Ecological Economics 148 (2018) 103–120

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Useful Exergy Is Key in Obtaining Plausible Aggregate Production Functions and Recognizing the Role of Energy in Economic Growth: Portugal 1960–2009

João Santos[a,*], Tiago Domingos[a], Tânia Sousa[a], Miguel St. Aubyn[b]

[a] MARETEC – Marine, Environment and Technology Center, Environment and Energy Scientific Area, Department of Mechanical Engineering, Instituto Superior Técnico (IST), University of Lisbon, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal
[b] UECE Research Unit on Complexity in Economics, Department of Economics, Instituto Superior de Economia e Gestão (ISEG), University of Lisbon, Rua Miguel Lupi 20, 1249-078 Lisbon, Portugal

ARTICLE INFO

Keywords:
Useful exergy
Aggregate production function
Cointegration
Granger causality
Cost shares

ABSTRACT

The role of energy in economic growth is controversial. Models based on aggregate production functions (APF) range from the neoclassical, which downplay energy due to a cost-share theorem, but typically rely on exogenous total factor productivity (TFP), to the ecological economic, which acknowledge energy's importance. The validity of the APF concept itself is questioned. Here, we apply cointegration analysis to identify APFs between output, capital, labor, and possibly energy, measured as primary energy or useful exergy. We test for TFP growth by including a time trend. We require that plausible APFs verify cointegration, non-negative output elasticities, and Granger-causality linking inputs to output. Our method recognizes cases where: a) plausible APFs do not exist (thereby addressing the APF critique); b) energy impacts growth directly; c) energy impacts growth indirectly, through capital and labor. We apply the method to Portugal (1960–2009), considering standard and quality-adjusted capital/labor measures. With a time trend or disregarding energy, plausible APFs are never found. Without a trend, plausible APFs are found only when considering capital-energy-labor combinations. Within these, with quality-adjusted capital and labor and useful exergy, results are consistent with the cost-share theorem but energy plays a central role, through a constraint on all factors of production.

1. Introduction

The role of energy inputs in economic production processes, and the true nature of the relationship between energy use and economic development have sparked an ongoing debate in the literature, with two contrasting approaches embedded within the neoclassical growth theory and ecological economics frameworks.

On the one hand, neoclassical growth theory – as represented in the Solow-Swan exogenous growth model (Solow, 1957; Swan, 1956) – attempts to explain long-run economic growth through the accumulation of capital inputs, labor force growth, and exogenous increases in total factor productivity. Energy inputs play no significant role in this approach, something which is justified – within the theory – by a cost share theorem equating a factor's productive power with its share of payments in total income, and energy being considered an intermediate product in the economy.

On the other hand, ecological economics argues that a better understanding of economic production and growth can only be achieved by treating the economy as a subsystem of a larger, environmental system, and interactions between these systems are grounded on physical laws, namely the laws of thermodynamics. Under this approach, energy inputs are seen as essential to economic production, as real-world economic processes cannot be fully understood without accounting for energy use. Some approaches within the ecological economics framework – so-called "biophysical models" – go so far as to propose energy as the only relevant factor of production, which is degraded in the process of providing services to the economy.[1]

The concept of the neoclassical aggregate production function (APF) is at the core of Solow-Swan growth models, and is also adopted in many applications throughout the ecological economics literature. These functions relate the level of economic output to a combination of inputs to production – weighed by their respective output elasticities –

* Corresponding author.
E-mail addresses: joao.dos.santos@tecnico.ulisboa.pt (J. Santos), tdomingos@tecnico.ulisboa.pt (T. Domingos), taniasousa@tecnico.ulisboa.pt (T. Sousa), mstaubyn@iseg.ulisboa.pt (M. St. Aubyn).

[1] In these approaches capital and labor are treated as flows of capital consumption and labor services, computed in terms of embodied energy associated with them.

https://doi.org/10.1016/j.ecolecon.2018.01.008
Received 16 March 2017; Received in revised form 17 November 2017; Accepted 8 January 2018
0921-8009/

and technical change, for a given period of time. The very concept of APFs is the subject of critique due to what some authors deem "aggregation issues". According to this critique, any attempt to extract relevant economic insight from aggregate-level relationships – which are often simply assumed with no mathematical arguments, and may be purely capturing an underlying accounting identify – might prove erroneous.

Based on the aforementioned circumstances, the first aim of our work is to develop a statistically sound methodological approach to identify APFs linking output with combinations of capital, labor, and energy inputs, from historical empirical data. This methodology employs cointegration analysis, and relies on the possible interpretation of long-run statistically significant stationary linear combinations of integrated variables representing output and inputs to production – i.e. cointegration relationships – as APFs. Rooting our analysis in firm econometric techniques allows testing multiple combinations of variables, namely inclusion of energy inputs to the APF framework, and alternative measures for all factors of production. The economic plausibility of resulting APF is assured by the imposition of a set of criteria targeting the magnitude and sign of cointegration coefficients, and Granger causality relations between variables. The combination of cointegration analysis with our defined APF criteria allows for the possibility of empirical refutation of the existence of an APF formulation, thus suggesting that we are not merely capturing an underlying accounting identity, as argued in the APF critique by Felipe and McCombie (2005, 2013).

Our second aim with this work is to test – via careful econometric analysis – that an empirically observable close relationship between economic growth and a particular energy use accounting metric – useful exergy, reflecting energy actually delivered to perform a final function in the economy, in qualitative terms – is instrumental in capturing the essentiality of energy resources to production and growth, as argued by ecological economists. This is done, within the developed methodological approach, by incorporating both standard energy use measures and useful exergy in econometric models. The outcomes from these tests allow to uncover not only dynamic relationships between energy use and output – thus providing insights to the actual contribution of energy to growth – but also to uncover additional dynamic relationships between energy use and the accumulation of capital and/or the human labor employed in production.

The remainder of this paper is organized as follows: Section 2 expands on the role of energy in production and growth, from both a mainstream neoclassical growth theory and an ecological economics perspective, while also briefly touching on the subject of the APF critique. Section 3 presents our methodological approach, including the criteria for statistically significant and economically plausible APFs, with an application to Portugal. Results are presented and discussed in Section 4. Section 5 concludes and provides suggestions for future work.

2. The Role of Energy in Production and Growth

2.1. The Role of Energy in Neoclassical Growth Theory

The theoretical Solow-Swan model – set in the framework of neoclassical economics – attempts to explain long-run economic growth by means of capital accumulation, labor force growth, and exogenous increases in total factor productivity. At its core is a neoclassical aggregate production function, typically homogeneous degree 1 and frequently of a Cobb-Douglas type.

Energy inputs are absent from the basic formulation of the Solow-Swan growth model. Standard neoclassical growth theory distinguishes between primary factors of production (those that facilitate production but are neither significantly transformed by the production processes, nor become part of the final product), and intermediate inputs (those created during and used up entirely in production). Capital, labor, and land are considered primary factors of production, while most of energy is considered an intermediate that can be "produced" by some combination of capital investment and labor (plus technology).[2] Under this approach, economic growth is essentially independent of energy use (Ayres and Warr, 2010).

For the component of energy which can be considered a proper primary factor of production, it is disregarded – according to Ayres et al. (2013) – on the basis of a reasoning involving: a) an accounting identity, commonly adopted in national accounts, which equates GDP to the sum of payments to capital (interests, rents) and labor (wages, salaries); b) a stylized fact historicallly observed across countries which verifies stable (average) cost shares for these factors, with labor receiving 70% of payments, and capital the remaining 30%[3]; c) a simplifying income allocation theorem – for a state of market equilibrium[4] and for a simple economy consisting of small price-taking firms – which equates a factor's output elasticity to its respective cost share (Gans et al., 2012).

Unlike capital and labor, payments to energy are seldom represented in national accounts. Even when these payments are roughly equated with revenues from energy industries, they correspond to <10% of income (Denison, 1979; US EIA, 2011; Platchkov and Pollitt, 2011).[5] Hence, by the cost share theorem, energy's output elasticity will be correspondingly small, justifying its exclusion from most neoclassical growth models. Even if energy is considered at all, the role attributed to it in mainstream economics is usually a marginal one (Aghion and Howitt, 2009; Kümmel and Lindenberger, 2014).

The Solow-Swan model has been extended by adding the energy factor and allowing for factor-augmenting technical change[6] (e.g. Azar and Dowlatabadi, 1999; Löschel, 2002; Acemoglu et al., 2012). There are also examples in the relevant literature of modeling approaches that acknowledge and allow for the role of intermediate inputs – namely energy – to impact economic growth directly, through "gross-output" APFs (Stern and Kander, 2012). Gross output measures differ from value-added measures for economic output, by allowing for the inclusion of energy as a regular factor of production alongside capital and labor. Still, the majority of APF neoclassical growth models used in analysis relegate energy inputs to a secondary role.

This neglect of energy as a relevant factor of production leads to difficulties in explaining the economic recessions accompanying energy crises in recent decades. As pointed out in Kümmel et al. (2008), under the assumptions of the cost share theorem – and assuming that energy inputs receive roughly 5% (<10%) of total income in payments –, the energy crisis resulting from the oil shocks of 1973–75, which produced a 5.2% decrease in energy input to the US economy, would have only

[2] Land – including all natural resource inputs to production – was once the centerpiece of the classical economic model. However, as its share of GDP diminished throughout the 20th century so did its attributed importance in economic theory, and is nowadays usually subsumed as a subcategory of capital (Schultz, 1951). However, while in neoclassical economic theory the role of land has been marginalized when compared to other factors of production as capital and labor, it still plays a major role in sub-fields such as regional and urban economics (Metzemakers and Louw, 2005). It can also be argued that land has unique characteristics that arise from its distinct physical or natural and institutional properties, which warrants its treatment as a distinct factor of production (Hubacek and Vazquez, 2002).

[3] This stylized fact was originally proposed by Kaldor (1961) for the US, and other studies support the long-term stability of cost shares for this country (Denison, 1974; Jorgenson et al., 1987). Young (1995) reports reasonably stable cost shares for 4 East Asian countries – Hong Kong, Singapore, South Korea, and Taiwan – between 1960 and 1990. Studies for 7 developed countries – Canada, France, Germany, Italy, Japan, the Netherlands, and the United Kingdom – indicate cost shares similar to those in the US (Christensen et al., 1980; Dougherty, 1991).

[4] Maximizing profits without technological constraints on factor combinations.

[5] Being considered an intermediate input to production, the costs of energy are seen as payments to the owners of the primary factors of production (capital and labor), for the services provided either directly by these factors, or embodied in the intermediate inputs (Stern, 1999).

[6] Saunders (2013) also adopts factor-augmenting technical change for capital, labor, energy and material inputs in a Translog cost function framework.