Economic growth model based on capital exergy efficiency for Portugal: historical calibration (1960-2014) and scenarios until 2050.

Afonso Sousa Borges
afonso.borges@ist.utl.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract – **Two scenarios of economic growth until 2050 were created for Portugal through the development of a model based on a production function which is based on the relationship between the Total Factor Productivity and the final-to-useful aggregate exergy efficiency. The development of the production function, based on the neoclassic economic theory, is done through the historical series of the Gross Domestic Product (1960 – 2014), having been the capital disaggregated in buildings, stationary machines, and non-stationary machines for a better estimation of this. The exergy efficiency is also disaggregated in stationary and non-stationary machine, being the historical series of these two variables subject to cointegration analysis in order to establish a relationship between these and the TFP. In this way it is possible to understand better the contribution which different types of capital goods have in the GDP, both through their elasticities, and their its productivity. The developed model is useful for decision making within the economic and energy policies spectrum, taking into account the results obtained from this suggest that increasing exergy efficiency allows to create economic growth even with reductions in the work force human labour, and the increased efficiency of non-stationary capital is the one that holds bigger potentially to make TFP grow and consequently GDP. This suggests that transition to electric mobility will bring economic benefits.**

Keywords: **Exergy; Economic growth; Energy efficiency; Total factor productivity; stationary machines; non-stationary machines.**

I. INTRODUCTION

In order to ensure wealth and well-being to a country, economic power needs to be ensured. Since the Industrial Revolution, energy and economics are closely related each other. We have never consumed so much energy as today and we have never had the level of wealth that we have today too. It is possible to say, in an overall view, that we live better today than a hundred years ago.

Having access to energy through technology, allowed mankind to control more power and move faster, becoming more productive in theirs jobs and in their tasks, contributing for the development of the economic, and consequently, to economic growth.

Mainstream economists do not consider energy as a primary factor of production, however many studies have been done to better understand the role of this utility in the economy.

Based on the model (based on a production function) built for the MEET2030 project [1], which found a suitable way to explain the historical Portuguese GDP growth time series through the link between the exergy efficiency and the TFP, the objective of this paper is to build a new model more accurate, since the MEET2030 still has some residual, which means a model that represents better the historical Portuguese GDP time series and allows it to perform scenarios until 2050. The new model has as objective to understand which type of capital have more influence in TFP variation and consequently GDP variation too. A more accurate model with this kind of knowledge can be particularly useful for decision making on the scope of economic and energy policies.

The new model is going to desegregate the capital in three types: buildings, stationary machines and non-stationary machines. Associated to the last two types of capital are going to be their own exergy efficiency, which together contribute for the variation of the TFP. Buildings do not have exergy efficiencies. The link between the two capital exergy efficiencies and the TFP is going to be submitted to cointegration analysis. The model production function is going to have the contribution of labour, corrected through the human capital index.

After building the model scenarios going to be performed in order to test it, observe the results and take some conclusions of possible future paths. In this phase the demographic projections of the IIASA are going to be used because of its alternative approach, which uses simultaneously probabilistic techniques, specialist analysis and induces a relationship between education level and fertility rate [2].

This paper is structured as follows: Section II – Literature review; Section III – Methodology; Section IV – Results; Section V – Conclusions.

II. LITERATURE REVIEW

A. Economic Growth

During the 19th and 20th century many economics believed that capital per capita was the engine of economic growth. It was in the middle of the 20th century that Robert Solow and Trevor Swan developed, independently, an aggregate production function of capital and human labour which allowed to measure the impact of these two primary factors of production as source of economic growth [3], [4].

It was demonstrated at a worldwide level that 1/3 of the GDP is given to capital (in the form of interests, rents and dividends), while 2/3 are attributed to labour (through wages).

The Solow-Swan model was applied to the 1909 – 1949 period in the United States (US), however a lot of the historical economic growth has remained to explain. This residual, between the expected growth through the accumulation of capital and labour and the real GDP growth it is called the Total Factor Productivity (TFP) and it usually corresponds to an exogenous measure, normally associated to technical, technological and institutional changes.

During the 80's Paul Romer [5] and Robert Lucas [6], among others, developed a theory reviewed of the economic growth where the growth is explained through endogenous factors as knowledge and human capital. Part of the innovation has started to contribute to capital accumulation, becoming endogenous for the model. Even so this model was not able to explain all economic growth.

The mathematical formula of the Solow-Swan model, which includes capital (*K*), labour (*L*), and TFP (*A*) is the following:

$$Y_t = A_t K_t^{\alpha_k} L_t^{\alpha_l} \tag{1}$$

Where α_l and α_k, are the output elasticities ($\alpha_l = 1 - \alpha_k$), which measure the responsiveness of output to a change in levels of either labour or capital used in production.

Considering GDP, capital and human labour factors that can be measured directly it is possible to estimate the TFP as follows:

$$A_t = \frac{Y_t}{K_t^{\alpha_k} L_t^{\alpha_l}} \tag{2}$$

B. Energy and economic growth

The Solow-Swan model ignores energy inputs as a primary factor of production. The mainstream economists consider energy as an intermediate input which can be combined with investment in capital and labour. This means that in this kind of approach, economic growth is essential independent of energy utilization [7].

Warr and Ayres [8] describe the role of energy as a driver of economic growth through a series of positive feedback loops: Cheaper energy inputs to economic activities result from new discoveries of energy sources, economies of scale and technological progress through learning process effects in the conversion of primary energy sources to useful energy inputs. These cheaper energy inputs reduces the cost of goods and services produced, simulating the demand for those goods and services, leading to an increase in economic output. As a large proportion of the value of that increase in energy output goes to increase wages and this will stimulate further effort to substitute energy-using machines for labour. This will increase energy inputs and stimulate further scale and learning improvements.

Machines play a fundamental role in economy, since allow us to use energy in order to control more power and move faster, having made us more productive. Increasing energy efficiency allows the machines to produce more with the same amount of energy inputs. Since the monetary value of the machines (capital) does not represent their productivity, increasing energy efficiency has as consequence increasing TFP [1].

So, to understand economic growth we have to look at useful stage of energy and to the final-to-useful conversion process. It is in the useful stage where the society is able to use and domain the energy resources in order to create economic value.

C. Exergy

Exergy is the right physical quantity to study the impact of energy in economy. In order to perform any economic activity it is needed physical work. The potentially that energy has to perform physical work is through the useful work. Exergy is the capacity of energy to perform useful work, since energy could not always be available to do this physical process [9].

According to the first law of thermodynamics, in any activity or physical process, energy is conserved, it is never created and it is never destroyed. In a physical process, energy can be transformed in another form(s) of energy, diminishing its potential to perform physical work. This means that energy cannot be destroyed but exergy can be, this is a consequence of the second law of thermodynamics.

Serrenho et. al [10] have developed work on exergy and useful exergy (exergy in the useful stage) accounting for Portugal following Ayres et. al's [11] methodology.

D. Linking exergy efficiency to TFP

For the MEET2030 project IST & BCSD Portugal [1] defined a methodology in which is created a link between TFP and aggregate final-to-useful exergy efficiency (*EF*). For the analysed time period this link is described by the constant *C*:

$$C = \frac{\ln\left(\frac{PTF_t}{PTF_0}\right)}{\ln\left(\frac{EF_t}{EF_0}\right)} \tag{3}$$

This constant *C* is after used to estimate the TFP growth as function of the exergy efficiency growth:

$$PTF_t = \left(\frac{EF_t}{EF_0}\right)^C * PTF_0 \tag{4}$$

As demonstrated by IST & BCSD Portugal, the use of exergy efficiency to estimate the TFP reveals a good approximation of the historical development of the Portuguese economy between 1960 and 2010. However the model still has a residual since the constant *C* was determined by empirical methods and not statistical, and the model it is a bit simple.

D. Forecasting the economic growth

IST & BCSD Portugal used their own developed model to perform scenarios of GDP growth for Portugal until 2030. The methodology is defined in [1].

The model is based on the equation (1), where *A* is computed through the equation (4). Capital is estimated trough equation (5):

$$K_t = K_{t-1} + i_{t-1}GDP_{t-1} - \delta_{t-1}K_{t-1} \qquad (5)$$

Where K_t is the capital stock in the year *t*, K_{t-1} is the capital stock of the year *t – 1*, $i_{t-1}GDP_{t-1}$ is the investment capacity of the present year and $\delta_{t-1}K_{t-1}$ is the capital depreciation. The investment capacity by percentage of GDP is defined by *i*, and the depreciation rate is defined by *δ*. Although widely used the method of equation 5 does not allow to distinguished between different types of capital, having low accuracy, since applies the same investment capacity and depreciation rate for all capital stock.

The human labour is measured by the number of total working hours in the economy (*L*). This value is after corrected multiplying by the human capital index (HCI). This index is a qualitative correction of the production of the human labour base on the average years of schooling of the population (*s*). In order to estimate *L,* it is considered the yearly total individual working hours (*h*), such as the population who is between the 15 and the 64 years old (Pop_{15-64}) on the same year, the unemployment rate (*td*) and the participation rate (*TP*).

$$L = h \times (1 - td) \times Pop_{15-64} \times TP \qquad (6)$$

$$\phi(s) = \begin{cases} 0{,}134 \times s;\ if\ s \leq 4 \\ 0{,}134 \times 4 + 0{,}101(1-4);\ if\ 4 < s \leq 8 \\ 0{,}134 \times 4 + 0{,}101 \times 4 + 0{,}068(s-8);\ if\ s > 8 \end{cases} \qquad (7)$$

$$HCI = e^{\phi(s)} \qquad (8)$$

The population projections came from Instituto Nacional de Estatística (INE), however there are another institutions, as IIASA, with more complex methodologies as it can be seen in [2].

III. METHODOLOGY

This work methodology is divided into two sections. The first one is where it is built the model based on a production function with the objective of representing the Portuguese historical GDP (1960 – 2014), and the second one is where the assumptions to perform scenarios until 2050 are defined.

A. Historical series (1960-2014)

1) Exergy efficiency

In order to produce two historical time series (1960 – 2014) of the aggregate final-to-useful exergy efficiency, one for stationary machines and another for non-stationary machines, data were collected from Serrenho et al. [10] and Felício et al. [12]. From the first one it was collected data about the amount of exergy in the final and useful stage for Portugal (1960 – 2014) from different energy carriers, organised by useful application. From the second it was collect data about the amount of final and useful exergy relative to electricity, since it was not possible to distinguish between stationary and non-stationary machines from Serrenho's data to this energy carrier.

There were considered stationary machines the ones with useful application as high, medium and low heat temperature, heat cogeneration, cooling, lighting, electronics, electrolyse and stationary mechanical drive. There were considered non-stationary machines the ones with useful application performing non-stationary mechanical drive, for example, the vehicles.

After the data being obtained and organized, the two historical time series were build, through the division of useful exergy by final exergy.

2) Capital

In order to build a historical capital stock time series disaggregated in *Buildings, Stationary machines* and *Non-stationary machines* it was collated data from three different databases: AMECO, EU KLEMS, and PWT.

As it is possible to see in figure 1 and figure 2, since the three databases provide different information, they were matched in order to create the pretended time series.

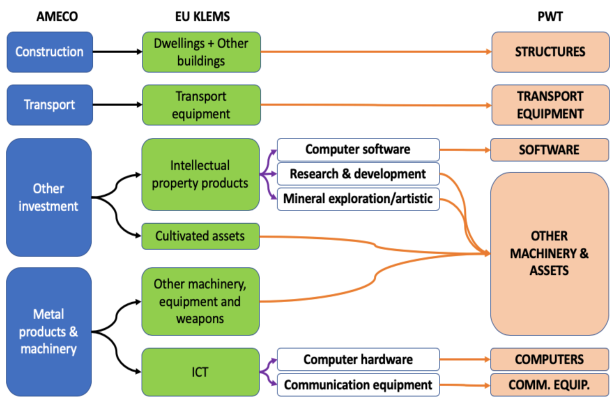

Figure 1. Correspondence between the categories of capital from AMECO, EU KLEMS and PWT databases.

AMECO database provides information for their own categories about gross fixed capital formation (GFCF) at 2010 prices, between 1960 and 2014. EU KLEMS provides more disaggregated capital goods categories as it is possible to see in figure 1, but only between 1995 and 2014. EU KLEMS provides the GFCF at 2010 prices for their own categories. The PWT provides information about the depreciation rate of each category of capital goods.

After estimated the GFCF time series though PWT categories, it was computed the initial capital stock in order to compute the disaggregated capital stock time series (1960 – 2014):

$$K_{n_{t-1}} \approx \frac{I_{n_t}}{g_{I_n} + \delta_n} \quad (9)$$

Where $K_{n_{t-1}}$ is the initial capital stock for each type of capital in the year *t – 1*, I_{n_t} is the GFCF for each type of capital in the year *t*, g_{I_n} is the average of the investment rates of the five first years for each type of capital (since 1960), and δ_n is the depreciation rate of each type of capital, given by the PWT.

To compute the capital stock for the following years it was used the perpetual inventory method:

$$K_{n_t} = K_{n_{t-1}} + I_{n_t} - \delta_n . K_{n_{t-1}} \quad (10)$$

Where K_{n_t} is the capital stock in year *t* (for each type of capital).

After the time series of capital stock built based on the PWT disaggregation, this one was organised in the pretend capital goods categories as is can be seen in figure 2.

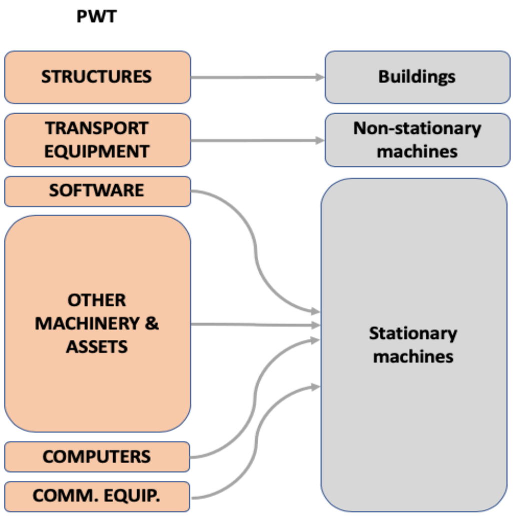

Figure 2. Correspondence between the categories of capital goods from PWT to the pretended ones.

3) Human labour

To estimate the human labour (yearly number of total hours worked), data were collected from PWT database. It was used for that the following equation:

$$L = h * Pop_{emp} * HCI \quad (12)$$

Where Pop_{emp} is the employed population, the other variables are described in equation 6 and 8.

4) Production function

In order to produce a production function based on the exergy efficiency of stationary machines, ε_{st}, exergy efficiency of non-stationary machines, ε_{n_st}, capital stock of these two, and builds, K_{st} , K_{n_st}, K_b, respectively, and labour, L, it was built the following aggregate production function:

$$Y = (\varepsilon_{st}^{c_1})^{\alpha_{kest}} . (\varepsilon_{n\_st}^{c_2})^{\alpha_{n\_st}} . K_{st}^{\alpha_{st}} . K_{n\_st}^{\alpha_{n\_st}} . K_b^{\alpha_b} . L^{\alpha_l} \quad (13)$$

Where, $\alpha_{k_{st}}$, $\alpha_{k_{n\_st}}$ and α_{k_b} are constants that relate the elasticities of each type of capital. These constants were estimated thought equation 14, which gives an approximation of the payments that are given to capital in *t*:

$$\alpha_{k_{n_t}} = 0{,}3 \frac{K_{n_t} \delta_{n_t}}{\sum_i K_{n_{i_t}} \delta_{n_{i_t}}} \quad (14)$$

Where, $\alpha_{k_{n_t}}$ is the elasticity of a *n* type of capital in year *t*, $K_{n_t}\delta_{n_t}$ is the depreciated value of a certain type of capital in year *t*, $\sum_i K_{n_{i_t}} \delta_{n_{i_t}}$ is the summation of the depreciation quantity of each category of capital goods (PWT categories) in year *t*. The constant 0,3 multiplies by the division, since the total payments made to total capital stock are 0,3 (approximately 1/3 of the production factors payments).

The variables ε from 13 were estimated through equation 15, where EF_t is the aggregate exergy efficiency in year *t*, and EF_0 is the aggregate efficiency in year 0 (i.e. 1960).

$$\varepsilon = \frac{EF_t}{EF_0} \quad (15)$$

Equation 13 can be written as follows:

$$Y = \varepsilon_{st}^{u_1} . \varepsilon_{n\_st}^{u_2} . K_{st}^{\alpha_{st}} . K_{n\_st}^{\alpha_{n\_st}} . K_b^{\alpha_b} . L^{\alpha_l} \quad (16)$$

All the variable are in the same year *t*.

This means that TFP (A) can be given by:

$$A = \varepsilon_{est}^{u_1} . \varepsilon_{n\_est}^{u_2} \quad (17)$$

All the variables are in the same year *t*.

In order to test the link between the exergy efficiency of the two capital good types and TFP, and to determinate the *u* constants (17), cointegration analysis was applied to the variables (between 1960 – 2014) of the following equation:

$$\ln(TFP_{historical}) = u_1 . \ln(\varepsilon_{st}) + u_2 . \ln(\varepsilon_{n\_st}) \quad (18)$$

The historical TFP was computed through equation number 19:

$$PTF_{historical} = \frac{GDP_{historical}}{K_{st}^{\alpha_{st}} . K_{n\_st}^{\alpha_{n\_st}} . K_b^{\alpha_b} . L^{\alpha_l}} \quad (19)$$

Cointegration analysis applied to the variables of equation 18 underwent some tests:

1. Initial analyses through unit roots test: first there were tested the series in levels (with time trend) and after in first differences (without time trend). All series were submitted to ADF, Schmidt-Phillips and KPSS tests.
2. VAR analysis with trend and without trend. The model was estimated by OLS. The following

step was model verification through Portmanteau test. After these, it was tested the correlation between variables.

3. Cointegration tests with constant and constant trend.
4. VECM analyses with intercept, intercept and trend, and without both. After this, it was made a residual analysis through Portmanteau test. The following step was to check, as made for VAR analyses, if a correlation exists, and next, causality tests were made.

B. Scenarios (2015 – 2050)

In the aim of this work it were created two scenarios: the *development scenario* and the *stagnation scenario*. The assumptions of each one are described in the following sections.

1) Exergy efficiency

Stationary machines exergy efficiency evolution takes into account increasing interaction between machines and the physical world.

Through information and communication technologies, machines are increasing their capacity of communication to each other, collecting information from the real world, processing it through algorithms (machines learning and artificial intelligence) and act in conformity to their own functions in the physical world. These kind of processes could open the door for increasing exergy efficiency of stationary machines, since they can perform their tasks with a huge amount of information in order to perform them in a more efficient way.

Taking into account the last paragraph, but not ignoring the stagnation that exists in stationary machines exergy efficiency since the end of the 80's, it was assumed for the *development scenario* a yearly growth rate of 0,5% in efficiency until 2050. For the *stagnation scenario* it was considered a yearly growth rate in efficiency of 0,1% until 2050.

Non-stationary machines exergy efficiency evolution takes into account the electrification of the vehicles, since electrical motors are more efficient than internal combustion engines.

Regarding the almost constant exergy efficiency trend of non-stationary machines between 12% and 13% (1960 – 2014) and taking into account the inertia involved in an energy transition of this kind, for the *development scenario* it is considered a yearly growth rate in exergy efficiency of 1% until 2050, while for the *stagnation scenario* it was considered a yearly growth rate in efficiency of 0,3%.

2) Capital

In order to compute the capital stock until 2050, the equation 5 was used. The assumptions of capital stock are the same for both scenarios. The criteria of future evolution of each capital goods type were based on the historical time series (1960 – 2014) of GFCF by GDP percentage analysis, and personal interpretation and knowledge about how GFCF by GDP percentage will evolve in the future (until 2050).

It is considered that GFCF by GDP percentage of *Structures* and *Transport equipment* will follow the past trends until they stagnate in 5% and 1%, respectively.

For the other capital goods categories (*Other machinery & assets*, *Software*, *Computers*, *Communication equipment*) it was assumed that they are keep following the past GFCF by GDP percentage trend. In order to estimate all the trends the liner trends of every time series were computed.

The depreciation rate of each type of capital goods were taken from the PWT database.

3) Human labour

For the realization of human labour scenarios, it was used data from the *Demographic and human capital scenarios for the 21st century* report [13] made by IIASA. In this report there were built tree scenarios: the "*Share Socioeconomic Pathway 1*" (SSP1), on which is assumed a future path into sustainability direction, rapid social development, with investment in education and health, with an acceleration in demographics transition with reductions in population. This scenario is associated to a high level of education and low fertility rates. The SSP2 scenario, which is considered the medium scenario, assumes the past trends. This scenario is associated to medium levels of fertility, mortality and education levels, respectively. Lastly the SSP3 scenario, which is considered the scenario of fragmentation and stagnant development, having associated with him low education levels, high mortality and high fertility rates [13].

For *development scenario* were used the demographic projections of SSP1 scenario from IIASA, and for *stagnation scenario* it were used the SSP3 one.

Taking into account that to estimate the human labour the equation 6 was considered. Projections were made for the participation and unemployment rate and also number of hours worked per individual. In order to corrected the human labour, this had to be multiplied by the HCI (8), based on the average education level projections.

The participation rate projections were taken from [13]. The unemployment rate projections were based on MEET2030 methodology. It was considered the same unemployment rate for both scenarios with a yearly decreasing rate of 6%, until the unemployment rate reaches the 5%, after this point it remains constant. About the number of total hours worked per individual per year, for the *stagnation scenario*, were considered constant until 2050, while for the *development scenario* it was considered a yearly decreasing rate of 0,6% as it was considered in MEET2030 project.

The data about the average scholar years comes from the SSP1 and SSP3 scenarios, respectively.

IV RESULTS

A) Production Function

In table 1 are showed the results of the elasticities of the three different types of capital present in equation 16.

α_b	α_{st}	α_{kn_st}	Σ
0,18	0,087	0,034	0,3

Table 1. Average value of the elasticities of each capital good type and their summation.

As it is possible to see, buildings are the capital good that its capital stock (monetary value) has more influence in GDP variation compared with the other two. The non-stationary machines are the ones that its capital stock has less influence in GDP, an increasing of 1% on non-stationary machines capital stock would just represent, approximately, an increasing of 0,03% in GDP.

Although the capital stock of non-stationary machines is the one that less contribute for GDP, it is the capital good with higher productivity through its exergy efficiency. As it is possible to see in table 2, where are showed the results of *u* constants from cointegration analysis, the exergy efficiency variation of non-stationary machines has been the one with more influence at TFP variation between 1960 and 2014.

u_1	u_2
1,190	2,551

Table 2. *u* constants results.

A possible interpretation for the previous paragraph lays on the fact that the transport sector is very relevant for the economy, but this relevance is not reflected in the capital stock value, it reflects on the mobility services they provide for the creation of wealth. Both people and transactional goods are very dependent of their mobility to generate human labour, economic value and in the case of goods they may be tradable. This mobility of people and goods is made by vehicles (measured in monetary value) but this in only possible because there is a changing of energy during the process, that is, what provides mobility is transformation of energy. If this transformation process increases its exergy efficiency it is possible to produce transportation costs by stimulating growth in the goods transaction and people transport, making them more productive and contributing in parallel to higher wealth.

There were considered the variables of equation 18 non stationary in levels and stationary in first differences and was detected correlation between them. The VAR analysis has demonstrated that there exists cointegration between the variables. After the VECM analysis applied causality tests were performed, which detected causality from the exergy efficiencies to TFP, but the reverse too, which can indicate bidirectional causality, which means that improvements in exergy efficiencies makes TFP grow and TFP growth makes exergy efficiencies increase.

About TFP estimation through the developed model, the comparation between the historical TFP and the estimated one (17) it can be seen in figure 3.

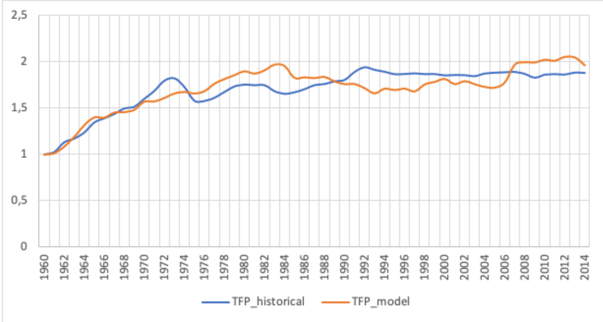

Figure 3. Historical TFP (1960 – 2014) and estimated TFP through the new model.

Table 3 shows the coefficient of determination of the TFP times series (1960 – 2014) using both the MEET2030 model and the new one. The new model, with the disaggregated exergy efficiencies seems to represent worse the historical TFP than the MEET2030 model, which uses only the total aggerated exergy efficiency.

	TFP MEET2030	TFP model
R^2	0,812	0,716
R^2 *ajusted*	0,809	0,705

Table 3. Coefficients of determination and coefficients of determination adjusted.

In figure 4 it is possible to compare the historical GDP (1960 – 2014) with the estimated one through the new model (16).

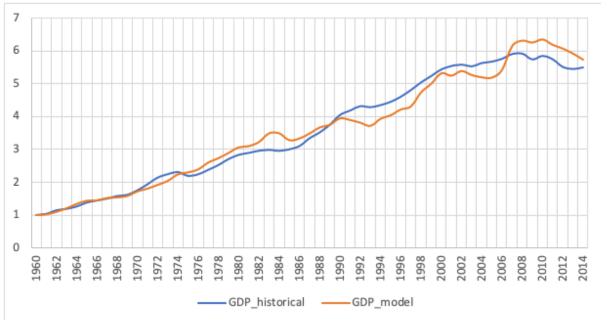

Figure 4. Historical GDP (1960 – 2014) and estimated GDP trough the new model.

Table 4 shows the coefficients of determination of the GDP time series (1960 – 2014) using the MEET2030 model and using the new one. It can be seen that there was a 2% improvement of representability of the historical GDP from one model to the other. One of the causes of this improvement was the methodology of capital stock estimation applied.

	GDP MEET2030	GDP model
R^2	0,961	0,983
R^2 *ajusted*	0,959	0,981

Table 4. Coefficients of determination and coefficients of determination adjusted.

B) Exergy efficiency

In figure 5 it is possible to see the results about the historical exergy efficiency of the stationary and non-stationary machines.

As it can be observed in figure 5, the exergy efficiency of stationary machines has increased during the time period in analysis, while the exergy efficiency of the non-stationary machines has remained almost constant, between the 12% and 14%. The rise of exergy efficiency of stationary machines in the first 20 years of the graphic is explained by the electrification process and the higher utilization of high heat temperature.

About the evolution of exergy efficiency of non-stationary machines, this has remained virtually constant because no considerable improvements in exergy efficiency of internal combustion engines and because of the very low percentage of electrical vehicles circulating. Taking into to account section A of chapter IV, this leads to believe that a significant penetration of electric vehicles into the economy, with considerable more efficient motors, will lead to a significant increase of TFP and consequent GDP growth.

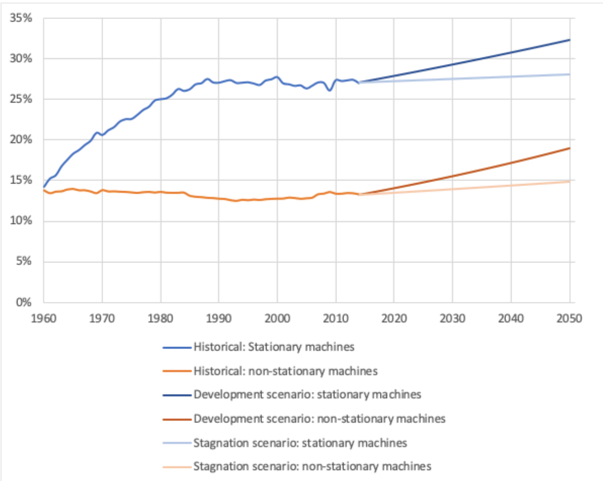

Figure 5. Historical (1960 – 2014) and scenarios (2015 – 2050) final-to-useful exergy efficiency from stationary and stationary and non-stationary machines.

Since 2015 it is possible to see the scenarios made for exergy efficiency evolution, reaching the stationary machines in 2050 an aggregate final-to-useful exergy efficiency of 32% and non-stationary machines of 19%.

C) Capital

Although the assumptions for the capital stock projections were the same for both scenarios, capital stock depends on GDP (5). This means that if GDP grows by influence of TFP, the capital stock is going to be different in both scenarios, as it can be checked in figure 6.

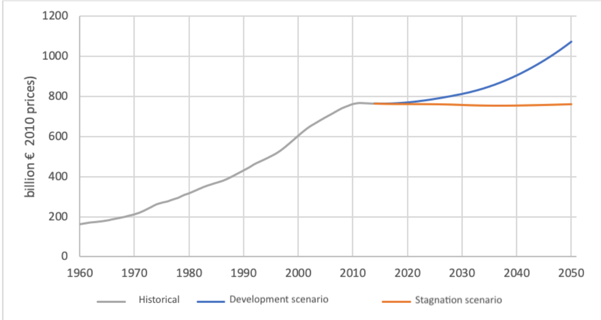

Figure 6. Historical (1960 – 2014) total capital stock, and scenarios (2015 – 2050).

D) Gross Domestic Product

As it can be seen in figure 7, the development scenario shows an exponential behaviour, generating economic growth on the long run. The projections of this scenario give approximately 526,57 billion euros (2010 prices) of GDP in 2050, and 60 thousand euros of GDP per capita. The stagnation scenario shows a logarithmic behaviour, with stagnation tendency, with low economic growth on the long run. The projections of this scenario give 229,24 billion euros (2010 prices) of GDP in 2050, and 25 thousand euros of GDP per capita.

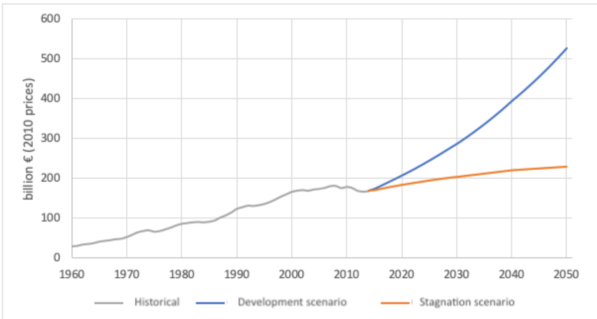

Figure 7. Historical (1960 – 2014) GDP and scenarios (2015 – 2050).

Based on the new model, figure 7 shows that improvements in final-to-useful exergy efficiency have as consequence economic growth. Even in both scenarios, in which the population is decreasing, machines play a fundamental role in economic growth. These ones, with improvements in exergy efficiency can compensate the reduction in human labour.

A considerable contributor for TFP growth in *development scenario* was improvements in exergy efficiency of the non-stationary machines. This is an indicator that investments in electric vehicles could bring, not only environment benefits, but economic ones too.

V. CONCLUSIONS

This paper concludes that the new developed model represents better the historical Portuguese GDP between 1960 and 2014 than the MEET2030 model. One of the causes was the capital stock estimation methodology used.

Although the new model represents worse the historical TFP than the MEET2030 model, the first one allows to distinguished between two types of exergy efficiency, allowing to understand which type of capital ,through its efficiency, has more influence in TFP variation. This paper concludes that it was the increasing of the stationary machines exergy efficiency that has been contributing for TFP growth, but non-stationary machines, the ones which efficiency has remained almost constant, have higher potential to make TFP grow, contributing for GDP increasing. This suggests that a revolution in transport sector, changing from internal combusting engines to electric ones, could boost the economy, contributing for economic growth.

REFERENCES

[1] Instituto Superior Técnico (IST), Business Council for Sustainable Development for Portugal (BCSD Portugal), 2018. Meet 2030 - Business, Climate Change and Economic Growth. Technical Report. BCSD Portugal, http://www.bcsdportugal.org/wp-content/uploads/2017/11/Technical_Report_Meet2030_final_WEB.pdf

[2] Lutz, W., Butz, W. P., & Samir, K. E. (Eds.). (2014). *World population and human capital in the twenty-first century*. OUP Oxford.

[3] Solow, R. M. (1956). A contribution to the theory of economic growth. *The quarterly journal of economics*, *70*(1), 65-94.

[4] Swan, T. W. (1956). Economic growth and capital accumulation. *Economic record*, *32*(2), 334-361.

[5] Romer, P. M. (1986). Increasing returns and long-run growth. *Journal of political economy*, *94*(5), 1002-1037.

[6] Lucas Jr, R. E. (1988). On the mechanics of economic development. *Journal of monetary economics*, *22*(1), 3-42.

[7] Ayres, R. U., & Warr, B. (2010). *The economic growth engine: How energy and work drive material prosperity*. Edward Elgar Publishing.

[8] Warr, B., & Ayres, R. (2006). REXS: A forecasting model for assessing the impact of natural resource consumption and technological change on economic growth. *Structural Change and Economic Dynamics*, *17*(3), 329-378.

[9] Ayres, R. U., & Warr, B. (2005). Accounting for growth: the role of physical work. *Structural Change and Economic Dynamics*, *16*(2), 181-209.

[10] Serrenho, A. G. C. H. (2013). Useful work as an energy end-use accounting method: Historical and economic transitions and European patterns. *University of Lisbon-Instituto Superior Técnico: Lisbon, Portugal*.

[11] Ayres, R. U., Ayres, L. W., & Warr, B. (2003). Exergy, power and work in the US economy, 1900–1998. *Energy*, *28*(3), 219-273.

[12] Felício, L., Henriques, S. T., Serrenho, A., Domingos, T., & Sousa, T. (2019). Insights from past trends in exergy efficiency and carbon intensity of electricity: Portugal, 1900–2014. *Energies*, *12*(3), 534.

[13] Lutz, W., Goujon, A., KC, S., Stonawski, M., & Stilianakis, N. (2018). *Demographic and Human Capital Scenarios for the 21st Century: 2018 assessment for 201 countries*. Publications Office of the European Union.