employment and have produced comparable results (Gollin 2002).

Chapter 4

Methodology

In this chapter the methodology used to design two different economic growth scenarios is described, this procedure was based on the Solow-Swan model with the TFP estimation as a function of the aggregate exergy efficiency. Different considerations to estimate the second law efficiency and useful work performed by transportation are described, given the discrepancies found in previous works within this sector. The assumptions for the final to useful efficiency development of each sector are presented, as well as those ones made to estimate the factors or production and their corresponding shares.

4.1 Exergy

The historical series of and useful exergy consumptions of Mexico from 1971-2009 were obtained directly from Guevara et al. (2016), who produced these results from the databases of the Instituto Nacional de Estadística y Geografía (2018a) and the IEA (2011) by using the useful exergy accounting methodology (UAEM) described in chapter 2.

The results from Guevara et al. (2016) however showed some inconsistency within the transportation sector when compared to the study performed by Serrenho et al. (2014). The last one showed an evolution on the efficiency of gasoline internal combustion engines of 15 different European countries from 9.6 to 10.3% over the studied period, while on the same timeframe Guevara estimated an increase from 10.8 to 12.7%. These numbers don't add up specially if the average age of the vehicle fleet of these regions is taken into account, while the average age in Europe in 2010 was 7.5 years (European Environment Agency 2014) in Mexico it reached 13 years, while almost one quarter of the registered vehicles are older than 16 years (Asociación Mexicana de la Industria Automotriz 2016).

The overestimation of the efficiency in this sector is mainly because Serrenho et al. (2014) considered the partial load coefficient to be decreasing over time, more specifically from 0.45 to 0.4, while Guevara et al. (2016) increased this factor from a value of 0.47 to 0.5 over the same period.

Guevara et al. (2016) also assumed a transmission coefficient of 0.9, which is valid for the European Union as most of the vehicle fleet is composed by manual transmission. No statistics were found on the market share of automatic and manual transmissions for Mexico, however for the purpose of the present work it was assumed that the distribution of transmission types was fifty-fifty, bringing the coefficient to an average of 0.825. This assumption was made considering that the market share of manual transmissions in the US have been decreasing over time, for instance in 2010 less than 7% of the new vehicles sold had manual transmission (EPA 2011) and also due to the high percentage of imported used cars from the US composing the Mexican vehicle fleet (Lacayo Ojeda and Juárez G. 2016).

To take into account the significant difference on the average age of the fleet vehicle between the EU and Mexico, a degrading coefficient was considered based on the decaying fuel efficiency over time. This coefficient was estimated by taking the efficiency for European gasoline vehicles as a reference and reducing it from this point onwards on a yearly 0.08%, this measure brought the range of this coefficient from 0.93 for 15 years old vehicles to 1.0 for 7 years old vehicles.

Once the efficiency of the transportation sector was adjusted, the scenario designing process was performed. This process began by taking the estimates of the population growth in Mexico, which is expected to reach almost 132 million people by 2030, an increase of 9.4% in respect from the year 2014, but with a yearly average growth significantly lower than in the previous decades (Consejo Nacional de la Población 2012).

It was observed from the previously studied period that the relationship of useful work consumption per capita increased with a linear growth, this made it reasonable to assume that this tendency will prevail for the following years, reaching a value of 13.23 GJ/cap, which is almost 40% higher than the per capita consumption of the year 2009.

Having estimated the per capita consumption and with the population projections it was possible to estimate the total useful work demand, which increased 60% in respect to the 2009 values. The trends of the consumption share of the last 10 years of available data, were used to allocate the share that each useful work category would represent from the total mix over the coming years, from these categories the exergy was further allocated in each of the sectors, based again on the trends of the last decade.

Two scenarios are presented in this work, a baseline scenario where the tendencies of machines and devices efficiencies remain constant or present significant increases based on their energy efficiency limits, and a second scenario, where the application of certain policies aims to tackle specific inefficiencies of some sectors by means of incentivizing a shift to less energy intensive technologies that take advantage of more efficient energy carriers. While the useful exergy remains constant for both scenarios, the difference in the efficiency of conversion technologies and switch in energy carriers resulting from the implementations of policies is expected to lead to different paths of final exergy consumption and therefore to different trends in final to useful exergy efficiency that in the end are likely to project different economic growth outlooks.

For the industry case a single scenario was developed, given that mechanical work together with high and medium temperature heat processes represent around 80% of the useful work consumption of this sector (Guevara et al. 2016), and that the technologies available for these processes are already close their maximum theoretical efficiency. Political incentives to industries might have as well a weaker impact on their productivity since they are already driven by the competition of the internal market forces and exports to become more efficient and increase their profit margins.

Evolution of the efficiency of heat processes was estimated logarithmically considering the actual efficiencies of the industry in European countries (Serrenho et al. 2014) and the limitations due to the geographical conditions of Mexico. On the other hand, for the electricity uses, the same methodology of using the last decade tendencies to estimate future shares was employed, while the efficiency of its end use was extrapolated from the estimations of Ayres et al. (2005).

With the estimates of useful work per category and their respective efficiencies it was possible to obtain the final exergy demand of the sector using equation 2.2.

Given that a higher potential for efficiency gains was identified on the Energy, Transportation and Residential sectors, these were the areas in which two different scenarios were performed. A description of the assumptions done for both scenarios is presented next.

4.1.1 Baseline Scenario

As mentioned in the previous section, in order to develop the baseline scenario the useful work consumption estimated from the previous per capita consumption trend and the population’s projection was used. Following the trends of useful work category and per sector consumption shares it was possible to allocate the useful exergy for every sector.

The case of the energy sector is similar to the industry in the sense that roughly 90 % of the useful work performed is done by medium temperature heat processes and mechanical work, having a share of 35 and 55% respectively (Guevara et al. 2016), which doesn't leave the door open for much improvement in conversion devices. The same criteria was applied as in the industry for a progressive increase in efficiencies following the trend over the last decade. The final exergy was estimated with equation 2.2 and was categorized by end use category and energy carrier.

Transport is a particular case as all the worked performed in this sector correspond to mechanical, while oil and its derivatives add up for almost 100% of the energy carrier that fuels it. As described at the beginning of this chapter, a different approach was employed to estimate the efficiency of this sector and therefore the useful work consumption differs from that estimated by Guevara et al. (2016). In order to estimate the final exergy projections of transport, an increase in the compression ratio of internal combustion engines was estimated to continue in the following years, however it is also expected to have a diminishing in this efficiency gains due to an projected raise in the average vehicle fleet age allowed by NAFTA (Lacayo Ojeda and Juárez G. 2016). These facts together with the expected lag on electric vehicle adoption due to the low purchasing power of the population and other social factors don't raise much expectations on an increased efficiency of the sector from a shift in the energy carrier. (Marchán and Viscidi 2015). Final exergy estimations were straightforward from equations 2.2 and 2.4.

The others sector's largest consumers are the residentials, and contrary to the rest of the sectors, other than mechanical power, low temperature heat processes are the second largest end use category contributors to the useful work mix. This is mainly attributed to water heating and cooking with 65% and 17.2% of the end use share (Franco and Velazquez 2014) and they have mostly been obtained through oil products such as liquified petroleum gas and combustible renewables (Guevara et al. 2016). As for the previously described sectors, the consumption trends over the last decades were used to estimate the final exergy consumption by using the extrapolated energy efficiency values following the UEAM.

4.1.2 Improved Policies Scenario

In order to contribute to a faster increase in aggregate final to useful exergy efficiency, potential improvements for the Energy, Transport and Residential sectors are suggested, as well as the assumptions that were inputted in the model in order to measure their effect. These improvements were suggested based on an analysis of the end use categories of each sector and the energy carriers used to perform work.

While most of the work performed in the Energy sector own uses corresponds to mechanical work performed by gas turbines in the extraction processes and medium heat temperature done by oil in the oil refining industry, there has been a slight share over the last decade performing this same work by electric equipment (IEA 2011). This becomes relevant as electric motors and medium temperature electric heating systems have significant higher conversion efficiencies than their fossil fuel based counterparts (Cullen and Allwood 2010). This means that shifting from one technology to another can have a significant impact on the aggregate efficiency of the sector.

Shifting oil to electricity in the refining industry would not imply any technical restrictions, as there is actual equipment available in the market with significant advantages over oil heating systems, such as being more environmentally friendly as there are no pollutant by-products in the process, having a comparative smaller size that eases the installation and operation and having both a lower initial investment and maintenance cost (EXHEAT 2018). This lead to the assumption that by 2030 a shift on medium heat process can be achieved, raising the share of electricity as a carrier from 2 to 12%, while reducing the respective shares of coal, oil and natural gas to perform this work.

Increasing the share of mechanical work produced from electricity could be more complicated given the trends on the location of the oil and gas wells, as offshore extraction has been increasing since the 80's (Sistema de Información de Hidrocarburos 2018) and it is expected to keep raising as deep waters extraction becomes common. This scenario considers the possibility of increasing the share of electric motors from the actual 17.5% to 22% in 2030 by strengthening the environmental regulation of the extraction industry in onshore wells.

Given that the main problem with efficiency in the transport sector is the rapidly increasing Mexico's vehicle fleet (Instituto Nacional de Estadística y Geografía 2018b), due to the lack of coverage of public transportation outside of the country's largest cities, a policy that contribute to the replacement of old vehicles and reduce the average fleet age was considered. Such policy was applied in Portugal between 2008 and 2010 and contributed to a significant reduction in CO2 emissions (Domingos et al. 2014). In contrast with the baseline scenario it is expected that with such a legislation the average age of the vehicle fleet in Mexico can be reduced to 8 years by 2030 from the actual 13 and it is assumed that such improvement will bring a 0.5% increase in the efficiency of the road vehicles.

Considering the trends on the useful work consumption of the residential sector together with the main end use of low temperature heating processes, it is considered that shifting the useful work performed to achieve this end use by incentivizing the adoption of solar thermal technologies could potentially improve the efficiency of the "Other uses of energy" sector in general. Such a program has been previously issued by Portugal by the means of subsidizing the cost of the equipment through taxes (Domingos et al. 2014). Considering the declining price of solar water heating (Cassard et al. 2011) and the excellent geographical location of Mexico for solar irradiation (IEA 2016a), it is assumed that reaching a shift from a share of 1 to 10% of solar thermal heating by 2030 is achievable, while this would imply a reduction on the shares of oil and biomass that have low efficiency values.

A comparative summary of the main different assumptions per sector for both scenarios is presented in Table 4.1

Table 4.1 Main assumptions made for each sector in both scenarios

Sector	Baseline Scenario	Improved Policies Scenario
Industry	The trend of useful work performed over the last ten years was used to determine the future shares, improvements in efficiency of thermal processes and electric and electronic equipment were assumed to be logarithmic.	

ESOU	No measures are taken regarding the oil & gas extraction and oil refining industries and the share of MTH processes performed by electricity evolved from the actual 1.9% to only 4% by 2030, while the share of mechanical work done by this carrier raised from 15.75 to 16.8% in the same period.	Policies requiring companies to operate under stricter energy efficiency standards and reduce their carbon footprint are applied and the share of MTH processes performed by electricity evolved from the actual 1.9% to 12% by 2030, while the share of mechanical work done by this carrier raised from 15.75 to 22.0% in the same period
Transportation	No regulations are considered regarding the entrance of used imported vehicles to the country, increasing the average age of the vehicle fleet to 18 years	The introduction of an incentive to replace old vehicles contributes to the reduction of the average age of the vehicle fleet to 8 years
Other Energy Uses	No actions are made in the residential sector and the actual trend remains raising the share of solar thermal for heating water from 1 to 3% in 2030	A subsidy for residential and commercial users is applied, incentivizing the adoption of solar thermal heating for water, increasing the share of solar energy as a LTH source from 1 to 10% in 2030.

With this efficiency improvements and shifts in energy usage, the final exergy consumption for this scenario is calculated by reversing the process of the UEAM and having estimated the final exergy for both scenarios allocated by industry and end use it is possible to estimate the trends in the aggregate exergy efficiency with equation 2.8.

A summary of the policies chosen to improve the efficiency of each sector in this scenario and the expected medium-term impact from each of them in the aggregate exergy efficiency of Mexico is presented in table 4.2.

Table 4.2 Summary of policies considered for the improved scenario and their expected impact

Sector	**Policy**	**Expected Impact**
Industry	None	Industry is expected to improve on its own as a result of internal and external market competition
ESOU	Efficiency improvement in extraction and transformation processes	A switch from natural gas and oil as fuel for performing mechanical work and medium temperature heat processes to electricity to increase the total final to useful efficiency of the sector

Transportation	Old vehicles replacement	A reduction on the average age of the national vehicle fleet and an increase in the aggregate efficiency of the sector with it
Other Energy Uses	Solar thermal subsidy	A switch from oil and combustible renewables as fuel for performing low temperature heat processes to solar thermal energy to increase the second law efficiency of the sector

4.2 Forecasting economic growth

As stated in Chapter 2 of this thesis, the neoclassical economic approach was used to develop the growth model, this was based on the Cobb-Douglas production function described in equation 2.9. Therefore, in order to estimate the GDP of the 2014-2030 period, it is necessary to know the Total Factor Productivity as well as labor and capital inputs together with their corresponding shares to the Gross Domestic Product.

The estimation of labor growth was entirely based on the projections of the population growth for Mexico from the Consejo Nacional de la Población (2012), although there are other valid methodologies to estimate labor, it was decided to use this one in particular. The reasons for choosing this approach are further discussed in Chapter 6.

Accumulation of capital stock in Mexico has showed a rather defined tendency over the studied period (University of Groningen 2017), therefore in order to project the growth of capital until 2030, assumptions were made that the depreciation rate will be constant at 3.88%, while the investment capacity will remain at a constant value of 20.56%. These assumptions are enough to estimate capital by means of equation 2.15, as the other variables needed correspond to previous values of measured capital and GDP (Alvarenga et al. 2018).

Although data from the Penn World Tables estimates the shares of labor and capital for Mexico to be on an average of 48 and 52% respectively, with a tendency of an increasing share of capital over the last 10 years (University of Groningen 2017), according to García-Verdú (2005) it is likely that there is an overestimation on these shares. He attributes this overestimation to the high percentage of informal employment in Mexico, that does not reflect on the employee compensation that is measured by the government in order to estimate GDP through the Perpetual Inventory Method.

By using information from household income survey data, García-Verdú was able to estimate the share of capital to be of 34%, which is in line with the theoretical one third, two thirds defined by the Cobb-Douglas production function for capital and labor respectively. Therefore, the shares estimated by García-Verdú were the ones used for the development of the economic growth model.

TFP for the 2014-2030 period was estimated following the methodology presented by the MEET 2030 Project (Alvarenga et al. 2018), by estimating a constant value for the relationship between its historical growth and the historical exergy efficiency, and then establishing a relationship between both, as in equations 2.13 and 2.14.

The TFP as a function of the final to useful exergy efficiency is then tested with the Cobb-Douglas function in order to test the validity of its relationship with growth, and if an accurate approximation is obtained for the available data period, then the second law efficiency values are inputted into the model to estimate the GDP of the forthcoming years.

Chapter 5

Two Scenarios for Mexico 2030

This chapter presents the results obtained after following the methodology described in the previous section. The outcome of the transport sector efficiency obtained through the new approach is compared with that of previous works. The results for the estimation the final to useful exergy efficiency through the Useful Exergy Accounting Methodology, presenting two different scenarios up to the year 2030 are compared between each other by sector and on an aggregate level. The relationship between second law efficiency and TFP for the case of Mexico is presented, as well as the results of using it to estimate the economic growth over the sampled period. The outcomes of economic growth are presented based on the two different exergy efficiencies obtained from the scenarios developed.

5.1 Exergy

Figure 5.1 compares the results of using the proposed approach to estimate the final to useful efficiency of the transportation sector. As mentioned before different considerations are taken into account such as a lower transmission coefficient due to the consideration that the share of automatic transmissions is significant within Mexico, this assumption is reflected on an efficiency on average 2% lower than the estimated by Guevara et al. (2016) during the first two decades of the analysed period. A significant impact is noticed specially after the mid 90's, as in Guevara's work a significant increase in efficiency occurs in this period due to advances in combustion engines technology, these improvements are diminished by the inefficiencies of an old fleet vehicles average age. This is due to the increasing imports of used vehicles from the US that raise after the NAFTA was signed in 1994, which consequently led to a lack of efficiency improvement of this sector in a forty-year period.

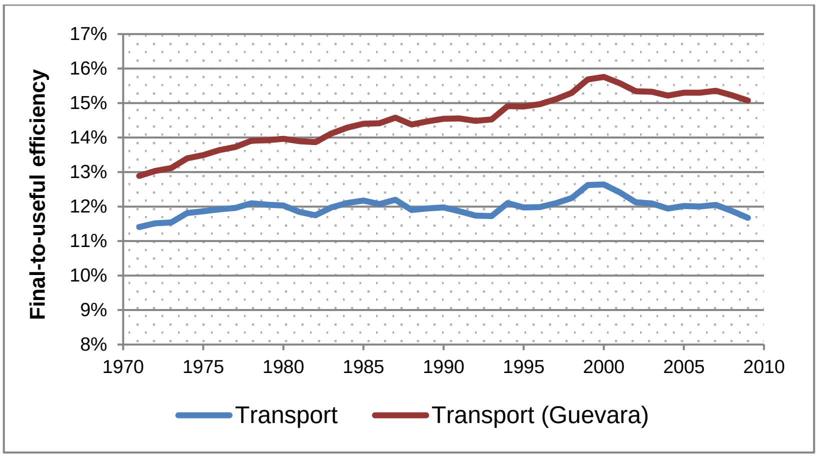


Figure 5.1 Comparison of the evolution of the efficiency in the transportation sector. Own calculations (blue line), Guevara et al. (2016) results (red line).

These adjustments in the transportation sector translated into a significant impact on the aggregate efficiency, this was expected considering that it is indeed the sector with the largest consumption of final exergy and the one with the lowest efficiency. Although similar trends are kept with both approaches there is a slower growth of the aggregate efficiency estimated in this work, previous results showed an average yearly improvement of 1.19%, the new results decrease this value to a mean of 1.06%.

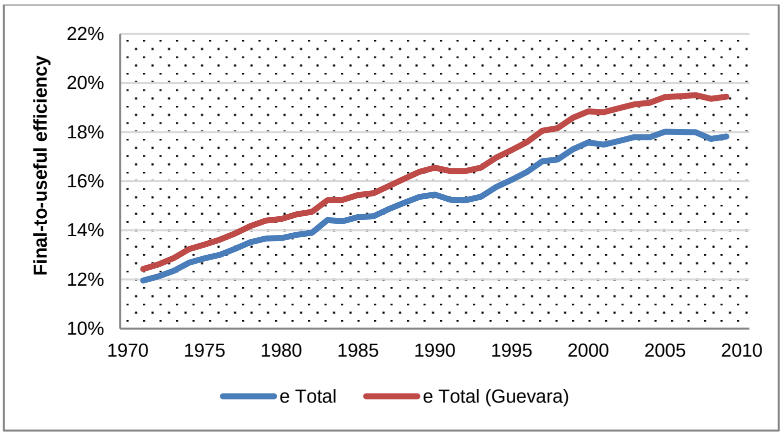


Figure 5.2 Comparison of the aggregate final to useful exergy efficiency. Own calculations(blue line), Guevara et al. (2016) results (red line).

With the estimation of the population growth and a clear tendency in the evolution of the useful work consumption per capita over the studied period it was possible to estimate the demand for the upcoming years. The results of this are shown in Fig 5.3, it is clear that the industry will keep on being the largest useful work consumer as the population grows and the industry needs to grow with it in order to absorb jobs and satisfy the needs of products for the people. The demand for transportation is also expected to keep increasing as long as the government doesn't take actions regarding the creation of an extended efficient transport system for the masses, specially in largest cities that concentrate high levels of vehicles per capita. The sector corresponding to other energy uses is also expected to increase its demand as population not only increases but adopts the uses of more electronical and electronic appliances at their homes, while the consumption of the energy sector is expected to come from the incentives of increasing productivity and explore deep water wells coming from the energy reform.

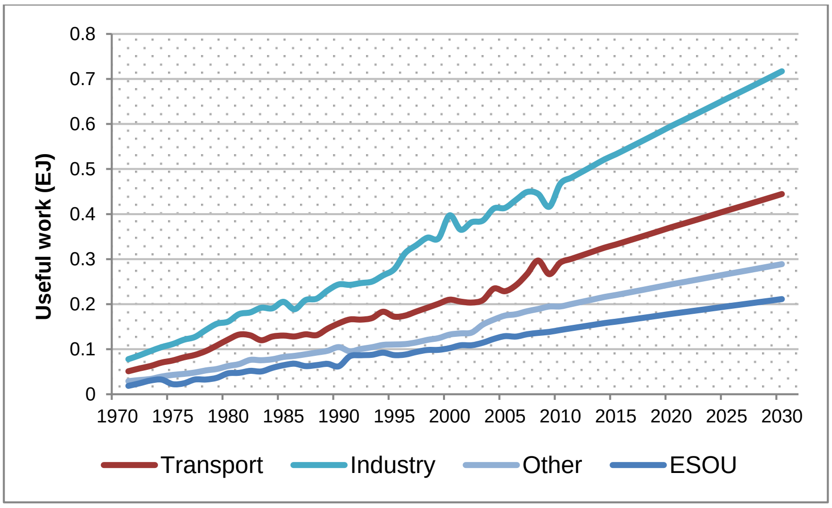


Figure 5.3 Estimations of useful work performed by each sector of the economy by 2030.

As mentioned in chapter 4 section only one scenario was developed for the industry sector as it is believed that the impact of the implementations of policies could be more easily measured in the rest of the economy sectors. Fig 5.4 shows the expected growth in demand from the industry with the assumptions described in the methodology.

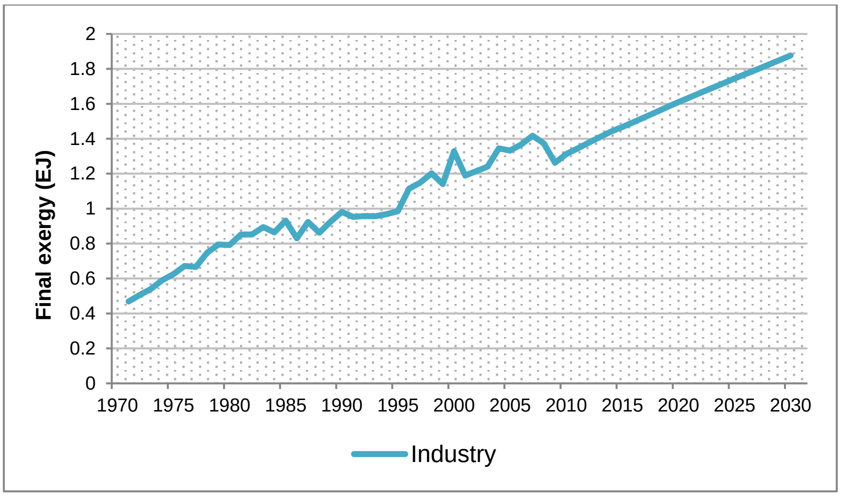


Figure 5.4 Final exergy demand of the industry sector by 2030

The first sector in which two different scenarios were studied was the energy sector own uses, where the baseline scenario reflects a growing demand final exergy of 36% compared to the 2009 values, as it can be observed in Fig. 5.5. On the other hand the proposed measure of including policies to shift the energy carriers used in this sector, led to a growth of demand of roughly 10% compared to the base year.

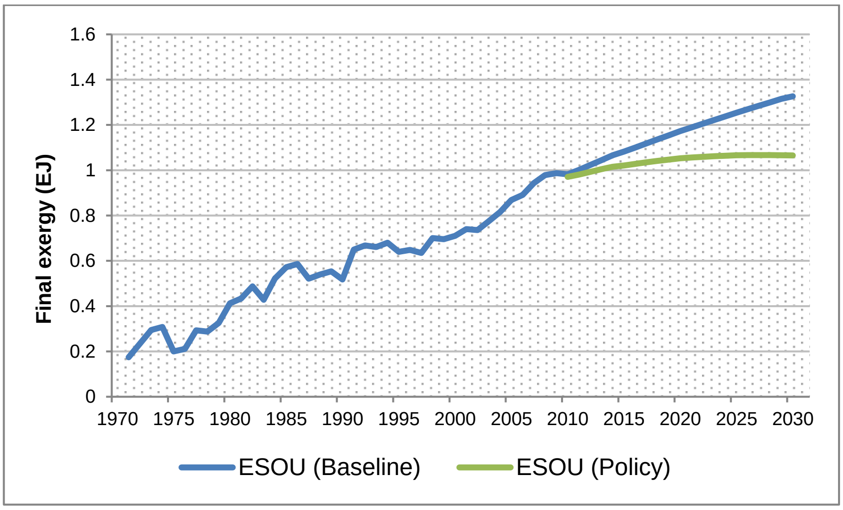


Figure 5.5 Comparison of the final exergy demand by the ESOU under different scenarios by 2030.

As it can be observed in Fig 5.6 the proposed improvements in policy did not produced a significant impact on the demand of the transport sector. This means that a more radical shift is needed in order to increase the sector efficiency. Although fuel taxes are often recommended to achieve this, this policy was not explore considering the social impact that the removal of the gasoline subsidy caused in 2016 and the actual influence it had on inflation that led to a higher shopping basket and ended up affecting the population segment with the lowest income.

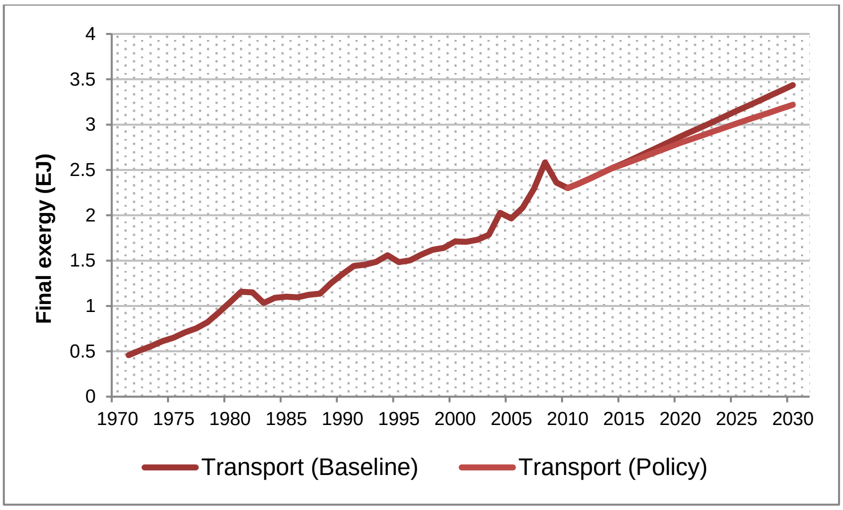


Figure 5.6 Comparison of the final exergy demand by transport under different scenarios by 2030.

The impact of the policies aiming to the residential sector proved to be the most efficient in terms of reducing final exergy demand, as it can be observed in Fig 5.7 not only an increase in consumption was avoided, but a decrease in demand to 2004 levels was achieved.

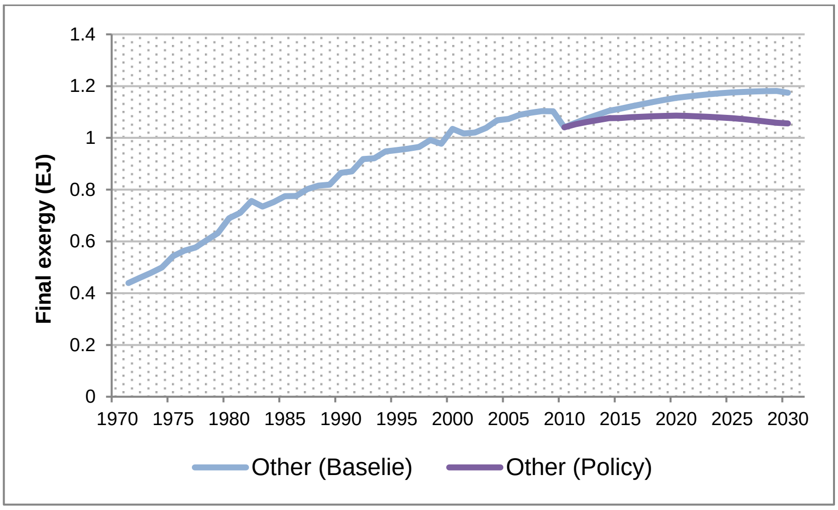


Figure 5.7 Comparison of the final exergy demand by other sectors under different scenarios by 2030.

The measures proposed for the energy and residential sector proved to be the most efficient in terms of final exergy demand reduction, both focused on identifying the major end uses of each sector and trying to accomplish this same end use by means of more efficient technologies that work on different energy carriers. On the other hand, the only useful work category employed in transportation is mechanical work, and the technologies available, for switching the main energy carrier that is oil, are yet not affordable for a country with the average purchase power conditions of Mexico, this made it harder to propose a similar approach, so the replacement of the actual state of the art technology which is internal combustion engines tried to be incentive to become more efficient but the effect of it was not as impactful as expected. Fig 5.8 shows the increase in the aggregate efficiency of each consuming sector and the gains generated by the applied measures.

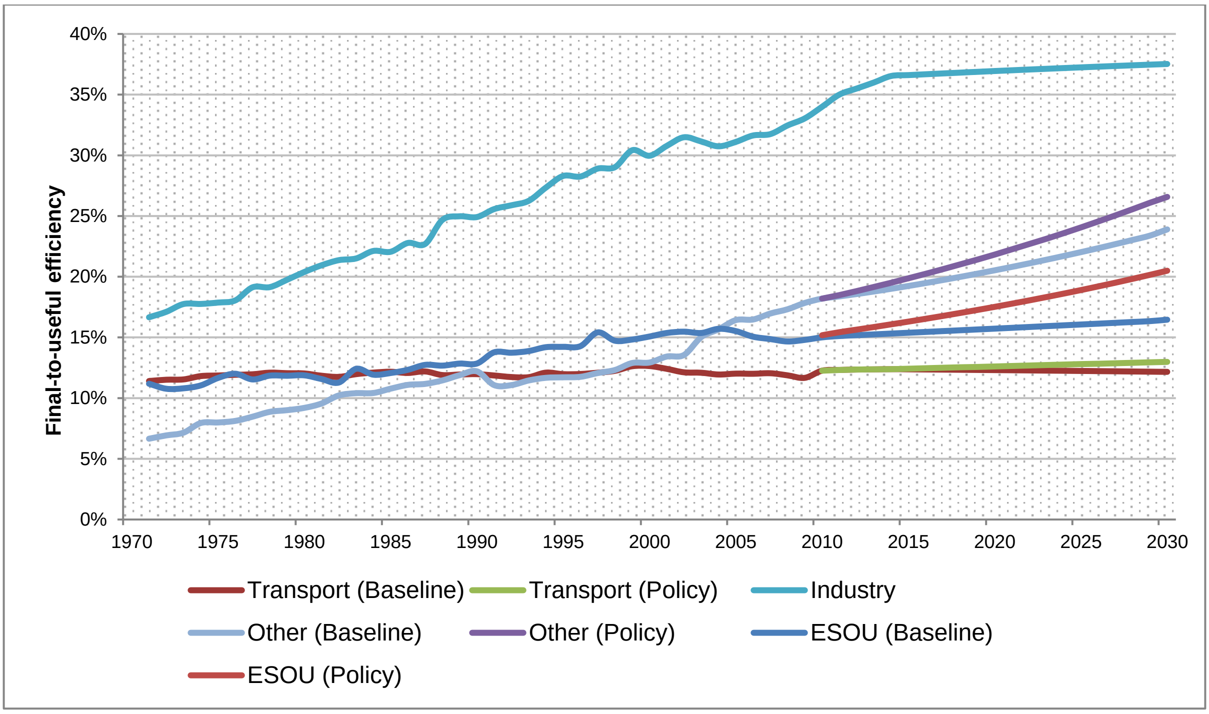


Figure 5.8 Evolution of the final to useful exergy efficiency by sector by the year 2030 under different scenarios (except industry).

Finally the aggregate final to useful exergy efficiency of the energy related sectors of Mexico is shown in Fig 5.9. As it can be seen, the scenario in which policies to enhance efficiency improvements proved to have gains of 1.5% over the scenario where no measures are taken as of the undergoing policies.

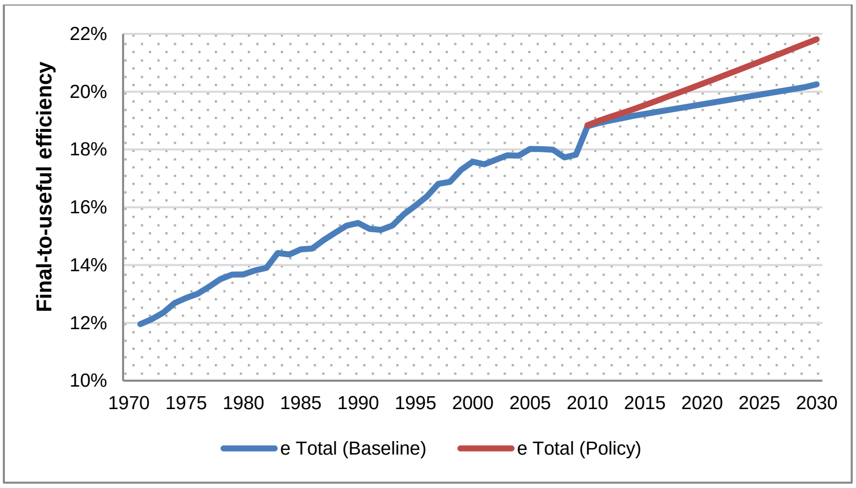


Figure 5.9 Evolution of the aggregate final to useful exergy efficiency under different scenarios by 2030.

Although a significant increase was achieved, it would be suggested to apply stronger measures regarding transportation specially in large cities, as the lack of efficient public transportation together with the ease of acquiring used vehicles from the northern border and an urban infrastructures that incentive the use of road vehicles has guided Mexicans to keep increasing the vehicle fleet over the years.

5.2 Economic growth

Data from the Penn World Table (University of Groningen 2017) has shown that the GDP of Mexico has grown just above four times in the period of 1970-2014, Fig. 5.10 (left) shows the comparison of growth generated by capital and labor, as a function of population growth, estimated through the Cobb-Douglas function. It can be observed, that even though capital and labor by themselves don't manage to explain the total growth of the economy, the difference is not as significant as the observed by Warr et al. (2010) in other developed nations such as US, UK and Japan, this trend also differ for the one presented by Alvarenga et al. (2018) for the case of Portugal. A possible explanation of these behaviour in the Mexican economy is that given that the population is expanding at a faster rate than the economy, it makes it difficult for the economy to track that growth. In Fig 5.10 (right) a comparison of the evolution of Total Factor Productivity and the exergy efficiency of Mexico are presented, as it can be observed the efficiency has shown a significant increase over time, growing 1.6 times over the studied period, while the TFP had a quick growth over the first decade and then presented a significant setback attributed mainly to the 1982 economic crisis, from which it didn't manage to recover and presented a marginal growth since.

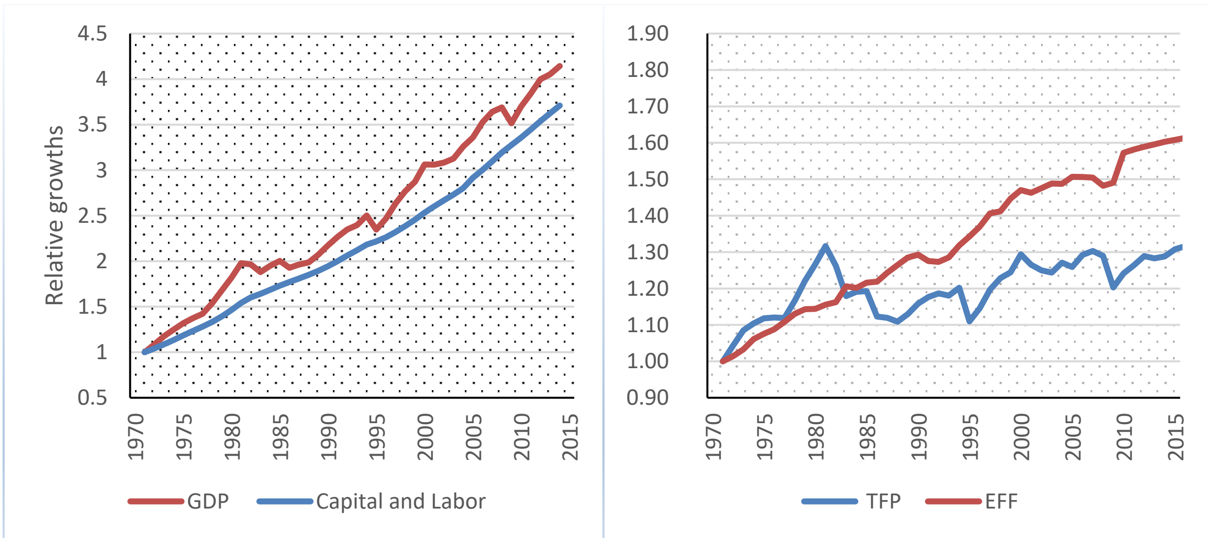


Figure 5.10 Left: Relative growth of GDP (red line) vs capital and labor (blue line). Right: Relative growth of exergy efficiency (red line) vs TFP (blue line)

Figure 5.11 shows the logarithmic relationship shown between the TFP growth and the efficiency, it can be seen that after the 1982 economic crisis it managed to stabilize at a constant value around 0.57, which was the rate taken into account to input in equation 2.14.

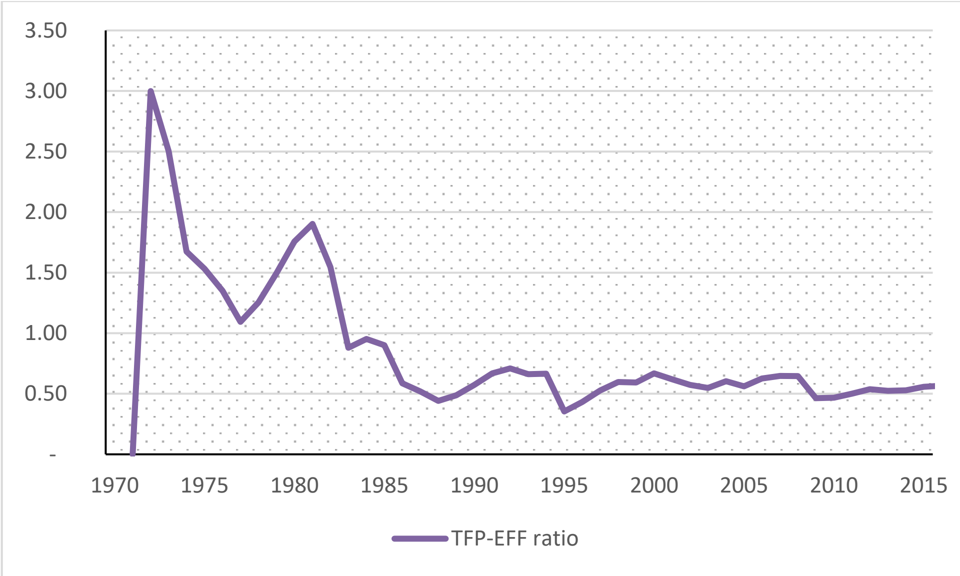


Figure 5.11 Logarithmic relation between exergy efficiency and TFP growth

The comparison of the measured and estimated TFPs obtained through equations 2.12 and 2.14 is shown in the left side of Fig 5.12, while on the right side, the estimation of the GDP from the exergy efficiency based TFP is compared to the measured GDP over the period. It can be observed that even though the Cobb-Douglas model is limited due to its assumption of constant shares of capital and labor over time, it is able to follow accurately the development of the measured GDP. It is worth notice though, that the model is not able to reflect the peaks and valleys of the actual GDP that came as consequence of structural changes or economics crisis.

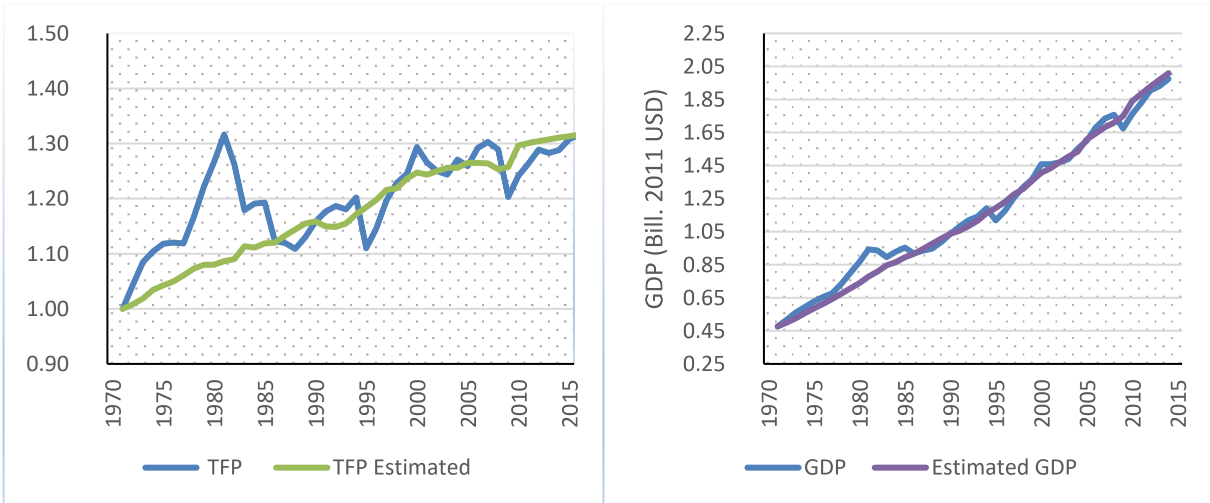


Figure 5.12 Left: Measured TFP (blue line) vs estimated TFP (green line). Right: Measured GDP (blue line) vs estimated GDP (purple line)

The results of the impact of different energy scenarios on the economy are shown in Fig 5.13, it can be observed that although there is an increase of the GDP in the scenario with policies applied to improve efficiency, the impact is not as significant as in the case study of Portugal (Alvarenga et al. 2018). This can be attributed to two reasons, the scenarios developed for Portugal included different development for the labor and capital over time, and the fact that the TFP for the case of Portugal increases in a higher proportion with the increase in efficiency that for the case of Mexico.

It is however worth mentioning that the GDP on the baseline scenario grew at an average rate of 1.33%, while on the scenario with the suggested policies, it grew a yearly 1.57%. While on absolute values the economy grew 18.67% for the first scenario and 21.93% for the second one regarding 2014 values. These growth rates are low for the average trend in developed economies, although they can be attributed to the slowdown in the population growth estimated by the government (Consejo Nacional de la Población 2012), as the population number has demonstrated to have a significantly higher impact on the growth of the Mexican economy than the rest of the factors of production.

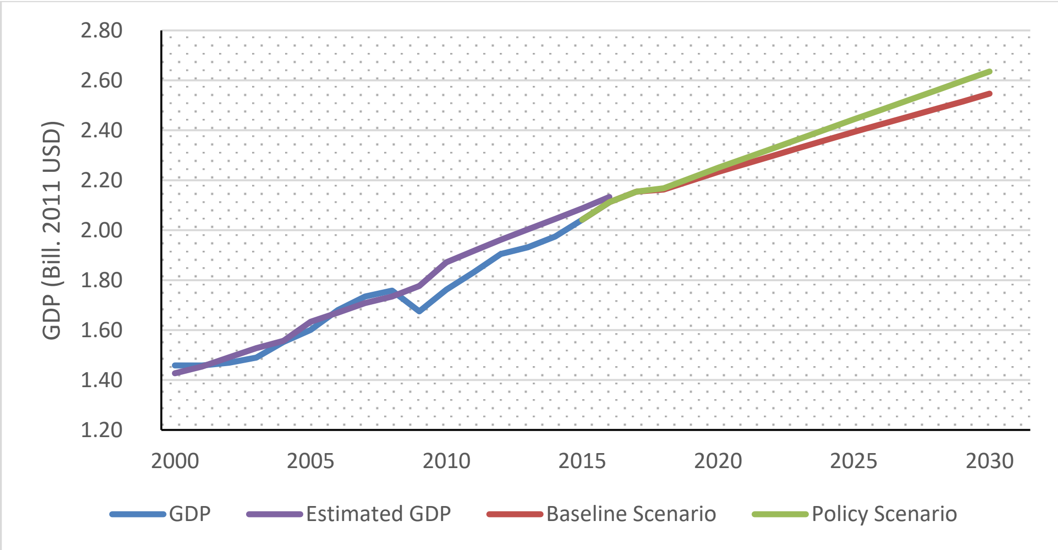


Figure 5.13 Projections of GDP growth under the two different scenarios by 2030

The assumptions of the useful work shares of each sector and the demand of final exergy as a result of the improvements in efficiency and switch in energy carriers are shown in more detail in Annex A.

Figure 5.14 show the final exergy and useful work intensities for both scenarios, the difference in useful work intensities is not as noticeable as in final exergy as the useful work consumption was assumed constant for both scenarios, it is worth mentioning however that the positive relation between energy efficiency and TFP helps to keep a stable intensity in the scenario under policy changes, this would imply that under such circumstances the amount of energy to produce a unit of GDP would be more or less the same by 2030 than in 2014. On the other hand, a significant reduction of the final exergy intensity is observed in the scenario under policy improvements, showing that these improvements in efficiency could make it possible to reduce in almost 8% the demand of final exergy to generate the same amount of economic output.

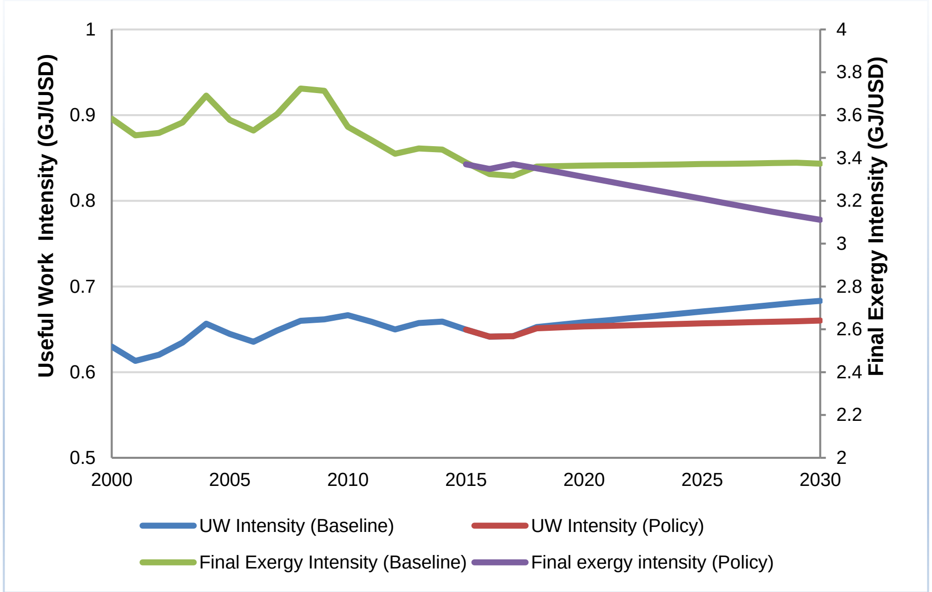


Figure 5.14 Projections of useful work and final energy intensities (GJ/USD) under the two different scenarios by 2030 (Bill. 2011 USD)

Chapter 6

Discussion

This chapter analyses the approach used to estimate the Total Factor Productivity for this thesis. It presents different interpretations of the TFP development in Mexico and compares it with other countries at the same and at different stages of development, taking into account different geographical regions as well. The objective of this chapter is to bring to the table the discussion of TFP in developing economies and incentive further research into this topic and its relationship to energy efficiency not only for developed countries.

As mentioned earlier in this work, in order to estimate the TFP of Mexico it was preferred to use the population growth as a measure of labor over the employed population and the total hours worked in the economy. The major reason to use this approach is the large contribution of the informal employment sector, this occurs in many developing countries and although information regarding this numbers is available for most of the cases, there are reasons to believe there might still be underestimations.

One of these underestimations is associated with the shadow economy, defined as those activities not taxed or legally registered that include black or clandestine labor including criminal activities. The contribution of this type of activities in Mexico was estimated to be 49% of the country's GDP during 1989 and 1990 (Charmes 2000).

As explained by Charmes (2000) and performed by García-Verdú (2005) a way of compensating this data is to use information on household final consumption, which allows to estimate the production and consumption going on in the informal sector and lead to estimate more or less constant values for the contribution of labor and capital to economic growth (Gollin 2002). A difference between the estimation of the TFP of Mexico by using labor and capital shares from the Penn World Table and from household consumption surveys is presented in Annex B.

An example of TFP underestimation has been observed for the case of Turkey, which has one of the largest informal sectors in relation to its GDP from the OECD countries, along with Mexico. Atesagaoglu et al. (2017) found that establishing an elasticity factor for the degree of substitutability between formal and informal sectors can have a significant impact on the country's productivity. While a lack of representation of informal labor showed a five-fold growth in the TFP of the country in the period of 1952-2012, it was shown that an increase in the share of this informality could represent a growth between 20 and 50% above the baseline estimation depending on the degree of substitution.

These would suggest that a deeper analysis of the informality in Latin America and its impact on TFP and therefore in economic growth could bring a better understanding of its relationship with energy efficiency, as many countries from the region show a similar tendency of a marginal development of their productivities, as can be seen in Annex B. This is a region of particular interest for the study of the impact of informality on growth, considering the estimates of 40% of the GDP being produced informally and 70% of the labor force being employed this way (Loayza et al. 2009).

Limam and Miller (2004) performed a study classifying countries in five different regions (Africa, East Asia, Latin America, South Asia, and the West) and found out that while capital accumulation proves an important share of the GDP growth explanation in each of this regions, labor only contributed positively and significantly in Africa, East Asia and the West, having a negative impact in Latin America and South Asia, implying that fast economic growth would be related to a decrease in efficiency improvements for these regions.

A possible explanation for this negative contribution of labor in these regions is the large efforts to increase education levels that have not produced a better development on human capital that translates into higher economic activity. This means that educational policies have not been enough, and they must be followed by proper economic and social policies that can reduce inefficient government expenditure and reduce bureaucracy that slows development (Limam and Miller 2004).

The differences of expenditure in human capital between developed and developing countries can be observed as advanced countries invest on natural resources and human capital to develop technology, while developing countries expenditure focuses on human capital that is devoted within their political and economic institutions in order to incentive the adoption of these foreign technologies. This leads the TFP to differ in accordance to the degree of development of countries, while innovations in technology contributes for the growth of advanced countries, developing countries need to spend to acquire and diffuse them (Limam and Miller 2004).

In Annex B the TFP growth of some developed economies can be observed, it is noticeable that they share a similar growth tendency, while this trend differs strongly from that observed for the Latin American group.

Torre Cepeda and Ramos (2015) went more in depth performing an analysis of the TFP development of Mexico for the period of 1991-2011 by industries, segmenting them by primary, secondary and tertiary. The intention of choosing this time scope was to study the impact that the NAFTA and the adhesion of China to the World Trade Organization had on the Mexican economy, as these two events were believed to have a significant influence on Mexico's productivity. The first one as a result of tariffs removal that incentive foreign investment and the adoption of new technologies, the later one as a consequence of a more competitive domestic and international market responding to the Chinese competition that would foster productivity. They found out however that the primary sector had a negative impact on GDP growth resulting from the NAFTA, while the secondary sector presented a low contribution from this agreement and a negative one from the competition with China, showing that only 3 out of 27 subsectors of the secondary industry presented a positive average rate of TFP growth on the first five years period, while only 5 in the following lustrum.

The results of Torre Cepeda and Ramos (2015) proved that structural changes in the economy did not have the impact on TFP and economic growth that was expected from them, attributing this poor performance to internal factors as monopolized markets, excessive regulations, low quality of human capital, deficient public infrastructure and inefficient tax system.

Padilla-Pérez and Villarreal (2017) performed a similar analysis and compared the results to the ones obtained for the US economy. They tried to attribute the low productivity of Mexico as a result of an industry transformation towards lower productive sectors and to the low contributions of high qualified factors, such as college-educated workers, to value added growth.

Although the transformation of the Mexican economy from a closed one to an exporting one brought an increase in the production of goods of medium and high technology to levels higher than those of the BRIC countries, and led to a share from 6.1 to 13.2% of the total US imports from 1990 to 2015, this outstanding performance in exports has not been enough to break the inertia of the slow and volatile economic growth associated with slow productivity growth.

To study the impact of the manufacturing sector, Padilla-Pérez and Villarreal (2017) classified it in four different categories: scale intensive industries, with efficiencies dependent on their operations scale and process improvements; supplier dominated industries, with improvements derived from capital and intermediate goods from suppliers; science-based and specialized suppliers, those that produced their own innovations; and producers of primary products. The share of exports of primary products in 1986 was of 43.9% of the total, while science-based suppliers accounted for only 23.1%, by 2015 these shares switched to 11.5 and 41.3% respectively.

These trends would indicate that a shift from low to high productive industries is taking place, however it has been shown that high technology industries in Mexico don't depend strongly on knowledge but rather on labor intensive processes and therefore the contribution of highly qualified workers is not as significant

An interesting comparison is made by these authors, as they point out that from 1990 to 2014 the US has had a manufacturing productivity growth of 4.2% while in Mexico it has only been of 2% for this same period despite the close integration of this sector of both countries. This higher growth shown by the US is attributed to the productivity growth of science-based and specialized manufacturing, which increase 10%, while in Mexico it only raised 1.7%. These numbers prove that despite the high share of technology manufacturing in Mexico, the fact that these industries are dominated by labor-intensive activities rather than knowledge-intensive has produced a much lower growth. On the other hand, both countries main driver of value added is the labor input of non-college educated workers, in which the US still has a higher level of schooling among this population sector, meaning a more productive workforce.

These findings coincide with the work of Díaz Bautista (2016) who argued that although labor was the main source of economic growth of Mexico during the 60's, the country has reached a phase of economic development where labor and capital resources can't keep contributing to growth in the manufacturing sector.

Other authors as Michelis et al. (2013) found a negative correlation between the growth rate of hours worked and the TFP, showing that an increase in 1% of hours led to a decrease of 0.5% in TFP. Although this study aimed to study the TFP performance of Canada and their sample took into account only developed economies from the OECD and the G-7. It would be interesting to observe if this correlations persist in developing economies, as Mexico is one of the countries with the highest amount of worked hours per capita (University of Groningen 2017) and developing countries such as those in Latin America tend to have a high number of worked hours given the strict regulations of the labor laws and the idiosyncratic belief that higher working time leads to higher profits.

Many approaches have been developed to explain the Total Factor Productivity in economy, some have shown significant correlations that have helped understanding the development of advance countries and their relationship with technological breakthroughs. These relations however have proven not to be so clear for countries at different stages of development and with different economic growth drivers. There is a significant importance in understanding this topic, as identifying properly the sources of growth can lead to an efficient design of policies that can help developing countries to catch up with the fastest growing economies.

It is noticeable that for the particular case of Mexico, structural changes that were expected to drive growth were not able to do so, therefore important attention must be put into some of the common factors found in different research works such as informal labor, efficient economic and social policies, investment in education and human capital, and an effort to switch from a labor-intensive to a knowledge-intensive manufacturing country.

Chapter 7

Conclusions

This is the final chapter of this thesis, it summarises the conclusions from this work and points out aspects to be developed in future works. Recommendations are made intending to improve the performance of energy use in the Mexican economy through the implementation of energy policies and potentially enhance economic growth.

The slowdown in the growth of the Mexican economy over the last year have been contributing to increase inequality and enhance other social problems as informal employment that contributes itself to keep the country from growing faster. After analysing the relationship that exist in Mexico between the efficient use of its energy resources and economic growth, through the Useful Exergy Accounting Methodology and the Solow-Swan approach for growth several conclusions were obtained.

While the industrial sector was not analysed in depth in this thesis, it has shown to be the best performing sector in terms of energy efficiency and it is expected to keep improving over time as the country continues to expand its export-based economy.

As shown in this work, improvements in the way energy is being use in the extraction and transformation processes within the energy industry could contribute significantly to reduce the final energy demand of the country, considering that the energy reform aims to boost the productivity of the sector it wouldn’t be so hard to think that such a policy or goal of further electrifying the sector could become a reality, especially if its implemented before the new wells and refineries begin construction and operation.

After comparing the results of Guevara et al. (2016) and Serrenho et al. (2014) regarding the second law efficiency of the transportation sector, it was decided to implement new assumptions to estimate a value for Mexico, given than the country presented an efficiency above the European Union levels, while having a vehicle fleet more than five years older in average. This was considered significant given that transport is the largest consumer of the final energy in the country and has also proven to be the less efficient. The assumptions used for this new estimation proved to reflect a behaviour that followed the trend of the Mexican vehicle fleet age, that has been significantly increasing over the years due to the laws established in the NAFTA.

The suggested policy to increase the efficiency of the transportation sector was based in the “Renove carro” program adopted in 2008 in Portugal. This measure was chosen over the modal shift due to its significantly lower marginal $CO2$ abatement cost (Domingos et al. 2014), and was preferred over the fuel tax, considering the high social cost that removing the gasoline tax in Mexico had in the previous years. Although it didn’t prove to be an effective measure, it would be suggested to make a more in-depth analysis of transport in Mexico given its overall impact in the energy sector, while also considering the effect that it is having on the air quality in the country’s largest cities, where it could potentially bring a spike in environmental and health care cost for the government.

The proposed policy of incentivizing solar thermal heating for water for residential and commercial users could come in the form of a subsidy, although it proved to be relatively costly in terms of abated $CO2$ for the case of Portugal (Domingos et al. 2014), the decreasing price on the technology due to the learning curve and the geographical conditions of Mexico could bring this cost down and make it more affordable both from governmental and end user perspectives. This could be a potential line of research to contribute to decrease the energy demand for the residential sector as well as the emissions coming from households.

The application of the suggested policies could be limited by financial constraints, as it is not considering the overall cost of applying them, neither by the government, investors or end users perspective. Although minimum energy performance standards are usually the most effective and cost efficient policy instruments: such as fuel tax to limit the growth of oil use, and the removal of subsidies which are still significant in electricity, considerations regarding the population economic status have to be taken into account as these measures could lead to periods of social instability as shown by the liberalization of gasoline prices in 2017.

Although results shown that an increase in exergy efficiency could boost economic activity, the impact of the energy usage in Mexico didn’t prove to have such a strong relation with economic growth as it has demonstrated to be in some developed countries. Part of this might be explained by the low productivity of the country that to some extent is attributed to the high share of informal labor and low levels of education that don’t incentive a demand for high qualified jobs.

The main intention of this thesis was to propose alternatives on the energy side that could enhance the economic development of the country in the near future, although the weak relationship found for these two variables would suggest that policies to fasten economic growth should be focus rather on labor and productivity, as it is the main driver of Mexico’s economy. Potential policies to enhance this increase in labor productivity should aim to incentive the formalization of the labor sector, invest more efficiently in education and create more jobs for high qualified professionals. This doesn’t mean that no focus should be put into energy, as once labor force becomes more productive, an efficient use of energetic resources might enhance economic growth on a larger extent.

This work does not consider different economic scenarios, adoption of a variation in the growth of capital and labor could be further researched, as the population is expected to keep growing at a lower rate than the one showed in the previous years and the uncertainty caused by the renegotiation of the North American Free Trade Agreement that is undefined as of today.

A possibility to improve the scenario development for future works, in regard to the evolution of energy technologies and the trends in the use of energy carriers, would be to encourage a participatory approach for each economic sector, such as that used for the MEET 2030 Project. The collaboration of industry and government representatives, researchers and end use consumers is key to understand how the energy outcome of the country might look like in the mid and long-term.

Another interesting aspect that could be included in the elaboration of forthcoming works related to this scenario creation methodology would be the estimation of CO_2 emissions, since they are expected to slow down as a result of the country’s renewable energy goal of achieving a 37.5% of clean electricity by 2030 (Secretaría de Energía 2016), but can be counterproductive if the conventional electricity mix switch to higher CO_2 intensive energy carriers or if the demand side is not controlled.

The use of longer time series for both economic growth and energy sector of Mexico could be of help to develop more accurate scenarios and understand better how this relationship has evolved over time, as the time series used for this work is relative short when compared to other works performed for instance on the US, UK and Japan.

Given that this is the first work following this methodology for a developing country, further research of this topic in developing countries with different growth tendencies as those from Latin America, Africa and Asia would be more than welcome in order to keep trying to understand how the economy grows and its link to the use of energy in our societies.

Annex A

Final and Useful Exergy Shares

In this annex the assumptions for the useful work shares of each energy consuming sector are shown as well as the resulting final exergy demand obtained from each of the scenarios.

A.1 Final and Useful Exergy Shares by Sector

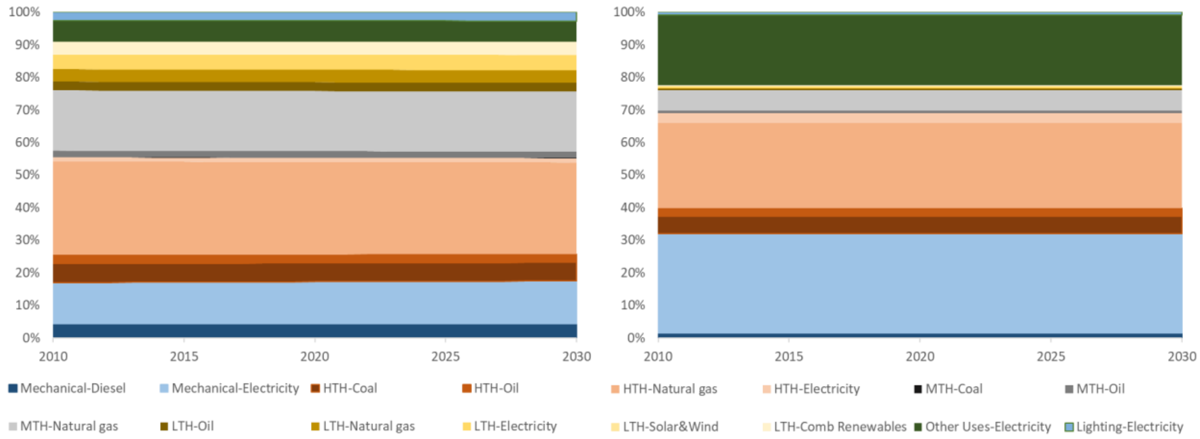


Figure A. 1 Shares by end use category and energy carrier for the industry sector. Left: Final exergy. Right: Useful work

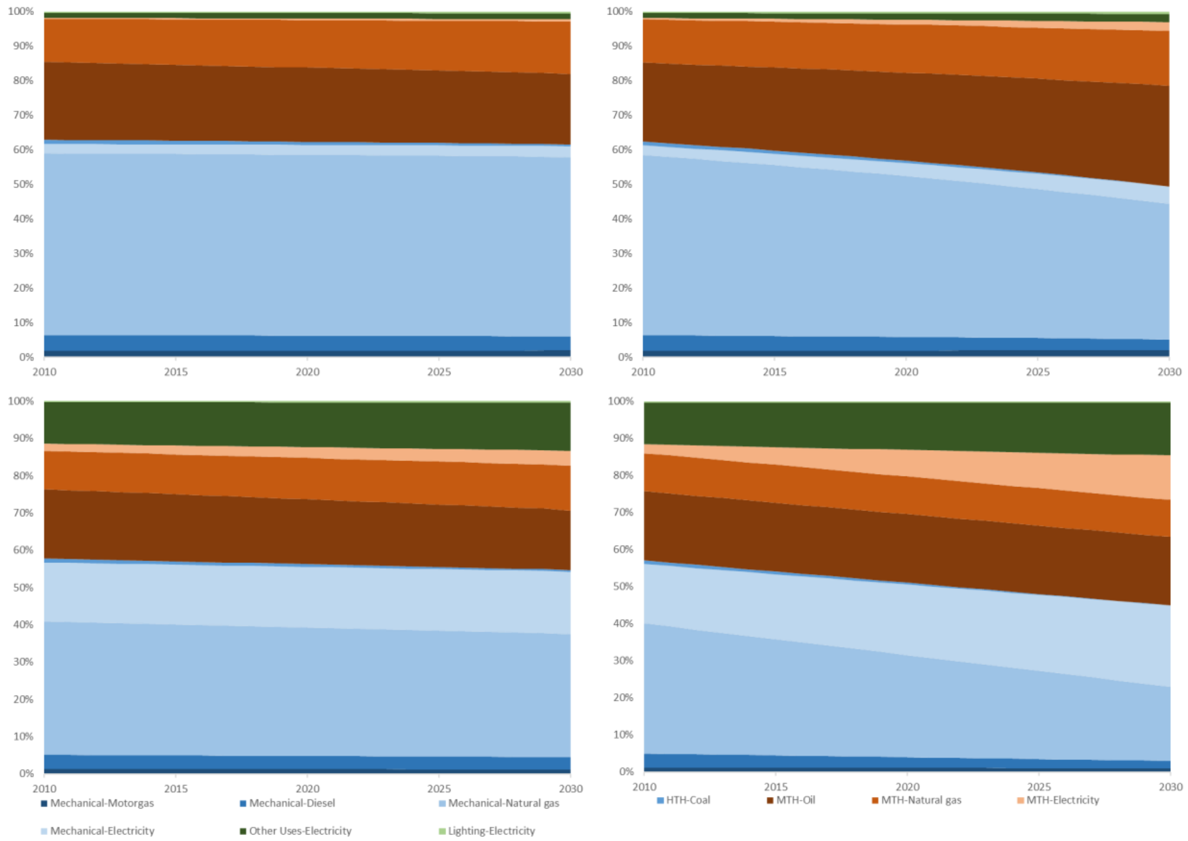


Figure A. 2 Shares by end use category and energy carrier for the energy sector. Top Left: Final exergy (Baseline scenario), Bottom left: Useful work (Baseline scenario). Top right: Final exergy (Policy improved scenario), Bottom right: Useful work (Policy improved scenario)

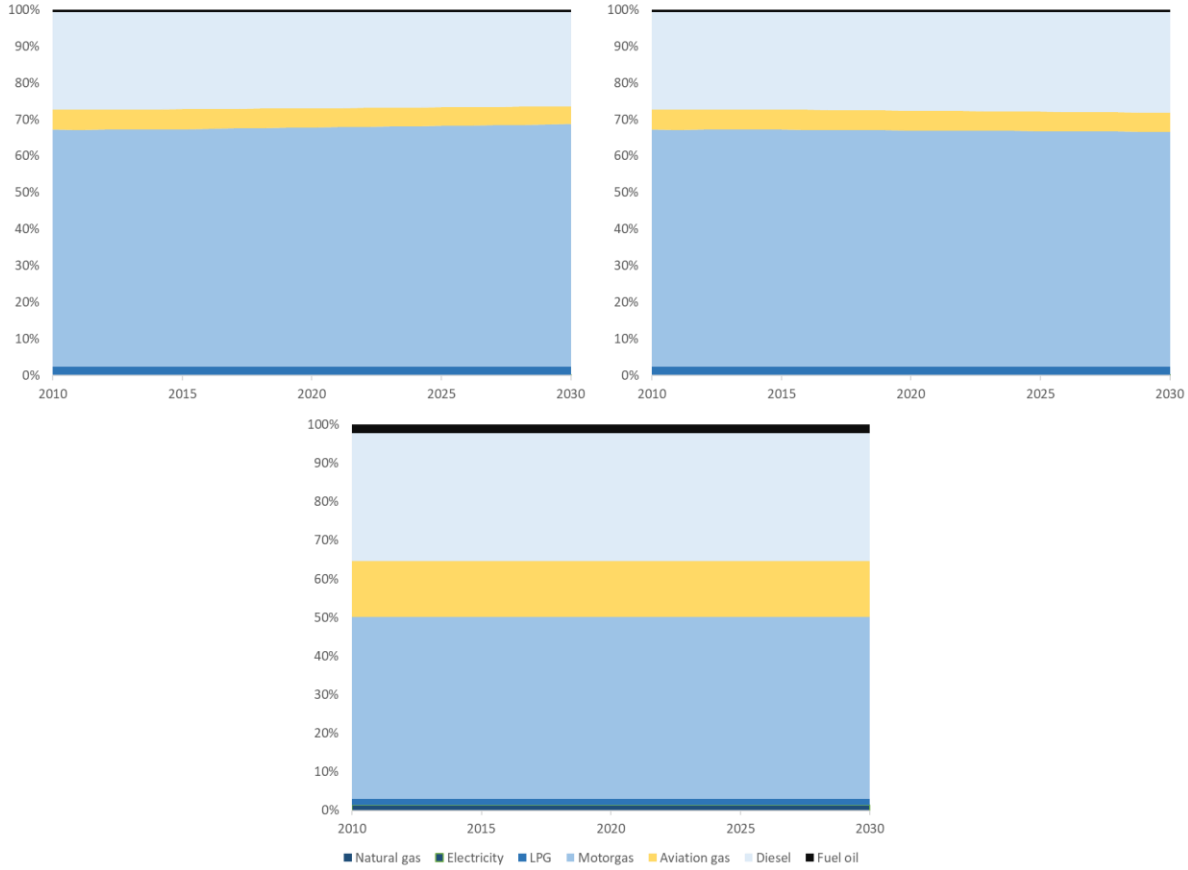
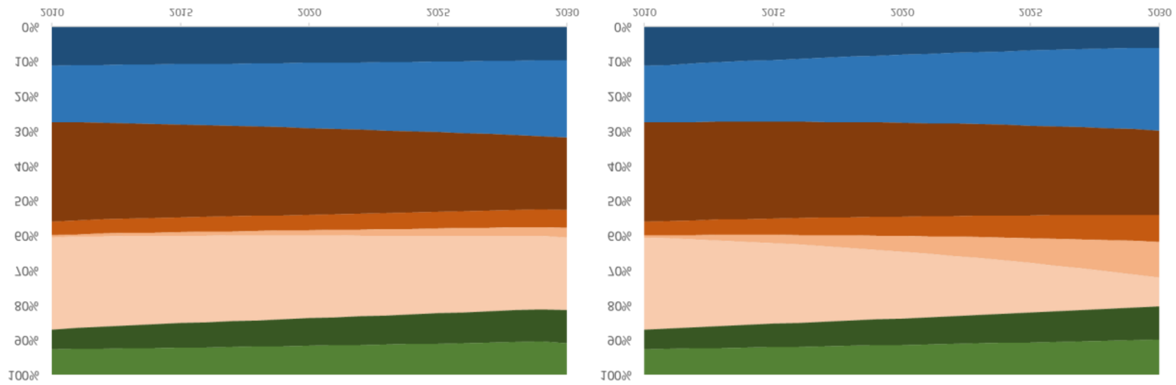


Figure A. 3 Shares by energy carrier for the transportation sector. Top left: Final exergy (Baseline scenario), Top right: Final exergy (Policy improved scenario), Bottom: Useful work



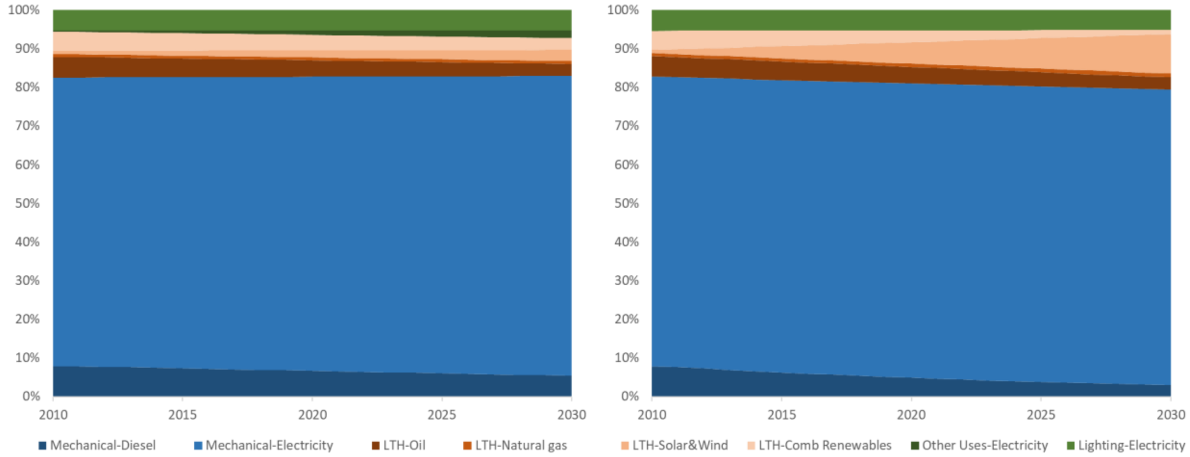


Figure A. 4 Shares by end use category and energy carrier for the other uses of energy sector. Top Left: Final exergy (Baseline scenario), Bottom left: Useful work (Baseline scenario). Top right: Final exergy (Policy improved scenario), Bottom right: Useful work (Policy improved scenario)

Annex B

Countries TFP

This Annex compares the TFP of different countries, the results of using different approaches for labor such as population, employed population and total number of hours worked within the economy corrected by human capital index are presented

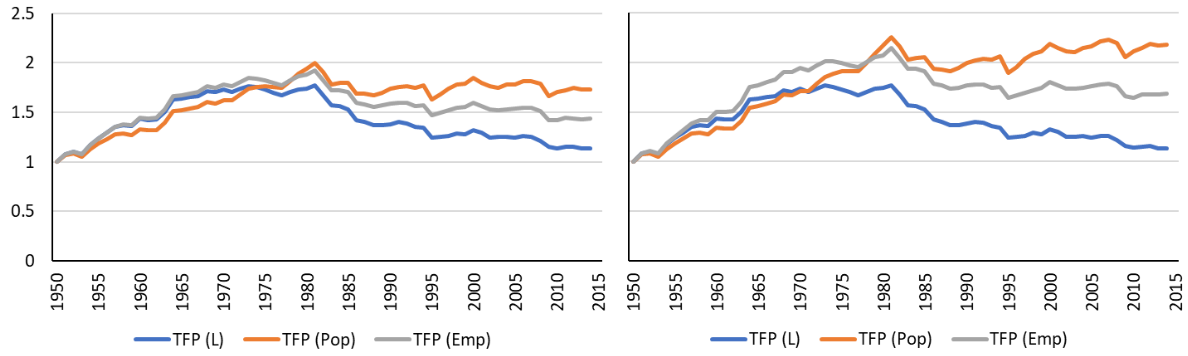


Figure B. 1 Mexico's TFP estimated with human capital index, population and employed population as a measure of labor. Left: L & K shares from PWT, Right: L & K shares from García-Verdú (2005)

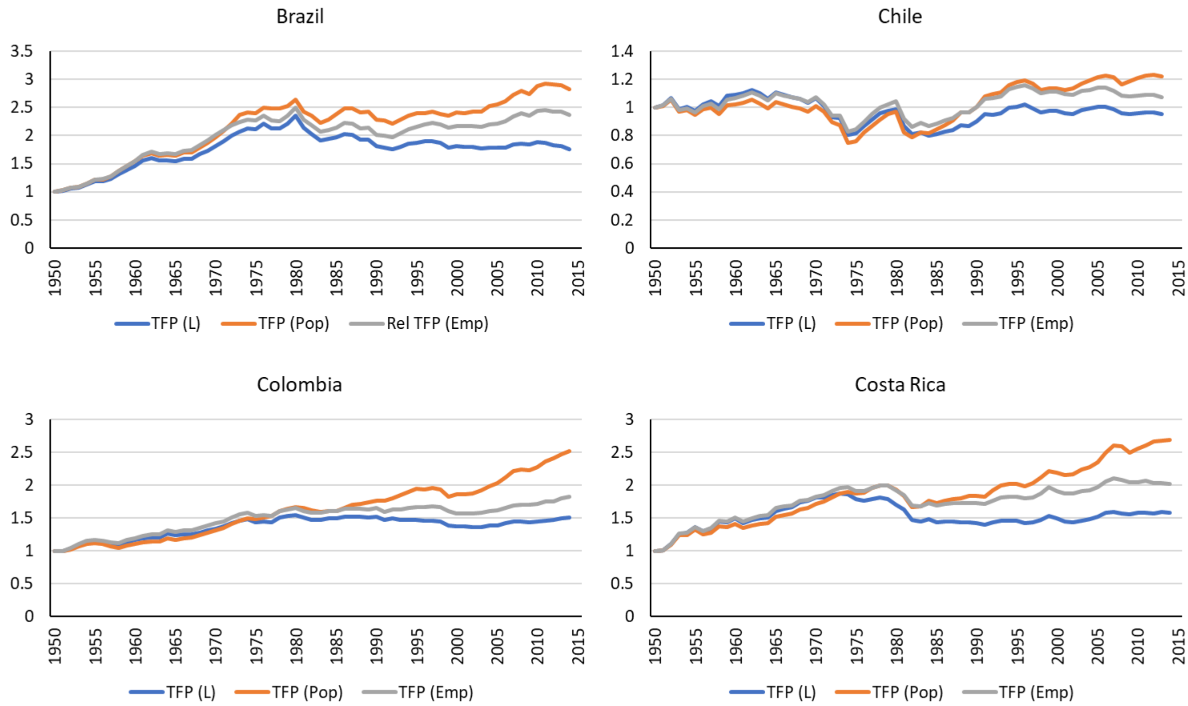


Figure B. 2 TFP of some Latin American countries estimated with human capital index, population and employed population as a measure of labor.

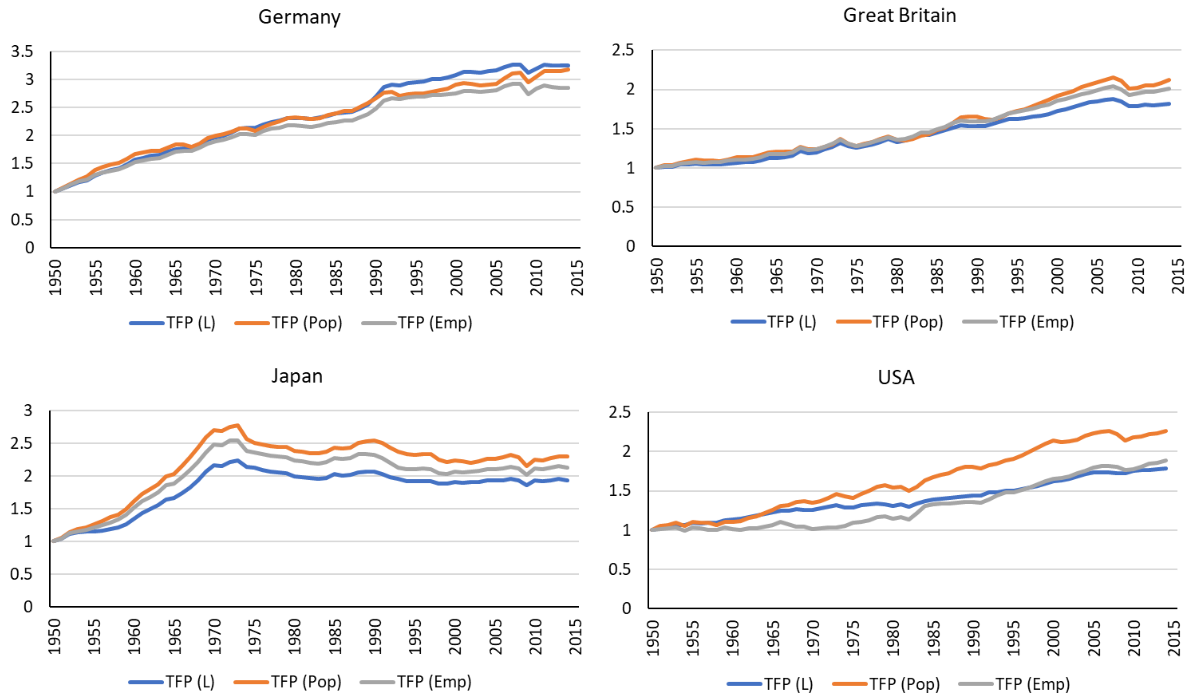


Figure B. 3 TFP of developed countries from different regions estimated with human capital index, population and employed population as a measure of labor

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