Energy Efficiency can help faster future Economic Growth in Greece

Scenario planning for 2030

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***Abstract*— The present study investigated two matters. One was the correlation between useful exergy and economic growth. The second was whether the faster recovery of the Greek economy by 2030 is possible through improving the country's aggregate exergy efficiency. To do that, first Greece's economy sectors exergy analysis was performed by implementing the Useful Exergy Accounting Methodology. The most important energy carriers (oil and electricity), useful exergy categories (mechanical drive and heat) and exergy intensive sectors were identified. It was shown that, there is a relatively stable relationship between useful exergy and GDP for the past three decades. Then, two extreme scenarios were formulated, assuming each, the pessimistic and optimistic developments of the labor, capital stock and exergy efficiency factors. Improvements in efficiencies were achieved, by implementing measures in the important sectors, which led to technology upgrades, and shifting from less to more efficient energy carriers (e.g. oil to electricity) and technologies (e.g. conventional burners to CHP). The economic model, which was used to forecast the future economic growth, links aggregate exergy efficiency and total factor productivity, and is based on the three factors of labor, capital and exergy efficiency. The outcomes of the two scenarios differed significantly, which proves that higher progress in the exergy efficiency of primary sectors can help economy grow more rapidly. Projections for useful and final exergy were made, based on the findings for useful work intensity and aggregate exergy efficiency, and they seem increase, following economic growth.**

Keywords: economic growth; Greece; exergy; energy efficiency; total factor productivity; useful work

I. INTRODUCTION

The first law of thermodynamics efficiency gives the ratio of the useful energy output to the total energy input of this process. However, this measure of efficiency shows limitations. To define a more precise efficiency of a process, the thermodynamic concept of *exergy* is introduced, which is the capacity of energy to do physical work. Exergy corresponds to the part of an energy flow, which can produce useful work after every consecutive transformation process, yet this fraction of energy is reduced in each step. The exergy efficiency, or second-law efficiency, is the ratio of the minimum energy input to the actual energy input of a process.

In mainstream economics, the standard economic model to measure the size of a national economy in GDP terms, is an aggregate production function, which considers the factors of labor, capital and total factor productivity (TFP), and is called the Solow-Swan model. Nevertheless, not all economists have been happy with the use of production functions because they show limitations. [1]. Some, also believe that, the related role of energy is thought to be minimal and another point of view, given by ecological economists, suggests that human development and economic progress are strongly correlated to exergy [1]. Past research (e.g. [2]) has shown correlation between the useful work injected in the US economy and its growth. Furthermore, another study tries to explain the TFP in Portugal with the help of the aggregate second-law efficiency of the Portuguese system [3]. Thus, besides capital and labor devoted for production, the third factor could also be qualitatively explained by considering the useful exergy generated and the technology utilized to do it. For the purpose of exergy analysis in country-scale the methodology of Useful Exergy Accounting (UEAM) by Ayres and Warr et al. [2], [4] was developed.

Greece has a relatively small economy in EU, which went through a big shock after the financial crisis of 2007-2008, resulting to loss of a quarter of GDP in a few years. A decade after the fall, the county's economy is trying to stand again on its own feet. This thesis has two main objectives. The first is to investigate the relationship between useful exergy and economic growth in Greece. The second is to examine how changes in the present energy system could contribute towards the faster recovery of the Greek economy, through potential suggested policies and implemented measures. In order to do that, initially exergy data and economic figures of the country will be analyzed and past trends will be revealed. This will help explore the relation between useful exergy and economy. Then, two main scenarios will be created, focusing mainly on energy savings, through changes in the energy mix and technological efficiencies' improvement. One will assume that, progress continues on the path that is already carved, which is expected to lead to mild development. The other will consider stronger adjustments that will eventually lead to better aggregate second-law efficiency, consequently to higher TFP, and in that manner, growth will be boosted. Ultimately, the results will be evaluated and discussed in terms of projected GDP as well as exergy.

The outline of the paper is as follows: Section II – Literature review & Past trends; Section III – Scenarios to 2030; Section IV – Final projections; Section V – Conclusions.

II. LITERATURE REVIEW & PAST TRENDS

A. Exergy analysis

Throughout the energy flow process, where extraction, transformation and consumption of energy (resources) happens, three stages can be identified: primary, final and useful. In a broader outlook, the different forms and stages of energy and exergy can be identified for the entire structure of a country's economy. In the present case, the exergy analysis of Greece was done using the Useful Work Accounting Methodology, following the work of Ayres and Warr et. al [2] and presented by Serrenho et. al [4], [5]. This methodology has four steps:

1. Final energy to final exergy data conversion
2. Allocation of the final exergy consumption to useful work categories, for each final use sector.
3. Second-law efficiencies estimation for every final-to-useful exergy transformation.

4. Sum of all useful work values to a total value for each useful work category.

The energy data were made available by the International Energy Agency (IEA) World Energy Statistics. The calculation sequence followed is similar to the ones described in [4]–[6].

1) Final energy to final exergy converison

Exergy can be defined as the maximum amount of work that can be obtained by a system as it approaches thermodynamic equilibrium with its surroundings through a sequence of reversible processes [2], [7]. Calculating exergy from energy values depends on the capacity that different energy forms have in order to deliver work. In energy calculation, energy is usually displayed in the forms of: fuel, electricity, mechanical work, heat and non-energy products, having each of them a different exergy content [4]. In the present case, the energy inputs for the conversion into exergy go beyond the conventional energy accounting statistics, considering: food and feed for humans and working animals, respectively, for muscle work.

a) Energy Industry own use, Industry, Transport and Other sectors

In the energy statistics database [8], data were provided disaggregated by 68 products (of natural resources) of final energy, and these data are disaggregated for the main economic sectors. These products were grouped in 10 sets of energy carriers according to their origin [4], [5]. As a result, a list of these main energy carriers was created along with their exergy factors and can be seen in Table 1.

To estimate the final exergy consumed in Greece throughout the years, the energy data of the main energy sectors of economy were taken under consideration. These are: 1.Energy industry own use (EIOU): includes fuel and energy producing industries, e.g. coal mining, oil refineries; 2.Industry: includes relevant sub-sectors, e.g Iron & Steel, non-ferrous metals; 3.Transport: includes all domestic sectors of transportation; 4.Other sectors: includes residential and services sectors, agriculture & forestry and fishing; 5.Food and Feed. The energy data are given, within each sector, disaggregated by sub-sectors (or as in IEA, "flows") and origin (the mentioned products).

The data, in energy values of TJ, are multiplied using eq. (1) where for each year y, $FEx_{ecp,y}$ is the final exergy of each energy carrier's product ecp, $FEn_{ecp,y}$ is the final energy of each energy carrier's product and, φ_i the respective exergy factor from Table 1. The result is a new final exergy database disaggregated by energy carriers' products, from 1960 to 2014. The sum per year, given by eq. (2), of all the final exergy values disaggregated by energy carrier product, $FEx_{ecp,y}$, and flows, ef, gives the annual final exergy $FEx_{ef,y}$ of each flow.

Table 1: Energy Vectors with their exergy factors.

Energy vectors	Exergy factors (φi)
Coal and Coal Products	1.06
Oil and Oil Products	1.06
Coke	1.05
Natural gas	1.04
Combustible renewables	1.11
Electricity	1
Food and Feed	1
CHP and geothermal heat	0.4
Solar thermal heat	0.25
Other non-conventional	1

$$FEx_{ecp,y} = FEn_{ecp,y} * \varphi_i \quad (1)$$

$$FEx_{ef,y} = \sum_{ec=1}^{68} FEx_{ecp,y} \quad (2)$$

$$FEx_{es,y} = \sum_{ef=1}^{n} FEx_{ef,y} \quad (3)$$

b) Food and Feed

For the of Food and Feed sector, the data for the population of Greece were taken from [9] and the food intake data were found in [10]. Working animal heads' data were taken from [11] and the feed intake from [12], [4].

In the case of humans, final exergy is estimated using eq. (4) where for year y, $e_{m,y}$ stands for the daily metabolizable energy content of supplied food *per capita*, p_y, is the population and 1.23 is the gross to metabolizable ratio [5], [13]. For working animals, the final exergy is estimated by eq. (5). In the equation, e_i is the daily metabolizable energy content of feed intake, estimated by Serrenho et. al [5] and Henriques, S. [14], for asses, horses and mules. The heads are noted as h_i in the equation, the gross to metabolizable ratio is considered as 1.54, while α_y is the *supplied to eaten* ratio and equal to 0.64 [5], [13].

$$FEx_{food,y} = 365 e_{m,y} p_y 1.23 \quad (4)$$

$$FEx_{feed,y} = 365 h_{i,y} e_i 1.54 \frac{1}{a_y} \quad (5)$$

c) Final Exergy

The final exergy of each energy sector as well as the total final exergy of Greece are displayed in Figure 1. From 1960 to 2007 the total final exergy used in Greece increased from around 188000 TJ to 1086000 TJ. After the financial crisis of 2008, this value started dropping, reaching 795000 TJ in 2014.

Regarding the summed final exergy of Food & Feed, it accounted for more than 50% in 1960, since Greece's the production relied significantly on the physical work of people and animals for agriculture. This share has dropped to less than 10% in the recent years. Opposite to that, the final exergy injected in Industries, transport and other sectors increased dramatically throughout the year with the industrialization of the country. Still, the biggest shares of final exergy nowadays are used in transportation and other sectors because of the continuous grow in welfare and service provision, with a combined share ranging between 60% and 70% of the total.

From another point of view, Figure 2 shows final exergy disaggregated by energy carriers' contribution. It is clear that oil is the energy carrier primarily used in the country. Comparing this trend with the one of GDP (presented later in Figure 13) it is safe to assume that oil has been the principal driver of the economy. The second most important energy carrier is electricity, thought with much lower values.

2) Allocation of the final exergy consumption to useful work categories

For the second step of the methodology, final exergy consumption is allocated in five main useful work categories: Heat, Mechanical drive, Light, Other electric uses and Muscle work [4]–[6]. These categories, are disaggregated in energy end-uses, based on the mapping made by IEA, acquired from the supplementary data of Serrenho et. al [4] and [5], [6]. These categories and their respective end-uses are listed in Table 2. The H-/M-/LTH stand for high/medium/low temperature heat.

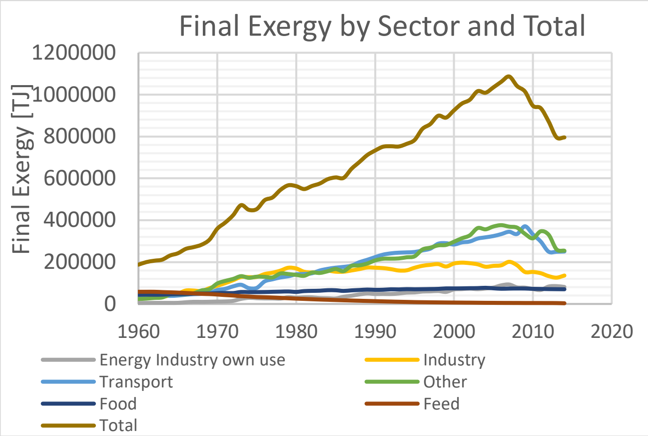

Figure 1: Final exergy by sector and total for Greece, 1960-2014.

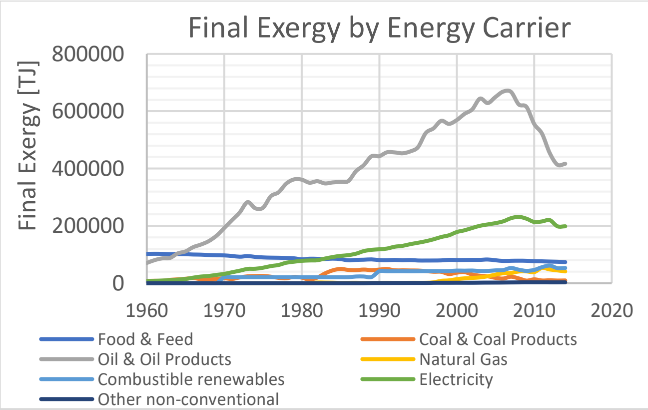

Figure 2: Final exergy by energy carrier in Greece, 1960-2014.

Table 2: Disaggregation of end uses by useful work category

Useful work category	End-use
High temperature heat	Fuel-HTH (500 °C)
Medium temperature heat	Fuel-MTH (150 °C); CHP-MTH (150 °C)
Low temperature heat	Fuel-LTH (120, 90, 50 °C); CHP-LTH (120, 90, 50 °C); Electricity-Industry LTH (120 °C); Electricity-Other sectors LTH (50 °C)
Mechanical Drive	Steam locomotive; Coal-Stationary Mech. Drive; Oil-Stationary Mech. Drive; Diesel vehicles; Gasoline/LPG vehicles; Natural gas vehicles; Aviation; Navigation; Diesel-electric; Electricity (Industry; Transport; Other sectors)-Mechanical drive
Light	Coal/Oil light; Electricity-Industry light; Electricity-Other sectors light
Other electric uses	Electricity-Industry other electric uses; Electricity-Other sectors other electric uses
Muscle work	Food; Feed

3) Second-law efficiencies estimation

The exergy efficiency is defined as the ratio of end-use/source, in exergy terms [14]. This kind of efficiency is widely accepted and used as a figure of merit for energy uses, since for each process it scopes the distance from the theoretical ideal process, by comparing the theoretical maximum with the actual amount of work output. Because of the second thermodynamics' law, the second-law efficiency is restrained to be $0 \le \varepsilon \le 1$ and as a result, for a given energy use, resembles a figure of closeness and quality towards an ideal process.

In order to obtain second-law efficiency values in this work, by applying the definition of exergy, the following definition is used [5],

$$\varepsilon = \frac{\substack{minimum\ amount\ of\ work\ required\ to \\ produce\ the\ desired\ energy\ output}}{\substack{maximum\ amount\ of\ work\ that\ could\ be \\ produced\ from\ the\ relevant\ energy\ input}} \quad (6)$$

The second law efficiencies are dependent on the energy carrier and on the end use, of each useful work category. They were either estimated based on the work of Serrenho et. al [4], or directly taken from its supplementary material.

4) Useful work

In the final step of the useful work estimation process, exergy efficiencies are applied to the final exergies found in 1)c) to compute the desired outcome – useful work. This is happening by multiplying the final exergy FEx_{ecp} of an energy carrier product *ecp*, which falls into a certain end use category *k* (Table 2), with the respective 2nd-law efficiency, for each year *y*, as in eq. (7). Then, all these useful work values of the individual energy carriers' products, are summed up for every end-use category, as in eq. (8). Lastly, the new values of each end-use category are summed up for each useful work category *i* (see Table 2), as in eq. (9).

$$U_{ecp,k,y} = FEx_{ecp,y} * \varepsilon_k \quad (7)$$

$$U_{k,y} = \sum U_{ecp,k,y} \quad (8)$$

$$U_i = \sum U_{k,y} \quad (9)$$

The final results for the useful work of each category as well as the total useful work of Greece estimated are presented in Figure 3. Overall, it can be observed that total useful work had a relatively linear increase from 1960 to 2007, driven primarily by the proportional increase of mechanical drive. Quantitatively, the total amount was 17300 TJ in 1960, growing to almost 204000 TJ in 2007. Simultaneously, mechanical drive held 40.6% share of the 1960's total reaching 69.7% in 2009. In 2007, the total useful work decreased in a stable linear drop until 2014, driven primarily by the mechanical drive uses' drop.

Observing heat categories separately, HTH started with a small share under 10% in 1960 and increased to be about 15% of the total useful work around the mid 1970s. Then, following a small drop to less than 5%, the category's share increased to around 18% in the mid 1980s and kept decreasing ever since. Since HTH is related to heavy industry processes, this decrease could be explained with the slower industry development.

Looking at MTH, the categories shares were oscillating above 20% up until early 1980s, decreasing afterwards and roughly stabilizing to just above 10% ever since. Finally, LTH category's share started as low as 5% in 1960 and raised to above 10% in early 1970s, oscillating at that level until the end of the series.

The Figure 4 is presenting the distribution of useful work in Greece for the different energy sectors. From the graph, it is clear that the highest amounts of useful work have been produced in the industry sector from the beginning of the studied period up until 2007, when there is a significant drop. Industry is the most consuming sector of useful work as it has associated end-uses with the highest exergy efficiencies: HTH, MTH, stationary mechanical drive and electricity mechanical drive. Transports and other have also high values of useful work associated throughout time. Other sectors even become the most useful work intensive sector after 2007 and remain relatively high ever since, because Greece always had strong residential activity and was focused in services, even after the crisis. In transports, the useful work produced drops sharply after 2009 following the financial crisis, since transportation is a prime lever of economy, but is influenced as well.

5) Aggregate Final-to-useful second-law efficiency

Knowing the final exergy and useful work amounts used in Greece from 1960 to 2014 it was possible to calculate the aggregate final-to-useful second-law efficiency of the country. This is simply equal to the ratio of useful to final exergy for each year, as in eq. (10). The results are displayed in Figure 12.

$$\varepsilon_{ag_y} = \frac{Useful\ work_y}{Final\ exergy_y} \qquad (10)$$

It can be seen that the aggregate 2nd-law efficiency was quite low in 1960 compared to other EU-countries [4], having the value of 9.21%. The efficiency seems to be increasing asymptotically throughout the time series until 2010. There is a fast growth in the first two decades of the time series reaching 17.3%, something explained by the reverse decrease of muscle work (which has a very small efficiency).

Later, there is a further slower increase until around 18-19%, because of the relatively stable shares of MTH and LTH, which have lower 2nd-law efficiencies and the simultaneous share increase of mechanical drive, which has a higher aggregate efficiency.

There is a small jump to 20% in the four last years of the series. This is probably due to the significant drop of useful work consumption in the transport sector (Figure 4), which involves technologies of diesel and gasoline vehicles with low efficiencies, while the industrial and other sectors' useful work and aggregate 2nd-law efficiencies remained high (Figure 11). For the individual energy sectors the respective results are displayed in Figure 11.

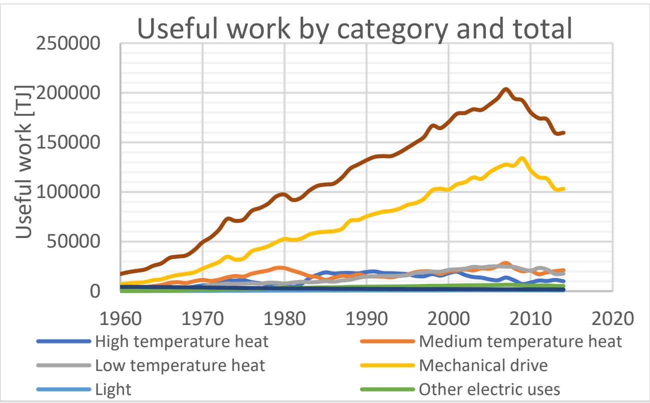

Figure 3: Useful work by category and total for Greece, 1960-2014.

A. *Economic analysis*

a) Gross domestic product

The gross domestic product (GDP), symbolized as well by Y, is expressed in monetary units and is the standard measure for the size of a country's economy. The production function used to estimate it is of Cobb-Douglas type adapted on the Solow and Swan theory and is given in eq. (11) [1]. The A stands for the TFP, K for the capital, L for the labor of year t, while α_L and α_K are the shares by which labor and capital contribute to GDP respectively. These shares are complementary, i.e. $\alpha_K = 1 - \alpha_L$, and are kept constant throughout the years when used in the equation. In this case, the GDP is not calculated by the equation but directly given by PWT [9] and is shown in Figure 13, for the period 1960-2014.

$$Y_t = A_t * L_t^{\alpha_L} * K_t^{\alpha_K} \qquad (11)$$

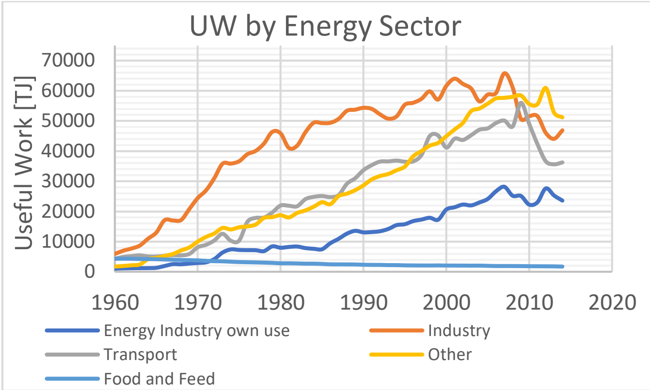

Figure 4: Useful work by energy sector in Greece, 1960-2014.

In the figure, roughly five different trends can be identified that can be explained with the brief historic trajectory described in the previous subchapter. First was the period from 1960-1974, which had an average annual growth rate around 8%, coinciding with the beginning of more intense industrialization and investment. Then was the shorter period, between 1974-1980, with still positive but lower growth. Following came the stagnant decade between 1980 and 1990, with very small positive or negative growth along the years, and enlargement of fiscal issues. Fourth was the period 1990-2008, with the progressively increasing growth, that led Greece to its peak financial development. This coincided with the planning prior and finally the entry in the single currency group. Finally, there were the years of the Greek crisis, from 2008 and till the end of the time series, characterized by aggressive recession.

b) Labor

Moving forward, the labor and capital shares of the income distribution in Greece, provided by the Penn World Table [9]. The average shares for PWT are 52.61% and 47.39% for labor and capital respectively, quite far from the 2/3 and 1/3 that is representing roughly the averages across the world [3].

From the PWT [9] were also acquired the average annual working hours per capita of Greece, while the employed population of the country for 1960-2014, was from AMECO [15]. The multiplication of the average annual working hours per capita and the employed population for each year gave the total working hours per year of the labor force, or just Labor (L), which is displayed in Figure 8.

c) Capital

The capital stock (K) of Greece, provided by [15] is presented in Figure 10, for the period 1960-2014. It started from as low as 118.14 € billion in 1960, peaked at 857.19 € billion in 2010 and mildly decreases since. Generally, it follows a rising trend similar to the GDP and its behavior can be explained with the investment in capital (Figure 9) in the relevant years. From 1960 to 1980 the curve in concave because of very high investment, then until 1993 it become convex because of small investment and later it became concave again because of higher investment, until the crisis.

d) Final exergy and Useful work Intensities

To examine the correlation between exergy and GDP, the final exergy intensities and useful work intensities are created, by dividing final exergy and useful work with GDP – using euros of 2010 as reference. The created trends are displayed in Figure 5.

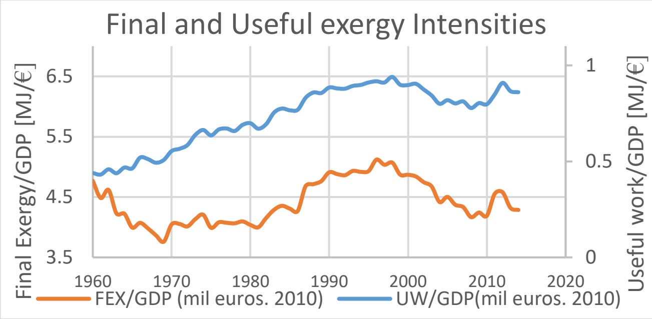

Figure 5: Final exergy and useful work intensities for euros of 2010 in Greece, 1960-2014.

Overall, the country's final exergy intensity oscillates around 4-5 MJ/€ in the examined time series, showing a concave part from 1960 to 1985 and a convex part from that year to 2010.

When looking at the curve of *useful exergy intensity*, similarities and differences to the final exergy intensity can be observed. The first part of the curve from 1960 to 1985 keeps a constant increase, while the second from 1985 to 2005 is convex. This happens because the aggregate final-to-useful second-law efficiency is rising fast from 1960 to 1980 and slightly more until 1985, but then stagnates for about 15 years.

The rapid decrease of muscle work from 1960 to 1980 and the booming useful work produced in industry the same period, implies, the shift from agriculture and physical work to mechanical drive. Alternatively, the industrialization as driver of economic growth is shown. Nevertheless, as suggested in [4], [5], [16], countries going through an era of industry development show increase in the useful work intensity index.

Next, in the decade 1980-1990 there is a further rise of the index, because of the small economic progress and the constant increase of UW in transportation and other sectors (while closing their gap with industry). At this period, the aggregate 2^{nd}-law efficiency was relatively stable.

Then, the fast growth from 1990 to 2007, with not such a significant useful work production in industry, transport and other sectors, resulted in a drop of the useful work intensity.

In the last years ratio increased anew, because the GDP drop in the last year of the time series was more intense than of the total useful work in society.

Overall, the index seems to become relatively stable after mid 1980s and until the end of the time series, oscillating between 0.77 and 0.93. Specifically, the average is 0.86 MJ/€. It could be said that, in the case of Greece, for euros referenced to 2010, and for this period, the relation between UW and GDP is relevant to this index value. Still, additional analysis on the matter could be done the next decades, to investigate further if this correlation is steady or not.

e) Total factor productivity

To estimate the Solow residual, as in the Total Factor Productivity, eq. (11) was solved this time for A (or TFP. The results are depicted in Figure 12, for the period 1960-2014, and will be addressed as real TFPs. Moreover, the TFPs are indexed by dividing the value of each year with the one of the first year. The outcome can be seen in Figure 6.

f) Link between TFP and exergy efficiency

The MEET2030 study, which was addressing the past of Portugal [3], managed to empirically show a correlation between the aggregate exergy efficiency of the country and its total factor productivity. To do that the ratios of the logarithm of the indexed TFP and of the logarithm of the efficiency ratios for each year were calculated, where efficiency ratios means the aggregate efficiency of every year divided with the efficiency of the initial year of the time series, as in eq. (12). The resulting ratio was roughly constant, meaning that the exergy efficiency approximately linked to TFP and economic growth. The same was replicated in this work for Greece. The ratio between the two logarithms in the last 40 years is close to one, while the average is 1.05.

$$\frac{\ln\left(\frac{TFP_t}{TFP_0}\right)}{\ln\left(\frac{EFF_t}{EFF_0}\right)} \approx c \qquad (12)$$

Following, there is an attempt to estimate a new indexed TFP based of the aggregate second-law efficiency of the country. This is done using eq. (13), which necessarily is the inverse process for the ratios of logarithms used above, however instead for a different exponent every year, the average of the ratios of logarithms is used, with the logic of trying to establish a constant relation. In that manner, the new estimated indexed TFP are displayed also Figure 6 along with the indexed form the real TFPs.

$$TFP = \left(\frac{EFF_t}{EFF_0}\right)^{1.05} \qquad (13)$$

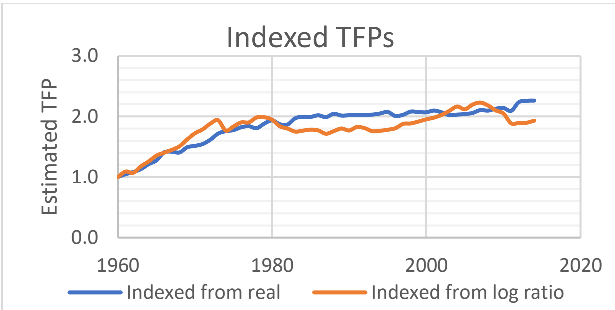

Figure 6: Estimated indexed TFPs from ratio of logarithms and from real TFP in Greece, 1960-2014.

III. Scenarios to 2030

A. Labor scenarios

1) Population scenario

The forecast presented for the evolution of the Greek population is one out of eight different scenarios, part of a study made by the Laboratory of Demographic and Social Analyses (LDSA) of the University of Thessaly, Greece [18] in 2016 and published by the research and policy institute diaNEOsis [19]. The methodology implemented is the cohort component method and takes under consideration demographic components of fertility, mortality and immigration.

The chosen scenario is driven by a concept of resilience for the Greek society. The course is based in the hypothesis of gradual return to 'normality' with mild growth rates and remaining in the eurozone. This scenario leads to a relatively constant decreasing trend of the total population, as in Figure 7.

2) Unemployment and labor scenarios

Regarding unemployment rate two scenarios will be assumed in order for each to accompany a different economic development.

In the first case, which will generally assume a mild progress of the country, the unemployment will follow the trend of the previous years (having dropped below 20% already in 2018 [15]) and will keep decreasing until it reaches the pre-crisis levels, where it stabilizes at 8%. The assumption has it that it will take more than 10 years to reach that level. In the second case, which will coincide with faster growth and progress, the unemployment rate will also drop more rapidly and will eventually reach around 5% in an asymptotic manner. The expected employed population is shown in Figure 7. Regarding the average annual working hours per capita, they are considered to stay constant after 2014 at 2042 h/a.

The projections for Labor in Greece until 2030 are displayed in Figure 8.

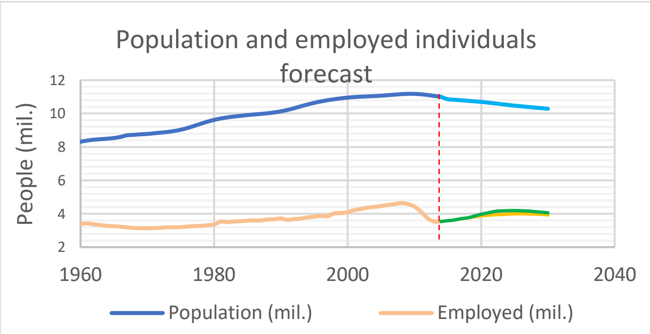

Figure 7: Past trends and forecasts for the population and actively engaged individuals up to 2030 in Greece.

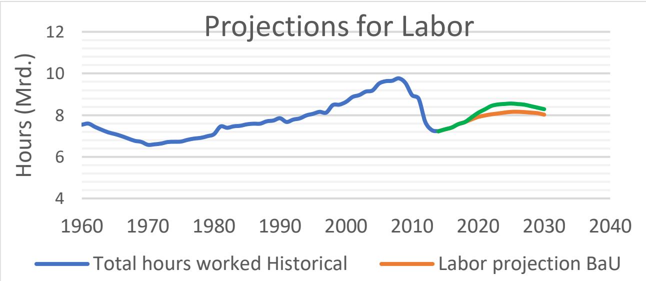

Figure 8: Past Labor in total annual working hours in Greece and projections to 2030.

A. Capital scenarios

Before crisis, the investment capacity had reached levels of almost 26% of the GDP, in comparison to 13% in 2017-2018 [15], [20]. Gross investment in 2007 peaked at 62 € billion and after crisis fell as low as 22 € billion in 2017 [15]. More specifically, investment related to business in 2017 was 15.5 € billion, which is 8.5 € billion less than in 2007. Still, this amount is almost equal to the money needed for compensating the deteriorating capital of the existing businesses (15.1 € billion). As a result, the remaining amount is leading to a very slight increase of their capital stock.

It is essential to find a new balance point inside the Greek economy regarding the size and mix of private investment. In EU the average investment capacity is 20% of the GDP, a goal that needs to be reached by Greece as well [20].

1) Business as Usual scenario in Capital

Currently, Greece's framework still contains a lot of obstacles for conducting business when it comes to processes such as contract enforcement and justice, immovable property transfer, access to loans and high taxation. Furthermore, civilians tend to spend a lot of their money in private consumption instead of saving for future investments [20].

Assuming that not important reforms take place and the current situation continues, then an annual pessimistic growth rate of 5% of investment is suggested for this scenario. The result of this assumption on the gross fixed capital formation (GFCF) as percentage of the previous year's GDP is shown in Figure 9. Following this path, the GFCF is barely not going to achieve the 20% of GDP in investment goal by 2030.

To estimate the future capital stock of the country, a projection for the depreciation rate of capital is needed. For that, the average of the past years, which is 3.4%, is used.

The capital stock is estimated using eq. (14) of the PIM method, where K_t is the capital stock of year t, GDP_t is the gross domestic product, i_t is the GFCF as percentage of the previous year's GDP and δ_t is the depreciation rate or else consumption of fixed capital (CFC [3]. Note that since the formula is taking under consideration also the GDP of previous years, the calculations are done in a loop after having estimated GDP as well in subchapter IV.A. Capital stock is shown in Figure 10. It is clear that this scenario would lead to a rather stagnant development of the country's capital stock.

$$K_t = K_{t-1} + i_{t-1} GDP_{t-2} - \delta_{t-1} K_{t-1} \qquad (14)$$

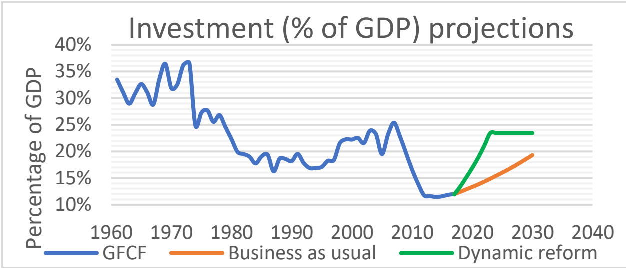

Figure 9: Past GFCF in GDP share of Greece from 1960 to 2017 and future scenarios.

2) Dynamic Reform scenario in Capital

According to the Hellenic Federation of Enterprises (SEV), Greece has the potential for a dynamic scenario of doubling its productive investment and reaching 20% of GDP three times faster than in the previous case. This could be achieved if the state manages to go through a reforming 'big bang', meaning the implementation of reformations that would make the country stand out from the global investment competition. Some mediums that would work towards this direction include reduction of bureaucracy and administrative stalling, simplification of tax procedures, focusing on more medium and small business exporting, privatization and liberalization of a number of sectors, increase in private investment and proportional decrease in private consumption [20], [21].

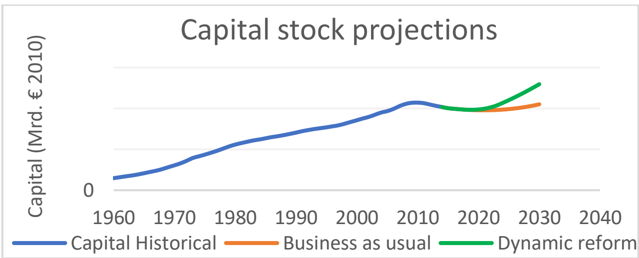

Figure 10: Past trends and future scenarios for capital stock of Greece until 2030.

In this optimistic case, considering that the trust of investors can be gained anew, the annual growth rate of investment could potentially be 15%. In this path shows, Figure 9 shows achieving the European average of 20% GDP share of GFCF in less than 5 years. When creating this scenario, after grasping pre-crisis values, the percentages were purposefully kept constant to avoid further extreme estimations. Using eq. (14), the capital stock would develop as in the respective curve of Figure 10. It seems that after a few years of lag, Greece's capital would finally start increasing quite rapidly, surpassing even the levels of pre-crisis times and reaching as high as 1037 € billion in 2030.

B. *Exergy efficiency scenarios*

1) *Analysis of important sub sectors*

To improve the aggregate second-law efficiency of Greece, two things can be done: i) increase the second-law efficiencies of respective end uses (Table 2) and/or ii) change the share of energy carriers in favor of those that can be used in more efficient processes, e.g. electrical mechanical drive rather than diesel engines. However, when not assuming change in activities of the various sub-sectors, it is important to keep the UW shares of the end-uses relatively stable.

Having that in mind, first the aggregate efficiencies of the different energy sectors (Figure 11) are taken under consideration. Nowadays, the lower efficiencies are of the Transport sector and of Other sectors, ranging between 15% to 20%, while the efficiencies of Industry and Energy industry own use are higher, ranging between 30% and 35%. Looking at Figure 4 as well, it can be seen that, Other sectors, Transport and Industry have the higher useful work shares of the total. This means that it would be beneficial to put more emphasis on improving the aggregate efficiencies of the first two less efficient sectors and secondarily also improve the other two industry sectors.

Moving deeper, it is essential to identify which sub-sectors in each main sector are the most useful work intensive in order to steer the focus on them. It was shown that, in Other sectors, the biggest UW shares are by far of the Residential flow and of Commercial & Public services In Transport first place hold the Road mediums and second the Domestic Navigation. In Industry, Non-ferrous metals and Non-metallic minerals are the most UW intensive. In the Energy industry, the most intensive sub-sector is the one of Oil refineries.

For each of those sub-sectors, it is important to pinpoint the primary energy carriers' products that are used in them, in order to examine what margins for share change are available. This was done in detail and can be found in the complete thesis.

Moreover, since for a lot of activities and processes related to heating, mainly fossil fuels are burned, and for that conventional technologies (Fuel – L-/M-/HTH) are used, it would be beneficial to change the energy carriers towards others less polluting and/or use CHP technologies, where they are available, since they have better 2nd-law efficiencies.

From another point of view, previously it has been identified that *mechanical drive* is by far the category with the highest UW share. From further analysis in the MD category, in 2014 it was recognized that the bigger shares of final exergy were injected in MD related to gasoline and diesel vehicles. However, their respective shares of UW were much lower, while first were the shares of electricity produced mechanical drive. As an induction, improving conventional vehicles efficiency or and/or shifting to EVs would be of great benefit.

2) *Policies*

The 4th National Energy Efficiency Action Plan of Greece [22] provides all the existing and new policies that aim primarily towards improving the overall energy efficiency of the country and decreasing energy consumption and GHG emissions. Various measures of the Plan in the different sectors, which are currently being implemented, or will in the future, and are relevant to the analysis of this work, can be found in the complete thesis. On that basis, the assumptions of the following scenarios were made.

3) *Scenarios*

a) *Business as Usual in energy efficiency*

The application of the energy saving policies and measures, associated with the final consumption sectors, is briefly supported by a mild economic growth. The majority of population, being preoccupied with satisfying other necessities, stays rather uninformed and insensitive in respect to the need for energy transition. Thus, the implementation of measures is modest, it requires low investment costs and can be realized when generally incomes are limited. The main assumptions are:

Small-scale penetration of modern and more efficient devices, equipment and machines in all the sector of the economy will lead lead to mild linear increase of the 2nd-law efficiencies of the end-uses, similar to past decades. The development of the exergy efficiencies is based on manipulation of estimates given in the EU Reference Scenario on the path leading to 2050 [23].

In *Other sectors*, by 2030, most of the changes in energy sources UW shares will happen related to LTH (50°C) uses, e.g. space and water heating. A small increase is assumed in CHP and geothermal technologies (CHP – LTH 50°C), rising up to <1.1%. Solar thermal system development is more focused, reaching a bit higher shares up to <4% of the UW produced, especially in the service sector. Simultaneously, burning of fossil fuels (e.g. diesel oil, charcoal) as well as use of electricity for heating, will decrease respectively. Moreover, residencies will continue shifting gently from diesel oil use to natural gas. The services of traditional biomass will be slightly limited as well. Regarding stationary mechanical drive, small shift of ≈1-1.3% from LPG towards electricity is expected. A small increase towards other electric uses will also take place.

In *Transport*, the use of gasoline (gasoline vehicles) and diesel oil (diesel vehicles) for road transportation will decrease briefly to 46% and 40% respectively, in order to promote biofuels, giving shares of 4% to biogasoline and 4% to biodiesel as well. Because of an assumed weak promotion of EV policies and limited installation of their charging stations, electricity will just reach 2% of the total road UW, by 2030. In the domestic navigation sub-sector, diesel and fuel oils will decrease briefly, to give a small space for the use of biodiesel (1% of produced UW).

The *Industry* sector, apart from having certain policies to regulate it, it needs to be more efficient because its driver is global competition. Furthermore, industries have to lower their GHG emissions following the EU regulations. In respect to that, the non-ferrous metals sub-sector will partly reduce the conventional combustion of fossil fuels, e.g. sub bituminous coal, used in MTH (150°C) processes, to give room for the entry of CHP (150°C) heat as 2% share of UW production, by 2030. This is assumed to be a similar case for the non-metallic minerals sub-sector, where heat MTH (150°C) from CHP is going to increase up to 4%. Solar thermal installations for LTH (120°C) processes are expected to take place as well, leading the respective share of UW to 1%. Also, a small shift of 1.2% from coal products used in HTH processes (500°C) to natural gas is considered.

In the *EIOU* sector, the oil refinery sub-sector is the largest as for UW produced. Its use in fossil fuels for MTH (150°C) processes produced more than 80% of the UW in 2014. Therefore, it is considered important to transfer a small fraction of them, of about 7.5%, to CHP MTH (150°C) technologies, by 2030.

Because of the mild economic improvement, the *Industry* and *Transport* sectors are assumed to increase by 1% of the total UW produced in the economy, while the *Other sectors* is going to decline by 2%, until 2030, assuming a small tendency of these sectors to move towards their past shares (Annex Figure 26 of the thesis). The *EIOU* is considered to keep the shame share, on this and the next scenario, while the share of muscle work produced from people and working animals, is going to briefly decline, following to the population decrease.

b) Enhanced Energy Efficiency

This scenario differs from the previous one in the sense that more ambitious energy saving policies are implemented in the final consumption sectors (promoting higher efficiency equipment, electrification of vehicle fleet etc.). This optimistic course is following a faster growth, thus enabling more players to get involved. People start developing a new mentality and become more motivated to embrace changes leading to a "greener" future. Generally, more expensive investments are made and eventually more significant efficiency improvements are to be achieved. The main assumptions are:

Bigger scale penetration of modern and more efficient devices, equipment and machines in all the sectors of the economy, leading to higher increase of the 2nd-law efficiencies of the end-uses. The development of the exergy efficiencies is based on manipulation of more optimistic estimates of the EU reference scenario [23], compared to the previous case.

In *Other sectors*, the commitment to promote RES and CHP technologies for water and space heating is higher and related measures are promoted anew. This is driving the shares of UW produced by solar thermal (CHP – LTH 50°C) up to >8% in 2030. Simultaneously, there is further limitation of diesel, traditional biomass and electricity use for heating in the residential sub-sector, compared to the previous scenario. On the contrary, the service of natural gas increases to 7.3% of the total UW. Even less LPG will be used for stationary MD, and more MD from electricity will be produced instead.

In *Transport*, the necessity to include biofuels in road transportation leads biodiesel and biogasoline to reach 6% of the total UW generated each, while gasoline declines at 40% and diesel at 38%. The effort to electrify transportation is more intense, by introducing electric buses and giving more incentives to buy EVs. Eventually driving electricity as an energy carrier to 6% of the UW by 2030. In domestic navigation, there is the introduction of CHP technologies, occupying 5% of the total UW produced, while biodiesel increases to 2%.

In *Industry*, the combustion of coal and coke products for MTH (150°C) processes is restricted more dynamically, in order to limit CO2 emissions more drastically by 2030. Instead, the shares of UW produced from CHP (150°C) technologies is going range between 5-10%, in the non-ferrous metals and non-metallic minerals sub-sectors. Additionally, biodiesel for HTH (500°C) processes will be introduced to take the share of 2.2% of UW in the second sub-sector mentioned. The service of natural gas is also going to increase further to 11% of UW produced for HTH (500°C) processes.

In *EIOU*, the service of fossil fuels for MTH (150°C) processes in the oil refining industry is assumed to decline significantly, allowing the respective temperature CHP technologies to acquire a share of >13% of the UW produced by 2030.

Due to more rapid growth, the UW shares of *Industry* and *Transport* from the total are assumed to grow by 1.5% each until 2030. The *Other sectors'* share is going to decline by 3%.

4) Projections of aggregate efficiency

To estimate the aggregate final-to-useful exergy efficiency of Greece for the two scenarios eq. (15) was conceived and used.

$$Agg.Eff_y. = \frac{1}{\frac{UW_{ecp,y}}{UW_{sub-sector,y}}(\%) * \frac{1}{\varepsilon_k} * \frac{UW_{sub-sector,y}}{UW_{sector,y}}(\%) * \frac{UW_{sector,y}}{UW_{total,y}}(\%)} \qquad (15)$$

All the shares started based on 2014. The ones changing did so linearly until 2030, while the rest remained the same. The shares of energy carrier products inside their respective sub-sector, the 2nd-law efficiency of the different end uses ε_k, as well as the shares of sectors from the total, are based on the assumptions mentioned in the two scenarios. The shares of sub-sectors in sectors remained the same.

The projections for the country's aggregate efficiency are presented in Figure 11, where it is shown that both scenarios bring significant improvement. The first scenario (BaU), is leading the efficiency to increase from 20.07%, in 2014, to 22.41% in 2030, when the second more optimistic scenario (EEE) is accomplishing twice the gains, with 24.97% efficiency in the end of the period. These results show that, the application of the assumed measures can help overcome the stagnation in efficiency observed the previous decades and eventually cause improvement in rates similar to those observed between 1970 and 1980. The respective aggregate efficiency projections of each of the main four sectors can be seen in Figure 11 as well.

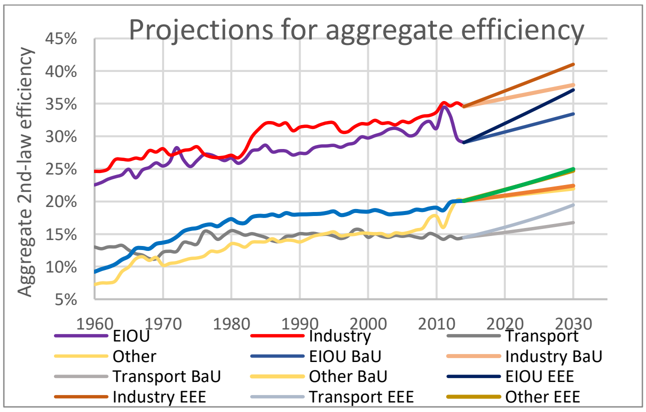

Figure 11: Past trends and future projections for the aggregate 2nd-law efficiency of Greece and its main sectors, 2015-2030.

a) Projections of TFP

To forecast the real TFP, first the projections of Greece's aggregate final-to-useful exergy efficiency were used in eq. (13), like in subchapter II.A.f), in order to calculate the future indexed TFPs. The outcome was two different indexed TFP development trends, each for one of the two energy efficiency scenarios. From these trends, the annual growth rates of TFPs were computed, being approximately 0.73% for BaU and 1.44% for EEE. Then, the growth rates were applied in order to develop the real TFPs curve from 2014 to 2030.

The real TFP projections for the two energy efficiency scenarios are depicted in Figure 12. In one case, the results show that for the "business as usual" scenario, total factor productivity increases moderately in the future, being able to just reach as high as the pre-crisis levels, by 2030. In the other case, as expected by the more optimistic scenario, the TFP is growing faster, surpassing by the end of the examined period the peak it met in 2007.

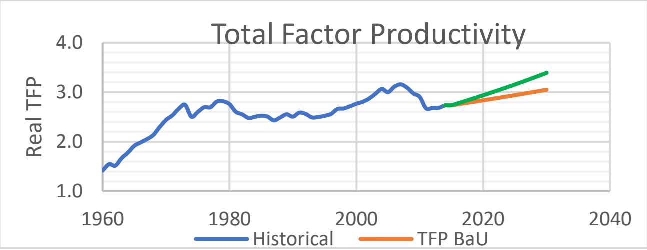

Figure 12: Real TFP past trends and projections for the two efficiency scenarios of Greece, 2015-2030

IV. Final Projections

A. *Economic growth*

To estimate the economic growth of Greece, the combination of the former scenarios on labor, capital stock and TFP, through the aggregate exergy efficiency, was necessary. On one hand, the pessimistic scenarios from the three factors were coupled together in one main scenario, since mild growth would keep unemployment higher, investment in capital would be limited, compensating by a big fraction for its depreciation throughout time, and consequently, less money would be available for improvements of efficiencies. This main scenario will be called "Business as Usual" (BaU). On the other hand, the optimistic scenarios of the same factors were coupled in a second main scenario, since greater investments would bring higher returns, faster economic growth would be expected, more employment would be possible, and eventually more wealth would be available for increasing efficiencies in all sectors This main scenario will be called "Metamorphosis" (Meta). The projections of GDP for Greece were made using equation (11) and are presented in Figure 13.

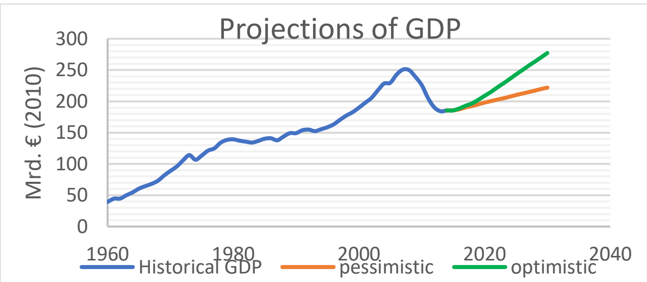

Figure 13: Past trends and projections of GDP for Greece, 2015-2030.

As expected, Meta predicts a faster growth for Greece, reaching the value of 277 € billion in 2030, much higher than the outcome of BaU, which only arrives at 222 € billion.

Taking a closer look, in the pessimistic scenario, the annual growth rates of the last 12 years average around 1.2%. This growth average could be likened to the one of the period 1986-1995, when Greece started advancing from the stagnation it occurred before. This is not an ideal scenario as the development is slow and will probably preserve the lack of competition and hinder progress in most sectors.

In the optimistic scenario, annual growth rates vary with an average of 2.9%, very similar to the period between 1993 and 2002, when the country started growing its economy considerably, for the first time after the regime change. In this path, Greece could achieve the comeback it needs, show it has the potential to excel in different sectors, and try to be part of the forefront in Europe. Though, it is equally important not to repeat the mistakes of past.

The present scenarios do not lead to excessive growth rates, so a steady and safe economy development could be expected.

In the frame of this thesis, these two extreme projections of GDP are boundaries of a range in which the economic growth could potentially maneuver in the future. Regarding labor, this factor is more or less defined by population projections. Therefore, the challenge would be to make the right, strategic moves in order to trigger the necessary capital development, which in turn can enable more dynamic efficiency improvements. This way the advance of economic growth could be closer to the upper limit of these GDP projections, and consequently, benefits for the society can be greater

B. *Exergy*

Having assumed future shares for useful work, it is also necessary to estimate UW in absolute values. To do that the concept adopted in MEET2030 was used, which implies constant correlation between UW and GDP.

To proceed, the useful work intensities found in sub-chapter II.A.d) and presented in Figure 5 were consulted. The average of the last 30 years for the useful work intensity is going to be assumed, which is 0.86 MJ/€. Projections for useful work are made by using eq. (16), and the outcome is shown in Figure 14.

$$UW_y = GDP_y * 0.86(\frac{MJ}{€}) \qquad (16)$$

As expected, the total useful work produced in the Meta scenario, related to enhanced energy efficiency and leading to a faster economic growth, is reaching levels much higher than in the past. The resulting value is 238 PJ in 2030. In BaU scenario, with the smaller improvement in efficiency, and consequently lower GDP growth, the total useful work increases as well, but with smaller rate, and arrives at pre-crisis levels.

Next, to estimate the total exergy injected for final consumption in the country, eq. (10) was used for the future years, and the resulting projections are shown in Figure 15.

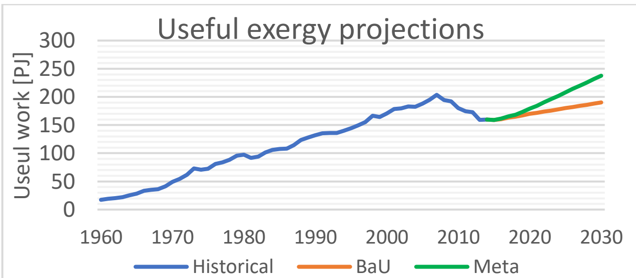

Figure 14: Useful work projections for Greece, 1915-2030.

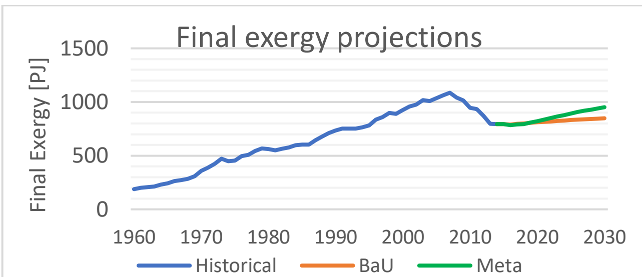

Figure 15: Final exergy projections for Greece, 1915-2030.

V. Conclusions

The thesis had two objectives. The first was to investigate the relationship between useful work and economic growth. The second was to examine whether the faster recovery of the Greek economy is possible, when measures are taken to improve its aggregate exergy efficiency. To do that, the exergy data and economic figures of the country were analyzed and past trends were revealed. The country's exergy analysis of the four main economy sectors was realized with the help of the Useful Exergy Accounting Methodology. Then, two extreme scenarios were created, one pessimistic and one optimistic, which included assumptions for the future development, by 2030, of three factors; labor, capital stock and aggregate exergy efficiency. Estimates of GDP based on these three factors were generated using the economic model of the MEET2030 project.

The exergy research in the main economy sectors up to 2014 showed that, the energy carriers consumed primarily are oil products, which have a share higher than 50%, while second comes electricity, with a share of 25%. The majority of total final exergy is injected to produce mechanical drive, which takes almost half of its share, while next come low temperature processes, with around 25% share. The greatest portion of useful work produced is occupied by mechanical drive, with more than 60% share, and then comes heat, mostly of medium and low temperature, with around 12% share each. The most useful work intensive sub-sectors of economy are those of road transportation, residencies, services, non-ferrous metals and non-metallic minerals industries, and oil refineries.

It was identified that, a relatively stable correlation between useful work and economic growth exists in Greece, considering the last three decades of the examined period. Specifically, the useful work intensity index was estimated around 0.86 MJ/€.

From the findings in UW shares and in UW intensity, it is shown that the main form of useful work that drives economy seems to be mechanical drive, while second comes heat.

It was shown that, the implementation of measures which address the exergy intensive sectors of economy, by improving their exergy efficiencies, appears to have positive influence on the economic growth of Greece. This was enabled through the link of exergy efficiency with total factor productivity.

The progress in exergy efficiency was achieved by two manners i) improving efficiencies in all technologies and ii) transitioning towards more efficient energy carriers. The later refers to a) the switch from conventional combustible fuels to non-conventional heating technologies, such as solar thermal and b) the further electrification of MD. In the case of stronger adjustments, the outcome was better. Namely, in the pessimistic scenario, the improvement in final-to-useful aggregate efficiency was from 20.07% to 22.4%, while in the optimistic scenario the efficiency rose up to almost 25%.

The two economic growth projection results differed significantly, substantially creating a range of possible outcomes by the end of the examined period. The pessimistic scenario, with annual average growth of 1.2%, led to GDP values comparable to pre-crisis levels. The optimistic one showed growth rates around 2.9% and reached a GDP of about 11% above the 2007 peak. Thus, it can be concluded that making decisions, pushing policies and taking measures inside the spectrums of those in the scenarios, has the potential to bring progress for the economy and the society.

Projections were made for the useful work and final exergy of the country as well, based on the previously found useful work intensity and aggregate exergy efficiency. Both tended to increase, following the GDP development. Yet, final exergy grew slower than useful work and GDP, because of the improvement in exergy efficiency. This decrease in final exergy intensity implies also the reduction of energy needed to generate wealth.

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