Useful work & economic growth: Portugal, 1960-2009.

João Santos[1*], Tiago Domingos[1**], Tânia Sousa[1***], Miguel St. Aubyn[2]

[1] IN+ Center for Innovation Technology and Policy Research, Environment and Energy Scientific Area, Dept. of Mechanical Eng., Instituto Superior Técnico, Technical University of Lisbon, Avenida Rovisco Pais, 1 - 1049-001 Lisbon, Portugal.
Tel: (+351) 218 417 000 / Fax: (+351) 218 499 242
∗ Email: joao.dos.santos@tecnico.ulisboa.pt / Tel: 919626155;
∗∗ E-mail: tdomingos@tecnico.ulisboa.pt / ∗ ∗ ∗ E-mail: taniasousa@tecnico.ulisboa.pt;
[2]UECE Research Unit on Complexity in Economics, Instituto Superior de Engenharia e Gestão, Technical University of Lisbon, Rua Miguel Lupi, 20 - P-1249-078 Lisbon, Portugal.
E-mail: mstaubyn@iseg.utl.pt / Tel: (+351) 213 925 996;

***JEL* classification:** Q40, O41, O52
Keywords: energy, exergy, useful work, economic growth, cointegration.

Abstract

Following increasing studies on the importance of energy quality measures for economic development, recent empirical results suggest a high correlation between useful work and Portuguese GDP, over the last decades. In order to compare the long-run effects of several energy consumption variables, defined according to different stages of production, on the Portuguese economic development for 1960-2009, the use of time series tools such as VAR analysis, Granger causality tests and impulse response functions is adopted in a detailed empirical analysis. Results suggest that useful work has a significantly greater impact on economic growth than other energy use variables, for Portugal.

I. Introduction/Motivation

The importance of energy for modern economies is empirically suggested by the simultaneous global increases in energy use and economic growth verified over the last decades. Advances in energy efficiency technologies, coupled with increasing energy consumption, have characterized industrialization and economic development processes in the past century.

General growth theory, however, has paid little attention to the role of energy in enabling economic growth. Assuming a single sector economy, production factor elasticities can be shown to be equivalent to factor payments' share in National Accounts. In this scenario, payments to energy resources are generally very small when compared to the shares received by the primary factors of production: capital and labour. It follows that reducing energy consumption will not significantly impact output growth, i.e. energy is neutral to growth. However, the dramatic oil price changes in 1973/74 and 1979/80, and the energy conservation measures adopted afterwards, suggest that constraints on energy consumption can adversely affect economic output.

By adopting a two-sector framework for the economic system, and identifying extractive and energy conversion activities within the economy as a separate sector, it is possible to equate the services provided by the energy output from this aggregate sector with the costs of capital and labour used to produce these services. In order to best capture the way energy is used productively in the economy, energy-flow aggregation approaches based on the application of the second law of thermodynamics are significant. Although no single method of aggregation is able to fully capture the productive usefulness of energy in the production processes, the concepts of *exergy* and *useful work* provide a science-based and time-invariant measure of energy used productively in the economy.

The relevant question of whether energy consumption causes economic growth or it is simply a consequence of this growth is highly relevant for policy measures concerning energy conservation. However, the empirical research provides no conclusive evidence to unambiguosly determine the existence and direction of causality between energy consumption and economic development.

The main objective of this paper is to compare the long-run relationships between economic growth and several distinct energy-related variables, from primary and final energy/exergy to useful work. Finding that useful work is causal on output growth would suggest that economic development can be stimulated by improving the exergy content of energy inputs, improving energy efficiency, or altering the pattern of energy service demand.

Section 2 exposes the relevant thermodinamically defined energy quality concepts used in the construction of the two-sector framework and the empirical analysis. A useful work accounting methodology applied by Serrenho et al (2013) [7] for the Portuguese economy between 1856 and 2009 produces interesting results concerning the relationship between this energy consumption variable and economic output.

The two-sector model framework is presented and developed in Section 3, based on the approach by Ayres & Warr (2010) [12]. It is concluded that total economic output can be seen as a function of total capital stock, labour supply and useful work inputs.

Section 4 discloses the empirical analysis performed using the two-sector model assumptions applied to available economic and energy consumption data. The VAR approach is explained and results are presented and interpreted, including the outcomes of Granger causality tests and impulse response functions and long-run elasticities estimation. Finally, Section 5 states conclusions and propositions for future work.

II. Energy/Exergy/Useful work

A number of economists have performed analysis with the inclusion of an additional input energy factor to Cobb-Douglas and CES[1] production functions, alongside capital and labour. Energy analysts differentiate between two components of a given energy quantity: *exergy* and *anergy*.

Exergy can be formally defined as the maximum work that could theoreticaly be performed by a system as it reaches thermodynamic equilibrium with its surrondings, reversibly. It corresponds to the component of a given energy quantity that can be converted into any type of physical work (as opposed to anergy, which can be seen as the "useless" component of energy).

The ratio of exergy content to energy can be considered a measure of energy quality.

[1] Constant Elasticity of Substitution.

As it is known, by the first law of thermodynamics energy is conserved in any activity or process. Then, energy consumption is really the increase, in any process[2], of useless anergy at the expense of useful exergy [4].

However, exergy still describes the *potential* work that can theoretically be performed. In reality, there are losses and irreversibilities in any transformation. A proposed concept for the amount of exergy actually used in a productive manner in the economy is that of exergy services, or *useful work*. Useful work can be formally defined as the minimum amount of work required to produce a given end-use, that is, it measures the result of an energy use, rather than the amount of energy transferred to that final use. Useful work values are obtained after the estimation of second-law final-to-useful efficiencies. These efficiencies are defined as the ratio of end use/source in exergy terms [2, 3]:

$$\epsilon = \frac{desired\ exergy\ transfer}{relevant\ exergy\ input},\ 0 \leq \epsilon \leq 1; \quad (1)$$

This second-law efficiency is widely accepted as a figure of merit for energy use. It measures, for each process, the distance from its theoretical ideal. It is possible to characterize an aggregate efficiency within and across activities, providing a unified framework to combine efficiencies of many different technologies. So, while exergy can be regarded as an input to the economy alongside labour and capital, it has to be converted to useful work in order to deliver economic value.

By capturing how energy is used productively within the economic system, useful work may be considered as the appropriate independent variable to represent energy inputs in a production function. One crucially important aspect of including useful work as a factor of production is that it forms a real, combined measure of both aggregate resource dependency and technological performance of the economy.

A useful work accounting methodology, based on the one applied by Benjamin Warr for a societal exergy analysis [5], has recently been adopted by André Serrenho for the Portuguese economy, spanning the period between 1856 and 2009 [7]. One of the major results obtained from this approach is related to exergy and useful work intensities[3]. Useful work intensity, unlike exergy intensity, does not exhibit a significant time trend throughout the 154 year period studied - Figure (1).

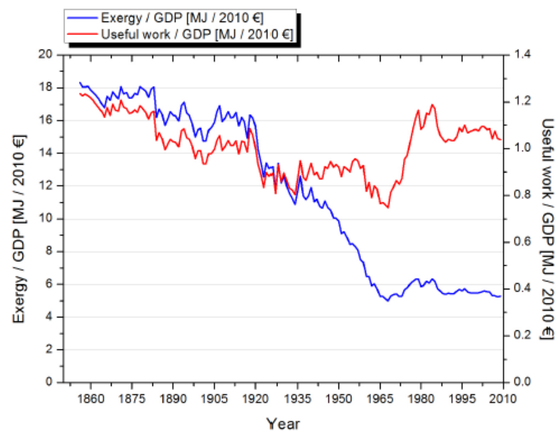

Figure 1: *Final exergy intensity and useful work intensity for Portugal between 1856 and 2009. Source: Serrenho et al (2013).*

When compared with useful work intensities measured for other countries, the results obtained for Portugal stand out due to their stability [5]. Generally, useful work intensities grew significantly after World War II, peaking almost simultaneously around 1970. On the other hand, Portuguese useful work intensity declined slightly between 1961-1974 due to the colonial war economy, similarly to what has

[2] By the second law of thermodynamics.

[3] Defined as final exergy/GDP and useful work/GDP ratios, respectively.

occured in the U.K. and U.S.A. during World War II.

Useful work intensity in Serrenho et al (2013) is determined by dividing the useful work consumption measures for each year by the corresponding GDP at constant prices. This constant price GDP is determined from the application of a consumer price index (CPI) to the nominal values of GDP. Alternatively, GDP at constant prices for a given base year can be determined by applying a price deflator (PD). Both the CPI and PD are measures of price inflation/deflation with respect to the base year. However, while the CPI is based on a fixed basket of consumer goods and services, the PD "basket" is allowed to change with people's consumption and investment patterns, thus reflecting up-to-date expenditure patterns, unlike the CPI.

When calculating the useful work intensity between 1960 and 2009 with a price deflator for GDP, instead of a consumer price index like in Serrenho et al (2013), the result is an even more stable intensity for this time period - Figure (2). The almost constant useful work intensity verified for the Portuguese economy constitutes a possible stylized fact. Moreover, useful work intensity for this period also exhibits the most stable behavior of all energy consumption variables considered throughout this work[4].

Useful work consumption is, for the Portuguese economy, the energy-related variable that correlates best with the long-term evolution of GDP. Hence, its inclusion as the appropriate variable to represent energy consumption in the economic system constitutes a defensible assumption.

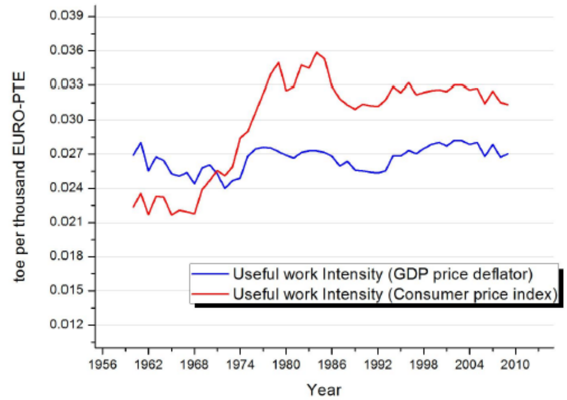

Figure 2: *Useful work intensity for the Portuguese economy, from 1960 to 2009, using GDP at 2005 prices determined through a consumer price index and a price deflator.*

III. The Two-sector Model

Multi-sector model analysis is common among the economic literature [8, 9], and some multi-sector models include energy inputs [10]. It is fairly straightforward to prove, for a single-sector economy producing a single composite good, that factor elasticities should correspond to factor payments' share in the national accounts [11]. Introducing a third production factor does not change this conclusion.

The formal proof of equivalence between output elasticity and cost share depends on assumptions such as constant returns to scale, perfect competition and profit-maximing firms in equilibrium. It also assumes that all production factors are mutually substitutable.

In reality, the mutual substitutability of all factors of production is a very strong condition. It implies that GDP can be produced from any one of the three factors alone, without any amount of the remaining two. Truly, substitution occurs, but only at a narrow range in the

[4]This includes, besides useful work, primary energy/exergy supply and total final energy/exergy consumption.

[5]Machines require workers to operate them, and labour requires tools to be productive. Moreover, both machines and workers require energy inputs (in the form of fuels and food).

neighborhood of the combination of factors at any point in time. There is also a high degree of complementarity between the factors of production[5].

Moreover, while payments to capital and labour can be straightforwardly associated with rents and wages, respectively, there are no payments to energy *per se*. This is because energy is a conserved quantity, as stated in the previous section, and there is no entity with finantial accounts to receive and disburse such payments.

Alternatively, considering the combined extractive and primary energy conversion activities within the economic system, whose inputs are capital, labour and gifts of nature, the cost of the output generated by this aggregate (which can be described as "energy services") can be equated with the cost of capital and labour used to produce these services. This thus identifies these activities within the economy as a separate sector.

As a first approximation, it is convenient to assume that the economy is a two-stage system with a single intermediate product, useful work U. In that sense, based on the semi-empirical approach defined by Robert Ayres and Benjamin Warr [12], the model for the economic system may be schematized as in Figure (3).

It is assumed that a three-factor production function is definable and meaningful for both stages of the economy, and verifies the same properties as the neoclassical production function. Namely: *(i)* constant returns to scale[6]; *(ii)* positive and diminishing marginal products, *(iii)* essentiality and *(iv)* the Inada conditions, on all three factors of production. On a first approach, factors such as imports/exports, taxes and subsidies, capital transfers and net lending/borrowing are dismissed. It is not, however, assumed that firms must operate or move along the frontier of a region in factor space, as they would if they were profit-maximizers with perfect information in a perfectly competitive market.

The economy is described as a two-stage process with a separation between the energy-related activities (*primary*, or *energy* sector) and the remaining economic processes (*secondary*, or *non-energy* sector). The energy sector produces the intermediate product useful work U from inputs of capital K^E, labour L^E and some fraction of the useful work produced U^E - Equation (2).

$$U = Q_1 \left[K^E, L^E, U^E \right]; \tag{2}$$

The useful work output from this sector results from the conversion of primary exergy inputs extracted from natural resources, in function of the capital and labour invested. The exergy inputs to useful work can be regarded as free gifts of nature. Primary exergy inputs and capital invested in this sector are assumed to be perfect complements, i.e. they must be consumed together to satisfy energy sector demand. While physical goods such as capital are inherently scarce, no such assumption is made concerning primary exergy inputs, at this stage of the analysis. Hence, being perfect complements, in order to increase primary exergy inputs it suffices to increase energy sector capital K^E. Useful work output U is therefore a function of only K^E, L^E and U^E, as expressed in Equation (2).

The enlarged energy sector introduced here is innovatively defined, when compared with general economic models and accounts, where this sector is tightly linked with energy industries[7]. The energy sector as defined in our

[6] Meaning that the production function is homogeneous of degree one, and also verifies Euler's theorem.
[7] Fuel extraction, manufacturing, refining and distribution.

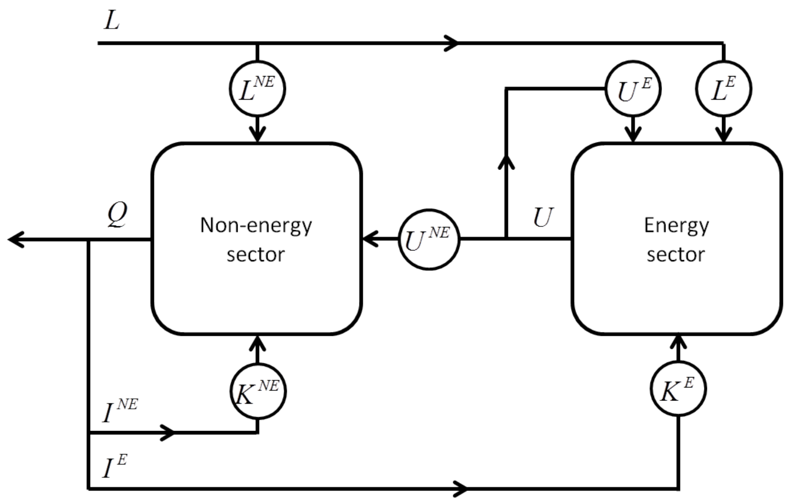

Figure 3: *Scheme for the two-stage model framework.*

two-stage model aggregates all processes that convert primary exergy from natural resources into final useful work in the economy. Any device, machine or process that performs this conversion (final-use device) is included in the energy sector. This means, for example, that ordinary consumer goods which perform this conversion (e.g. automobiles, appliances, etc), whether used by households or firms, are redefined as investment in the energy sector, I^E.

Generation of a useful work supply from natural exergy resources involves conversion losses - Figure (4). In fact, this conversion consists of at least two conversion stages. Primary work is work done by the first stage of energy conversion (e.g. electric power generation by means of a steam turbine). Secondary work is work done by electric devices or machines in producing useful work outputs. The second-law efficiency introduced in the previous section, ϵ, can be subdivided between a primary-to-final efficiency (ϵ^D, related to the transformation of "raw" exergy into a final consumable form) and a final-to-useful efficiency (ϵ^A, related to the end-use devices that convert final exergy into actual useful work.). Exergy conversion efficiency is defined as the ratio of *actual work* (output) to *maximum work* (exergy input), for any process. Useful work can then be divided into several categories: muscle work by humans or animals, mechanical drive by stationary or mobile prime movers, heat delivered to a point of use, light and other electrical uses. The aggregate efficiency measure adopted by Ayres and Warr, unlike proxies for technological progress used in endogenous growth models, is a quantification of technological performance, comparing outputs (useful work) to inputs (total exergy consumed). As opposed to attempts to quantify natural capital alongside man-made capital as a factor of production, Ayres and Warr's exergy measures only the real-time resource dependency of the economy, quantified using physical units of energy (Joule) rather than focusing on prices and costs.

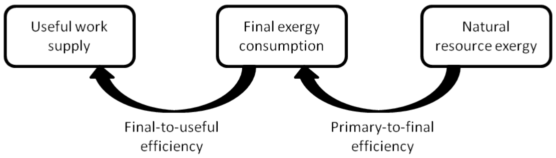

Figure 4: *Conversion from primary to final exergy and final exergy to useful work.*

Capital, labour and useful work needed to produce the aggregate output from the energy sector, U^E, should be subtracted from the total inputs of capital, labour and useful work (K, L and U, respectively) to the whole economy, in order to avoid double counting. Therefore, the inputs to the secondary sector production function (K^{NE}, L^{NE}, U^{NE}), responsible for producing all downstream goods and services (i.e. GDP) for consumption and investment, will correspond to the total capital, labour and useful work minus the capital, labour and useful work used as inputs to the energy sector - Equation (3).

$$\begin{cases} K^{NE} = K - K^E \\ L^{NE} = L - L^E \\ U^{NE} = U - U^E \end{cases} ; \quad (3)$$

Consequently, the non-energy sector production function may be written as:

$$Q = Q_2 \left[K - K^E, L - L^E, U - U^E \right]; \quad (4)$$

The output from the non-energy sector constitutes the gross domestic product for the whole economy, which is divided between total consumption C and total investment I. Total investment is further subdivided between investment allocated to the energy sector I^E and investment allocated to the non-energy sector I^{NE}.

Following Ayres & Warr (2010) [12] it seems reasonable to postulate, as a first approximation, that capital, labour and useful work are used in the same proportions in the production of useful work U as they are in the economy as a whole. Following this assumption, it is assumed that the mathematical form for sector-specific production functions Q_1 and Q_2, and the global production function for the whole economy Q, are identical, except for a constant multiplier λ. Therefore:

$$\frac{K - K^E}{K} = \frac{L - L^E}{L} = \frac{U - U^E}{U} = \lambda; \quad (5)$$

From Equation (5), it results that:

$$\begin{cases} K - K^E = \lambda K \\ L - L^E = \lambda L \\ U - U^E = \lambda U \end{cases} ; \quad (6)$$

And the sector-specific production functions can be rewritten as:

$$\begin{matrix} Q_1(K^E, L^E, U^E) = (1 - \lambda) \cdot Q(K, L, U) \\ Q_2(K^{NE}, L^{NE}, U^{NE}) = \lambda \cdot Q(K, L, U) \end{matrix} ; \quad (7)$$

Which means that the global production function, for the whole economy, can be written as the sum of the sector-specific production functions - Equation (8).

$$Q = Q_1 + Q_2; \quad (8)$$

The logic presented above is valid not only for the Cobb-Douglas case, but also for any production function that is homogeneous or order unity[8]. Of course, in reality it is possible (and even probable), that the proportion of inputs to each sector of the economy is distinct

[8] Such as, for example, the LINEX (linear exponential) production function [13].

for each factor of production. The energy sector, for example, may be more capital-intensive and less labour-intensive than the secondary sector. Adjusting for these differences constitutes a second-order correction, that does not concern the present analysis.

The main consequence of the economic system as defined in this section is that the total output for the whole economy will be proportional to the output of each of the two sectors that constitute the system. That is, total output (GDP) will be a function of total capital, total labour and total useful work.

IV. Empirical Analysis

The purpose of this section is to estimate the long-run structural relations between gross domestic product (GDP), the primary factors of production capital stock K and labour inputs L, and a series of variables representing energy use at various stages of economic production (primary and final energy/exergy, and useful work).

In terms of methodology applied, similar analysis have been conducted for the Portuguese economy, specifically concerning the cointegration of different levels of education with GDP and investment [18]; the structural relations between total factor productivity, human capital and innovation [22]; or the macroeconomic returns on human and public capital [23]. The analysis presented here intends to apply the same methodology to the cointegration of GDP, investment, labour supply and energy use related variables.

There is a large body of literature focusing on the causality relationship between energy consumption and economic growth, spanning different countries (or groups of countries) and time periods. This literature is summarized by the recent papers of Ozturk [24], Odhiambo [25] and Payne [26]. Empirical outcomes on the direction of causality, and its short or long-run impacts, seems to depend on available data, countries' characteristics, and econometric methodologies.

There are four hypothesis, from an empirical point of view, for the causality between energy use and growth: *i) the growth hypothesis* states a unidirectional causality running from energy to growth, implying that growth requires energy; *ii) the conservation hypothesis*, stating a unidirectional causality running from economic growth to energy use, denoting that an economy is not fully dependent on energy consumption for growth; *iii) the feedback hypothesis*, which assumes bidirectional causality between energy use and growth; and *iv), the neutrality hypothesis*, which asserts that energy use and economic development are neutral with respect to each other.

Cointegration analysis is a prerequisite of testing for causality when the variables are not covariance stationary, i.e. they exhibit unit roots. The first application of cointegration analysis to the specific case of GDP and energy consumption was performed by Yu & Jin (1992), using a bivariate model [35]. These authors concluded that there is no long-run cointegration between energy consumption, industrial production or employment. Stern (1993), however, conducted analysis with a multivariate vector error-correction model (VECM) and obtained the opposite conclusion, i.e. that cointegration does occur among the variables and that quality-adjusted energy consumption Granger-causes GDP growth [36]. The contradiction between these studies is justified by Stern as the consequence of the inclusion of two more variables in the model, which allow for indirect substitution effects not possible when only two variables are considered. Stern's results were later reconfirmed by himself [37]. More recently, an application of the multivariate method as applied to Canada concluded that Granger-causality runs both ways [38].

I. Data/Sources

Throughout the empirical analysis presented here we use annual data spanning the period between 1960 and 2009. Economic variables such as GDP and capital stock K are in Mrd EURO-PTE. Labour supply L corresponds to hours worked. Energy-related variables are in TeraJoules (TJ)[9]. Prior to analysis, all variables (GDP $= Q$, capital stock $= K$, labour supply $= L$, primary and final energy $= E^{P,F}$, primary and final exergy $= B^{P,F}$, and useful work $= U$) are indexed by dividing their value each year by its initial 1960 value.

GDP at constant 2005 prices for Portugal is collected directly from the European's Commission annual macro-economic database (AMECO - consulted February 2014).

The separation of the economy in two distinct sectors, as shown in Section 3, implies that the energy sector aggregates all processes that perform the conversion of exergy from natural resources into useful work. Thus, total investment I in the following analysis will be redefined in order to include several final-use devices ordinarily considered as consumption goods in standard accounts. For example, automobiles convert exergy from fuel into useful work in the form of mechanical drive. For that reason, they are considered as investment in the energy sector of the economy, whether they are used for production or personal leisure. Likewise, household appliances such as refrigerators and kitchen stoves are redefined as energy sector investment, instead of household consumption. The redefinition is made according to some simplifying criteria which should not, in principle, affect the accuracy of the empirical results.

For labour inputs L, total hours worked for the whole Portuguese economy are considered. Amaral (2009) [14] estimates a time series for annual hours worked per person, for the time period in question. This calculation assumes the weekly working hours series in manufacturing to be representative of all economic sectors, and the author splices this data with the annual hours worked per person series obtained from the Groningen Growth and Development Center (GGDC) database. The total hours worked for the whole Portuguese economy are then estimated by multiplying the annual hours worked per person by the total employment time series also obtained from the GGDC database.

Obtaining useful work statistics implies the calculation of exergy from available energy datasets. Energy data for the period 1960-2009, for the Portuguese economy, was collected mainly from International Energy Agency (IEA) Energy Statistics and Energy Balances, and complemented by Sofia Henriques (2011) [15]. Serrenho et al (2013) takes into account exergy inputs that go beyond conventional energy accounting statistics, namely: food for humans, feed for working animals, and non-conventional sources[10].

Final energy use regarding coal and coal products, oil and oil products, natural gas, combustible renewables, and electricity and CHP heat were obtained from the IEA energy balances.

Food intake data was obtained from the Food and Agriculture Organization of the United Nations database (FAO). Feed for working animals was estimated from the number of working animals inventories from Henriques (2011). Energy data concerning non-

[9] 1 TeraJoule = 10^{12} Joules

[10] Such as wind and water streams for mechanical drive uses.

conventional carriers was obtained directly from Henriques (2011).

The IEA datasets provide statistics on primary energy supply E^P, gross energy consumption, energy industry own-use and final energy consumption. We adopt the same definition as Serrenho et al (2013) concerning final energy consumption E^F: it corresponds to total effective consumption, i.e. standard final energy consumption as commonly defined in official energy statistics plus energy sector own energy uses [16].

Primary energy supply and total final energy consumption are converted to exergy equivalents (primary exergy supply B^P and total final exergy consumption B^F) based on different exergy factors[11] for each group of energy carriers.

Useful work is classified within 5 different categories according to final use: heat, mechanical drive, light, other electric uses and muscle work. Non-energy uses are not considered. Final exergy consumption of each economic sector is allocated to useful work categories and second-law efficiencies are estimated for each final-to-useful transformation. Summing the total values obtained for each useful work category results in overall useful work values for the whole economy U.

Throughout the whole empirical analysis, the software EViews 7.2 ®was used to obtain the presented results.

II. Methodology

In order to estimate and compare the impact of energy-related variables on economic output, a series of VARs (Vector Autoregression) are estimated, containing different combinations of variables. In the following analysis, all variables that constitute the estimated VAR are taken as ratios of economic (GDP, Q and capital stock, K) and energy variables (primary and final energy/exergy E^P, E^F, B^P, B^F and useful work U) over total hours worked L. That is, the following variables are defined, from the time series data available:

$$q = \frac{Q}{L};\ k = \frac{K}{L};$$
$$e^P = \frac{E^P}{L};\ e^F = \frac{E^F}{L}; \tag{9}$$
$$b^P = \frac{B^P}{L};\ b^F = \frac{B^F}{L};\ u = \frac{U}{L};$$

Each variable representing energy/exergy/useful work consumption per hours worked is analysed *de per se*, alongside total output and capital stock per hours worked. Including all economic and energy variables simultaneously in a VAR would dramatically decrease the degrees of freedom. Therefore, a total of five different models are tested: one corresponding to each energy variable included. All variables are expressed in logarithms, in order to eliminate any exponential time trend.

II.1 Stationarity tests

The augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests are two alternative unit root tests used in statistics to determine if a given time series sample is non-stationary (that is, if it has a unit root). The ADF test is an extension of the Dickey-Fuller test for larger and more complicated sets of time series models. The procedure of the ADF test is applied to the model:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \delta_1 \Delta y_{t-1} + ... + \delta_{p-1} \Delta y_{t-p+1} + \epsilon_t; \tag{10}$$

[11] Exergy factor is commonly defined as the ratio of exergy to energy.

The relevant time series is represented by y_t in (10), where α is a constant, β is a coefficient on a time trend, and p is the lag order of the autoregressive process. Imposing $\alpha = 0$ and $\beta = 0$ corresponds to modelling a random walk, and setting $\beta = 0$ corresponds to modelling a random walk with a drift. The lag order p has to be chosen before applying the test, by examining relevant information criteria. The unit root test is then carried out under the null hypothesis $\gamma = 0$ against the alternative hypothesis of $\gamma < 0$. A value is determined for the test statistic:

$$DF_\tau = \frac{\hat{\gamma}}{SE(\hat{\gamma})}; \tag{11}$$

This value is then compared with a critical value for the Dickey-Fuller test. If the test statistic is less[12] than the critical value, the null hypothesis is rejected and no unit root is present in the time series sample.

The PP test builds on the Dickey-Fuller test of the null hypothesis $\delta = 0$ in a model:

$$\Delta y_t = \delta y_{t-1} + v_t; \tag{12}$$

Like the ADF test, the PP test addresses the issue that the process generating data for y_t might have a higher order of autocorrelation than what is admitted in the test equation. However, while the ADF test introduces lags of Δy_t as regressors in the test equation - Equation (10) - the PP test makes a non-parametric correction to the t-test statistic.

II.2 Cointegration Analysis

Given the characteristics of non-stationarity inherent in the series of our study - Table (1), the use of cointegration techniques is considered as the most adequate estimation method [19] [20]. Considering the following VAR, with Y_t defined as the vector including the relevant variables in this analysis (q, k, $x = e^P, e^F, b^P, b^F$ or u):

$$Y_t = c + \sum_{j=1}^{p} \Gamma_j Y_{t-j} + \varepsilon_j; \tag{13}$$

If the variables in Y_t are integrated of order one, I(1), the VAR in equation (13) is non-stationary. If there is no cointegration, statistical inference is not possible using the usual tests and p-values, as statistics will not have standard tabulated distributions. In this case, it is appropriate to first-difference the series in Y_t and to estimate the first differences VAR of the form:

$$\Delta Y_t = c + \sum_{j=1}^{p} \Gamma_j \Delta Y_{t-j} + \varepsilon_j; \tag{14}$$

When cointegration exists, there is at least one linear combination of Y_t (cointegrating vector) that produces a stationary variable. In this case, the VAR in equation (14) can be written as:

$$\Delta Y_t = c + \sum_{j=1}^{p} \Gamma_j \Delta Y_{t-j} + \Pi Y_{t-1} + \varepsilon_j; \tag{15}$$

Where Π is a rank r matrix that can be decomposed as:

$$\Pi = \alpha \beta'; \tag{16}$$

With α being a $3 \times r$ loading matrix and β a $3 \times r$ matrix of cointegrating vectors. The number of cointegrating vectors is r. The number of cointegration vectors in (13) is tested following the Johansen [19] procedure. If no cointegrating vectors are determined, the analysis proceeds by taking first-differences VAR.

[12] The test is non-symmetrical, so the absolute value is not considered.

If there is one or more cointegrating vectors detected, these are estimated and a cointegrated VAR is considered, as in (15).

II.3 Granger Causality

Granger causality between two series, A and B, implies that, if B can be better predicted by the past behavior of both A and B than by the behavior of B alone, then A can be said to Granger-cause B. In the methodology first proposed by Granger [32], the absence of causality between variables can be tested by estimating a VAR model of the sort:

$$Y_t = a_0 + a_1 Y_{t-1} + ... + a_p Y_{t-p} + b_1 X_{t-1} + ... + b_p X_{t-p} + u_t; \tag{17}$$

Testing the null hypothesis $H_0 : b_1 = b_2 = ... = b_p = 0$ against the alternative hypothesis that any of these coefficients is not zero constitutes a test of whether the variable X Granger-causes Y. In the same way, whether Y Granger-causes X or not can be tested by estimating the similar VAR:

$$X_t = c_0 + c_1 X_{t-1} + ... + c_p X_{t-p} + d_1 Y_{t-1} + ... + d_p Y_{t-p} + u_t; \tag{18}$$

And testing the null hypothesis $H_0 : d_1 = d_2 = ... = d_p = 0$. In each case, a rejection of the null hypothesis implies that there is Granger causality.

Causal analysis for a multivariate VAR corresponds, in other words, to testing the restrictions that all cross-lags coefficients are all zero. This can be tested by Wald statistics using EViews.

II.4 Impulse Response Functions

It is standard pratice in VAR analysis to identify structural shocks as orthogonal innovations to each variable, by imposing some restrictions. Impulse response functions trace deviations of a variable from a baseline following a shock to another variable. In this paper, we are specially interested in responses of GDP per hours worked (q) to innovations in energy/exergy/useful work consumption per hours worked (e^P, e^F, b^P, b^F, u). By taking into account the response of capital stock per hours worked (k), a full interpretation of all dynamic effects between these variables is possible, since GDP growth depends also on investment and past lagged GDP growth changes.

In order to do this, some restrictions are imposed. The variables are ordered according to the Cholesky decomposition. In the analysis presented here, the energy variables are placed in the third and last place, implying that innovations to the energy-related variables do not influence q or k in the same period that they occur. On the other hand, innovations to q and k immediatly affect the energy-related variables. These are assumed to be sensible restrictions for two reasons: First, the economic benefits of energy-related innovations only take place some time after they occur; second, shocks to GDP and capital stock, specially at the level of the energy sector, will surely affect the hability to transform and convert energy from primary sources.

Long run elasticities and semi-elasticities are computed from the accumulated responses obtained from shocks to each of the energy-related variables. Semi-elasticities measure the percentage increase in q and k due to a unit increase in energy units per hours worked. In this analysis, semi-elasticities are computed in order to assess whether it pays, productionwise, more to increase primary/final energy/exergy or useful work per hours worked.

The elasticity of q to changes in energy-related variables is given by:

$$\xi_X = \frac{\textit{percentage increase in } q}{\textit{percentage increase in } X}; \qquad (19)$$

With $X = e^P, e^F, b^P, b^F, u$. In a VAR defined in log changes, such as the ones in this analysis, ξ_X is estimated as the ratio of the accumulated change in q (or k) over the accumulated change in a given energy-related variable. Semi-elasticities are then computed by dividing the long-run elasticity by the sample average value for the respective energy-related variable:

$$\eta_X = \frac{\xi_X}{\bar{X}}; \qquad (20)$$

Where $\bar{X}$ is the sample average of the considered energy-related variable. The semi-elasticities take into account the full effects of an increase in energy/exergy/useful work per hours worked. When the considered energy-related variable innovation induces more physical investment, the positive effects of a higher capital stock on output are included when computing the output response to an impulse in that energy variable. In this case, this dynamic feedbacks semi-elasticity is higher than a *ceteris paribus* one.

III. Results

III.1 Unit Roots Tests

Augmented Dickey-Fuller (ADF) and Phillips-Perron test results for all level variables considered in this study are presented in Table (1). When the ADF or PP statistic is smaller than the critical value, the null non-stationarity hypothesis is rejected, and the time series has a unit root. For the ADF tests, the final number of lags was chosen according to the minimum observed value for the Akaike Information Criteria (AIC) statistic[13].

For the PP tests, the badwidth parameter for the kernel-based estimator of the residual spectrum at frequency zero was obtained by the Newey-West [17] method using Bartlett kernel.

All considered variables exhibit significant time trends - Figures (5), (6), (7) and (8). Therefore, a trend was included for all tests of level variables. The hypothesis of non-stationarity was never rejected for any variable. This implies that none of the time series considered is stationary, and they all acuse the presence of unit roots.

Table (2) shows the ADF and PP test results for the first-differenced series of the variables. Since these represent annual growth rates, there is no need to include a time trend. Here, non-stationarity is immediatly rejected for the time series of q and k, as well as the energy/exergy/useful work consumption variables. In almost every case, ADF statistics and PP statistics reject the non-stationarity hypothesis, at the 1% level, for first-differences time series. The only exception is the useful work variable, where the non-stationarity hypothesis is rejected at the 1% level according to the PP statistics, but only at the 10% level according to the ADF test statistic. It is well-known that stationarity tests are not very powerful in small samples. The result obtained from the ADF tests probably results from the fact that the data sample used is small [18].

Evidence from Table (2) and the considerations above imply that all considered time series can be considered as I(1), non-stationary variables. This implies that the series could perhaps be cointegrated, i.e., there could be one or more stationary linear combinations of the series, suggesting a stable long-run relationship between them.

[13]The upper bound for the lag length was chosen as the integer part of the formula proposed by Shwert [21], $p_{max} = 12(T/100)^{1/4}$ where T is the number of observations.

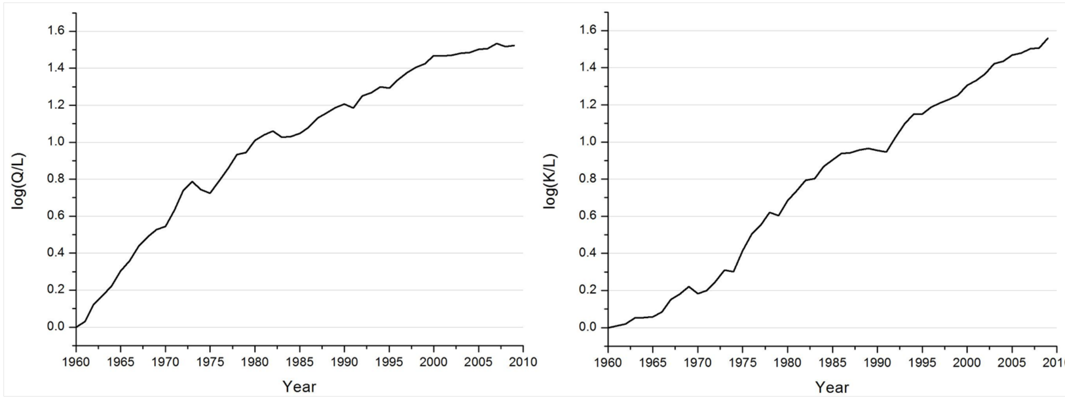

Figure 5: ***Left graph:*** *Logarithm of indexed gross domestic product per indexed hours worked, q.* ***Right graph:*** *Logarithm of indexed total capital stock per indexed hours worked, k.*

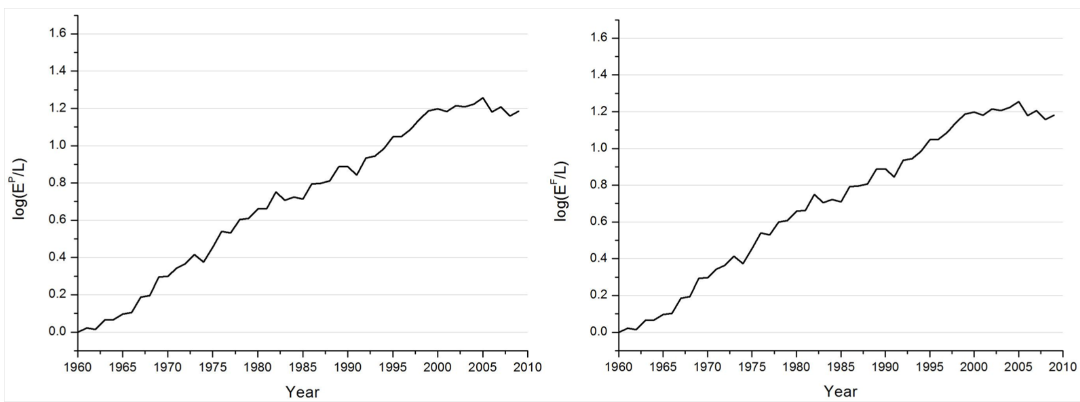

Figure 6: ***Left graph:*** *Logarithm of indexed primary energy supply per indexed hours worked,* e^P. ***Right graph:*** *Logarithm of indexed final energy supply per indexed hours worked,* e^F.

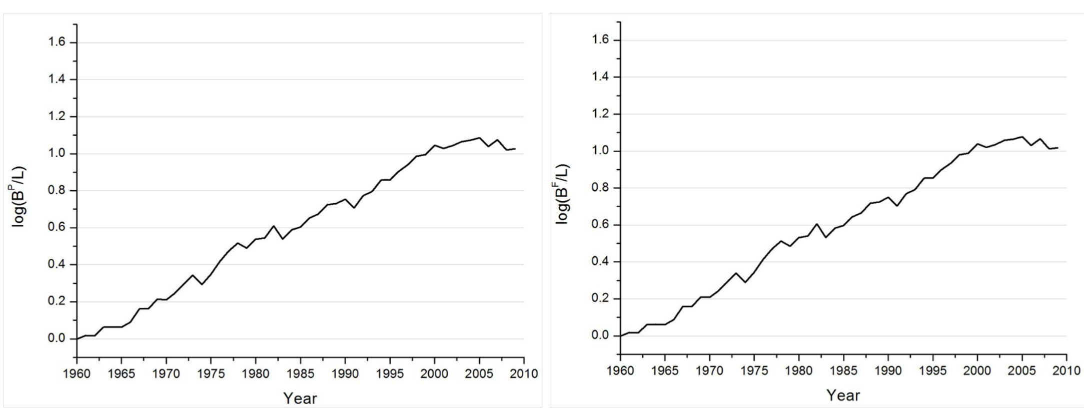

Figure 7: ***Left graph:*** *Logarithm of indexed primary exergy supply per indexed hours worked,* b^P. ***Right graph:*** *Logarithm of indexed final exergy supply per indexed hours worked,* b^F.

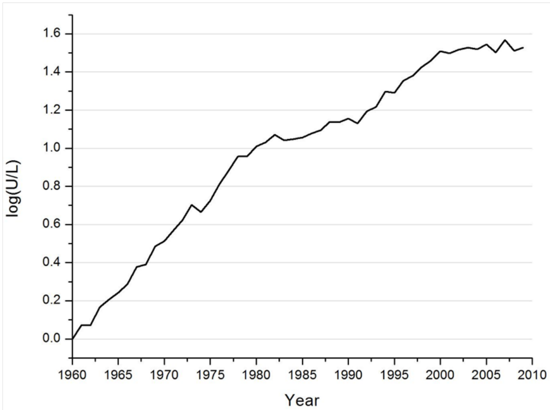

Figure 8: *Logarithm of indexed total useful work consumption per indexed hours worked, u.*

III.2 Johansen Cointegration Tests

Multivariate cointegration analysis based on Johansen's multiple cointegration test has been widely accepted has the most suitable method to analyse the causality structure of non-stationary macroeconomic time series. A multivariate methodology is important because changes in energy use are likely to be countered by the substitution of other factors of production, resulting in little overall impact on output [6]. Given that the number of cointegration vectors is unknown, and since it is necessary to guarantee that all variables are potentially endogenous (and then test for exogeneity), the tests for cointegration between variables are conducted according to the Johansen procedure [19][28]. If the considered economic and energy consumption variables are I(1), then there is the possibility that the four variables (q, k and an energy consumption variable e^P, e^F, b^P, b^F or u) are cointegrated. Results from several VARs used to determine the number of cointegrating vectors are summarised in Table (3).

Before testing for cointegration, the number of appropriate lags for an unrestricted VAR model should be determined. For the econometric specification considered, the maximum number of lags chosen was 7 and the lag order was set to that suggested by a democratic selection from all available criteria (LR, Akaike, Schwarz and Hannan-Quinn). Residual analysis criteria were also consulted (autocorrelation) to verify the lag choice. In order to carry out the cointegration test, a choice was also made concerning the trend underlying the data. A linear deterministic trend was allowed in the level data, but the cointegrating equations were chosen to only have intercepts, since it was assumed that all trends are stochastic.

The results obtained from the Johansen methodology using the trace test and the max-eigenvalue test are somewhat contraditory for the primary and final energy and exergy inputs, concerning the number of CV. Both the trace test and the max eigenvalue test reject the hypothesis, at the 1% level, that there is no cointegration between any of these energy variables and the economic variables q and k. However, the hypothesis that there is at most 1 cointegrating vector between the variables is rejected by the trace test at the 1% significance level, but cannot be rejected by the max eigenvalue test. Despite this discrepancy in results, there is at least compelling evidence that the energy variables in question cointegrate with q and k.

For the useful work variable u, both tests are in agreement that there exist at most two cointegrating vector between this energy variable and output and capital stock per hours worked. We can therefore argue that the economic variables q and k have a statistically significant relationship with the useful work variable u.

III.3 Granger Causality Tests

The analysis presented in this work deals with VARs constituted by several non-stationary variables. In this case, using a Wald test to test linear restrictions on the parameters of the VAR model leads to unobservable nuisance parameters in the test statistics' asymptotic distribution [34], making it totally non-standard. That is, under these conditions, the Wald test statistic does not follow its usual asymptotic chi-square distribution under the null.

In order to conduct Granger causality tests in this environment, it is better to follow the Toda & Yamamoto procedure [33]. According to this methodology, after estimating well-specified VARs for each group of variables (q, k, plus an energy-related variable e^P, e^F, b^P, b^F or u), m additional lags are added as exogenous variables to the VAR model, where m is the highest integration order of all the variables in a given group[14]. The Wald test statistics will then be asymptotically chi-square distributed with p d.o.f, under the null, and the Granger causality results will be meaningful.

The results from Granger causality tests performed in this way are presented in Table (4). Two null hypothesis are tested for each estimated VAR with several energy-related variables: 1) the null hypothesis that the relevant energy variable does not Granger-cause GDP per hours worked (q); and 2) the null hypothesis that q does not Granger-cause the relevant energy-related variable. If each of these hypothesis is rejected, then it can be said that there is unidirectional Granger causality from the energy-related variable to q, or vice-versa. If both hypothesis are rejected, it can be said that there is bidirectional Granger causality between the two variables.

From the results presented in Table (4), there is no evidence of bidirectional causality between GDP per hours worked and any of the energy-related variables. Results with primary and final energy variables e^P and e^F suggest that neither of these variables Granger-causes q and, conversely, q does not appear to Granger-cause variations in these energy-related variables. Therefore, the neutrality hypothesis cannot be rejected concerning primary and final energy variables.

Looking at results from primary and final exergy b^P and b^F, there is again no evidence of unidirectional causality running from either of these variables to q. However, at a 5% significance level, the hypothesis that q Granger-causes b^P or b^F (conservation hypothesis) cannot be rejected.

Finally, results with the useful work variable indicate that the hypothesis that causality runs from u to q can be rejected, but only at the 10% significance level. However, there is no evidence of causality in the opposite direction, from q to u. In any case, useful work is the energy-related variable which exhibits a significant confidence level (approximately 93.7%) for a direct causal effect on economic growth. This suggests that the growth hypothesis may hold concerning this energy variable, for the Portuguese economy in the last 50 years.

III.4 Impulse Response Functions

In order to estimate impulse response functions that allow a comparison between the several energy-related variables in this analysis, and since the Johansen test results have produced mixed results concerning the cointegration between q, k and primary/final energy/exergy variables, two hypothesis are considered for each of these variables: cointegrated VAR with only one cointegrating equation (CE); and cointegrated VAR with two cointegrating equations. The number of lags selected for each cointegrated VAR are represented in the third column of Table (5). The impulse response functions estimated, for a 50 year period, for each case are presented in Figures (9), (10), (11) and (12) (VAR with only one CE) and Figures (13), (14), (15), (16) and (17) for the

[14] In our case, for example, all considered variables are I(1), so $m = 1$ lags are included as exogenous variables.

cointegrated VAR with two CE.

A first observation is that the graphs for the model including primary energy/exergy variables, whether obtained through VAR with one or two CE, are virtually indistinguishable from the graphs obtained for the model including final energy/exergy variables.

In all cases considered, impulses to the energy-related variable appear to produce a positive response on GDP per hours worked in the long-run. For primary and final energy/exergy variables, there are differences regarding the number of CE assumed. For the VAR with one CE only, a positive q response is particularly relevant in the first 5 periods (years). For the VAR with two CE, the q response is increasingly positive throughout the entire 50 year window studied.

In terms of total capital stock per hours worked response to innovations in primary and final energy/exergy variables, there are also some differences. For the VAR with one CE, and including primary of final energy variables (e^P, e^F), there is an overall positive long-run effect, after an initial 5 year negative response. Including primary of final exergy variables (b^P, b^F) in a one-CE VAR, k shows an overall negative long-run response to changes in these variables. However, considering any of these primary and final energy/exergy variables in a two-CE VAR results in a long-run positive effect on k.

The inclusion of the useful work variable in a two-CE VAR constitutes a distinct case from the remaining energy/exergy variables. Concerning the long-run responses of both q and k to innovations in this variable, they exhibit significant fluctuations. However, in any case, the periods when the response functions are above the baseline more than compensate for the periods below it. Therefore, there is an overall positive effect of changes in u on q and k. All energy variables included in a two-CE VAR reveal a crowding in phenomenon in the sense that there is a positive effect from these energy variables on economic growth both directly and indirectly, through the increase of capital stock k. This is also true for the VAR including a useful work variable u.

The seventh and ninth columns of Table (5) also summarize this analysis' results concerning long-run elasticities and semi-elasticities. A long-run semi-elasticity of q gives the percentage increase in GDP per hours worked resulting from a unit increase in one of the relevant energy-related variables[15].

The long-run elasticities of q are given by the ratio between q change (fourth column) and the energy-related variable change (sixth column). These are presented in column seven of Table (5). These long-run elasticities are not a very good measure for comparison between the energy-related variables, since a one-percentage point increase differs across variables, in absolute terms. Semi-elasticities are more directly comparable, because they measure the effect of absolute changes in energy-related variables, which are measured in the same units (GJ). Since semi-elasticities are measured as the ratio of elasticities and energy-related variables' values, they are time varying. They are therefore computed using average sample values, and presented in column nine of Table (5).

From Table (5), one can argue that increasing energy use has a direct positive effect on economic production, and it also stimulates growth indirectly, through higher physical investment. This observation is valid for all energy-related variables considered included in a two-CE VAR. In the case of one-CE VAR with primary or final exergy variables, the overall negative response of k to innovations is reflected in the low values obtained for long-run

[15]For the sake of clarity in the results obtained, in this part of the analysis, the energy-related variables time series are converted to GigaJoules (GJ) per hours worked.

and semi-elasticities.

It is also observable that the semi-elasticity obtained with the model including the useful work variable is significantly higher than the remaining semi-elasticities. Comparing only two-CE estimated VAR results, it is shown that, while an increase in one GJ of primary or final energy/exergy variables leads to a 0.8-1 percent change in GDP, a similar increase in useful work variable results in a 5 percent change in GDP. This means that there is compelling evidence from this empirical analysis that useful work impacts economic growth in a more significant way than either primary or final energy/exergy, despite all energy-related variables showing a positive link with economic development.

V. Conclusions

The main goal of this work is to investigate and compare the effects of several energy-related variables, defined according to energy used at different stages of production, on economic growth. The impact of different energy-related variables on Portuguese economic growth was estimated through the use of time series tools, such as VAR analysis, Granger causality tests and impulse response functions on annual time series data.

Due to the inherent characteristics of the variables used, this estimation was carried out using cointegration techniques, specifically the Johansen methodology.

The results obtained while testing for cointegration between GDP per hours worked, capital stock per hours worked, and each of the defined energy consumption variables produced mixed results when either primary or final energy/exergy variables (e^P, e^F, b^P or b^F) were considered. This implies that definite interpretation of these results may be misleading, especially when later cross-checked with the results from the Granger causality tests. As for the cointegration with the inclusion of a useful work variable, u, as the energy variable, the Johansen procedure results are solid, and there is evidence for a cointegration relation between the variables. This is a sign that GDP and capital stock per hours worked have a statistically significant connection with useful work consumption per hours worked.

The causal relation between energy consumption and economic growth has been well-studied in the relevant literature. Energy is one of the essential factors in any country's economic development, and plays an important role in economic activities. On the other hand, a higher level of economic development can induce an increase in energy consumption. The impact of changes in energy policy and energy consumption on economic growth deserves a careful analysis.

This study has investigated the causality relationship between the distinctively defined energy consumption variables and economic growth in Portugal, between 1960 and 2009. A Granger causality methodology using the Toda & Yamamoto approach was conducted in order to examine the causal relation between economic growth and primary or final energy/exergy, or useful work.

These tests indicate no causality of any kind (neutrality hypothesis) running between economic growth and the energy variables concerning primary and final energy (e^P, e^F). For the inclusion of primary or final exergy variables (b^P, b^F) the results suggest unidirectional causality running from GDP per hours worked to these energy-related variables. The conservation hypothesis cannot, therefore, be rejected concerning primary and final exergy consumption.

The Granger causality results with the inclusion of a useful work variable are the only ones that exhibit unidirectional causality running from the energy-related variable to economic growth (at a 10% significance level). These results seem to favour the growth hypothesis for this energy variable, in the Portuguese economy.

Finally, estimating the impulse response functions of GDP and capital stock per hours worked to innovations in each of the considered energy variables allows the assessment of direct and indirect effects of these energy variables on economic growth. The accumulated responses obtained for the 50 year period under study also permit the estimation of long-run elasticities and semi-elasticities, which measure the changes in GDP caused by increases in the different energy variables.

Results show that, estimating cointegrated VAR with one or two CE for primary and final energy/exergy[16] produces different results. All energy/exergy variables included in a one-CE VAR show a significant positive effect on GDP per hours worked that is attenuated after 5 periods (years). As for energy/exergy variables included in a two-CE VAR, this positive effect is increasingly higher throughout the entire time period (50 years).

Energy and exergy variables also have distinct effects on capital stock per hours worked, k, when one-CE VAR are considered. For two-CE VAR there is a similar increasingly positive effect on both GDP and capital stock per hours worked. Inclusion of a useful work variable in a two-CE VAR results in an overall positive response on q and k from innovations to this energy variable.

All energy variables in two-CE VAR show significantly high levels of long run elasticity with GDP. The definition of semi-elasticities, as adopted in this work, illustrates a more directly comparable measure of the effects of absolute changes in energy variables on GDP. The results obtained in this case indicate that a change in one unit of the useful work variable u (in GigaJoules) results in an increase of GDP per hours worked approximately five times greater than a one unit change in any of the other energy variables. This again suggests that useful work, the energy-related variable defined as closest to the productive processes of the economy, has the most significant impact on Portuguese economic growth.

Overall, the results obtained throughout this work seem to favour the proposition that useful work, as defined by Ayres & Warr [12], is the appropriate variable to measure energy inputs to the economic system, for Portugal. Therefore, it can be argued whether or not it is possible to decouple energy consumption and economic growth whilst still increasing energy services through improved effciency in energy conversion technologies. Further investigation can extend this analysis to other countries in order to strengthen this proposition.

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[16] Again, due to the mixed results obtained in the cointegration analysis.

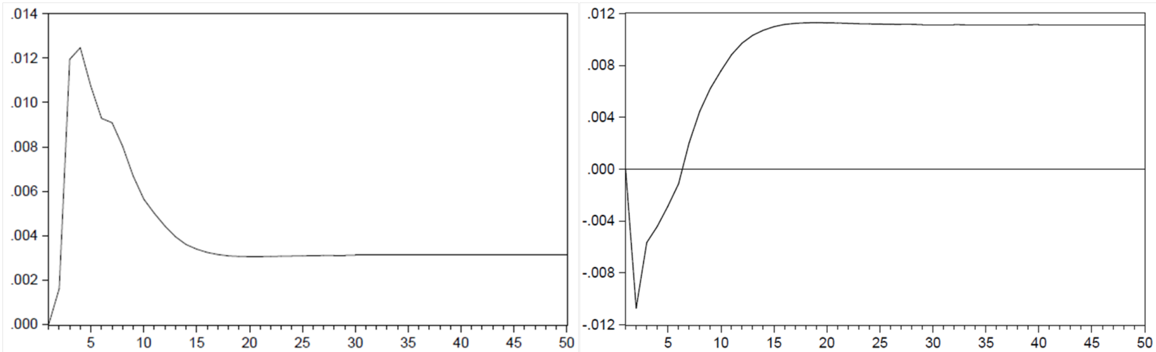

Figure 9: *Cointegrated VAR (1 CE) between q, k and e^P.* ***Left graph:*** *Impulse response function of q to one standard deviation primary energy e^P innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy e^P innovation.*

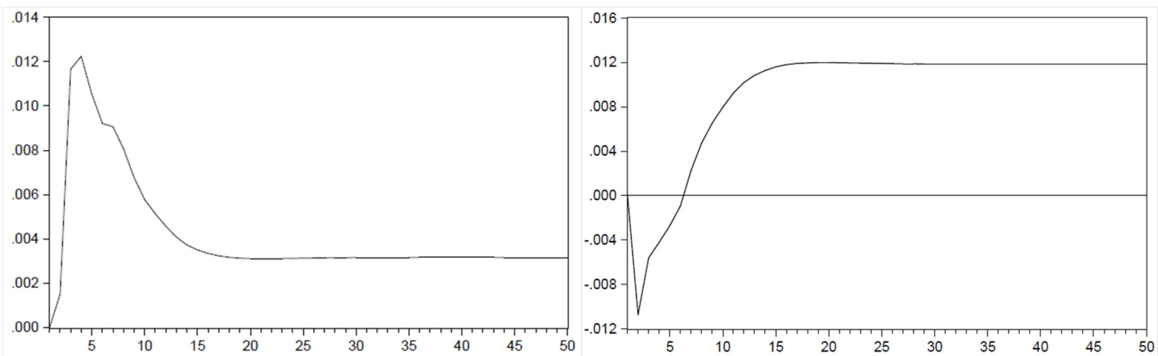

Figure 10: *Cointegrated VAR (1 CE) between q, k and e^F.* ***Left graph:*** *Impulse response function of q to one standard deviation primary energy e^F innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy e^F innovation.*

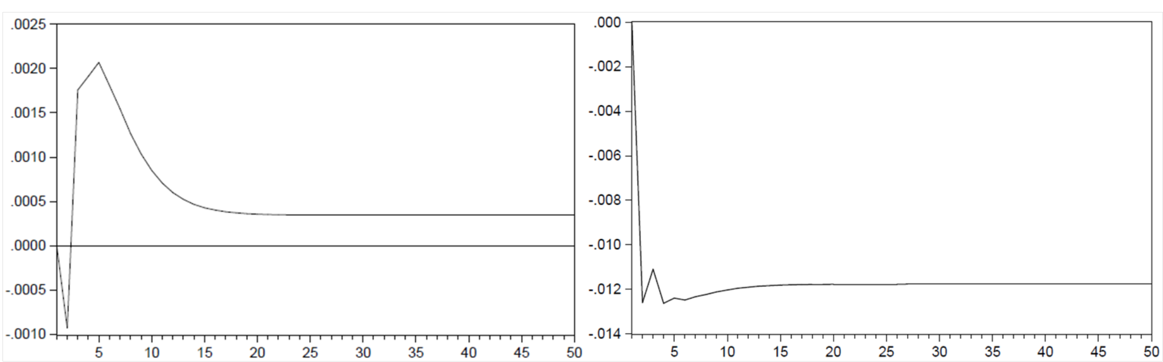

Figure 11: *Cointegrated VAR (1 CE) between q, k and b^P.* ***Left graph:*** *Impulse response function of q to one standard deviation primary energy b^P innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy b^P innovation.*

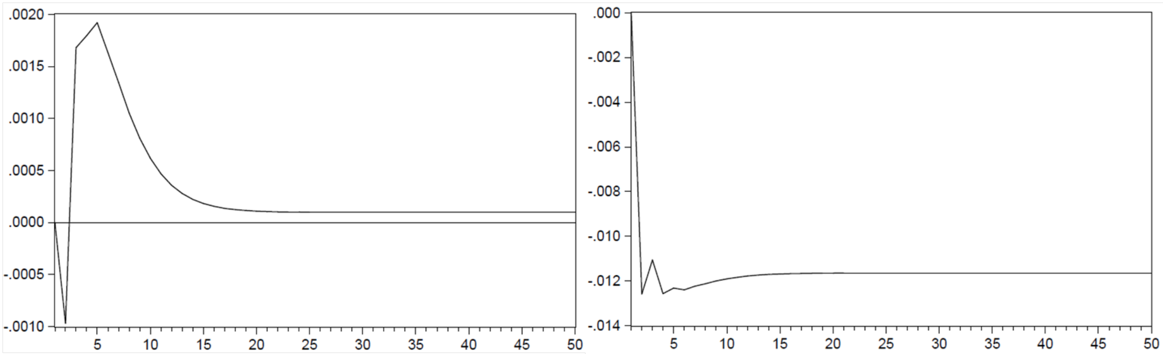

Figure 12: *Cointegrated VAR (1 CE) between q, k and b^F.* ***Left graph:*** *Impulse response function of q to one standard deviation primary energy b^F innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy b^F innovation.*

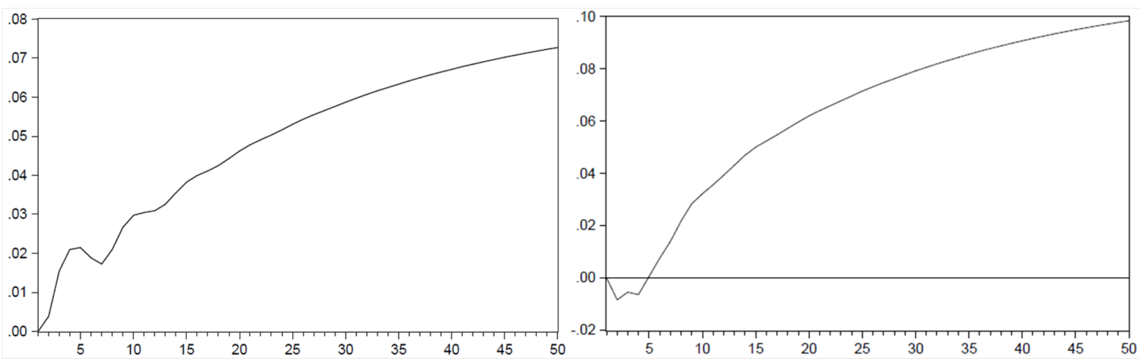

Figure 13: *Cointegrated VAR (2 CE) between q, k and e^P.* ***Left graph:*** *Impulse response function of q to one standard deviation primary energy e^P innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy e^P innovation.*

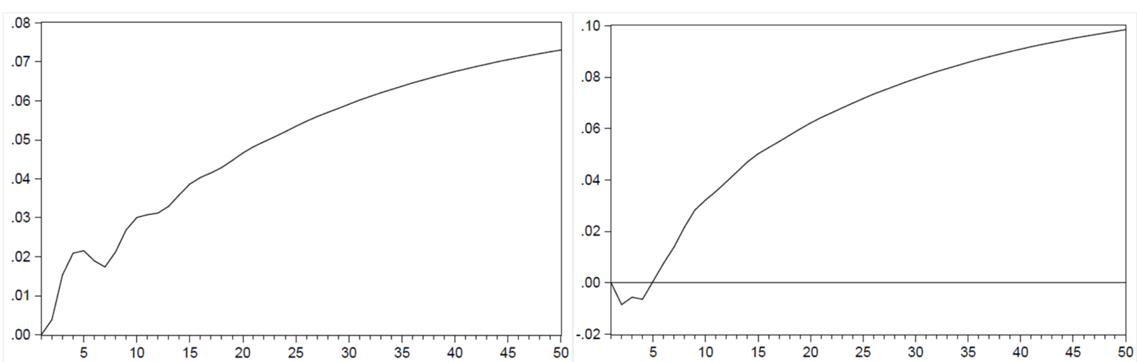

Figure 14: *Cointegrated VAR (2 CE) between q, k and e^F.* ***Left graph:*** *Impulse response function of q to one standard deviation primary energy e^F innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy e^F innovation.*

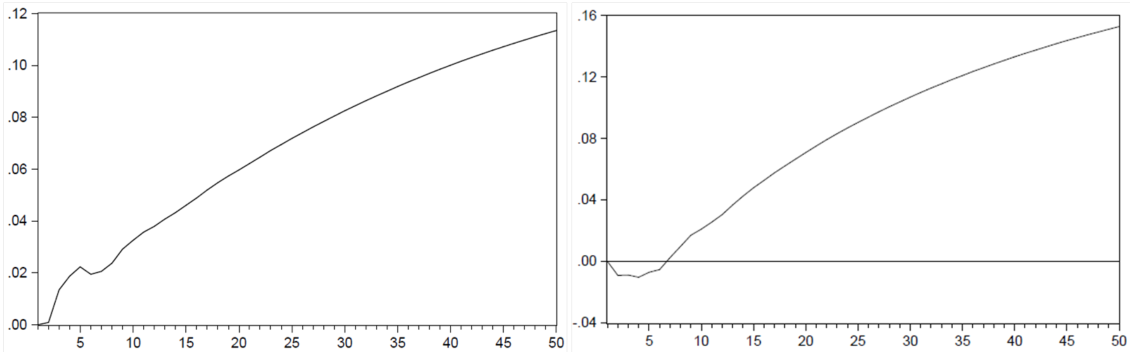

Figure 15: *Cointegrated VAR (2 CE) between q, k and* b^P. ***Left graph:*** *Impulse response function of q to one standard deviation primary energy* b^P *innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy* b^P *innovation.*

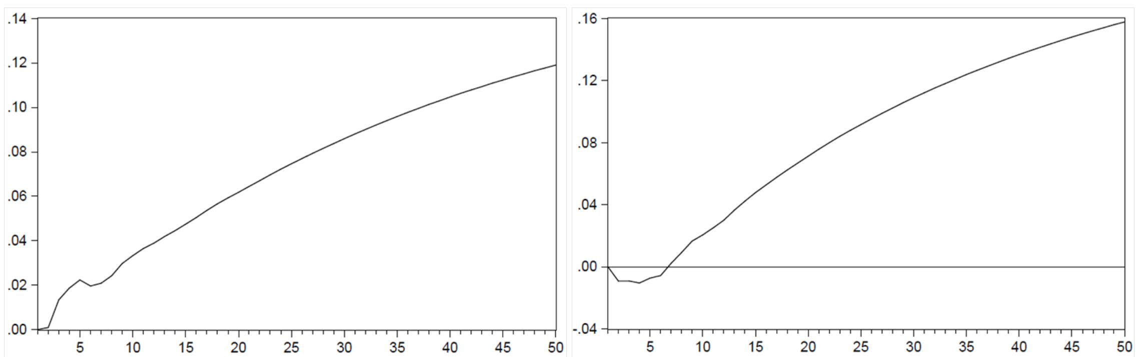

Figure 16: *Cointegrated VAR (2 CE) between q, k and* b^F. ***Left graph:*** *Impulse response function of q to one standard deviation primary energy* b^F *innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy* b^F *innovation.*

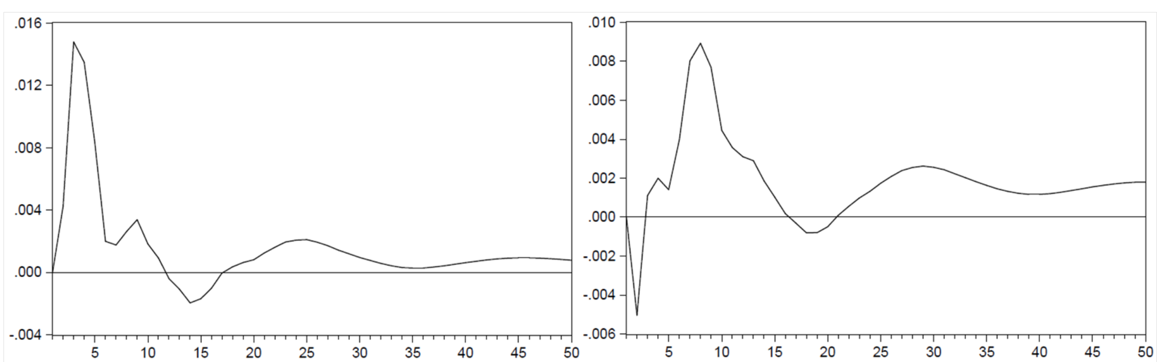

Figure 17: *Cointegrated VAR (2 CE) between q, k and u.* ***Left graph:*** *Impulse response function of q to one standard deviation primary energy u innovation.* ***Right graph:*** *Impulse response function of k to one standard deviation primary energy u innovation.*

Variable	Lags	CT / C	ADF statistic	PP statistic	Presence of Unit Root?
q	0	CT	-1.626302	-2.751399	Yes
k	0	CT	-1.847703	-1.953042	Yes
e^P	1	CT	0.548302	-0.569335	Yes
e^F	1	CT	0.566068	-0.555172	Yes
b^P	0	CT	-1.436045	-1.107004	Yes
b^F	0	CT	-1.429635	-1.101960	Yes
u	0	CT	-1.103764	-0.914065	Yes

Table 1: *Unit roots test - variables in levels. * Rejection at 1% level. ** Rejection at 5% level. *** Rejection at 10% level. CT - Inclusion of a constant and time trend. C - Inclusion of constant without time trend.*

Variable	Lags	CT / C	ADF statistic	PP statistic	Presence of Unit Root?
q	0	C	-4.874654*	-4.971801*	No
k	0	C	-6.363367*	-6.352298*	No
e^P	0	C	-10.04892*	-9.592206*	No
e^F	0	C	-10.03987*	-9.589909*	No
b^P	0	C	-9.469980*	-9.319946*	No
b^F	0	C	-9.475578*	-9.326746*	No
u	1	C	-2.789979***	-8.093375*	No

Table 2: *Unit roots test - variables in first differences. * Rejection at 1% level. ** Rejection at 5% level. *** Rejection at 10% level. CT - Inclusion of a constant and time trend. C - Inclusion of constant without time trend.*

		None		At most 1		At most 2	
Var.	Lags	Trace (35.45817)	Max (25.86121)	Trace (19.93711)	Max (18.52001)	Trace (6.634897)	Max (6.634897)
e^P	4	64.39525*	43.71737*	20.67788*	16.06394	4.613932	4.613932
e^F	4	64.40023*	43.99061*	20.40962*	15.84704	4.562580	4.562580
b^P	4	55.29597*	31.55109*	23.74488*	18.41931	5.325572	5.325572
b^F	4	55.66368*	31.81873*	23.84494*	18.47845	5.366491	5.366491
u	4	58.76953*	27.47924*	31.29029*	24.99674*	6.293548	6.293548

Table 3: *Johansen cointegration tests - variables in levels, assuming only intercept (no trend) in CE and test VAR. Trace test and Max test in p-values. Critical values in parenthesis. * Rejection of the hypothesis, at 1% level.*

Null hypothesis	Lag order	Additional lag (m)	Probability (p-value)
e^P does not Granger-cause q	4	1	0.1843
q does not Granger-cause e^P			0.7055
e^F does not Granger-cause q	4	1	0.1851
q does not Granger-cause e^F			0.7135
b^P does not Granger-cause q	4	1	0.1225
q does not Granger-cause b^P			0.0427**
b^F does not Granger-cause q	4	1	0.1211
q does not Granger-cause b^F			0.0416**
u does not Granger-cause q	4	1	0.0630***
q does not Granger-cause u			0.2644

Table 4: *Granger causality tests for the estimated VARs of q, k and several energy-related variables, following a Toda & Yamamoto approach. Results correspond to the joint significance of energy-related coefficients in q and vice-versa. * Rejection at 1% level. ** Rejection at 5% level. *** Rejection at 10% level.*

Energy var.	CV	Lags	q change	k change	En. var. change	Long run elasticity	En. var. sample av.	En. var. semi-elasticity
e^P	1	2	0.20477	0.43721	1.43820	0.14238	82.167	0.00173
	2	3	2.43192	3.11586	3.45610	0.70366		0.00856
e^F	1	2	0.20635	0.46646	1.47666	0.13974	86.772	0.00161
	2	3	2.44804	3.12269	3.48723	0.70200		0.00809
b^P	1	1	0.02629	-0.58146	0.54822	0.04796	67.757	0.00071
	2	3	3.38719	4.08256	4.88602	0.69324		0.01023
b^F	1	1	0.0150	-0.57560	0.55843	0.02686	71.197	0.00038
	2	3	3.52457	4.16760	5.01517	0.70278		0.00987
u	2	3	0.07820	0.09162	0.12023	0.65041	12.598	0.05163

Table 5: ***Long run effects of independent impulses in energy-related variables.*** *Changes in q, k and energy-related variables correspond to accumulated responses to an orthogonal impulse in a given energy-related variable. Energy-related variables sample averages in GigaJoules (GJ) per hours worked. Semi-elasticity values correspond to the year 2009.*

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