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UNIVERSITY OF LA LAGUNA

School of Engineering and Technology

ESSAYS ON ENERGY ECONOMICS: CONSUMPTION, GROWTH AND POWER SYSTEMS MODELING

JOSUE BARRERA SANTANA

Ph.D. Thesis

Presented in Fulfillment of the Requirements for the Degree Doctor of Philosophy from the University of La Laguna

Graduate Program in Industrial Engineering

Advisor

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Universidad de La Laguna

December 2021

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su disposición para ayudarme a crecer y a cumplir mis metas.

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ABSTRACT

In the recent era, energy has become a strategic asset for all sectors of society. It is essential for business, transport, industry, engineering, medicine, and sports, among many others. The production and use of energy strongly influence many aspects of the economic and political decision-making, as it is considered one of the most influential factors driving economic growth and emissions. As a consequence, energy policy has focused on identifying all those aspects in the field requiring some type of intervention (e.g., improving energy efficiency or reducing CO_2 emissions) and developing the most appropriate measures to address such aspects. However, the relationships between energy, economy, efficiency and governance are very complex and encompass different areas of knowledge, so there are still many challenges to be addressed. This thesis analyzes four of them throughout three chapters using a multidisciplinary approach that combines the most up-to-date techniques from economics and engineering.

The first chapter analyzes the relationship between energy consumption and economic growth, and the role of energy governance driving such relationship. Although there are numerous studies

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addressing this issue, the lack of adequate metrics to control for double causality between both variables and to measure energy governance has led to a multitude of mutually contradictory findings. To properly assess this relationship, this chapter starts by constructing the first quantitative energy governance index representative for a set of 32 OECD countries between 2000 and 2015. This index draws upon an extensive theoretical framework and assesses more than 1800 energy regulations. The indicator is used in an instrumental variable approach to assess the causal relationship between energy consumption and economic growth.

The second chapter uses the aforementioned energy governance index to improve the measurement of energy efficiency in a panel of developed countries using stochastic frontier approaches. It also contributes to estimate the impact of energy governance on energy efficiency in the set of countries.

Finally, the third chapter provides a two-stage optimization framework designed with a twofold purpose. First, by drawing on a case study focused on the case of island power systems, it helps to analyze how certain elements that make up energy governance (e.g., budget allocation, regulations, energy plans) may affect compliance with energy policy targets. Second, this optimization framework is also intended to assist in the long-term energy planning decisions, contributing in this way to the improvement of energy strategic and action plans and, eventually, to energy governance

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RESUMEN

En la era actual, la energía se ha convertido en un bien estratégico para todos los sectores de la sociedad. Es esencial para los negocios, el transporte, la industria, la ingeniería, la medicina y los deportes, entre otros muchos. La producción y uso de la energía influencia fuertemente muchas facetas de la economía y el diseño de políticas, dado que se considera uno de los factores más importantes para el crecimiento económico y las emisiones. En consecuencia, la política energética se ha centrado fundamentalmente en identificar todos aquellos aspectos del ámbito que requieren algún tipo de intervención (por ejemplo, mejorar la eficiencia energética o reducir las emisiones de CO_2) y en desarrollar las medidas más apropiadas para tratar dichos aspectos. Sin embargo, las relaciones entre la energía, la economía, la eficiencia y la gobernanza son muy complejas e involucran diferentes áreas de conocimiento, por lo que aún quedan muchos retos por superar. Esta tesis analiza cuatro de ellos a lo largo de tres capítulos haciendo uso de un enfoque multidisciplinar que combina las técnicas más actualizadas de la economía y la ingeniería.

El primer capítulo analiza la relación entre el consumo de energía y

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el crecimiento económico, y el papel de la gobernanza energética en dicha relación. Aunque existen numerosos estudios que abordan este tema, la falta de métricas adecuadas para controlar la doble causalidad entre ambas variables y medir la gobernanza energética ha llevado a una multitud de hallazgos mutuamente contradictorios. Para evaluar adecuadamente esta relación, este capítulo comienza con la construcción del primer índice cuantitativo de gobernanza energética representativo de un conjunto de 32 países de la OCDE entre 2000 y 2015. Este índice se basa en un amplio marco teórico y evalúa más de 1800 regulaciones energéticas. El indicador se utiliza en un enfoque de variable instrumental para evaluar la relación causal entre el consumo de energía y el crecimiento económico.

El segundo capítulo utiliza el índice de gobernanza energética antes mencionado para mejorar la medición de la eficiencia energética en un panel de países desarrollados utilizando enfoques alternativos de frontera estocástica. También contribuye a estimar el impacto de la gobernanza energética en la eficiencia energética en el conjunto de países mencionado.

Finalmente, el tercer capítulo proporciona un marco de optimización de dos etapas diseñado con un doble propósito. En primer lugar, partiendo de un caso de estudio centrado en sistemas eléctricos insulares, ayuda a analizar cómo ciertos elementos que componen la gobernanza energética (por ejemplo, asignación presupuestaria, regulaciones, planes energéticos) pueden afectar el cumplimiento de los

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objetivos de la política energética. En segundo lugar, este marco de optimización también está destinado a asistir en la toma de decisiones de planificación energética a largo plazo, contribuyendo de esta manera a la mejora de los planes energéticos estratégicos y de acción y, con ello, a la gobernanza energética.

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VITA

2022	Master of Science in Big Data and business Intelligence (*currently undertaken*)
2016	Master of Science in Renewable Energies
2014	Master of Science in Radioelectronics Engineering
2012	Bachelor Engineering in Radioelectronics

FIELDS OF STUDY

Major Field:	Energy Economics and Power Systems Engineering
Specialization:	Energy modeling and planning
Minor field:	Statistics

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ACRONYMS

2SLS ..... Two-Stage Least Squares
AC ..... Alternating Current
BC95 ..... Battese and Coelli (1995)
BES ..... Battery Energy Storage
CC ..... Combined Cycles
DE ..... Diesel Engines
EE ..... Energy Efficiency
EEGI ..... Energy Efficiency Governance Index
EI ..... Energy Intensity
ESS ..... Energy Storage Systems
EV ..... Electric Vehicles
GT ..... Gas turbines
HVDC ..... High Voltage Direct Current
IEA ..... International Energy Agency
MMLE ..... Marginal Maximum Likelihood Estimator
MMSLE ..... Marginal Max. Simulated Likelihood Est.
OLS ..... Ordinary Least Squares
O&M ..... Operation and Maintenance
PCA ..... Principal Component Analysis
PDE ..... Pairwise Difference Estimator
PHES ..... Pumped-Hydro Energy Storage
SFA ..... Stochastic Frontier Analysis
ST ..... Steam Turbines

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SW ..... Sanderson-Windmeijer

TFE ..... True Fixed Effects

TFEC ..... Total Final Energy Consumption

TPEC ..... Total Primary Energy Consumption

TRE ..... True Random Effects

TSO ..... Transport System Operator

V2G ..... Vehicle-To-Grid

WGI ..... World Governance Index

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INTRODUCTION

Energy is at the center of the policy agenda in most developed countries because it plays a fundamental role in two different but interconnected aspects. From an economic perspective, in addition of being an essential final consumption good for the households, energy is an intermediate input affecting productivity on strategic sectors (e.g., services, industry or transport, among others) and hence on overall economic growth. From an environmental lens, energy production and consumption activities have relevant consequences on emissions. For example, electricity generation alone is responsible for approximately 20% of global CO_2 emissions and, in general, energy production is responsible of almost 70% of CO_2 emissions around the world. In addition to its effect on health and welfare, the environmental damage may also have important consequences on total factor productivity and on future economic growth.

The year 2021 constitutes a relevant example of how essential is energy for the economy. The important unbalance generated between supply and demand in international energy markets has implied a considerable increase in the Henry Hub natural gas spot price, from 2.38 €/MBtu in January 2021, to an average value of 4.32 €/MBtu between August and October. A similar trend has been observed in the European CO_2 emission rights market. The price of the emitted ton has keep growing since January 2021, reaching an average value of 50.2 €/Tm in November, compared to an average of 24.75 €/Tm in 2020. As a result, energy prices –and in particular those of electricity– have increased like never before. This situation can affect the economic recovery after the Covid-19 crisis worldwide and has raised the debate about a future

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energy blackout in Europe.

Accurately estimating the impact of the energy sector on the economy requires a truthful understanding of the causal relationships between energy consumption, energy efficiency and economic growth. This is still one of the most active and extensive debates in the literature. There is a large number of works addressing this concern, but they have provided inconclusive or even contradictory findings.

Many of these works use methodologies that do not properly handle the double causality between energy and income. In this situation, the ideal approximation must consider a source of exogenous variation as an external instrument to control for double causality. Precisely, one of the challenges addressed in this thesis is the construction of an external instrument, which is related with energy efficiency governance, as discussed in more detail below.

Energy efficiency is also an essential driving factor for the relationship between energy and economic growth. Indeed, a more efficient country is capable of reaching a given level of productivity by making less use of the energy factor. However, there are also important inquiries regarding this issue. For instance, there is still a lack of consensus on how to measure energy efficiency. The traditional approaches draw upon the use of the energy intensity indicator. That is, the relationship between energy consumption and GDP. However, this index has been highly questioned since its variations may be caused by changes in the economic cycles or in the country's economic structure, which have nothing to do with improvements in efficiency.

In this context, different works state that energy efficiency governance is an important driver linking energy consumption with income growth. It is also a key mechanism affecting energy efficiency. All in all, our hypothesis is that energy efficiency governance

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has a direct impact on energy efficiency and energy consumption, but it mainly affects income growth through its impact on energy. At this point, it is worth mentioning that energy governance differs from the classic definition of general governance since it is specific to the energy field, and includes not only the policies of this sector, but also the rest of the elements that make up the energy structure of a country. That is, energy governance should include the quantity and quality of energy related laws and decrees, financing mechanisms, agencies that encourage the adoption of more efficient technologies, the network of energy objectives and their interrelationships, or the proper evaluation mechanisms to measure the performance of the implemented initiatives, among other elements. Up to date, the lack of an appropriate measure of energy efficiency governance has prevented carrying out a rigorous analysis that studies the relationship between energy governance, energy efficiency and income growth. One of the main contributions of this thesis is the elaboration of a synthetic energy governance index for OECD countries, that is used as an external instrument to control for double causality and estimate the energy-income nexus (Chapter 1) and characterize its impact on energy efficiency in a stochastic framework approach (Chapter 2).

Some of the mechanisms through which energy governance affects energy consumption and energy efficiency are the definition of energy targets, the establishment of regulatory frameworks, or the design of strategic and action energy plans. However, this effect may have different implications depending on the quality of energy governance. A high-quality governance may favor compliance with energy policies and targets by enhancing the proposal or realistic goals, the development of a regulatory framework covering the main sectors of interest, or the establishment of reasonable funding mechanisms. On the contrary, a low-quality energy governance can lead to the definition of unattainable goals

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or the allocation of inadequate human or economic resources, hindering the achievement of policy aims. Therefore, analyzing how energy governance affects compliance with energy policies and targets is another important challenge to be addressed (Chapter 3).

This thesis consists of three self-sustained chapters that analyze in detail the challenges described above and offer a solid response to several gaps found in the literature. Chapter 1 contributes to improve the understanding of the relationship between income and energy consumption, which is essential for the correct design of energy policy. This study draws on a panel dataset between 2000 and 2015 for 32 OECD countries, for which we construct the first available index on energy governance quality. In order to overcome some of the most common pitfalls identified in the literature, we propose an instrumental variable approach that draws on the previous index in order to control for double causality bias and characterize the energy-income nexus. The results obtained reveal insights of great interest for the design of energy policies. The elasticity between (energy-governance-driven) energy consumption and income growth is close to unity, which almost doubles that commonly found in the literature. For the other side of causality, we found a negative elasticity (around -3.0), which is of opposite sign to the usual result of the scientific papers. Energy governance affects growth only through energy consumption, favoring a more efficient use of energy in the production process and, thus, fostering growth.

The key message of the results derived from Chapter 1 is that energy governance is strongly related to energy efficiency. Consequently, Chapter 2 analyzes the impact of energy governance on the efficiency levels in a set of 29 OECD countries. Instead of the classical energy intensity-based approach, a Stochastic Frontier Analysis (SFA) model is conducted to estimate the energy efficiency levels in this sample of countries between

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2000 and 2015. Energy governance quality is determined by the energy governance index constructed in Chapter 1, which proves its great interest to the literature of the field. The results of this study suggest that increasing the average quality of energy governance by 10% could raise energy efficiency levels by around 9.20%, although this impact may be even higher according to different SFA models. Improvements in efficiency are strongly related to two key requirements: setting quantified and achievable targets, and carrying out an extensive evaluation of the results of energy policies.

Finally, once the energy-GDP nexus has been characterized, and so has the role that energy governance plays both in this relationship and in efficiency levels, Chapter 3 offers an analysis on how different elements of energy governance can affect the fulfillment of energy targets. Since energy policy is a broad concept, the study has focused on the field of electricity production and consumption for two fundamental reasons. First of all, because of its great strategic importance. Second, as mentioned above, activities related to electricity production are responsible for about 20% of global CO_2 emissions, so it is reasonable that a large part of energy policy strives to introduce improvements in this area. The study has been particularized for the case of isolated power systems (taking the Spanish Canary archipelago as a reference) since they are much more sensitive than continental ones from the environmental, technical and economic points of view.

Specifically, Chapter 3 presents a two-stage optimization model for island power systems that is designed to assist in long-term energy planning decisions. The model draws on the energy plans of the region, taking into account those aspects related to energy governance such as energy strategic and action plans, budget allocation, policy targets, and regulatory constraints, among others. The model proposed determines the optimal mix of generation and transmission capacity required to satisfy energy demand

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at the lowest cost, while respecting the complex and strict technical and planning constraints inherent in island power systems. This approach combines the use of thermal generation, renewable systems, electric vehicles providing vehicle-to-grid services, and AC and HVDC interconnectors. The results suggest that, in the absence of any mechanism to internalize the social cost of carbon, thermal generation is the lowest-cost source of energy. However, environmental considerations like the imposition of CO_2 fees highlight the benefits of renewable generation, and so the contribution of clean energies to the generation mix should be around 40% on an energy basis.

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Chapter 1

Income, energy and the role of Energy Efficiency Governance

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1. Introduction

One of the main challenges facing the world are climate change and global warming. Given that the use of energy is responsible for nearly two-thirds of world CO2 emissions (IEA, 2019), figuring out the relationship between energy consumption and economic growth is crucial to understand the trade-off between the latter and environmental damage (Den Butter & Verbruggen, 1994; Barrera-Santana et al., 2021). Since the seminal work of Kraft & Kraft (1978), there is a growing literature analyzing the relationship between energy consumption and economic growth. Energy is a fundamental factor in the production process (Pindyck & Rotemberg, 1983; Wei, 2003) and, at the same time, improving energy efficiency favors economic growth (Díaz et al., 2019; Q. Wang & Wang, 2020).[1]

However, there is still a lack of consensus on the direction in which causality occurs between economic growth and energy consumption (P.-Y. Chen et al., 2016). Probably, this circumstance is largely related to the fact that the double causality bias has not been treated properly. Using an Instrumental Variable (IV) model is likely to be the ideal approach to control for the double causality bias in a macroeconomic panel data framework (Ciccone et al., 2012; Brückner, 2013 Acemoglu et al., 2019). Following the philosophy of these authors, we construct a panel database for energy consumption and per capita GDP, and propose an IV approach drawing on the role of energy governance as a valid exogenous instrument to characterize the causal relationship between energy

[1] The models of energy use analyze the relationship between economic value-added, physical capital and energy use, and emphasize the channels through which energy is substituted for capital in the production process, and the role of the technology in such substitution (see Andrew Atkeson & Kehoe, 1999; Díaz, Puch, & Guilló, 2004; Díaz & Puch, 2019).

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consumption growth and per capita GDP growth.

We use remarkable insights found in the energy economics literature (as described in Section 2) to motivate the construction and use of an Energy Efficiency Governance Index (EEGI) as our candidate instrument: energy efficiency governance has a direct impact on energy consumption, but its impact on economic growth is mostly indirect and channeled through changes in energy consumption (e.g., see Wilson 2016, among many others).

The construction of the EEGI is one of the most important contributions of this paper, for which we draw upon the theoretical framework proposed by the IEA (IEA, 2010) giving rise to a representative index for the period 2000-2015 in 32 OECD countries.[2] This index relies on the information contained in more than 1,800 entries extracted from the IEA's Energy Efficiency Database (2016), and provides a reliable measure of energy governance quality endorsed by an exhaustive information gathering and processing procedure (details are in Section 3).

The EEGI is used as an external instrument in a Two-Stage Least Squares (2SLS) approach that characterizes the effect of energy consumption on income growth. This approach is valid if our EEGI (the instrument) only affects income growth indirectly, through its impact on energy consumption, a condition that is traditionally referred as the exclusion restriction of the instrument. In the empirical application, we test the validity of this instrument and, in all cases, the EEGI provides the expected results (i.e., the exclusion restriction is not rejected).

Using the EEGI as external instrument is an appropriate strategy to estimate the

[2] In Section 3, we explain the reason for the selection of this sample.

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causality from energy consumption to per capita GDP growth. Following Brückner, (2012, 2013), and Brueckner & Lederman (2018), we handle the other side of the causality (from GDP to energy consumption growth) by instrumenting economic growth with an adjusted series in which the response of economic activity to (energy-governance-driven) consumption is ruled-out.

It is well known that governance quality is a relevant factor for economic growth (Ji et al., 2014; Dées, 2020). However, energy governance is a different concept to that of the general governance of a country (IEA, 2010; 2016). Specifically, energy governance is defined as the combination of a regulatory framework, institutional arrangements, and the coordination mechanisms necessary for a successful development of energy policies (IEA, 2010).[3] Indeed, energy governance can favor a more efficient use of energy (Goldthau & Sovacool, 2011; Holley & Lecavalier, 2017; Ringel & Knodt, 2017; Haley et al., 2020), which can benefit overall productivity (Boyd & Pang, 2000; Worrell et al., 2003; IEA, 2014) and eventually economic growth (Florini & Sovacool, 2011; Bazilian et al., 2014; Lesage & de Graaf, 2016; Díaz, Marrero et al., 2019). But, this benefit has been generated through a more efficient use of energy consumption. Hence, while the connection between general governance and economic growth could be direct, our hypothesis is that energy governance mainly affects economic growth through the efficient use of energy.

Our results suggest, firstly, that increasing energy governance by one standard deviation (around 32% over its average score) could reduce energy consumption growth by approximately 0.50%, which roughly matches the average drop of this variable in our

[3] For expository reasons, we use energy efficiency governance and energy governance indistinguishable throughout this paper.

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sample. Secondly, the estimated elasticity from energy to income growth is close to unity, which almost doubles the results commonly found in the literature (Masih & Masih, 1996; Fatai et al., 2004; Esseghir & Khouni, 2014, among others). Thirdly, we identify a sizable negative elasticity from income to energy consumption growth (around -3.0), that is of opposite sign to our OLS fixed effects estimates and the usual finding of the literature (P.-Y. Chen et al., 2016; S. Wang et al., 2018). Therefore, while energy is a growth enhancing factor for our sample, economic growth may favor a more efficient use of energy in the economy. To the extent that energy use is the main source of greenhouse gases (Tahvonen & Salo, 2001; Bosello, Buchner, & Carraro, 2003; Hassler & Krusell, 2012), improvements in energy governance would help to combat climate change and environmental damage by increasing energy efficiency without hampering income.

We assess the robustness of these results by means of an alternative instrument in which the EEGI interacts with international oil price series, since their shocks have a high impact on energy consumption and its use (Bélaïd & Abderrahmani, 2013), as well as on income growth (Gunning et al., 1976; Lippi & Nobili, 2012; Blanchard & Riggi, 2013). For validity purposes, in addition to the use of the traditional over-identification and weak instrument tests, we construct two counterfactual instruments and analyze their results. The first alternative is based on the average level of a general governance index (the Word Governance Index –WGI– from Kaufmann et al. 1999) between 2000 and 2015 (the WGI alone and interacted with oil price shocks). In the second alternative, we use oil exports and imports relative to GDP interacted with oil prices, as proposed by Ciccone et al., (2012). We show that these alternatives are not suitable to estimate the causal effect of energy on economic growth (i.e., they generally fail the exclusion restriction and/or the weak instrument test), while the EEGI and its cross effect with oil

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prices are strong instruments and systematically affect income growth through its impact on energy consumption growth.

Our work contributes to the literature in three noteworthy fields. First, we offer the first available quantitative measure of energy governance quality. As described in Section 3, the EEGI draws on seminal works like those of OECD (2008), Dabla-Norris et al. (2012), and Gisselquist (2014) in order to ensure its replicability, robustness and objectivity, among other aspects. Yet, we acknowledge that our index has certain limitations as we explain later, but it provides a valuable first step towards the establishment of a definitive methodology to construct an energy governance index. Second, we help to disentangle the underlying relationships between energy consumption and economic growth, controlling appropriately for double causality using an external valid instrument based on energy efficiency governance. Finally, we also contribute to the understanding of the effect of energy governance on economic growth and energy consumption, as well as its driving and relevant role in explaining the energy-income nexus.

The remaining of the paper proceeds as follows. Section 2 provides a literature review on the relationship between energy governance, economic growth, and energy consumption, which allows us to understand, among other things, how energy governance may affect economic growth through its impact on energy consumption. In Section 3, we detail the construction process of the EEGI, and show the results for our sample. An extensive robustness analysis relative to the construction and the strength of the EEGI can be found in the Appendix 1. Section 4 describes the database, the construction of alternative instruments for energy consumption and economic growth, and summarizes the IV methodology. In Section 5, we analyze the causal relationship between energy

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consumption and economic growth, including multiple robustness tests.

2. The growth-energy link and the role of energy governance: a review

The seminal work of Kraft & Kraft (1978) is the starting point of an extensive literature analyzing the growth-energy nexus (Pindyck & Rotemberg, 1983; Wei, 2003; Linn, 2008; Yuan et al., 2008; Wong et al., 2013; Bretschger & Schaefer, 2017; S. Wang et al., 2018; Díaz et al., 2019; Q. Wang & Wang, 2020; among many others). Our paper is strongly related to several strands of this literature, which we describe below. This review also gives support to the empirical strategy presented in Section 4, which is based on the following hypothesis: energy efficiency governance has a direct impact on energy consumption, but its impact on economic growth is indirect and channeled through changes in energy consumption.

First, a long-standing literature has studied the relationship between energy and income, which is in general inconclusive on both sides of causality. On the one hand, energy is a complementary input to physical capital in the production function, and a more efficient use can foster growth (Bretschger & Schaefer, 2017). In this line of research, Linn (2008) reveals how a reduction in energy driven by the price of energy is associated in the short term with lower economic growth, but subsequent increase in investment in more efficient technologies can compensate the direct effect in the long term (Andrew Atkeson & Kehoe, 1999). On the other hand, more income implies an increase in energy demand, but also more investment in energy-saving technologies (Wong et al., 2013), improvements in energy governance (Bazilian et al., 2014; Holley & Lecavalier, 2017) and changes in less energy-intensive sectors of activity (C. Wang, 2013).

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As a consequence, the results of many works in the field lead to disagreeing results (P.-Y. Chen et al., 2016). In this line of enquiry, a total of four types of causal relationships may be identified (Yuan, Kang, Zhao, & Hu, 2008; and S. Wang, Li, & Fang, 2018, Payne, 2010). The growth hypothesis supports an unidirectional causality from energy to income (Halicioglu, 2009; Lean & Smyth, 2010; Menyah & Wolde-Rufael, 2010b; Pao & Tsai, 2010; Alam et al., 2011), while the conservation hypothesis states the reverse direction, from income to energy (Ang, 2007; Zhang & Cheng, 2009; Menyah & Wolde-Rufael, 2010a; Hossain, 2011). The feedback hypothesis if confirmed if a bidirectional causality exists (Apergis & Payne, 2009; Costantini & Martini, 2010; Acaravci & Ozturk, 2010; Pao et al., 2011; Pao & Tsai, 2011; Al-Mulali & Sab, 2012; Chandran & Tang, 2013). It is also possible to find a lack of causality, that is, the neutrality hypothesis (Cheng, 1995; Chen et al., 2007; Chiou-Wei et al., 2008). However, it is worth noticing that for a cross-country analysis the feedback hypothesis is widely confirmed (P.-Y. Chen et al., 2012, 2016; Dedeoglu & Kaya, 2013).

From a methodological point of view, most of these works uses Vector Autoregressive (VAR) models, time series unit root and cointegration tests, or panel data unit root and cointegration techniques (see, among others, Esseghir & Khouni, 2014; Mehrara, 2007). However, none of these papers considers an exogenous source of variation as an external instrument to control for the potential bias generated by double causality, which is the ideal approach to handle this problem in a macroeconomic panel data framework (Ciccone et al. 2012; Brückner, 2013; Acemoglu et al., 2019, among many others).

The second strand of literature to which our paper is related is about the impact of institutional and governance quality on the economy. It includes a large number of empirical contributions studying the effect of governance on economic growth (Acemoglu

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et al., 2005, 2019; Rodrik et al., 2004), foreign investment (Beverelli et al., 2018) or trade (Alguacil et al., 2011; Aleksynska & Havrylchyk, 2013). More recently, governance has also been considered to understand the link between economic growth and energy consumption (Bhattacharyya, 2011; Florini & Sovacool, 2011; Bazilian et al., 2014; Wilson, 2016 Ringel & Knodt, 2017; among others).

We draw upon several results in this literature to motivate the use of an energy governance index as an external instrument to estimate the causal relationship from energy consumption to per capita GDP growth (i.e., recall the hypothesis presented at the beginning of this section). For instance, Bhattacharyya (2011) suggests that governance can directly regulate the demand for inputs, such as energy, which may indirectly affect income growth. Florini & Sovacool (2009) supports the hypothesis that energy consumption and economic growth are directly related, but energy governance is probably driving this relationship. Ringel & Knodt (2017) assess the efficiency and effectiveness of governance in the European Union, suggesting that governance could indirectly affect growth. Bazilian et al. (2014) show that governance may affect a large set of economic aspects, like poverty. Finally, Wilson (2016), shows that general governance has beneficial effects on economic growth, but they take place through indirect channels.[4]

These works analyze the role of overall governance in the growth-energy relationship. Instead, our paper focuses on energy efficiency governance, and the channel of transmission provided by energy consumption. The IEA (2010) emphasizes that overall

[4] For instance, bureaucratic professionalization reduces opportunities for corruption, fostering productive investment (Dahlström et al., 2012). Also, institutional and policy perspective, laws and regulations provide an environment conducive to economic growth (Acemoglu et al., 2001; North, 1990). The legal system plays an important role in resolving commercial disputes, ultimately favoring economic growth (Clarke et al., 2008).

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governance is not the same than energy governance. This report develops a theoretical framework describing the features, structure, and agents supporting the concept of energy governance, providing the first attempt to establish structural differences between energy governance and general governance. Motivated by these differences and by the information provided in this report, we use this framework to construct an EEGI, which is the one we use as instrument in the energy-GDP relationship.

Therefore, our paper is also related to third strand of the literature, that is the construction of composite indicators. Indeed, as mentioned above, the absence of available metrics for energy governance is probably the reason explaining why energy governance issues are treated only through qualitative approaches, or using general governance indicators to proxy energy governance. According to Gisselquist (2014), the construction of governance indicators implies to overcome a set of difficulties, such as dealing with a complex theoretical framework, allowing comparability among countries, the establishment of a proper time dimension, the treatment of subjective information, and ensuring replicability.

These difficulties probably explain the lack of indicators for a relatively new concept like energy governance. Gisselquist (2014) proposes a set of 10 questions that any governance indicator should satisfactorily addressed in order to minimize subjectivity and to assure its applicability in quantitative studies. As indicated below, our energy efficiency indicator has been constructed following carefully these rules, as well as those indicated by the OECD (2008), and many other seminal works in the literature (e.g., Dabla-Norris et al., 2012). The details in the construction of the EEI is presented in the next section.

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3. An index of energy efficiency governance

In this section, we build a composite index to measure the quality of energy efficiency governance in a set of 32 OECD countries.[5] To do this, we draw upon the theoretical framework proposed by the International Energy Agency (IEA, 2010), in which the energy efficiency governance areas are established and defined. The information used to build the index is obtained from the IEA's Energy Efficiency Database (2016) for the 2000-2015 period. The EEGI is built after analyzing almost 1,800 entries in the aforementioned database related to energy efficiency for the 32 countries in the sample. These entries include energy policies, specific programs and financing mechanisms, among others. Thus, a very important effort has been made to compile all the available information about energy efficiency measures from a theoretical reference model. In this way, the aggregate index (the EEGI) reasonably reflects the strength or intensity in the application of EE measures.

To build the index, we follow the recommendations from OECD (2008) and the work of Dabla-Norris et al. (2012), who build an indicator of efficiency in public investment management, and Gisselquist (2014), who provides a set of 10 basic rules in order to minimize subjectivity in the composite indicators and to maximize replicability, robustness and applicability. The methodology used allows us to obtain a homogeneous and comparable energy efficiency governance measure between countries, which is mainly based on qualitative information. In this sense, it is necessary to establish criteria for the scoring and aggregation of the different indicators and to carry out an extensive

[5] The countries included in the sample are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. Israel and Iceland have been excluded from the final sample due to lack of data.

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robustness analysis in order to minimize subjectivity and to ensure the replicability and applicability of our measure.

3.1. The diagnostic framework and the components of the index

Following IEA (2010), Figure 1 summarizes the theoretical diagnostic framework used to construct the EEGI. The energy efficiency governance is defined by the combination of a regulatory framework, the existence of institutional agreements and coordination mechanisms aimed at improving energy efficiency. Following this definition, we consider synthetically the information available in the following three areas to construct the index: Enabling Frameworks, Institutional Arrangements and Coordination Mechanisms. In turn, each area is composed of a series of identifying indicators.

The first area, Enabling Framework, includes the legal and financial basis that permits the implementation of policies and programs linked to national energy efficiency objectives. Therefore, this area partially encompasses the other two, by establishing the regulatory framework on which the entire structure of the energy efficiency governance is based. It consists of three indicators: (i) Laws & Decrees, (ii) Strategic & Action Plans (i.e., practical guides for the achievement of the proposed goals) and (iii) the existence of Funding Mechanisms.

The second area, Institutional Arrangements, refers to the design and application of practical instruments that regulate the degree of intervention of the different agents that participate in the sector. The information from six indicators is used: (i) the existence and type of Energy Agencies, (ii) Resourcing Requirements (i.e., human and economic resources), (iii) the Role of Energy Providers, (iv) Stakeholder Engagement (i.e., the extent of participation of public and private agents in the proposal of policies and plans, among others), (v) Cooperation mechanisms between Public and Private Sectors and (vi)

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International Assistance for the development and improvement of energy efficiency.

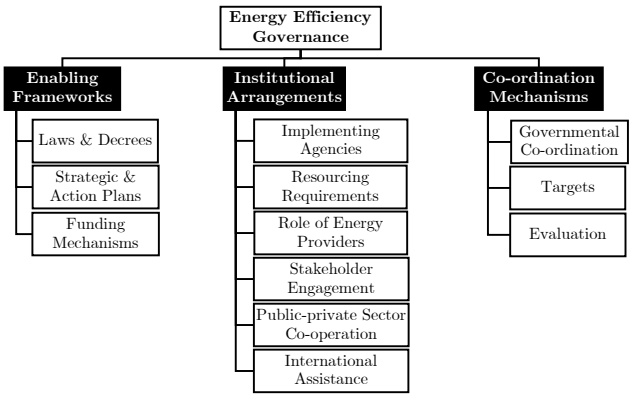


Figure 1. The structure of Energy Efficiency Governance. *Source* IEA (2010).

The third area, Coordination Mechanisms, comprises the necessary mechanisms for the coordination of the different agents of the energy sector in order to achieve the objectives of the national energy policy. It also includes the monitoring and evaluation of the results. This area is made up of three indicators: (i) Governmental Coordination – both vertical and horizontal, (ii) Targets (i.e., the setting of quantified and precise objectives) and (iii) the existence of mechanisms for evaluating and monitoring the results.

3.2. Data collection and scoring procedure

The construction of the index is based on an exhaustive compilation, classification and analysis of the existing regulations on energy efficiency for the 32 OECD countries considered. Thus, we have collected information from the IEA's Energy Efficiency Database (2016), generating our own database drawing upon the information we get from

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1,796 entries.[6] Most of the energy efficiency measures have been applied after the year 2000 or are already in force at that time, so we consider that our indicator is representative of the 2000-2015 period. After considering only those entries in force at some time in the aforementioned years, the final number of entries used is 1,699.

The information contained in each entry is mostly qualitative and provides the details of one or more policies, regulations or programs. Hence, each entry might contain information that is relevant for one or more indicators described in Figure 1. Consequently, we have performed a thorough analysis of each entry to define its characteristics and identify which area of the energy efficiency governance each piece of information is linked with. We have also distinguished between those measures that may be linked to more than one indicator.

Table 1 presents the number of entries analyzed initially (column 3) and finally (column 4) for each country. For the same country, the initial and final entries are similar. However, the numbers of entries between different countries are very diverse. In our sample, the average number of records finally considered per country is 54, with countries like Canada, USA or Germany with 245, 169 and 141, respectively, and countries like Chile, Estonia, Slovenia and Mexico at the other end, with less than 10 entries each (the number of entries in Switzerland, Turkey and Greece are also low). In the middle of these extreme cases, there are other countries, ranging from 30-31 records in the Czech Republic and Austria, to 78-89 in the UK or Italy. Likewise, for illustrative purposes, we also indicate in Table 1 the items found for the indicators Laws & Decrees and Strategic &

[6] The countries that are part of the IEA are subject to strict evaluation criteria at the time of accession, which must continue to be satisfied even once they are adhered to. Among other aspects, the members must obligatorily be part of the OECD and, in addition, they must guarantee the existence of legislation and sufficient measures to be able to provide all the information requested by the IEA.

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Action Plans from the first area. The detailed analysis of these specific indicators is essential for the construction of the EEGI. Each law or strategic plan may have relevant information for the construction of several indicators from different governance areas.

Given the qualitative nature of the information, it is necessary to establish evaluation criteria and a scoring scale for each indicator in order to minimize subjectivity and to ensure replicability, consistency and objectivity. On the one hand, the criteria draw on the recommendations provided by Gisselquist (2014) and OECD (2008), which includes aspects like the normalization of the data, considering different weighting and aggregation methods, and performing robustness and sensitivity tests, among others. On the other hand, the scoring scale is based on the work of Dabla-Norris et al. (2012), who establish a score between 0 and 4, with the highest score corresponding to a better quality. Depending on the type of indicator and the information available, the intermediate scores may vary, but the minimum and maximum values are always 0 and 4, respectively. For example, while the Laws & Decrees indicator has steps of 0.8, the Stakeholders Engagement indicator has steps of 1.33. This is because the available information is much more extensive and detailed in the first case. Below, we explain some of these criteria and show some examples, leaving a much more detailed description for Appendix 1.A.

In the Enabling Frameworks area, information has been obtained for two of the three indicators: (i) Laws & Decrees and (ii) Strategic & Action Plans.[7] In the first case, the extent of the existing regulation in each country is analyzed, paying special attention to the sectors of activity contemplated (transport or industry, among others). For example, the score for Italy is 4, because there are more than 80 legal references that cover all

[7] The third indicator, Funding Mechanisms, is not evaluated because homogeneous information on EE expenditure is not available for a reasonable sample of countries. However, the Appendix 1.B. offers an assessment of the effect of introducing this indicator in the EEGI for a short sample of 18 European countries.

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sectors. Conversely, Mexico has been assigned a 0.8, since only two references have been found in all the revised documentation. Regarding the Strategic & Action Plans indicator, we have analyzed their quantity, checking if the proposed objectives have been quantified and if the costs incurred have been estimated. For example, for the United Kingdom, the score is 4 points as 19 strategies of this type were found with costs and objectives estimated in 15 of them.

Table 1. Energy Efficiency Database entries by country and entries related to the indicators Laws & Decrees and Strategic & Action Plans.

Country	Country code	Total entries	Revised entries	Laws & Decrees	Strategic & Action Plans
Australia	AUS	58	58	7	9
Austria	AUT	40	31	11	6
Belgium	BEL	68	66	30	7
Canada	CAN	256	245	13	20
Chile	CHL	4	4	1	1
Czech Rep.	CZE	30	30	46	4
Denmark	DNK	62	58	17	18
Estonia	EST	4	4	0	2
Finland	FIN	35	34	5	6
France	FRA	76	68	32	8
Germany	DEU	149	141	36	13
Greece	GRC	30	25	17	3
Hungary	HUN	65	54	30	9
Ireland	IRL	47	44	7	10
Italy	ITA	89	89	80	19
Japan	JPN	57	57	10	16
Korea	KOR	51	41	7	7
Luxembourg	LUX	50	43	22	6
Mexico	MEX	6	6	2	1
Netherlands	NLD	41	35	3	7
New Zealand	NZL	33	32	20	7
Norway	NOR	42	40	8	5
Poland	POL	28	28	12	9
Portugal	PRT	57	57	50	10
Slovak Rep.	SVK	16	16	15	8
Slovenia	SVN	3	3	0	2
Spain	ESP	47	47	28	13
Sweden	SWE	58	57	23	9
Switzerland	CHE	28	21	4	4
Turkey	TUR	18	18	7	3
UK	GBR	79	78	11	19
USA	USA	169	169	36	19
T O T A L		1796	1699	590	280

Source: Own elaboration using information obtained from IEA's Energy Efficiency Database (2016)

Regarding the Institutional Arrangements area, we were able to evaluate four of the six indicators shown in Figure 1: (i) Energy Agencies, (ii) the Role of Energy Providers,

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(iii) Stakeholder Engagement and (iv) Cooperation mechanisms between the Public and Private Sectors.[8] Regarding the Role of Energy Providers, we analyze the number of programs they promote or in which they are involved. Canada is the only country that receives the highest score, given that 58 programs have been found, of which 10 have been promoted directly by energy providers. Conversely, Korea obtains only 1 point, since only 3 initiatives have been detected. Regarding the Energy Agencies, for example, their proactivity is analyzed to propose energy efficiency measures and the legal support they have. In the case of Spain, the score is 4 because the national energy agency (IDAE) promotes a large number of plans and programs, and also has legal backing. Conversely, Belgium's score is 0.8 in this indicator, as there is no national energy agency.

Finally, in the Coordination Mechanisms area, we have quantified two indicators: (i) Targets and (ii) Evaluation.[9] In the second indicator, for example, we examine the number of evaluation and monitoring protocols that we have found in relation to the number of strategic and action plans of the country in question. Thus, while the score for Switzerland is 4 points, since mechanisms of this type are contemplated in 75% or more of the existing plans, the rating of Poland is a 2, given that the proportion (44%) is much lower.

3.3. The results of the index

Once each indicator has been scored, the next step is to add and weigh them. In general, individual indicators are added within each area, thus obtaining a (composite)

[8] On the one hand, the indicator Resourcing Requirements has not been considered because it has been included in very few measures in the sample. In addition, the initiatives that have been taken into account still show little degree of detail in their results (IEA, 2010). On the other hand, International Assistance is not considered due to the lack of homogeneous information for a reasonable sample of countries.

[9] The Governmental Coordination indicator is not evaluated because the information available is national in nature. There is no data at regional or international level to evaluate the vertical and horizontal coordination of governments.

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sub-index for each area. Subsequently, the three resulting sub-indices are aggregated again to obtain the baseline EEGI. With respect to the weighting process, the EEGI weighs equally to each sub-index and indicator (i.e. it draws on the average), which coincides with the most common practice in the literature (OECD, 2008; Knack et al., 2011; Dabla-Norris et al., 2012). In the Appendix 1.B., an extensive robustness analysis relative to the weighting and aggregation methods for indicators and sub-indices is conducted, highlighting that the results are robust to the different alternatives considered.[10]

We show below the results of the baseline EEGI for each country. Figure 2 illustrates the score of the three areas and the EEGI, while Table 2 shows the detail of that score. In both cases, countries are ordered from best to worst result and a breakdown of the score of each sub-index is included. The average value of the EEGI is 2.420, with a standard deviation of 0.785, indicating a remarkable variability between countries. Also, Table 3 shows the thresholds of the EEGI quartiles (Q) and its sub-indices. On the one hand, it is always true that countries with scores higher than 3 (in the EEGI or in its sub-indices) are part of the first quartile (Q1), while those with scores below 2 are part of the fourth quartile (Q4). The thresholds of the intermediate quartiles (Q2 and Q3) admit greater variability. On the other hand, it can be seen that the thresholds of the EEGI quartiles are quite similar to those of the first sub-index.

In Q1 we find countries such as Germany, Canada, Denmark, New Zealand or the United Kingdom, with Germany the country with the highest rating (3.55 out of a

[10] In the robustness analysis, aspects such as the consistency of the aggregation and weighting process are evaluated (making use of the Principal Components Analysis –PCA, among others) or the sensitivity of the index with respect to the addition (or lack) of indicators. The constructed sub-indices and the baseline EEGI are also validated by means of the scale of reliability coefficient and an analysis of the correlations between indicators and sub-indices. Furthermore, several agreement measures are also assessed.

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maximum of 4). In Q2, we find Spain, Japan, the United States, Belgium or Hungary, among others. In Q3, there are countries such as Ireland, Finland, Norway, the Netherlands or Turkey. Finally, in Q4 we have Switzerland, Mexico, Chile, the Slovak Republic, Slovenia or Estonia. These last two countries share the worst score: 0.55 out of a maximum of 4.

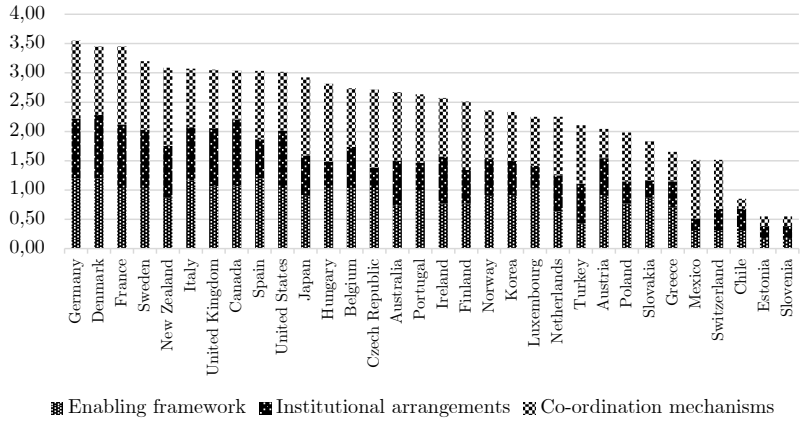


Figure 2. Energy Efficiency Governance index for OECD countries.

According to Table 2, it is easy to figure out which area must be enhanced for each country to achieve a higher level of EEGI. For example, Estonia (the worst in the ranking) shows very low scores in all areas. Hence, for example, it could enhance its Enabling Frameworks area by drafting additional laws and decrees that cover new sectors (e.g., transport or industry), by developing building codes and labeling of appliances (if not available) or by expanding the existing regulation, among other possibilities. This country could also establish strategic plans that identify both the quantitative objectives of these laws, as well as the economic costs necessary to monitor and enforce them. In fact, given the low score of the Enabling frameworks sub-index for Estonia, enacting just

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a few measures like the ones just mentioned could significantly improve the score of this sub-index. Another relevant examples are Austria and Greece, among those with the lowest levels of EEGI, which could improve their Co-ordination Mechanisms area by defining evaluation mechanisms that help policy-makers to verify the development of their strategic plans and the achievement of their energy targets.

Table 2. Energy Efficiency Governance index and sub-indices for OECD countries: scores and rankings

Country	Code	Baseline EEGI		Enabling framework		Institutional arrangements		Co-ordination mechanisms	
		Score	Rank	Score	Rank	Score	Rank	Score	Rank
Germany	DEU	3,55	1	3,60	1	3,05	4	4,00	1
Denmark	DNK	3,45	2	3,60	1	3,25	2	3,50	7
France	FRA	3,45	2	3,10	7	3,25	2	4,00	1
Sweden	SWE	3,20	4	3,10	7	3,00	5	3,50	7
New Zealand	NZL	3,09	5	2,60	19	2,67	9	4,00	1
Italy	ITA	3,07	6	3,50	4	2,72	8	3,00	13
UK	GBR	3,06	7	3,20	5	2,97	6	3,00	13
Canada	CAN	3,04	8	3,20	5	3,42	1	2,50	21
Spain	ESP	3,03	9	3,60	1	2,00	15	3,50	7
USA	USA	3,02	10	3,10	7	2,95	7	3,00	13
Japan	JPN	2,92	11	2,70	15	2,07	13	4,00	1
Hungary	HUN	2,82	12	3,10	7	1,35	22	4,00	1
Belgium	BEL	2,74	13	3,10	7	2,12	12	3,00	13
Czech Rep.	CZE	2,72	14	3,00	13	1,15	24	4,00	1
Australia	AUS	2,67	15	2,20	24	2,32	11	3,50	7
Portugal	PRT	2,63	16	3,00	13	1,40	21	3,50	7
Ireland	IRL	2,57	17	2,30	21	2,42	10	3,00	13
Finland	FIN	2,51	18	2,30	21	1,73	20	3,50	7
Norway	NOR	2,36	19	2,70	15	1,88	17	2,50	21
Korea	KOR	2,33	20	2,70	15	1,80	19	2,50	21
Luxembourg	LUX	2,25	21	3,10	7	1,15	24	2,50	21
Netherlands	NLD	2,25	21	1,90	26	1,85	18	3,00	13
Turkey	TUR	2,11	23	1,30	27	2,02	14	3,00	13
Austria	AUT	2,04	24	2,70	15	1,93	16	1,50	28
Poland	POL	1,98	25	2,30	21	1,15	24	2,50	21
Slovak Rep.	SVK	1,83	26	2,60	19	0,90	29	2,00	27
Greece	GRC	1,65	27	2,10	25	1,35	22	1,50	28
Mexico	MEX	1,52	28	0,90	28	0,65	30	3,00	13
Switzerland	CHE	1,52	28	0,90	28	1,15	24	2,50	21
Chile	CHL	0,85	30	0,90	28	1,15	24	0,50	30
Estonia	EST	0,55	31	0,50	31	0,65	30	0,50	30
Slovenia	SVN	0,55	31	0,50	31	0,65	30	0,50	30
AVERAGE		2,42		2,48		1,94		2,83	
Std. Dev.		0,785		0,907		0,827		1,006	

Source: Own elaboration using information obtained from IEA's Energy Efficiency Database (2016).

However, since the different indicators are correlated, there is no exact number of measures that allows shifting from one step to the next. The truly important factor in order to improve the EEGI score is the set of all the available policies and the way they

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interact (i.e., properly coordination, ensuring the coverture of important sectors, etc.). In this vein, the three sub-indices show a positive correlation, but it is far from being considerably high, which is a desirable property for a composite indicator.

In Appendix 1.C, we provide an extension of these results. We describe the variability detected in the EEGI and in the different sub-indices. We also highlight several cases of interest. In general, the EEGI provides a high variability of scores between countries and between areas, which constitutes a desirable feature for a composite index such as the one we construct (OECD, 2008; Dabla-Norris et al., 2012). We also assess the correlation between the EEGI and the number of entries available for each country in the database, observing that it is not relevant for our main results from Section 5.

To conclude this section, we compare our energy governance index with the Public Investment Management Index (PIMI) from Dabla-Norris et al. (2012), as we use the construction of such index as our main point of reference. Moreover, this comparison helps to understand the metric used in our index. By doing so, we demonstrate how the methodology developed in this paper minimizes the degree of subjectivity in the scoring procedure (see Appendix 1.B for more details). Furthermore, in Appendix 1.D we also offer a comparison between the EEGI and other well-known metrics, such as the WGI and per capita GDP, which emphasizes the need to properly address the differences between energy and general governance.

The EEGI is constructed for 32 countries drawing upon three main areas, while the PIMI covers 71 countries and four different areas. Despite these structural differences, we find that the descriptive statistics obtained for our EEGI are consistent with those derived from the PIMI. The average score of the public investment index is around 1.8, which is slightly lower than the one of the EEGI (2.4). However, its maximum and

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minimum values are 3.53 and 0.27, respectively, which are very similar to those found for the EEGI (3.55 and 0.55). As a result, the standard deviations of both indices are similar (0.65 versus 0.78). In addition, although the details of the robustness assessment are reserved to Appendix 1.B, we anticipate that the EEGI performs better in terms of robustness than the PIMI. We also extend upon the works of OECD (2008); Dabla-Norris et al. (2012); and Gisselquist (2014) by introducing additional robustness checks, like the use of concordance tests.

Table 3. EEGI and sub-indices thresholds for quartiles.

IGEEbase	Enabling frameworks	Institutional Arrangements	Co-ordination Mechanisms
Q1 $\geq$ 3.036	Q1 $\geq$ 3.100	Q1 $\geq$ 2.690	Q1 $\geq$ 3.500
2.603 $\leq$ Q2 $<$ 3.036	2.700 $\leq$ Q2 $<$ 3.100	1.908 $\leq$ Q2 $<$ 2.690	3.000 $\leq$ Q2 $<$ 3.500
2.014 $\leq$ Q3 $<$ 2.603	2.150 $\leq$ Q3 $<$ 2.700	1.150 $\leq$ Q3 $<$ 1.908	2.500 $\leq$ Q3 $<$ 3.000
Q4 $<$ 2.014	Q4 $<$ 2.014	Q4 $<$ 1.150	Q4 $<$ 2.500

Source: Own elaboration using information obtained from Table 2.

4. Data and methods

In this section, we first present data on per capita energy consumption and per capita real GDP and show their correlations (between and within countries) to illustrate the controversy existing in the literature when characterizing the income-energy relationship. The results of this analysis cannot be extrapolated to a causality finding. To analyze causality properly, we implement an IV approach, as described in the second part of the section. We use the EEGI as an exogenous instrument for energy consumption to estimate the effect from (energy-governance-driven) energy consumption growth to economic growth. Finally, following Brückner (2013), we construct an energy-adjusted income instrument to estimate the reverse causal relationship from income to energy consumption growth.

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4.1. Energy consumption and economic activity

We measure energy consumption through per capita Total Primary Energy Consumption (TPEC), while economic activity is measured by means of the real per capita GDP. Data come from the IEA's World Energy Balances (2018) database. TPEC is expressed in tonnes of oil equivalent (toe) per capita and real GDP in thousand USD per capita.[11] Table 4 shows the sample average, initial and final values, and the yearly log-change in the 2000-2015 period of per capita TPEC (left panel) and real per capita GDP (right panel) for our sample of 32 OECD countries.

Drawing on the average levels (first column in each panel), we observe a clearly positive correlation between both variables. For instance, Canada, Luxembourg and USA are the countries with the highest levels of energy consumption (8.06, 8.13 and 7.42 per capita toe, respectively) and, at the same time, they are among the richest countries (with a per capita GDP of 39.93, 83.73 and 48.29 thousand USD per person, respectively). A similar result is observed if we look at the countries with the lowest level of energy consumption (about 1.60 per capita toe), which are Chile, Mexico and Turkey. In turn, these countries are among the poorest in the sample, with a per capita GDP of 17.14, 15.09 and 16.95 thousand USD per person, respectively. It is worth noting that the cross-correlation has apparently reduced between 2000 and 2015: from 0.704 in the former year to 0.613 in that latter. The cross-correlation across countries for the growth rates along this period is also positive and equal to 0.660. Thus, correlations between energy per capita consumption and per capita GDP in our set of OECD countries are positive and significant for both the levels and the growth rates.

[11] The equivalent of 1 toe is 11.63 GWh.

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Table 4. Energy consumption and GDP in 32 OECD countries: 2000-2015.

	Per Capita TPEC (toe/person)[a]				Per Capita Real GDP (Thousand USD/person)[b]			
	Average 2000-2015	Level 2000	Level 2015	Ln-change 2000-2015	Average 2000-2015	Level 2000	Level 2015	Ln-change 2000-2015
Australia	5.60	5.38	5.21	-0.21%	41.13	36.11	44.77	1.43%
Austria	3.90	3.57	3.80	0.41%	41.01	37.68	42.80	0.85%
Belgium	5.31	5.67	4.75	-1.17%	39.24	36.39	41.00	0.79%
Canada	8.06	8.26	7.54	-0.61%	39.93	36.91	42.27	0.90%
Chile	1.82	1.63	2.00	1.35%	17.14	13.42	20.81	2.92%
Czech Rep.	4.23	4.01	4.00	-0.02%	25.93	20.64	29.72	2.43%
Denmark	3.39	3.49	2.83	-1.38%	43.34	41.45	44.57	0.48%
Estonia	3.96	3.36	4.14	1.38%	21.80	14.90	26.09	3.74%
Finland	6.57	6.25	5.93	-0.35%	37.94	33.96	37.98	0.75%
France	4.05	4.14	3.71	-0.73%	35.88	34.12	36.93	0.53%
Germany	4.03	4.13	3.77	-0.61%	39.14	36.03	42.52	1.10%
Greece	2.52	2.51	2.14	-1.07%	27.05	24.38	23.57	-0.22%
Hungary	2.56	2.45	2.56	0.30%	21.16	17.21	23.93	2.20%
Ireland	3.26	3.63	2.86	-1.60%	44.62	38.69	58.14	2.72%
Italy	2.92	3.01	2.51	-1.21%	35.18	35.40	33.18	-0.43%
Japan	3.83	4.08	3.38	-1.25%	33.40	31.58	35.14	0.71%
Korea	4.69	4.00	5.39	1.98%	27.87	20.77	34.41	3.37%
Luxembourg	8.13	7.61	6.54	-1.01%	83.73	75.73	89.05	1.08%
Mexico	1.60	1.49	1.55	0.24%	15.09	14.20	16.45	0.98%
Netherlands	4.79	4.74	4.36	-0.55%	43.61	40.88	45.42	0.70%
New Zealand	4.24	4.42	4.47	0.07%	30.74	26.79	33.63	1.51%
Norway	5.98	5.83	5.71	-0.14%	57.86	54.09	59.29	0.61%
Poland	2.47	2.32	2.47	0.41%	18.95	14.27	24.23	3.53%
Portugal	2.29	2.39	2.12	-0.80%	26.66	26.12	26.66	0.14%
Slovak Rep.	3.28	3.29	3.02	-0.55%	22.30	15.48	28.11	3.98%
Slovenia	3.48	3.22	3.19	-0.07%	26.46	22.01	28.25	1.66%
Spain	2.92	3.01	2.56	-1.06%	31.61	29.50	31.72	0.48%
Sweden	5.38	5.36	4.64	-0.97%	40.44	35.77	44.13	1.40%
Switzerland	3.38	3.45	2.96	-1.01%	51.18	47.52	53.88	0.84%
Turkey	1.37	1.18	1.66	2.28%	16.95	13.26	22.97	3.66%
UK	3.36	3.79	2.78	-2.07%	35.91	32.55	38.04	1.04%
USA	7.42	8.05	6.80	-1.12%	48.29	45.02	51.59	0.91%
AVERAGE	4.09	4.05	3.79	-0.35%	35.05	31.34	37.85	1.46%
STD. DEV.	1.75	1.77	1.56	1.00%	13.84	13.61	14.34	1.20%

[a] TPEC: Total Primary Energy Consumption. TPEC is expressed in tonnes of oil equivalent (toe) per capita. [b] Unit reference: 2010 USD PPPs. [a,b] Data come from the IEA's World Energy Balances (2018) database.

However, the sign of the correlation is not clear when looking at the evolution within each country. For instance, on average, the growth rate within this period has been -0.35% and 1.26% for per capita TPEC and per capita GDP, respectively; their standard deviations are about 1.0% and 1.2% for per capita TPEC and per capita GDP, respectively. If we examine each country, we find that both variables have increased in 9 countries (Austria, Chile, Estonia, Hungary, Korea, Mexico, New Zealand, Poland, Turkey), both variables have decreased in two countries (Italy and Greece), none countries show a negative GDP growth and a positive energy growth rate and, in the

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remaining 21 countries, per capita GDP has increased while energy consumption has decreased. In this latter group, the largest differences between the GDP and energy growth rates are shown in Denmark, UK and Belgium. This simple analysis emphasizes the existence of a positive correlation across countries, but the evidence is mixed if we look at correlations within each country.

4.2. The construction of the instruments for energy consumption

We need an exogenous source of variation (i.e., an exogenous instrument) to robustly estimate the causal effect from energy consumption growth to income growth (Hsiao, 2014). To do this, we exploit the cross-section variability of our EEGI. As shown below, the EEGI is correlated with both income and energy consumption. The EEGI has a direct and significant effect on energy consumption, since it provides an effective regulatory and financial framework that enables energy efficiency and energy consumption improvements (IEA, 2010; Florini & Dubash, 2011; Pereira & Pereira Da Silva, 2017). However, to be the EEGI a valid instrument, we hypothesize that energy governance only affect economic growth through its impact on energy consumption.

Our baseline IV model uses the EEGI as instrument for energy consumption growth. However, since the EEGI provides a single value for each country, it could present a methodological limitation because it only captures the cross-section dimension of the sample. Moreover, this sort of instruments arises a conflict when including a cross-country fixed effect in the model, which is needed to estimate within-group causality (Brückner, 2013; Bruckner & Ciccone, 2008). Therefore, using an instrument capable of capturing the time-varying effects driving energy consumption growth is necessary to avoid potentially biased estimates (Acemoglu et al., 2019).

In this vein, we follow the strategy proposed by Ciccone et al. (2012), and we construct

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an alternative instrument, which varies across countries and over time:

$$EEGIOil_{it} = EEGI_i \cdot \Delta ln(OilPrice_t) \quad (1)$$

where $\Delta ln(OilPrice_t)$ is the yearly growth rate of international oil prices, which is common to all countries but it is time variant. This series is measured as the average price in $/barrel between Dubai, Brent and Texas markets, obtained from UNCTAD (2018). Ciccone et al. (2012) shows that the log-change of this series is a good proxy to international oil shocks, because its level contains a unit root, but the first difference is stationary (Figure 3). Therefore, this second instrument, in addition to vary across time and countries, captures to some extent the manner in which energy governance modulates the impact of international oil price shocks on energy growth (Gunning et al., 1976).

In Section 5, we also consider two alternative counterfactual instruments, which disregard the use of the EEGI. The first one substitutes the EEGI in equation (1) by the average value between 2000 and 2015 of the general governance index (the WGI); the second alternative is the instrument originally proposed by Ciccone et al. (2012).[12,13] By comparing the results of these two latter –counterfactual– instruments with the two instruments including the EEGI, we can further analyze the goodness of energy governance as a relevant instrument for energy consumption growth to characterize its causal effect on economic activity in OECD countries.

[12] The WGI measures the quality of general governance by averaging the information of six indicators: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, compliance with the law and control of corruption.

[13] In the instrument originally proposed by Ciccone et al. (2012), the $EEGI_i$ is replaced by another fixed term (θ_i) that represents oil export minus oil imports relative to GDP over the whole time period 2000-2015. This instrument is used to determine how oil price shocks affect democracy through economic growth. Data on oil imports and oil exports are obtained from: NBER–United Nations Trade Database (Feenstra et al., 2005).

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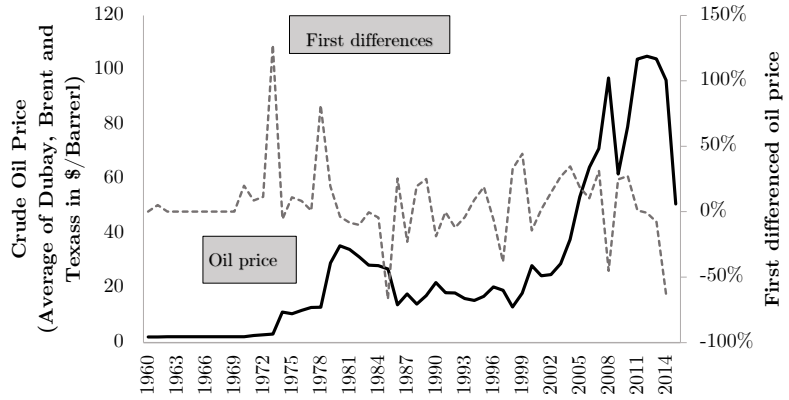


Figure 3. Time series plot of the oil price and its first difference, 1960-2015. Source Oil prices are measured as the average price in $/barrel between Dubai, Brent and Texas markets, from UNCTAD (2018).

4.3. The instrumental variable approach

We propose the next approach to estimate both sides of the causality: from energy consumption to income growth, and from income to energy consumption growth. Although the use of multivariate models can alleviate the problem of omitted variables bias and capture multiple causality channels, bivariate models provide a simpler interpretation of the results and can be applied to small data sets (Yuan et al., 2008). In this vein, the consideration of an exogenous instrument (i.e., the EEGI) allows also to reduce the bias due to unobserved variables and to analyze the different channels of causality, while avoiding the need for additional controls (Brückner, 2013; Acemoglu et al., 2019).

Following Dées (2020), Galiani et al. (2017), Brückner (2013), and Ciccone et al. (2012), our energy-income models are expressed in first differences of the logs (variables are always in per capita terms). Thus, for the first side of causality:

$$\Delta \ln(y_{it}) = \lambda_i + \delta_t + \varphi \Delta ln(e_{it}) + u_{it}, \quad (2)$$

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where $\Delta\ln(y_{it})$ is the log-change of real per capita GDP (i.e., real per capita GDP growth) and $\Delta ln(e_{it})$ is the log-change of per capita TPEC (i.e., per capita TPEC growth); λ_i are country fixed effects that capture the long-run (unobservable) difference across countries, and δ_t are year fixed effects that capture the global business cycle effects and other global shocks that may be jointly driving economic activity and energy consumption in our sample. For the reverse direction of the causality (from per capita GDP growth to per capita TPEC growth):

$$\Delta ln(e_{it}) = \eta_i + \kappa_t + \pi\Delta\ln(y_{it}) + \nu_{it}, \quad (3)$$

where now η_i and k_t correspond to the country and temporal fixed effects of this reverse causal regression.

If per capita GDP growth has a significant effect on energy growth (i.e., in equation (3), $\pi \neq 0$), and the other way around (i.e., in equation (2), $\varphi \neq 0$), then the Ordinary Least Square (OLS) or the within group estimates of φ and π in (2) and (3), respectively, are biased, since $cov(\Delta ln(e_{it}), u_{it}) \neq 0$ and $cov(\Delta\ln(y_{it}), \nu_{it}) \neq 0$.

On the one hand, to handle the double causality bias in (2), we use the instruments described in 3.2 and estimate equation (2) by 2SLS. The first-stage model regress per capita TPEC growth over the corresponding instrument. Using a general notation, Z_{it} represents any of the aforementioned instruments. Thus, this first stage regression of (2) is described in equation (4):

$$\Delta\ln(e_{it}) = \theta_i + \phi_t + \beta Z_{it} + w_{it}, \quad (4)$$

where θ_i and ϕ_t are the correspondent fixed effects, β captures the strength of the energy governance and energy consumption relationship, and w is an i.i.d. error term. Notice that when the instrument Z contains the EEGI as a variable, we cannot use

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country fixed effects in this first-stage regression. Likewise, according to the exclusion restriction, the instruments should only systematically affect the endogenous variable (i.e., per capita GDP growth) through their impact on per capita energy consumption growth. Next, roughly speaking, the second stage uses the fitted part of the per capita energy growth explained by the instrument (i.e., the EEGI and their variations), $\hat{\beta}Z_{it}$, to estimate equation (2).

On the other hand, to evade the double causality bias in (3), following again Brückner (2013), we construct an adjusted per capita GDP growth series, $\Delta ln(y_{it})^*$, in which the response of economic activity to energy consumption growth is partialled out as in equation (5):

$$\Delta ln(y_{it})^* = \Delta \ln(y_{it}) - \hat{\varphi}\Delta ln(e_{it}) \quad (5)$$

where $\hat{\varphi}$ is an unbiased estimate (i.e., the IV estimates from equation (2)). Then, this adjusted series, $\Delta ln(y_{it})^*$, is used as an instrument of $\Delta \ln(y_{it})$ in equation (3). By construction, the IV estimator using this adjusted series does not suffer from the simultaneity bias providing, hence, a consistent estimate of the parameter π in equation (3).[14]

To test the validity of our instruments (in the estimation of equations (2) and (3)), we will conduct several widely used tests. First, we use the Hansen J-test of overidentifying restrictions, which assesses whether the instruments only affect the endogenous variable through the instrumented variable (i.e., the exclusion restriction). Second, we use the Chi-square underidentification test of Sanderson-Windmeijer (SW) in

[14] If there were omitted variables that are part of both equations (2) and (3), the zero covariance assumption would be violated and the IV estimator would not solve the omitted variables problem. However, the IV would still solve the simultaneity problem.

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order to assess if our instruments are properly correlated with the endogenous regressor. The rejection of the null hypothesis supports identification, although not necessarily the absence of weak identification (Kleibergen & Paap, 2006).[15] Third, the Cragg-Donald Wald F-statistic complements the SW test to check the weakness of the instruments.[16]

5. Results

This section shows the results of estimating equations (2), (3) and (4) using the 2SLS approach described above. To analyze the differences in the estimates to control for double causality, we compare the 2SLS results with those obtained from traditional OLS with fixed effects. The section carries out an extensive robustness analysis.

5.1. The effect of energy consumption growth on economic growth

We start showing the estimated results for the causality from energy consumption growth to income growth. First, we estimate the reduced-form of this causality relationship, i.e., the relationship between the instruments and the dependent variable, which is per capita income growth in our case (left panel in Table 5). Second, we analyze the first stage results (equation (4)), i.e., the relationship between energy governance and energy consumption (right panel in Table 5). In this part of the section, we use the $EEGI_i$ and the $EEGIOil_{it}$ as instruments. Finally, we show the estimated results for equation (2) (see Table 6).

[15] Based on the Sanderson-Windmeijer (SW) test, the null hypothesis is that the matrix of coefficients from the first-stage conditional regressions is not full rank, signaling a complete failure of identification (i.e., the excluded instruments are uncorrelated with the endogenous regressor).

[16] The null hypothesis is that the instruments are weak, and it is rejected if the F statistic exceeds the critical value. It is typical to considered that a F-statistic higher than the threshold of 10 should not arise weak instrument concerns (Staiger & Stock, 1997). However, it is merely a rule of thumb (Brueckner & Lederman, 2018). Thus, we also use the Stock & Yogo (2005) approach and critical values. These authors express the weakness in terms of the size of the bias of the IV (i.e., 2SLS) estimator relative to that of the OLS estimator.

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All regressions are controlled by year fixed effects and also by country fixed effects when they do not interfere with the instrument used. Each column in the tables uses a different set of instruments: the $EEGI_i$ in columns (a) and (e); the $EEGI_i$ and the $EEGIOil_{it}$ jointly in columns (b) and (f); the $EEGIOil_{it}$ alone in columns (c), (d), (g) and (h), but in columns (d) and (h) we also control for country fixed effects. The consideration of the model using $EEGIOil_{it}$ without fixed effects in columns (c) and (g) is justified only for comparative purposes with columns (b) and (f), respectively. All instruments are individually significant at 1% level (or very close to this level) for both per capita GDP growth and per capita TPEC growth. Likewise, the four instruments show negative coefficients, with very consistent magnitudes through the different specifications, regardless the use of country fixed effects.

Table 5. First-stage estimates linking energy consumption growth, economic growth and energy governance.

	Reduced-form model: pc income growth vs. energy efficiency governance				First-Stage equation: pc energy growth vs. energy efficiency governance			
	$\Delta \ln GDP_{pc}$				$\Delta \ln TPEC_{pc}$			
	(a) OLS	(b) OLS	(c) OLS	(d) OLS	(e) OLS	(f) OLS	(g) OLS	(h) OLS
$EEGI_i$	-0.006 (0.000)	-0.006 (0.000)			-0.006 (0.007)	-0.006 (0.015)		
$OilEEGI_{it}$		-0.018 (0.007)	-0.021 (0.001)	-0.018 (0.010)		-0.020 (0.011)	-0.023 (0.002)	-0.020 (0.017)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	No	No	No	Yes	No	No	No	Yes
Number of observations	480	480	480	480	480	480	480	480

Note. The method of estimation is Ordinary Least Squares (OLS), with p-values in parentheses. The dependent variable in columns from (a) to (d) is the yearly log-change real per capita GDP; in columns from (e) to (h) the dependent variable is the yearly log-change in per capita Total Primary Energy Consumption (TPEC). The excluded instrument in columns (a) and (e) is the $EEGI_i$; in column (b) and (f) the $EEGI_i$ and the $EEGIOil_{it}$; in columns (c), (d), (g) and (h), the excluded instrument is the $EEGIOil_{it}$, but also considering country fixed effects in columns (d) and (h).

On the one hand, the coefficient of the $EEGI_i$ is the same in all regressions (columns (a), (b), (e) and (f)). Therefore, the estimated coefficients for the $EEGI_i$ in columns (a) and (e) are equivalent to the impact that energy governance would have on economic growth and energy consumption growth, respectively, when oil prices remain constant

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(i.e., when $\Delta ln(OilPrice_t) = 0$). The size of the effect implies that increasing the EEGI in one standard deviation of its range (i.e., 0.785 points, which represents a total change close to 32% over its average score, which is 2.42) would lead to a reduction in energy consumption growth close to 0.5% (-0.006x0.785x100 = -0.47%). Given the fact that the 2000-2015 average change in energy consumption growth for our sample of countries is -0.35% and the standard deviation is about 1%, our results are quantitatively meaningful.[17] Consequently, to the extent that energy industries are the major responsible for CO2 emissions growth in OECD countries, energy governance may play a remarkable role in the abatement of environmental damage and climate change.

On the other hand, the effect of the $EEGIOil_{it}$ is significant and consistent throughout the different models (columns (b), (c), (d), (f), (g) and (h)), with an average coefficient of about -0.020. This result indicates that the effect of the $EEGI_i$ on energy consumption growth –also on economic growth– depends on international oil price shocks. An increase in the international oil price causes a reduction in energy consumption growth. In the same vein, according to Ciccone et al. (2012), increases in oil price shocks perform a negative effect on economic growth for oil-importer countries (as are the vast majority of countries in our sample).

Looking at the models including the $EEGI_i$ and the $EEGIOil_{it}$ together (columns (b) and (f)), and taking into consideration an oil price growth of 10% (i.e., $\Delta ln(OilPrice_t) = 0.10$), the same change in one standard deviation of the $EEGI_i$ has now a slightly greater impact on energy consumption growth. This impact is now about -0.63% (-0.0047-

[17] The negative coefficient of the $EEGI_i$ in the reduced-form of the model is reflecting the fact that, in our sample, energy governance is positively correlated with per capita GDP (i.e., the average cross-country correlation is 0.31), which, in addition, coincides with countries showing a slower growing process (i.e., there exists evidence of per capita GDP conditional convergence in OECD countries). A similar argument can be used to interpret the results in columns (b), (c) and (d).

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0.020x0.785x0.10 = -0.00628). A similar impact is found when the $EEGIOil_{it}$ is used alone (columns (c), (d), (g) and (f)).

The second-stage results are presented in Table 6. The table includes the baseline OLS with fixed effects and the 2SLS estimates of the effect that per capita TPEC growth has on per capita GDP growth. In columns (a) and (b) this effect is assessed using OLS and controlling for year fixed effects, and in column (b) we also control for country fixed effects. In these columns, the OLS estimates show a positive coefficient around 0.20, which implies that increasing per capita TPEC growth by 1% would increase per capita GDP growth, on average, by 0.2%. However, if per capita GDP growth has a significant effect on per capita TPEC growth, this OLS point estimate can be severely biased.

The remaining columns in Table 6 presents the 2SLS estimates that use the instruments described above: the $EEGI_i$ in column (c), the $EEGI_i$ and the $EEGIOil_{it}$ in column (d) and the $EEGIOil_{it}$ in columns (e) and (f). We control all regressions by year fixed effects, and in column (f) we also control for country fixed effects. To compare results with those in column (d), we do not include country fixed effects in column (e). For the 2SLS results in the table, in square brackets, we report the p-value of the Anderson-Rubin test of statistical significance (Andrews & Stock, 2005), which is robust to weak instruments (the weak instrument issue is analyzed in more detail below).

All estimates are significant at 1% level and its elasticity is much larger than the corresponding OLS estimate in columns (a) and (b). Indeed, when the $EEGI_i$ is the excluded instrument (column (c)), the estimated 2SLS elasticity is almost the unity (1.02). Using the alternative sets of instruments (columns (d)-(f)), estimated coefficients vary from 0.90 to 0.96. Thus, increasing per capita TPEC growth by 1% is associated with an average growth in per capita GDP between 0.9% and 1%. The Hausman test

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rejects that the OLS estimate is equal to the 2SLS estimate at the 1% level (p-value < 0.01), thus pointing out to a significant difference between the OLS and the IV estimates.

From the comparison between OLS and 2SLS estimates, we can draw two main conclusions: (i) the OLS with fixed effects estimates are downward biased; (ii) the energy consumption growth driven by energy efficiency governance shows a stronger effect on income growth than total energy consumption growth. The fraction of energy consumption driven by energy efficiency governance is related with improvements in energy efficiency and the consequent impact on overall productivity might explain this result.

Table 6. The effect of per capita energy consumption growth on per capita economic growth.

		$\Delta\ln GDP_{pc}$					
		(a) OLS	(b) OLS	(c) 2SLS	(d) 2SLS	(e) 2SLS	(f) 2SLS
$\Delta\ln TPEC_{pc}$		0.231 (0.000)	0.181 (0.000)	1.019 [0.000]	0.960 [0.000]	0.901 [0.001]	0.881 [0.006]
Underidentification test	Sanderson-Windmeijer Chi-sq			7.660 (0.007)	15.850 (0.000)	9.610 (0.002)	6.380 (0.012)
Weak identification test	Cragg-Donald F			9.740	8.675	9.816	7.469
	Stock-Yogo 10%			16.38	19.93	16.38	16.38
	Stock-Yogo 15%			8.96	11.59	8.96	8.96
	Stock-Yogo 20%			6.66	8.75	6.66	6.66
	Stock-Yogo 25%			5.53	7.25	5.53	5.53
Overidentification test	Hansen J (p-value)			Exactly-identified	(0.785)	Exactly-identified	Exactly-identified
Year FE		Yes	Yes	Yes	Yes	Yes	Yes
Country FE		No	Yes	No	No	No	Yes
Number of observations		480	480	480	480	480	480

Note. The method of estimation in columns (a) and (b) is Ordinary Least Squares (OLS). The method of estimation in columns from (c) to (f) is Two-Stage Least Squares (2SLS). P-values are reported in parentheses; below the 2SLS estimates, p-values in square brackets are reported based on the Anderson-Rubin test of statistical significance. The dependent variable in columns from (a) to (f) is the yearly ln-change in real per capita GDP. The independent variable is the yearly ln-change in per capita Total Primary Energy Consumption (TPEC). The IV in column (c) is the $EEGI_i$. In column (d) we have two IVs: the $EEGI_i$ and the $EEGIOil_{it}$. The IV in columns (e) and (f) is the EE governance shock, but in column (f) we control for country fixed effects. Stock-Yogo values for maximal IV size are based on Stock & Yogo (2005)

To assess causality, the instruments must fulfill the exclusion restriction (i.e., the instruments can only affect the endogenous variable through the instrumented one). The model is exactly identified (i.e., we use one excluded instrument for per capita energy

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growth) in columns (c), (e) and (f), hence we can only use the Hansen J-test in model (d), where the excluded instruments are $EEGI_t$ and $EEGIOil_{it}$. Here, the p-value of the Hansen J-test is 0.785, much higher than 0.1, which means that the test does not reject that the instruments are uncorrelated with the second-stage error term (i.e., u_{it} in equation (2)), hence they are not rejected as valid instruments for energy consumption growth.

Reporting the 2SLS estimates when the instruments are added to the right-hand side of the second-stage equation (i.e., equation (2)) provides a more specific and intuitively way to show that there are no systematically direct effects of our instruments on per capita GDP growth (Brückner, 2013). Based on column (d) from Table 6, Table 7 shows the estimated results when the $EEGI_i$ and the $EEGIOil_{it}$ are added as potential explicative variables to per capita income growth. The magnitude of the coefficient of the $EEGI_i$ on per capita GDP growth (column (a)) is, at least, one-sixth of the size of the coefficient that was obtained in the reduced-form (columns (a) and (b) in Table 5). Furthermore, the coefficient is not significant at any conventional confidence level. The same occurs when the $EEGIOil_{it}$ is added to the right-hand side of the second-stage equation. In fact, the estimated coefficient flips sign, another symptom of lack of significance. These results resonate the outcome of the Hansen J-test, which does not reject the validity of $EEGI_i$ and the $EEGIOil_{it}$ as instruments for energy consumption growth.

To finish with the analysis about the validity of instruments, we assess whether the instruments are properly correlated with the endogenous regressors (i.e., the instruments are not weak). Otherwise, the estimators would perform poorly and the IV results would not yield consistent second-stage estimates (Nelson & Startz, 1990). In this vein, the SW Chi-square underidentification test provides a significance close to the 1% level in all

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cases (columns (c)-(f) in Table 6). Furthermore, according to the F-statistics reported, the maximal IV relative bias (with respect to OLS) is less than 20%. Keeping these findings in mind, the correct identification of models in columns (c-f) is supported and weak instruments should not be an important concern in our estimations. Moreover, as commented above for 2SLE, we are also reporting p-values based on the Anderson-Rubin test of statistical significance (in square brackets), which is valid even under the existence of weak instruments.

Table 7. Test of exclusion restriction: energy and income growth extended with instruments.

		ΔlnGDP$_{pc}$	
		(a) 2SLS	(b) 2SLS
ΔlnTPEC$_{pc}$		0.881 [0.006]	1.039 [0.000]
EEGI$_i$		-0.001 (0.771)	
OilEEGI$_{it}$			0.003 (0.794)
Underidentification test	Sanderson-Windmeijer Chi-sq	6.710 (0.010)	6.130 (0.013)
Weak identification test	Cragg-Donald F	7.474	7.397
	Stock-Yogo 10%	16.38	16.38
	Stock-Yogo 15%	8.96	8.96
	Stock-Yogo 20%	6.66	6.66
	Stock-Yogo 25%	5.53	5.53
Overidentification test	Hansen J	Exactly-identified	Exactly-identified
Year FE		Yes	Yes
Country FE		No	No
Number of observations		480	480

Note. The method of estimation is Two-Stage Least (2SLS). P-values are reported in parentheses; below the 2SLS estimates p-values in square brackets are reported based on the Anderson-Rubin test of statistical significance. The dependent variable in columns (a) and (b) is the ln-yearly change real per capita GDP. In column (a) the IV is the $EEGIOil_{it}$, whereas the $EEGI_i$ is added to the right-hand side of the second-stage equation. In column (b) the IV is the $EEGI_i$, whereas the $EEGIOil_{it}$ is added to the right-hand side of the second-stage equation. Stock-Yogo values for maximal IV size are based on Stock & Yogo (2005).

5.2. The effect of economic growth on energy consumption growth

We show next the estimated results for the causality from GDP growth to energy consumption growth. As commented in Section 4.2, for this side of the causality, we use the adjusted per capita GDP growth series $\Delta ln(y_{it})^*$ obtained from equation (5) to

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instrument per capita income growth in equation (3). To construct the adjusted series, we use the 2SLS estimates from equation (2). Hence, the per capita GDP growth is adjusted by the (energy-governance-driven) energy consumption growth. By construction, this instrument is highly correlated with income growth, and weakly correlated with the error term in (3). For that reason, for this side of the causality, we just show results for the second stage regressions (first stage results are available upon request).

Table 8 presents the baseline OLS and 2SLS estimates of the effect that per capita GDP growth has on per capita TPEC growth (equation (3)). In columns (a) and (b), this effect is assessed using OLS and controlling for year fixed effects, but in column (b) we also control for country fixed effects. The two OLS estimates are very similar, with a positive average coefficient of 0.47, which implies that increasing per capita GDP growth by 1% is associated with an increase in per capita TPEC growth around 0.47%. This positive effect is the one usually obtained in the literature (Masih & Masih, 1996; Fatai et al., 2004; Esseghir & Khouni, 2014; among others), but recall that these works (as our OLS estimates) do not control for double causality. In our case, since energy consumption growth significantly affects economic growth (as showed in Table 6), the OLS estimate of equation (3) can be severely biased, which is what happens in our case.

The remaining columns in Table 8 present the 2SLS estimates using the adjusted GDP series as the instrument of per capita GDP growth. The instrument is constructed from equation (5), using 2SLS estimates from columns (c)-(f) in Table 6. In all cases, the regressions are controlled for year fixed effects and, in column (f), we also consider country fixed effects. We provide again the p-values (in square brackets) of the Anderson-Rubin test of statistical significance. Our 2SLS estimates produce considerably changes

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in the estimates of the effect that economic growth has on energy consumption growth, not only in size, but also in sign. All estimates are significant at the 1% level and are meaningful in magnitude. We obtain negative coefficients (elasticities) ranging from -2.84 to -3.24, which implies that increasing the per capita GDP growth by 1% is associated, on average, with a reduction of per capita TPEC growth by about 2.9%.

As commented above, since the adjusted income growth instrument does not suffer from simultaneity bias (by construction), all IV tests result satisfactory. First, the overidentifying test (the Hansen J-test) indicates that the model is exactly-identified in all cases. Second, the underidentification test also provides the expected results, since the SW test is significant in all our models (columns (c)-(f)). Finally, the weak identification test (i.e., the Cragg-Donald F statistic) is clearly over 10, which implies that weak instruments are not a concern.

Table 8. The effect of per capita economic growth on per capita energy consumption growth.

		$\Delta\ln TPEC_{pc}$					
		(a) OLS	(b) OLS	(c) 2SLS	(d) 2SLS	(e) 2SLS	(f) 2SLS
$\Delta\ln GDP_{pc}$		0.482 (0.000)	0.459 (0.000)	-3.242 [0.000]	-2.837 [0.000]	-2.477 [0.000]	-2.992 [0.000]
Underidentification test	Sanderson-Windmeijer Chi-sq			14.540 (0.000)	17.350 (0.000)	20.830 (0.000)	18.160 (0.000)
Weak identification test	Cragg-Donald F			62.157	78.221	98.427	84.769
	Stock-Yogo 10%			16.38	16.38	16.38	16.38
	Stock-Yogo 15%			8.96	8.96	8.96	8.96
	Stock-Yogo 20%			6.66	6.66	6.66	6.66
	Stock-Yogo 25%			5.53	5.53	5.53	5.53
Overidentification test	Hansen J			Exactly-identified	Exactly-identified	Exactly-identified	Exactly-identified
Year FE		Yes	Yes	Yes	Yes	Yes	Yes
Country FE		No	Yes	No	No	No	Yes
Number of observations		480	480	480	480	480	480

Note. The method of estimation in columns (a) and (b) is Ordinary Least Squares (OLS). The method of estimation in columns from (c) to (f) is Two-Stage Least Squares (2SLS). P-values are reported in parentheses; below the 2SLS estimates p-values in square brackets are reported based on the Anderson-Rubin test of statistical significance. The dependent variable in columns from (a) to (f) is the ln-yearly change in per capita Total Primary Energy Consumption (TPEC). The independent variable is the ln-yearly change in real per capita GDP. The IVs for columns from (c) to (f) are the ln-yearly change of per capita GDP series that are adjusted for the reverse effect that ln-yearly change per capita TPEC has on ln-yearly change on per capita GDP, according to the estimates of the models presented in columns from (c) to (f) in Table 6 (see table's footnote). Stock-Yogo's maximal IV sizes for Cragg-Donald F statistic are based on Stock & Yogo (2005).

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According to these results and those from Section 5.1., the existence of a bidirectional causal relationship between energy consumption and income growth is verified in our sample of OECD countries. The causal relationship obtained from energy consumption growth (driven by energy governance) to income growth is positive and its elasticity is almost equal to one. However, the causal relationship obtained from economic growth to energy consumption growth is highly negative. Improving the use of energy driven by the progress of energy efficiency governance shows a double benefit on the economy. It favors energy efficiency and income growth and, at the same time, the consequent improvement of income growth would reduce per capita energy consumption growth. Energy efficiency governance is the main driver for the existence of these two positive effects simultaneously. Therefore, since economic growth and energy consumption are essential aspects for the abatement of environmental damage, our results indicate that energy governance can play a remarkable role for decoupling carbon emissions from GDP growth.

The reasons explaining the negative sign from GDP to energy consumption growth in a heterogeneous panel of countries may be diverse. The first and most reasonable explanation is that, when correcting for double causality bias, the underlying effect of economic growth on energy consumption growth is identified. Economic growth allows the adoption of more efficient technologies, enhances technological progress and improves factor's productivity, among others, which eventually may lead to reductions in energy consumption growth (but not necessarily in the level of energy consumption). That is, an increase in energy efficiency (see Comin & Hobijn, 2004; Filippini & Hunt, 2011, 2015; Stern, 2012, for instance). Another plausible reason is that, as stated in Payne (2010) and Filippini et al. (2014), economic growth may be accompanied by reductions in energy consumption and/or increases in energy efficiency in the presence of a strong governance

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and energy policy infrastructure. Therefore, given that our GDP series have been adjusted by the reverse effect of energy-governance-driven energy consumption, we obtain this negative sign for our sample of OECD countries.

In fact, although a positive causality from GDP to energy consumption is the usual finding in the literature, some works have also identified the opposite. For instance, Narayan & Popp (2012) provide evidences of negative causality between GDP and energy consumption for a total of 93 countries from all over the world (including Europe, Asia, Middle East, Latin America and Africa). The authors found significant and negative coefficients for many of them, ranging from -0.10 up to around -1.2.

Our results are especially relevant for (energy) policy making. At the aggregate level, the existence of a bidirectional causality implies that the adoption of conservationist energy policies (i.e., measures aimed at reducing the amount of energy consumed) can damage economic growth.

On the contrary, the negative sign of the causality from economic growth to energy consumption implies that policies aimed at improving economic growth tend to reduce energy consumption growth, which implies an increase in energy efficiency. Consequently, energy governance in the OECD should be focused on ensuring that energy policy making is designed to increase energy efficiency, rather than to reduce energy consumption (Esseghir & Khouni, 2014).

Each of the elements underpinning energy governance (recall from Figure 1) should reflect this condition. As a result, economic growth could be improved, while energy consumption growth can be reduced, which is what our 2SLS estimates suggest. For instance, laws and energy plans aimed at promoting the development of renewable energies, which are more efficient than oil-based technologies, must preferred to those

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which promote a reduction in energy consumption. Similarly, policies that advocate for the use of more efficient cooling and heating systems (through equipment labeling standards, for example) will be preferred, rather than those aimed at reducing heating and cooling energy demand. This same idea may easily be extended to the industrial sectors, building, electrical appliances, lighting, etc.

5.3. A counterfactual analysis: Using alternative instruments

We replicate our energy-income analysis, but using the two counterfactual instruments proposed in Section 4 for per capita energy consumption growth. We show that, while our instruments based on EEGI are suitable for the double causality assessment, alternative instruments based on general governance or oil trade variables do not provide proper instruments for an energy-income model.

For the first alternative, we use the cross-section value of the WGI between 2000 and 2015, given by WGI_i, which captures general governance quality, in order to substitute the EEGI as instrument for energy consumption growth. Following equation (1), we also construct the alternative time-varying instrument as $WGI_i \text{x} \Delta ln(OilPrice_t)$, and we denote this new instrument by $WGIOil_{it}$. For the second alternative, our $EEGI_i$ is replaced by a fixed term, θ_i, which represents oil export minus oil imports relative to GDP over the whole time period 2000-2015 (the one used in Ciccone et al., 2012). Thus, the time-varying instrument is now given by $\theta_i \text{x} \Delta ln(OilPrice_t)$, and we denote it by $TradeOil_{it}$.

Table 9 presents the 2SLS estimates of the effect that per capita TPEC growth has on per capita GDP growth using these counterfactual instruments. To simplify the exposition of results, we present the results relative to the time-invariant instruments, the combination of the time-invariant and time-varying instruments and, finally, the time-varying instruments when country fixed effects are considered (the remaining results

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are available upon request). Therefore, the instruments used are the WGI_i in column (a), the WGI_i and the $WGIOil_{it}$ jointly in column (b), and the $WGIOil_{it}$ in column (c); in column (d) we use the θ_i, the θ_i and the $TradeOil_{it}$ jointly in column (e), and the $TradeOil_{it}$ in column (f). All regressions are also controlled for year fixed effects.

Table 9. The effect of per capita energy consumption growth on per capita economic growth considering counterfactual instruments.

		$\Delta\ln GDP_{pc}$					
		(a) 2SLS	(b) 2SLS	(c) 2SLS	(d) 2SLS	(e) 2SLS	(f) 2SLS
$\Delta\ln TPEC_{pc}$		0.896 [0.001]	0.959 [0.000]	2.817 [0.037]	24.33 [0.002]	0.288 [0.002]	0.212 [0.700]
Underidentification test	Sanderson-Windmeijer Chi-sq	6.76 (0.009)	6.94 (0.031)	0.30 (0.584)	0.00 (0.982)	0.33 (0.850)	0.27 (0.605)
Weak identification test	Cragg-Donald F	7.798	4.026	0.266	0.002	0.370	0.751
	Stock-Yogo 10%	16.38	19.93	16.38	16.38	19.93	16.38
	Stock-Yogo 15%	8.96	11.59	8.96	8.96	11.59	8.96
	Stock-Yogo 20%	6.66	8.75	6.66	6.66	8.75	6.66
	Stock-Yogo 25%	5.53	7.25	5.53	5.53	7.25	5.53
Overidentification test	Hansen J	Exactly-identified	(0.300)	Exactly-identified	Exactly-identified	(0.100)	Exactly-identified
Year FE		Yes	Yes	Yes	Yes	Yes	Yes
Country FE		No	No	Yes	No	No	Yes
Number of observations		480	480	480	480	480	480

Note. The method of estimation is Two-Stage Least Squares (2SLS). P-values are reported in parentheses; below the 2SLS estimates p-values in square brackets are reported based on the Anderson-Rubin test of statistical significance. The dependent variable in columns from (a) to (f) is the ln-yearly change in real per capita GDP. The independent variable is the ln-yearly change in per capita Total Primary Energy Consumption (TPEC). The IV in column (a) is the WGI_i, in column (b), the WGI_i and the $WGIOil_{it}$ together, and in column (c), it is the $WGIOil_{it}$. The IV in column (d) is the θ_i, in column (e), the θ_i and the $TradeOil_{it}$ together, and in column (f), it is the $TradeOil_{it}$. Stock-Yogo values for maximal IV size are based on Stock & Yogo (2005).

On the one hand, the estimated coefficient when the WGI_i is used as instrument (column (a)) is significant and comparable to that found when the $EEGI_i$ instruments energy consumption (columns (c) and (d) in Table 6). However, the resulting (weak identification) F-statistic is slightly lower in this case, which provides a relative higher Stock-Yogo bias (close to 20%). Moreover, when the instrument used is $WGIOil_{it}$ (in columns (b) together with WGI_i and in (c) alone), the estimated coefficients are higher (specially in (c)), but the instruments are weak and performs poorly (i.e., the F-statistic is about 4.0 and 0.27 in columns (b) and (c), respectively), thus providing coefficients

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that are biased. The non-significance of the under-identification test in column (c) resonates this conclusion.

On the other hand, the effect of per capita TPEC growth on per capita GDP growth is significant at 1% level when the instrument θ_i is used alone or combined with $TradeOil_{it}$ (columns (d) and (e), respectively). However, this effect is not significant at any conventional level when the $TradeOil_{it}$ alone is considered (column (f)). Moreover, in these three cases their under-identification tests are not rejected (p-values much higher than 0.10), and the Cragg-Donald F statistics are very low, which implies that the instruments are strongly weak and the point estimates are severely biased. In addition, the Hansen J-test in column (e) is only significant at the 10% level, which suggest that θ_i and $TradeOil_{it}$ have also a direct effect on income growth, thus they are invalid instruments for energy consumption growth.

5.4. Further robustness checks

We conduct a robustness analysis to our main results. First, we consider Total Final Energy Consumption (TFEC) instead of the primary energy sources TPEC. Second, we extend our model and include several additional explicative variables, such as energy prices or the general quality of governance.

With respect to the first assessment, in general, when analyzing the determinants of energy consumption, the literature uses the primary source (S. Wang et al., 2018), while it tends to use the final consumption when analyzing efficiency (Metcalf, 2008). In our sample of 32 OECD countries, between 2000 and 2015, primary consumption of oil, natural gas and coal represents 82%, while this same item accounted for only 72% in final consumption, due to the greater weight of renewables. Therefore, it is important to check if our results are robust to the use of primary or final energy consumption.

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Panel A in Table 10 presents the 2SLS estimates of the effect that per capita TFEC growth has on per capita GDP growth.[18] We consider the same instruments and their combination in columns (a)-(d) than in Table 6. Results are similar to those in Table 6, showing elasticities systematically greater than one (ranging between 1.1 and 1.2) and significant at the 1% level. Meanwhile, panel B in Table 10 shows the estimates of the other side of the causality, from per capita GDP growth to per capita TFEC growth, using the equivalent adjusted per capita GDP as instrument. All estimates are significant at the 1% level, with similar coefficients ranging from -2.53 to -3.23, thus leading also to a similar result than for primary energy consumption. Moreover, in both cases, the different tests indicate the validity of the instruments used. Thus, the exclusion restriction and the identification condition are fulfilled. Likewise, the resulting F-statistics are very close to 10 in Panel A, which indicates that weak instruments should not be a concern. We only obtain a low F-statistic when using the $EEGIOil_{it}$ as instrument (column (d)). However, the maximal IV relative bias is around 20%, which can be accepted as a reasonable threshold, as proved in Brückner (2013).

Table 11 summarizes results for the second type of robustness checks. Panel A shows results for the causality from energy to income, and panel B the other way around. Regressions in column (a) of both panels are controlled for the lagged level of the dependent variable, following (Brückner, 2013; Ciccone et al., 2012). In column (b), we include the effect of the lagged level of per capita GDP and per capita GDP squared on per capita primary energy consumption growth. Finally, in columns from (c) to (e), we control for exogenous variables such as the general governance quality (measured through

[18] Data on TFEC is extracted from the IEA's World Energy Balances (2018) database.

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the WGI), the energy prices growth and both variables together, respectively.[19] In all cases, we have used the $EEGIOil_{it}$ as reference instrument since it captures both time-varying and country fixed effects affecting energy consumption.

Table 10. Relationship between per capita economic growth and per capita energy consumption growth measured through Total Final Energy Consumption.

PANEL A		$\Delta\ln GDP_{pc}$			
		(a) 2SLS	(b) 2SLS	(c) 2SLS	(d) 2SLS
$\Delta\ln TFEC_{pc}$		1.216 [0.000]	1.165 [0.000]	1.109 [0.001]	1.091 [0.006]
Underidentification test	Sanderson-Windmeijer Chi-sq	9.270 (0.002)	21.410 (0.000)	10.55 (0.001)	7.290 (0.007)
Weak identification test	Cragg-Donald F	9.562	8.243	9.035	6.899
	Stock-Yogo 10%	16.38	19.93	16.38	16.38
	Stock-Yogo 15%	8.96	11.59	8.96	8.96
	Stock-Yogo 20%	6.66	8.75	6.66	6.66
	Stock-Yogo 25%	5.53	7.25	5.53	5.53
Overidentification test	Hansen J	Exactly-identified	(0.776)	Exactly-identified	Exactly-identified
Year FE		Yes	Yes	Yes	Yes
Country FE		No	No	No	Yes
Number of observations		480	480	480	480
PANEL B		$\Delta\ln TFEC_{pc}$			
		(a) 2SLS	(b) 2SLS	(c) 2SLS	(d) 2SLS
$\Delta\ln GDP_{pc}$		-3.225 [0.000]	-2.867 [0.000]	-2.527 [0.000]	-3.113 [0.000]
Underidentification test	Sanderson-Windmeijer Chi-sq	9.320 (0.002)	11.170 (0.001)	13.580 (0.000)	10.660 (0.001)
Weak identification test	Cragg-Donald F	42.648	52.261	64.741	52.226
	Stock-Yogo 10%	16.38	16.38	16.38	16.38
	Stock-Yogo 15%	8.96	8.96	8.96	8.96
	Stock-Yogo 20%	6.66	6.66	6.66	6.66
	Stock-Yogo 25%	5.53	5.53	5.53	5.53
Overidentification test	Hansen J	Exactly-identified	Exactly-identified	Exactly-identified	Exactly-identified
Year FE		Yes	Yes	Yes	Yes
Country FE		No	No	No	Yes
Number of observations		480	480	480	480

Note. The method of estimation in panels A and B is both Two-Stage Least Squares (2SLS). P-values are reported in parentheses; below the 2SLS estimates p-values in square brackets are reported based on the Anderson-Rubin test of statistical significance. In Panel A, the dependent variable is the yearly ln- change in real per capita GDP and the independent variable is the yearly ln-change in per capita Total Final Energy Consumption (TFEC). In Panel B, we use the same variables but their roles are swapped. In Panel A, the instrumental variable in column (a) is the $EEGI_i$; in column (b), both the $EEGI_i$and the $EEGIOil_{it}$; in columns (c) and (d), the $EEGIOil_{it}$. In Panel B, the instrumental variables are the yearly ln-change in per capita GDP series that are adjusted for the reverse effect that the yearly ln-change in per capita TFEC has on GDP series. Stock-Yogo's maximal IV sizes for Cragg-Donald F statistic are based on Stock & Yogo (2005).

[19] Data on energy prices growth is extracted from the IEA's Energy Prices and Taxes (2018) database.

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According to column (a) in Table 11 when we control for the lagged level of the dependent variable, the size of the coefficients obtained for both causality relations is slightly lower than the magnitude shown in Tables 6 and 8. The estimated GDP-energy consumption growth elasticities are positive and between 0.8 and 0.9, while those elasticities estimated for the other side of the causality (the energy-GDP growth) are negative and between -2.0 and -3.0, approximately. In all cases, they are significant at the 1% level. Moreover, the under-identification and the over-identification tests provide similar results, while the F-statistic for weak instrument is slightly improved in both cases.

Table 11. Relationship between per capita income growth and per capita energy consumption growth (robustness of IV estimates to different exogenous variables).

PANEL A		$\Delta\ln GDP_{pc}$				
		(a) 2SLS	(b) 2SLS	(c) 2SLS	(d) 2SLS	(e) 2SLS
$\Delta\ln TPEC_{pc}$		0.781 [0.010]	0.881 [0.006]	0.881 [0.006]	0.845 [0.027]	0.845 [0.027]
$L1.\ln GDP_{pc}$		-0.055 (0.012)				
WGI				-0.009 (0.747)		-0.007 (0.798)
$\Delta\ln$Energy prices					-0.096 (0.079)	-0.096 (0.079)
Underidentification test	Sanderson-Windmeijer Chi-sq	6.600 (0.010)	6.380 (0.012)	6.380 (0.012)	4.750 (0.0293)	4.750 (0.029)
Weak identification test	Cragg-Donald F	7.830	7.469	7.469	6.342	6.342
	Stock-Yogo 10%	16.38	16.38	16.38	16.38	16.38
	Stock-Yogo 15%	8.96	8.96	8.96	8.96	8.96
	Stock-Yogo 20%	6.66	6.66	6.66	6.66	6.66
	Stock-Yogo 25%	5.53	5.53	5.53	5.53	5.53
Overidentification test	Hansen J	Exactly-identified	Exactly-identified	Exactly-identified	Exactly-identified	Exactly-identified
Year FE		Yes	Yes	Yes	Yes	Yes
Country FE		Yes	Yes	Yes	Yes	Yes
Number of observations		480	480	480	480	480

Note. The method of estimation is 2SLS in both panels. P-values are reported in parentheses; below the 2SLS estimates p-values in square brackets are reported based on the Anderson-Rubin test of statistical significance. In Panel A, the dependent variable is the yearly ln-change in real per capita GDP and the instrumental variable is $EEGIOil_{it}$. Stock-Yogo's maximal IV sizes for Cragg-Donald F statistic are based on Stock & Yogo (2005).

Focusing on column (b) of Panel B, when we control for the lagged levels of per capita GDP and per capita GDP squared, the size of the coefficient for per capita GDP growth and its significant remains almost unchanged. The lagged level of per capita GDP shows

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a positive coefficient, whereas the quadratic term has a negative coefficient. Both of them are significant at the 10% level. This result suggests that the initial growth of the economy induces a higher energy consumption but, at some stage, if the economy continues growing, energy consumption growth reduces. As in the previous case, the different tests indicate the validity of the instruments used (the $EEGI_i$ and the $EEGIOil_{it}$).

Table 11. Continued.

PANEL B		ΔlnTPEC$_{pc}$				
		(a) 2SLS	(b) 2SLS	(c) 2SLS	(d) 2SLS	(e) 2SLS
ΔlnGDP$_{pc}$		-2.235 [0.000]	-3.102 [0.000]	-2.992 [0.000]	-2.748 [0.000]	-2.748 [0.000]
L1.lnTPEC$_{pc}$		-0.178 (0.002)				
L1.lnGDP$_{pc}$			4.016 (0.068)			
(L1.lnGDP$_{pc}$)^2			-0.210 (0.061)			
WGI				0.081 (0.198)		0.081 (0.237)
ΔlnEnergy prices					-0.467 (0.005)	-0.467 (0.005)
Underidentification test	Sanderson-Windmeijer Chi-sq	25.970 (0.000)	166.720 (0.000)	18.160 (0.000)	19.800 (0.000)	19.800 (0.000)
Weak identification test	Cragg-Donald F	136.708	81.385	84.769	98.372	98.372
	Stock-Yogo 10%	16.38	16.38	16.38	16.38	16.38
	Stock-Yogo 15%	8.96	8.96	8.96	8.96	8.96
	Stock-Yogo 20%	6.66	6.66	6.66	6.66	6.66
	Stock-Yogo 25%	5.53	5.53	5.53	5.53	5.53
Overidentification test	Hansen J	Exactly-identified	Exactly-identified	Exactly-identified	Exactly-identified	Exactly-identified
Year FE		Yes	Yes	Yes	Yes	Yes
Country FE		Yes	Yes	Yes	Yes	Yes
Number of observations		480	480	480	480	480

Note. The method of estimation is 2SLS in both panels. P-values are reported in parentheses; below the 2SLS estimates p-values in square brackets are reported based on the Anderson-Rubin test of statistical significance. In Panel B, the dependent variable is the yearly ln-change in per capita Total Primary Energy Consumption (TPEC). In Panel B, the instrumental variables are the yearly ln-change in per capita GDP series that are adjusted for the reverse effect that the yearly ln-change in per capita TPEC has on GDP. Stock-Yogo's maximal IV sizes for Cragg-Donald F statistic are based on Stock & Yogo (2005).

According to column (c) in Table 11, the effect that the WGI has on both per capita TPEC growth and per capita GDP growth is not significant at any conventional level. However, the IV tests remains valid, which means that our instrument is robust to the inclusion of additional exogenous variation. In column (d), we control for the energy prices growth. As expected, the effect that this variable has on per capita primary energy

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consumption growth is negative and significant (at the 10% level). The effect of energy prices growth on per capita GDP growth is also negative, but it is significant at the 1% level. Exclusion restriction and identification condition are fulfilled. Likewise, despite that the F statistic is slightly lower than in the previous cases, the maximal IV relative bias is very close to 20% again. Finally, if we control for the effect of the WGI and energy prices growth at the same time (column (e)), the results obtained do not differ from the results provided when controlling individually for each variable.

6. Conclusions and final remarks

We analyze the causal relationship between energy consumption growth and income growth for 32 OECD countries between 2000 and 2015. Traditional OLS fixed effects estimates are biased, unless we have an exogenous source that control for double causality. Energy governance combines aspects related with energy efficiency laws, decrees and financing mechanisms, the existence of energy agencies, or the existence of coordination mechanisms necessary for a successful development of energy policies. The literature has emphasized the relevance that energy governance improvements might have in the use of energy and, as a consequence, in income growth. The construction of an Energy Efficiency Governance Index (EEGI) for our OECD sample, which is used as a potential exogenous source to characterize the causal relationship from energy consumption growth to income growth, is a relevant contribution of this paper. We then use the 2SLS estimates of this causal relationship to construct an adjusted per capita GDP growth series, which is used to estimate the other side of the causality.

Our EEGI results show that countries such as Germany, Denmark and France have a

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highly developed energy governance, while others such as Slovenia, Estonia or Chile have ample room for improvement. In those countries with better energy governance performance, the regulatory aspects (laws, decrees, strategic planning) are the ones showing a higher level of development. Also, to a lesser extent, the establishment targets and evaluation mechanisms are common practices in better energy governance economies. Our EEGI breaks new ground in the energy governance literature, since indices about energy governance are not available to date and it can complement available general governance indices, such as the World Governance Indicator.

Concretely, our results suggest that increasing energy governance quality by one standard deviation (around 32% over its average score) could reduce energy consumption growth by approximately 0.50%. The meaning of increasing the EEGI by one standard deviation varies across countries. For example, in a country with a low developed Enabling Frameworks area (e.g., Netherlands or Turkey), energy governance can be easily improved by drafting additional laws and decrees that cover new sectors (e.g., building, industry, appliances) or by expanding the existing regulation. Furthermore, energy governance could also be improved in these cases by establishing strategic plans that identify both the quantitative objectives of these laws, as well as the economic costs necessary to monitor and enforce them. On the contrary, a country with an underdeveloped Co-ordination Mechanisms area (e.g., Austria) can easily improve its energy governance score by defining evaluation mechanisms that help policy-makers to verify the development of their strategic plans and the achievement of their energy targets.

We also provide new insights on the channels through which energy use and economic development interact. Specifically, we show the existence of a bidirectional causal

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relationship between energy consumption and income growth, in which energy governance plays a crucial role. On the one hand, from energy to income growth, we find that the estimated elasticity is close to unity in most cases. This result almost triples the elasticities estimated under OLS with fixed effects and, at least, doubles the elasticities commonly found in the literature. Therefore, (energy-governance-driven) energy consumption growth has a much stronger effect on income growth than overall energy consumption growth. On the other hand, from income to energy consumption growth, the instrumental variable estimates show a sizable negative elasticity (around -3.00), which is of opposite sign to the usual finding in the literature and to our OLS fixed effects estimates. This negative sign may be related to several facts, like the adoption of more efficient technologies, improvements in technological progress and a better factor's productivity. Thus, for our set of OECD countries between 2000 and 2015, improving the use of energy driven by progress in energy efficiency governance is growth enhancing and, at the same time, the consequent improvement of income growth would reduce per capita energy consumption growth.

The need to correctly identify the causal relationship between energy consumption and economic growth is important to ensure the effectiveness of the energy policies and to minimize their negative impacts on the economy. According to our results, adopting conservationist energy policies in our sample of 32 OECD countries (i.e., reducing total energy use) can harm aggregate economic growth. In these cases, improving energy governance allows a more efficient use of energy, which can improve energy efficiency and hence income growth, at the same time the posterior change of overall energy consumption can be reduced. Therefore, this work, in addition to offering for the first time a measure of the quality of energy governance, contributes to improving the

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understanding of the relationship between energy consumption and economic growth, favoring the development of effective energy policies that do not hinder the economy. Moreover, to the extent that energy use is the main source of greenhouse gases, improvements in energy governance would help to combat climate change without hampering economic growth.

Futures lines of research could focus on two fundamental aspects. First, in evaluating the role of energy governance on economic growth through other channels of interest, such as the Total Factor Productivity (TFP). Second, it would be convenient to analyze the rebound effect on efficiency improvements, since policies may not necessarily be as effective as expected, and they may boost energy consumption if the rebound effect is large enough.

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Appendix 1

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Appendix 1

1.A. Scoring criteria for indicators

The application of scoring criteria for each indicator is inspired on the Dabla-Norris et al. (2012), who build an indicator of efficiency in public investment management.

Table 1.A.1. Scoring criteria for indicators.

No.	Question	Indicator		Scoring criteria
		1.	Enabling Frameworks	
1.	Is the regulation enough?	1.1.	*Laws and decrees*	The score is 0 if no document has been found; 0.8 if some regulation has been found but it is extremely limited; 1.6 if the regulation is adequate but the sectors covered are scarce (residential, industry, buildings, transport, lighting, energy utilities, commercial/industrial equipment); 2.4 if the regulation is adequate and several important sectors are covered; 3.2 if the regulation is abundant and dedicated to several important sectors; and 4 if the regulation is extremely abundant and dedicated to several important sectors.
2.	Are strategies and actions plans enough? Are the costs of the plans estimated and the targets set for strategic and action plans?	1.2.	*Strategies and action plans*	The score is 0 if strategies and action plans have not been found; 1 if the number of plans is extremely limited; 2 if some plans have been found and in some cases costs are estimated and/or targets are set; 3 if abundant plans have been found and in some cases costs are estimated and/or targets set OR if an adequate amount of plans have been found and the costs are estimated and/or targets set for most of them; 4 if abundant plans have been found and for the most costs have been estimated and/or targets have been set.
3.	What percentage of GDP is dedicated to Energy Efficiency?	1.1.	*Funding mechanisms*	The score is 0 if no energy efficiency spending has been detected; 0.8 if the percentage of energy efficiency spending over GDP is lower than 0.01%; 1.6 if the percentage is in the range $0.01 \leq \% < 0.05$; 2.4 if the percentage is in the range $0.05 \leq \% < 0.1$; 3.2 if the percentage is in the range $0.1 \leq \% < 0.5$; and 4 if the percentage is greater than or equal to 0.5%

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Table 1.A.1. Continued.

No.	Question	Indicator		Scoring criteria
		1.	Institutional Arrangements	
4.	Does the Energy Efficiency agency promote actively plans or programmes? Is the Energy Efficiency agency supported by a proper legal basis?	1.1. *Implementing agencies*		The score is 0 if no national energy agencies have been found; 0.8 if despite the fact of the absence of national agencies, local or regional agencies can be found; 1.6 if national agencies are not supported by a legal basis; 2.4 if national agencies account with limited legal basis OR the legal basis is adequate but scarce programs are promoted; 3.2 if national agencies account with adequate legal basis AND the amount of programs promoted is adequate; 4 if the legal basis is abundant and programs are broadly promoted.
5.	Do energy providers play a null, discreet or significant role implementing policies and programmes based on Energy Efficiency?	*1.2. Role of energy providers*		The score is 0 if no plans or programmes aimed at improve energy efficiency and promoted by energy providers have been found; 1 if a scarce promotion of plans and programmes to improve energy efficiency have been detected, oriented to at least one of the main sector (residential, industry, buildings, transport, lighting, energy utilities, commercial/industrial equipment); 2 if a scarce promotion of plans and programmes to improve energy efficiency has been detected oriented to some important sectors; 3 if energy providers play a limited active role promoting numerous plans, programmes and actions to improve energy efficiency in the majority of the important sectors; and 4 if energy providers play a wide active role promoting numerous plans, programmes and actions to improve energy efficiency in the majority of the important sectors
6.	To what extent is promoted the stakeholder engagement?	*1.3. Stakeholder engagement*		The score is 0 if no regulation, plans and programmes which promote the stakeholder engagement have been found; 1.33 if the promotion of stakeholder engagement is extremely limited; 2.66 if it has been found regulation, plans or programmes which promote a weak stakeholder engagement (stakeholders are involved by surveys or similar methods); 4 if the regulation or programmes found promote a close engagement (committees, councils and working groups are constituted).
7.	Is the public-private sector co-operation properly promoted?	*1.4. Public-private co-op.*		The score is 0 if no programmes or regulation have been found to promote public-private co-operation; 1 if public-private co-operation is extremely limited; 2 if some programs promoting public-private coop. have been found but the amount of them is not enough adequate; 3 if an adequate amount of programmes or regulations have been detected promoting public-private sector co-operation in several of the main aspects (voluntary agreements, public-private partnerships, mobilising energy service companies and regulating end-use equipment); and 4 if abundant programmes or regulation have been detected promoting public-private sector co-operation in several of the main aspects.

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Table 1.A.1. Continued.

No.	Question	Indicator		Scoring criteria
			2.	Enabling Frameworks
8.	Have targets been set for the most important sectors? Have been the costs for these targets estimated?	*3.1.*	*Targets*	The score is 0 if targets have not been found; 1 if numerical targets have been found but for a very limited amount of the main sectors (one or two between residential, industry, buildings, transport, lighting, energy utilities, commercial or industrial equipment); 2 if numerical targets have been found for three or four of the main sectors; 3 if numerical targets have been found for five sectors or for four sectors including estimations of the costs; 4 if numerical targets have been found for all the main sectors or for five sectors including estimations of the costs.
9.	There are evaluation mechanisms or means to assess the outcomes of each strategy or action plan?	*3.2.*	Evaluation	The score is 0 if no evaluation mechanisms have been detected; 1 if evaluation mechanisms have been detected in less than 25% of strategic and action plans; 2 if evaluation mechanisms have been found for between 25% and 50% of strategic and action plans; 3 if evaluation mechanisms have been detected for between 50% and 75% of strategic and action plans; 4 if evaluation mechanisms have been found for a higher percentage of strategic and action plans.

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1.B. Strength and robustness of the index

In this appendix, we analyze the process of building the index. First, we assess whether a sufficient number of elements (indicators) have been incorporated in the construction of the index, and to what extent those indicators reflecting similar aspects have been grouped together. Secondly, we check whether the results of the baseline EEGI are robust to different aggregation and weighting alternatives.

The analysis begins by examining the construction of the index, that is, the groups of indicators and sub-indices. We use two measures: (i) Spearman's rank correlation (average inter-item correlation) and (ii) the scale of reliability coefficient (OECD, 2008; Dabla-Norris et al., 2012; Gisselquist, 2014;). On the one hand, the correlations analyze the relationship between the different indicators that make up the same sub-index or between the sub-indices that constitute the EEGI. Relatively low correlations, between approximately 0.15 and 0.50, report that the indicators are properly related without raising concerns about multicollinearity. On the other hand, the reliability coefficient takes values between 0 and 1 (the closest to 1, the higher the reliability). It is a positive function of average inter-item correlation and of the number of items included (Dabla-Norris et al., 2012). Values close to 1 indicate a strong robustness of the indicator.

We consider four alternative indices to check for robustness (Dabla-Norris et al., 2012). The first is our baseline index, which we denote by EEGI8-A1: it uses 8 indicators added first at the sub-index level and then at the general index level, all of them weighted equally. Second, we build an extended version of the baseline, denoted by EEGI9-A1, which includes an additional third indicator –Funding Mechanisms– into the first sub-

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index (thus, we also have an extended version of the Enabling Frameworks sub-index). This extension is available only for 18 European countries.[20] Third, we consider the versions EEGI8-A2 and EEGI9-A2, which differ from the EEGI8-A1 and EEGI9-A1 in that the different indicators are averaged directly without being added first in sub-indices.

Table 1.B.1 shows the results of the average inter-item correlation and the scale of reliability coefficient for the sub-indices and the four versions of the EEGI considered. The second column includes the estimated Spearman inter-item rank correlations; column 3 specifies the number of indicators of each sub-index, and column 4 shows the scale of reliability coefficient. In general, the figures shown for the Spearman rank correlations are similar to those obtained by Dabla-Norris et al. (2012), while the reliability coefficients are higher in our case.

Table 1.B.1. Robustness of the alternative indices for energy efficiency governance: average inter-item Spearman's Rank correlation and scale of reliability coefficient.

	Average inter-item Spearman rank correlation	No. of items	Reliability coefficient
Sub-indices			
Enabling frameworks	0.335	2	0.64
Enabling frameworks$_{extended}$	0.036	3	0.48
Institutional arrangements	0.371	4	0.71
Co-ordination mechanisms	0.369	2	0.66
Baseline EEGI (EEGI8-A1)	0.553	3	0.82
EEGI9-A1	0.316	3	0.67
EEGI8-A2	0.349	8	0.84
EEGI9-A2	0.235	9	0.84

Baseline EEGI (EEGI8-A1): Average of 3 sub-indices with 8 indicators; EEGI9-A1: Average of 3 sub-indices with 9 indicators; EEGI8-A2: Average of 8 indicators; EEGI9-A2: Average of 9 indicators

The average inter-item Spearman's rank correlation takes small and non-significant values when considering the extended versions of the index. For instance, the correlation for the indicators included in the extended Enabling Framework sub-index is 0.036, while

[20] The countries assessed in the extended versions of the EEGI are Austria, Belgium, Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Italy, the Netherlands, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Turkey and the United Kingdom. The data used comes from Janeiro, Groenenberg, Surmeli-anac, & Monschauer (2016).

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it rises to 0.335 in the baseline situation. A similar result is obtained for the reliability coefficient, where the extended sub-index performs worse than the baseline one. Thus, according to this analysis, the index constructed with 8 indicators is more robust than the index constructed with 9 indicators; moreover, the former provides information for a larger sample of countries. The alternative strategies to aggregate the sub-indices (i.e., comparing EEGI8-A1 with EEGI8-A2, or EEGI9-A1 with EEGI8-A2) do not make a big difference. Therefore, we can conclude that the baseline EEGI (EEGI8-A1) is a robust and recommended alternative.

Our second robustness check relies on alternative weighting strategies. This test consists of assessing whether the EEGI scores are modified (and to what extent) if we choose a different weighting method. Thus, in addition to the four indices explained above, four additional variants have been constructed. Now, we use a Principal Components Analysis (PCA) for weighting the sub-indices and indicators, obtaining other four versions of the index: EEGI8-A1-PCA, EEGI9-A1-PCA, EEGI8-A2-PCA and EEGI9-A2-PCA. Table 1.B.2 collects the rankings of these 8 versions of the index.[21]

[21] The rankings are used instead of the original scores since the numerical scores of PCA are measured in a very different scale, which would difficult the understanding of the results.

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Appendix 1

Table 1.B.2. Country ranking for different EEGI versions.

Country	Ranking							
	EEGI8-A1	EEGI9-A1	EEGI8-A2	EEGI9-A2	EEGI8-A1-PCA	EEGI9-A1-PCA	EEGI8-A2-PCA	EEGI9-A2-PCA
Germany	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0
France	2.5	2.0	2.5	2.0	3.0	2.0	3.0	1.0
Denmark	2.5	-	2.5	-	2.0	-	1.0	-
Sweden	4.0	-	4.0	-	4.0	-	8.0	-
New Zealand	5.0	-	8.5	-	8.0	-	9.0	-
Italy	6.0	3.0	8.5	3.0	6.0	3.0	7.0	4.0
UK	7.0	5.0	6.0	4.0	7.0	4.0	6.0	3.0
Canada	8.0	-	5.0	-	5.0	-	4.0	-
Spain	9.0	4.0	10.0	5.0	10.0	5.0	10.0	5.0
USA	10.0	-	7.0	-	9.0	-	5.0	-
Japan	11.0	-	11.0	-	11.0	-	11.0	-
Hungary	12.0	7.0	15.0	9.0	12.0	8.0	14.0	7.0
Belgium	13.0	9.0	12.5	7.0	13.0	9.0	12.0	6.0
Czech Rep.	14.0	6.0	16.5	8.0	14.0	6.0	17.0	12.0
Australia	15.0	-	12.5	-	15.0	-	13.0	-
Portugal	16.0	10.0	16.5	10.0	16.0	10.0	16.0	10.0
Ireland	17.0	8.0	14.0	6.0	17.0	7.0	15.0	8.0
Finland	18.0	11.0	18.0	11.5	18.0	11.0	18.0	9.0
Norway	19.0	-	19.0	-	19.0	-	20.0	-
Korea	20.0	-	20.0	-	20.0	-	21.0	-
Netherlands	21.5	12.0	21.0	13.0	22.0	12.0	19.0	11.0
Luxembourg	21.5	-	24.0	-	21.0	-	23.0	-
Turkey	23.0	16.0	22.0	15.0	24.0	14.0	24.0	13.0
Austria	24.0	13.0	23.0	11.5	23.0	13.0	22.0	14.0
Poland	25.0	14.0	25.0	16.0	25.0	15.0	25.0	15.0
Slovak Rep.	26.0	15.0	26.0	14.0	26.0	16.0	26.0	17.0
Greece	27.0	17.0	27.0	17.0	27.0	17.0	27.0	16.0
Switzerland	28.5	-	28.0	-	28.0	-	28.0	-
Mexico	28.5	-	29.0	-	29.0	-	29.0	-
Chile	30.0	-	30.0	-	30.0	-	30.0	-
Slovenia	31.5	18.0	31.5	18.0	31.5	18.0	31.5	18.0
Estonia	31.5	-	31.5	-	31.5	-	31.5	-

Baseline EEGI (EEGI8-A1): Average of 3 sub-indices with 8 indicators; EEGI9-A1: Average of 3 sub-indices with 9 indicators; EEGI8-A2: Average of 8 indicators; EEGI9-A2: Average of 9 indicators; EEGI8-A1-PCA: PCA of 3 sub-indices with 8 indicators; EEGI9-A1-PCA: PCA of 3 sub-indices with 9 indicators; EEGI8-A2-PCA: PCA of 8 indicators; EEGI9-A2-PCA: PCA of 9 indicators

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1.C. Further results on the Energy Efficiency Governance Index

We describe next some aspects of interest related to the EEGI results that, for reasons of space, were not detailed in the main document. First, we analyze the relationship between the EEGI and its sub-indices. Next, we assess in more detail the case of some countries that offer striking results. Finally, we examine the sensitivity of the EEGI score with respect to the number of entries available in the database for each country.

If we compare the different areas of the EEGI, the average value of the sub-indices Enabling Frameworks, Institutional Arrangements and Coordination Mechanisms sub-indices is 2.48, 1.94 and 2.83, respectively. The score in the third area is, on average, the highest. This fact highlights the growing interest in establishing objectives and monitoring results as a means to promote energy efficiency. As expected, a positive and significant correlation is observed between the baseline EEGI and its three sub-indices (the average correlation is 0.858, significant at 1%). Specifically, the indicator of Laws & Decrees (within the first sub-index) is the one that seems to maintain a greater relationship with the EEGI score.

However, there are some interesting cases to be discussed. The first is Canada, located in Q1 in the sub-indices Enabling Frameworks and Institutional Arrangements, but in Q3 for Coordination Mechanisms. The same is valid for The US, although it is located in Q2 for the third sub-index. Other examples to highlight are New Zealand and Australia, for which each sub-index is located in a different quartile: Enabling Frameworks in Q3, Institutional Arrangements in Q2 and, finally, Coordination Mechanisms in Q1.

In general, there is significant variability in the energy efficiency governance quality

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score when comparing countries, and also when analyzing each of the three areas considered. This variability is a good symptom to measure the usefulness of an index of these characteristics. Thus, for example, we find countries such as Denmark, which has high scores in all areas, or the opposite cases in Chile or Estonia, which show low scores in the three areas. There are also intermediate situations, such as Spain, with high scores in the areas of Regulatory Framework and Coordination Mechanisms, but low in the corresponding Institutional Agreements. Even, cases like those already mentioned in Australia and New Zealand. Finally, the results for Slovenia, Estonia, Mexico and Chile should be interpreted with caution, due to the limited information found for these countries.

To conclude the description of our results, it is important to analyze the correlation between such results and the number of entries available for each country in the database (recall Table 1). In this sense, having a reduced (or high) number of regulations and programs may be indicative of a lower (or greater) degree of energy governance. However, as we see below, the existing correlation is far from perfect. For the total sample, the correlation is 0.6, significant at 1%. It seems logical to find that countries with the lowest number of entries (Slovenia, Estonia, Mexico or Chile, which have less than 10 entries in the database) obtain much lower scores than other countries with the highest number of entries (Canada, USA or Germany, which have more than 100 entries). However, if we calculate the correlation for groups of countries with similar index values (dividing the sample by quartiles, Q1, Q2, Q3 and Q4), the results are different. In fact, the correlation is not significant between countries in Q1 and Q3, while it is only 0.32 for those in Q2. On the other hand, the correlation is only high and significant among the countries belonging to Q4 (0.77). In the analyses carried out in Section 5, we take into account this

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anomalous behavior of the countries in Q4 and we demonstrate that it does not affect to our results, since they remain consistent even when we control our models for the number of entries (results available upon request).

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1.D. Energy governance and other related metrics

We analyze the correlation of the EEGI with the WGI published by the World Bank for our set of 29 OECD countries and 2000-2015 (see Figure 1.D.1). This analysis is useful to check whether these governance indexes are measuring different aspects, as already pointed out by the IEA (2010).

We use the normalized version of the WGI, which goes from -2.5 (the lowest governance) to 2.5 (the highest governance). The correlation between both governance indices is positive (0.37). On average, countries with lowest WGI values (close to 0.5) are associated with levels of our EEGI of about 1.5 and 2.5, while countries with the highest WGI (close to 2.0) has associated average values of the EEGI higher than 2.5. For instance, Denmark, Sweden and Germany belong to the Q1 for both measures, while Mexico, Greece and Poland are countries with among the lowest levels of both the WGI and the EEGI. However, some countries stand out for showing a much higher EEGI score than its WGI level, such as Italy or France (with relatively low levels of the WGI in comparison with their high levels of the EEGI), and some others with a much lower score, such as Switzerland (with the highest WGI and with an EEGI of 1.52). Nevertheless, this correlation is far from being perfect, what is consistent with the theoretical framework exposed in IEA (2010). This report states that a distinction must be stated between the general governance and the governance of EE, since they measure different things. This aspect, now empirically tested, reinforces the interest of our EEGI.

To put the scatter plot between EEGI and the WGI in perspective, Figure 1.D.2 presents the correlation between the average value of per capita GDP (in logs) and the EEGI between 2000 and 2015. The correlation is positive (0.47) and significant at 1%

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level, which is even slightly higher than the correlation between the EEGI and the WGI. Countries with the lowest per capita GDP in our sample (about 18,000-20,000 USD) are associated with average values of the EEGI between 1.5 and 2.0, while countries with highest per capita GDP (close to 45,000 USD) has associated average values of the EEGI higher than 2.5. For instance, the graph shows that Denmark is in the Q1 for both the EEGI and the per capita GDP, while Belgium, Spain or South Korea are in the Q2 and Q3 for both variables, and Estonia and Slovak Republic are in the fourth.

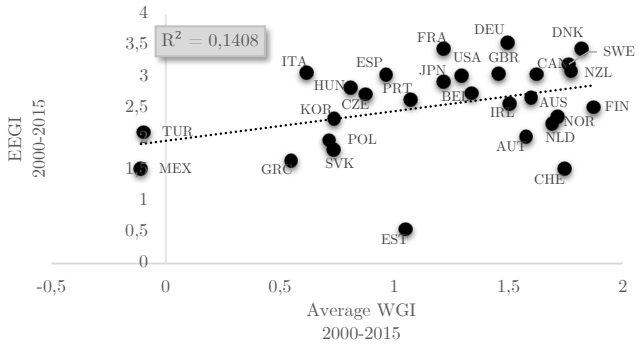


Figure 1.D.1. EEGI vs average World Governance Index between 2000 and 2015.

Source: Own elaboration. Data on the WGI has been extracted from the World Bank's database.

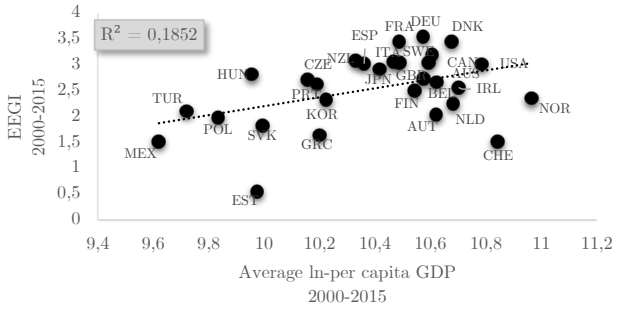


Figure 1.D.2. EEGI vs average ln-per capita GDP between 2000 and 2015.

Source: Own elaboration. Data on per capita GDP has been extracted from the IEA's World Energy Balances database (2018).

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Chapter 2

Energy efficiency and energy governance: A stochastic frontier analysis approach

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1. Introduction

Improving Energy Efficiency (EE) is a primary objective in the energy policy in OECD countries, as it is one of the most cost-effective ways to reduce greenhouse gases and energy dependence, and to guarantee the security of supply (IEA, 2019). However, the effectiveness of these policies is conditioned by the existence of regulatory failures, an improper coordination between the government and the private sector or the lack of specific laws that correctly incentivize improvements in EE (Gillingham, Newell, & Palmer, 2009). For this reason, the International Energy Agency (IEA), in its report from 2010, highlights that the success of energy policies aimed at improving EE is closely related to the performance of energy governance (IEA, 2010). Furthermore, the report emphasizes the importance of analyzing and measuring energy governance (more specifically, EE governance) separately from the general governance of a country, highlighting up to three main areas: the regulatory framework, institutional agreements and coordination mechanisms of EE policies.[22]

As stated in Chapter 1, the impact of general governance on the economy has been widely studied in the literature (Acemoglu, Johnson, & Robinson, 2001, among many others), whereas the effect of energy governance on the energy sector has been analyzed to a much lesser extent (Pereira & Pereira Da Silva, 2017). This fact can be partially explained because general governance is properly measured by well-known indexes (e.g., World Governance Index –WGI– or Polity IV), while there is rather scarce quantitative

[22] Despite the fact that IEA (2010) describes the environment underpinning EE governance, many of the measures mentioned are related to energy policy in general, rather than to EE in particular. Therefore, in this paper we will use the terms of EE governance and energy governance interchangeably.

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information on energy governance.[23] In this sense, following IEA (2010), in Barrera-Santana, Marrero & Ramos-Real (2020) and in Chapter 1 we built a composite index of EE Governance (the EEGI) for 32 OECD countries and representative for the period comprised between 2000 and 2015, using information about strategic plans, laws and decrees, or financing mechanisms, among others. The objective of this work is to use the EEGI to quantify, for the first time in the literature, the impact of energy governance on EE in OECD countries for the aforementioned period.[24] Furthermore, we will also compare our results with the most commonly used efficiency measure in the literature: Energy Intensity (EI).

Our work draws on the theoretical framework developed by Filippini & Hunt (2011), who adapt the parametric Stochastic Frontier Analysis (SFA) proposed by Aigner, Lovell, & Schmidt (1977) to energy demand. The result is a frontier that represents the optimal level of derived demand for energy, measured through aggregate primary energy consumption. The location of each country with respect to such a frontier provides a measure of EE.

The SFA has acquired remarkable relevance in the last decade in the field of energy (Tovar, Ramos-Real, & de Almeida, 2015; Filippini & Hunt, 2016).[25] On the one hand,

[23] Among others, Park (2015) analyzes the effect of energy policies on the development of renewable energies using general governance indicators (e.g., the existence of democratic governments); Filippini, Hunt, & Zorić (2014) study the impact of four types of energy policy on the EE levels in the EU-27 countries; Saussay, Saheb, & Quirion (2012) evaluate the effect of building codes on EE in a sample of European countries. However, none of these works use energy governance indicators. Likewise, they are limited to the evaluation of a very small group of policies. Therefore, these quantitative studies do not actually provide a proper assessment about the impact of energy governance on the energy sector.

[24] Despite the absence of studies that truly analyze the impact of governance on the energy sector, some interesting descriptive papers exist: Haley, Gaede, Winfield, & Love (2020) identify the key elements of energy governance for an effective transition to low-carbon societies; Ringel & Knodt (2017) analyze the role of energy governance in the acceptance of European Union (EU) energy policies; Pereira & Pereira Da Silva (2017) classifies a sample of countries according to the degree of compliance with their energy policies ; Jollands, Heffner, Pasquier, & Saussay (2011) develop a comprehensive review of the key points for good EE governance.

[25] Although less common, some papers also use non-parametric frontiers, based primarily on the Data Envelopment Analysis (DEA) technique. See Mardani et al. (2017) for a more detailed discussion.

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it is an alternative strategy to the use of EI as a measure of EE, since the SFA overcomes the criticism made of EI (see Adom, Amakye, Kwabena Abrokwa, & Quaidoo, 2018).[26] On the other hand, this methodology imposes a functional form on the demand function, which provides three fundamental advantages very convenient for our application: (i) the efficiency estimates are more precise with respect to other alternative procedures (Filippini, Hunt, & Zorić 2014); (ii) the SFA reduces bias due to unobserved heterogeneity (Greene, 2015); (iii) external factors (e.g., the EEGI) can be included in the parametric function to explain EE (Filippini & Hunt, 2015).

We introduce the EEGI as an explanatory factor of the EE level in the three SFA specifications most widely used in the literature: Battese & Coelli (1995) (BC95), Greene's fixed effects (TFE) model (Greene, 2005a) and Greene's random effects (TRE) model (Greene, 2005b). However, since these methodologies show relevant concerns that should be addressed, we introduce three alternative approaches: the Marginal Maximum Likelihood Estimator (MMLE), proposed by Chen, Schmidt, and Wang (2014); the Marginal Maximum Simulated Likelihood Estimator (MMSLE) and the Pairwise Difference Estimator (PDE), both proposed by (Belotti & Ilardi, 2018).[27] As far as we are aware, these last two approaches have not been applied before to estimate an EE frontier.

Our results show a highly significant and positive effect of energy governance on EE. Increasing the EEGI score by 10% –an amount that can be interpreted as an acceptable

[26] Changes in EI can be due to climate variations, economic restructuring or changes in the EE itself, for example (Adom, 2015; Huang, Hao, & Lei, 2018). To correct this effect, some authors use the Index Decomposition Analysis (IDA), which is in principle a Bottom-up framework that allows the disaggregation of EI into different components that capture these effects separately (Su and Ang 2017).

[27] For instance, BC95 and TRE are sensitive to unobserved heterogeneity, while TFE suffers from the incidental parameters problem (i.e., its efficiency estimates may be biased for large panel data sizes).

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goal in the medium or long term in OECD countries– could raise the EE level, on average, around 9.20% according to the PDE model and up to 27% in TRE.[28] In the most efficient countries, energy governance is characterized by the presence of both measurable (i.e., quantified) targets and extensive evaluation mechanisms. To a lesser extent, these countries also show a broad number of public-private co-operations, a well-developed regulatory framework and energy providers highly involved in energy policy.[29]

This work contributes to the literature on energy economics in several aspects. First, we provide an unprecedented and thorough assessment of the role of energy governance (and different specific energy policies) in the EE level for a large sample of OECD countries. Secondly, the work also contributes to the definition and estimation of EE through the SFA, since the use of our EEGI improves the accuracy of the econometric models by reducing the bias due to the heterogeneity of unobserved variables. Moreover, we contribute in the use of novel SFA approaches (Chen et al., 2014; Belotti & Ilardi, 2018), which overcome some of the problems raised by traditional methods, and also in the endogeneity assessment between relevant variables of the analysis, which is a relatively new concern in the SFA literature (Karakaplan & Kutlu, 2017; Karakaplan, 2017).

The remainder of this paper proceeds as follows. The construction of the EEGI is explained in detail in Chapter 1 and in Appendix 1, so next we directly describe the methodology used in this chapter in Section 2. In Section 3 we estimate the effect of the

[28] The available information on energy governance prevents the construction of a time-varying EEGI, which is an important weakness that should be addressed, since it may lead to biased estimates. This pitfall is partially overcome by constructing two time-varying versions of the index through its interaction with both world oil price series (Ciccone et al. 2012) and a general governance index.

[29] These findings prevail across the use of different SFA models and time-varying versions of the EEGI. The result is consistent with the use of a regression approach in which EI is decomposed using an Index Decomposition Analysis (IDA). Likewise, we also demonstrate that these estimates are not seriously affected by an endogeneity bias of the regressors (Karakaplan & Kutlu 2017).

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EEGI on EE drawing on different SFA models. In Section 4, we assess different indicators included in the construction of the EEGI, to analyze the most effective energy policies for improving the countries' efficiency. Finally, we provide a set of final remarks.

2. Methodology: The stochastic frontier analysis

We propose a Stochastic Frontier Analysis (SFA) in order to assess the impact of energy governance on EE estimates. This analysis also allows us to characterize the effectiveness of different energy policies in a cross-country comparison.

The analysis of the evolution of EE using the EI as a proxy is a common practice in the literature (Metcalf 2008). However, changes in EI may be due to other factors that have nothing to do with the evolution of EE. Therefore, the empirical analysis should identify changes due exclusively to EE (i.e., the efficiency component) from other changes related to sectoral changes (i.e., the activity component). The Index Decomposition Analysis (IDA) is the methodology commonly used to separate out structural shifts in the economy from more fundamental improvements in the use of energy (see Metcalf, 2008; Mulder & De Groot, 2012; Marrero & Ramos-Real, 2013), among others). However, this approach is very dependent on the availability of sectoral energy demand and economic activity data, which can lead to unreliable decompositions (Alghandoor et al. 2008; Zahur 2013; Grossi & Mussini 2017).[30] In addition, the variation of the efficiency component may be due to other factors that have nothing to do with EE, such changes

[30] The components of EI are only based on the economic and energy structure of a given country in a specific point in time. Important economic interactions between variables like GDP, energy consumption or energy prices are disregarded. In addition, the information corresponding to cross-country variation is lost in this type of analysis, so the scope of its results is much more limited. Moreover, EI changes can also be affected by changes in the combination and form of the final energy used (e.g., electricity or gas) due to differences in productivity between the different types of energy (Ma and Stern 2008).

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in the weather of the country, or structural changes within each sector not properly captured without a very detailed decomposition by economic activities. Therefore, as Filippini & Hunt (2015) points out, it is difficult to make conclusions about EE based upon the exclusive analysis of EI. Instead, these authors have opted to measure EE using the SFA approach, which is the one considered in this paper.[31]

In the SFA framework, the energy demand function is theoretically derived from the solution of a minimization input cost function to produce a particular level of output and subject to a given technology (Kopp 1981). Thus, the resultant (aggregate) demand for energy (an input in the production process) is derived from the demand of outputs, such as goods, services or final energy services, such as heating, cooling and lighting (Filippini & Hunt 2011). The SFA provides information on the difference between the observed use of energy and the optimal use of energy (i.e., on the frontier) corresponding to the solution of the aforementioned minimizing cost problem. This difference can be interpreted as an approximated measure of energy inefficiency (Filippini & Hunt, 2011 and 2015).[32]

Following Kopp (1981), the seminal work of Filippini & Hunt (2011) adapts the SFA function presented by Aigner et al. (1977) to an aggregate energy demand function. We follow Filippini & Hunt (2011) and estimate the following reduced energy demand function, for a panel of 29 OECD countries and between 2000 and 2015:

[31] However, in Appendix 2.C, we conduct a simple EI regression model, taking into account an IDA approach, which properly justifies the importance of SFA as an alternative measure of EE, and confirms many of the pitfalls of using EI as an indicator of inefficiency.

[32] The model in Filippini & Hunt (2011) is an ad-hoc model, since it does not consider the theoretical restriction imposed by production theory and it estimates one input demand frontier function. According to Kumbhakar & Lovell (2000), the difference between the observed input and the cost-minimizing input demand (derived from a production function) represents both technical and allocative inefficiencies. However, the approach also provides information on the overall inefficiency (i.e., on the efficiency level), as it measures the difference between optimal energy use and the observed level.

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$$e_{it} = \alpha^0 + \alpha^p p_{it} + \alpha^y y_{it} + \alpha^{pop} pop_{it} + \alpha^c Cold_i + \alpha^o Oceanic_i + \alpha^{co} Continental_i + \alpha^a a_i + \alpha^I ISH_{it} + \alpha^S SSH_{it} + \alpha^{UR} UR_{it} + \delta^t D_t + \varepsilon_{it} \quad (1)$$

where e_{it} is the ln-aggregate primary energy consumption (ktoe), p_{it} represents the actual ln-index of energy prices (reference in 2010), y_{it} is the ln-GDP (billions of 2010 USD PPP), pop_{it} is the ln-population (in millions of inhabitants) and a_i the ln-area of the country in question (expressed in km^2). On the other hand, the variables ISH_{it}, SSH_{it} and UR_{it} represent the Gross Added Value (GVA) ratio of the industrial and services sectors over GDP, and the urbanization rate, respectively; $Cold_i$, $Oceanic_i$ and $Continental_i$ constitute dummies for cold, oceanic and continental climates, respectively; D_t is a linear temporal trend related with time-varying factors that are common to all countries, such as energy technical progress.[33] One of the main advantages of this methodology is that it enables differentiation of the unobserved heterogeneity to analyze the level of EE by country (Greene, 2015). In Equation 1, the compound error term ε_{it} is made up of two types of errors:

$$\varepsilon_{it} = u_{it} + v_{it}, \quad (2)$$

where v_{it} represents a random disturbance that is normally distributed, $v_{it} \sim iid\ N(0, \sigma_v^2)$; secondly, u_{it}, represents the level of underlying energy inefficiency for each country-year. The u_{it} term changes over time and it is positively truncated, by imposing that no country can be located above the frontier. The distribution of this term may vary according to the model used (e.g., exponential, truncated-normal or half-normal). The ratio between the standard deviations of u_{it} and v_{it} (σ_u/σ_v) is used as a

[33] In the sample, important countries with oceanic and continental climates were detected according to the Köppen-Geiger classification (e.g., France, Germany or the United Kingdom). For this reason, we decided to control using these climate dummies to capture relevant effects of different climates on EE, rather than of using only cold and hot dummies.

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signal-to-noise ratio (λ) to measure the accuracy in estimating inefficiency. Similarly, the standard deviation of the compound error term is sometimes used instead (i.e., $\sigma_\varepsilon = \sigma_u + \sigma_v$).

The main objective of the SFA is to properly estimate the level of inefficiency: it provides a measure of the difference between the efficient energy demand at the frontier in year t (E_t^F) and the actual aggregate demand of country i in year t (E_{it}). Then, EE is measured as the ratio $E_t^F/E_{it,}$, which takes values between zero and one: one indicates that the observation is on the frontier, so it has maximum efficiency (or null inefficiency). Following Aigner et al. (1977), this ratio can be expressed as follows:

$$EE_{it} = E_t^F / E_{it} = exp\ (-\hat{u}_{it}). \quad (3)$$

In the standard model presented above, u_{it} and v_{it} are homoskedastic (i.e., they do not depend on any variable). However, since we want to analyze the effect of the EEGI (i.e., energy governance) on EE, we follow Battese & Coelli (1995) and modify Equation 2 to include the EEGI as an explicative factor of u_{it} (i.e., u_{it} is now heteroskedastic),[34]

$$u_{it} = \beta Z_{it} + \omega_{it}, \quad (4)$$

where Z_{it} represents the explanatory factors of u_{it} that, in our case, is the EEGI; ω_{it} is a random error, $\omega_{it} \sim iid\ N(0, \sigma_\omega^2)$. We estimate simultaneously Equations 1, 2 and 4 (see previous comments on the drawbacks of using a time-invariant EEGI).

Filippini et al. (2014) identifies three alternatives to estimate this model: (i) the pooled model proposed by Battese & Coelli (1995) (BC95), (ii) the true fixed effects model (TFE) and (iii) the true random effects model (TRE); these last two models were

[34] In all our models we consider that v_{it} is homoskedastic. The reason behind this is that ignoring heteroskedasticity in the random error term (v_{it}) still gives consistent estimates of the frontier function parameters, while ignoring heteroskedasticity in u_{it} would cause biased estimates of the frontier's parameters as well as the estimates of technical inefficiency (Kumbhakar and Lovell 2000).

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proposed by Greene (2005a and 2005b). We consider these three traditional alternatives in our analysis, together with other three more novel approaches, as discussed below.[35]

The TFE and TRE models introduce fixed and random individual effects, respectively. Although these effects should take into account all the unobserved socio-economic and environmental characteristics that are time-invariant, the estimated inefficiency overlooks the persistent inefficiencies that remain more or less constant over time, which may lead to a relatively high level of EE estimates. Furthermore, the TRE and BC95 models can suffer from unobserved heterogeneity bias, because of the unobserved characteristics may not be distributed independently of the explanatory variables (Filippini et al. 2014). The time-invariant explanatory variables introduced in Equation 1 (i.e., the land area and climate dummies) are expected to partially capture this unobserved heterogeneity.

Likewise, the TFE is also subject to the "incidental parameters problem", which implies that estimators may be inconsistent and subject to a small sample bias for large panel data sizes (Greene 2005a). While this issue does not affect the frontier coefficients, it can affect the inefficiency and random error estimates, which may underestimate σ_v and overestimate σ_v, and thus bias EE estimates. However, given the size of our data, a rather small bias is expected (Chen et al. 2014). To overcome the potential problems in traditional TFE models, we have expanded upon the work of Filippini et al. (2014) and have considered three alternatives. The first one is the approach proposed by Chen et al. (2014), who develop a consistent Marginal Maximum Likelihood Estimator (MMLE) for the TFE model exploiting a within-group data transformation and the properties of the

[35] The BC95 model only admits a truncated-normal distribution for the inefficiency parameter. For a simple matter of homogeneity, the results we present relative to other models draw on this same distribution. However, as described in Section 4, these results are robust to other distributions of the inefficiency parameter.

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closed skew normal class of distributions. However, this model restricts both error components (u_{it} and v_{it}) to be homoskedastic, a strong assumption that may be easily violated in practice (Belotti & Ilardi 2018). In this sense, Belotti & Ilardi (2018), motivated by the fact that homoskedasticity of u_{it} is not a realistic assumption, propose an extension to the MMLE model. The first one is the Marginal Maximum Simulated Likelihood Estimator (MMSLE) estimated from the marginalization of the inefficiency term. The main contribution of this specification is that it can be used to estimate both homoskedastic and heteroskedastic models. The second alternative, the Pairwise Difference Estimator (PDE), reduces the computational requirements of the MMSLE model. It draws on all pairwise quasi-likelihood contributions in the model, and it requires at least one error term (u_{it} or v_{it}) to be heteroskedastic.

Among these alternatives, only the MMLE approach have been used in the field of energy economics. Hence, using these alternative approaches, together with the traditional BC95, TFE and TRE models, is a contribution of this work in the energy economics literature.

3. Results: Effects of energy governance on energy efficiency

We start this section presenting the data used to estimate the energy demand function (Equation 1). Then, for alternative SFA models, we show the estimated results of this function and characterize the relationship between the EEGI and EE. We finish showing the EE estimates for each country and analyzing its average time evolution.

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3.1. Data

Our sample is a set of 29 OECD countries between 2000 and 2015 (countries are described in Chapter 1). We construct a yearly panel data and use homogenous sources for all variables included in the energy demand function (Equation 1). Table 12 summarizes the descriptive statistics of these variables for our entire sample.

Table 12. Descriptive statistics.

Variable	Description	Units	Mean	Std Dev	Min	Max	Obs	Source
E_{it}	Primary energy consumption	kToe	183.12	405,99	4,710	2,337,370	456	IEA
Y_{it}	GDP	Billion 2010 USD PPP	1,439	2,701	20.86	16,597	456	IEA
POP_{it}	Population	Million inhabitants	41.00	59.71	1.31	321.7	456	IEA
A_i	Land area	Km^2	1,177	2,660	31.32	9,590	456	IEA
EI_{it}	Energy Intensity	Mtoe/Billion USD	0.121	0.038	0.049	0.226	456	IEA
Y_{it_pc}	Per capita GDP	10^3 USD per capita	34.283	10.725	12.305	60.597	456	IEA
P_{it}	Energy prices	Index (base. 2010)	94.51	12.64	65.8	125.9	456	IEA
ISH_{it}	Share Industrial GVA over GDP	n.u.	25.75	5.13	13.68	40.27	456	WB
SSH_{it}	Share Service GVA over GDP	n.u.	62.22	6.15	48.13	76.38	456	WB
UR_{it}	Share urban population over total population	n.u	75.72	10.16	53.89	97.88	456	WB
$EEGI$	EE Gov. Index	n.u.	2.54	0.677	0.55	3.55	456	[a]

Source. IEA: World Energy Balances (2018); OE: Own Elaboration; WB: World Development Indicators Database (2019).
[a] Barrera-Santana et al. (2020).

Following the SFA literature (Filippini & Hunt 2011), aggregate variables (energy consumption and GDP) are included in log-levels, while population and land area (both in logs) are included as additional explicative variables to control for the size of the country. These variables come from the IEA's World Energy Balances database. In the table, for illustrative purposes, we also present the EI (energy/GDP) and the GDP per capita (GDP/Population). The information for the energy prices index is obtained from the IEA's World Energy Prices database, and it draws on different energy sectors (e.g.,

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industrial and households) and different energy sources (e.g., oil, coal o heavy fuel-oil, among others), taking 2010 as the reference year. The source of the remaining explicative variables (e.g., the share of industrial and service GVA, and the share of urban population over total population) is the World Bank's World Development Indicators database.

Our sample shows significant variability in most of these variables. Large differences are observed in the aggregate variables, which are conditioned by the population size of the country.[36] A similar picture is shown for real GDP and population. Nevertheless, if we look at these variables in relative terms (i.e., Energy/GDP and GDP/population), the heterogeneity observed in the sample is also remarkable. For instance, the country with the lowest average EI is Switzerland (0.066 Mtoe/Billion USD), the country with the highest one is Canada (0.202 Mtoe/Billion USD) and countries such as Australia or Sweden show an EI level close to the average of the sample (0.121). If we look at per capita GDP (in kUSD per habitant), the lowest level corresponds to Mexico (15.09), the highest to Norway (57.86), and countries such as France or Japan are in the average of the sample (34.28). A closer inspection of these two series reveals a negative correlation between EI and per capita GDP for the entire pool of data (-0.199).

In addition to these important differences between countries, we observe that these variables are non-stationary, hence their variability over time is also very important. Figure 4 summarizes these trends (normalizing at 100 in 2000), showing the average yearly evolution of primary energy consumption, real GDP, population and energy prices. A more exhaustive exploration of these data reveals that energy, GDP, population and prices show a unit root (i.e., their first differences are stationary), as frequently happens

[36] For instance, the minimum energy consumption (4,710 kToe) corresponds to Estonia in the year 2000, the maximum (2,337,370 kToe) to USA in 2007, while the average is 183,12 kToe, a value close to the average energy consumed by Italy.

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in SFA applications using aggregate panel data (Filippini & Zhang 2016).[37]

With respect to the remaining set of variables, we highlight the following aspects. We have countries with totally different sectoral structures. For instance, the minimum share of Industrial GVA over GDP (13.7%) corresponds to Greece in 2011, while the maximum Industrial share is about 40% and corresponds to Norway in 2008; the minimum share for the service sector (48%) corresponds to Norway in 2006. The urban rate is also very different between countries. For instance, the minimum average urban rate corresponds to the Slovak Republic (55%), while the maximum, to Belgium (97.5%).

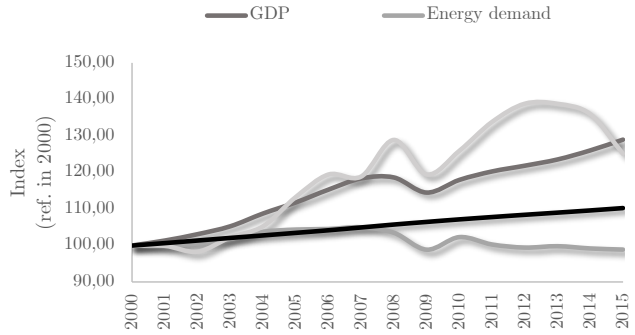


Figure 4. Trends in GDP, energy demand, energy prices and population

Source: Own elaboration. Data on per capita GDP has been extracted from the IEA's World Energy Balances database (2018).

3.2. Energy demand function and the effect of the EEGI on energy efficiency

We show next the estimation results of the energy demand function for the SFA models defined in Section 2 (Equations 1, 2 and 4). Table 13 shows results for both the traditional models (i.e., BC95, TRE and TFE) and the set of alternative novel fixed

[37] We have conducted a variety of tests for unit roots in panel datasets (Harris and Tzavalis 1999; Breitung 2000; Choi 2001; Levin, Lin, and Chu 2002; Im, Pesaran, and Shin 2003; Breitung and Das 2005). Most of them fails to reject the null hypothesis, which states that there is a unit root in the panel dataset, for GDP, energy demand, population and energy prices (p-values ranging from 0.703 to 0.9997). However, the corresponding first-differenced variables are stationary (p-values ranging from 0.000 to 0.04).

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effects specifications (i.e., MMLE, MMSLE and PDE). These latter models correct the potential incidental parameters problem presented by the traditional TFE approach. This analysis provides also robustness to our results to alternative SFA specifications.

For each model, we show two columns of results. In the first one, we do not consider the EEGI in the estimation of EE in Equation 4, while, in the second column, we include the EEGI and show the estimates of β, which determines the effect of energy governance on energy inefficiency. Regarding the MMLE and PDE models, as explained in Section 2, the former do not allow inefficiency to vary with respect to any variable, while the latter only allows the heteroskedastic specification. Since the PDE model is an extension of the MMLE model, we set the results of both specifications together (column 1 for MMLE, and column 2 for PDE). For all cases, we show the estimates of the standard deviations of the different error terms (e.g., σ_u, σ_v and σ_ε) as well as the signal-to-noise ratio λ.

We start commenting the estimated results of the explicative variables included in the energy demand function (Equation 1). In general, they show the expected sign, and most of them are statistically significant and consistent between the different models. A remarkable exception is the sign of the energy prices' coefficient in the BC95 model, which is positive (first column in Table 13), contrary to economic theory. However, this sign turns negative when introducing the EEGI in the model (second column). A similar result for energy prices was found by Filippini et al. (2014). This result can be related to the fact that BC95 is more sensitive to unobserved heterogeneity bias (the EEGI in our case). The estimated coefficients for energy prices in all other models are negative, significant and their absolute values are clearly smaller than one (i.e., the demand is strongly inelastic): an increase of 1% in the energy prices is associated with a reduction

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of consumption between 0.06% (in MMSLE, first column, and PDE) and 0.09% (in TFE, second column). The signs of the GDP coefficients are always positive and significant, with an estimated elasticity between 0.56 (in TFE, first column) and 0.68 (in TRE, first column). The same occurs with the population and country size coefficients, the average elasticities are 0.50 and 0.02, respectively.[38]

The estimated coefficient of *UR* (positive and significant) is consistent and homogeneous to the alternative models considered. However, the estimated coefficients for *ISH* and *SSH* show some differences between the different models estimated. For instance, ISH is not significant in all fixed effects specifications (TFE, MMSLE, MMLE, PDE), while they are positive for BC95 and TRE; SSH estimated coefficients are positive for BC95 and TRE, while they are negative for fixed effects specifications. Probably, since *ISH* and *SSH* show little variation over time, they are strongly correlated with fixed effects and this fact strongly alters their estimates depending on whether true fixed effects are included or not in the model. Finally, the time trend (D) is significant and negative in all cases, which points to the existence of a common trend in all countries of a gradual reduction in aggregate demand for primary energy. The existence of a common and log-linear technological innovation process and common measures related with the rational use of energy in our sample explains this result. According to our estimates, this effect has implied an average annual reduction in energy consumption between 1% and 2%.

[38] Neither the size of the country and the climate dummies (i.e., the fixed effects variables) are included in the set of fixed effects models (TFE, MMSLE, MMLE, PDE), since their influence is already captured by the time-invariant country specific effects (Filippiniet al. 2014). Thus, the influence of these variables is analyzed in the estimated results of BC95 and TRE: cold or continental climatic zone is associated with an energy consumption that is approximately 48% higher, on average, than when the zone is neither cold nor continental; belonging to an oceanic climatic zone is associated with around 26% more energy consumption. Energy consumption is inelastic with respect to all these variables, as Filippini & Hunt (2011) and Filippini et al. (2014) demonstrate.

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Table 13. Estimated results of the energy demand function and inefficiency equation using alternative SFA models.

Coefficient		BC95		TRE		TFE		MMSLE		MMLE/PDE	
		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Parameters of the demand function											
Energy prices (p_{it})	α^p	0.008	-0.008	-0.077**	-0.075**	-0.082***	-0.093***	-0.062*	-0.077**	-0.070**	-0.062**
GDP (y_{it})	α^y	0.643***	0.564***	0.684***	0.579***	0.559***	0.587***	0.602***	0.615***	0.574***	0.649***
Population (pop_{it})	α^{pop}	0.314***	0.400***	0.462***	0.507***	0.620**	0.694***	0.691***	0.691***	0.662***	0.610***
Indust. share (ISH_{it})	α^I	0.012***	0.018***	0.026***	0.008***	0.001	0.0006	0.002	-0.003	-0.001	0.001
Serv. share (SSH_{it})	α^S	0.022***	0.027***	0.022***	0.001	-0.007*	-0.007**	-0.008**	-0.009***	-0.009**	-0.005
Urban. rate (UR_{it})	α^{UR}	0.012***	0.010***	0.001***	0.006***	0.004**	0.005**	0.007***	0.007***	0.006***	0.006*
Time trend (D_t)	δ^t	-0.019***	-0.018***	-0.015***	-0.012***	-0.010***	-0.012***	-0.012***	-0.013***	-0.011***	-0.014***
Fixed effects:											
Land area (a_i)	α^a	0.044***	0.026***	-0.004	0.007						
Cold	α^c	0.453***	0.466***	0.489***	0.359***						
Oceanic	α^o	0.086***	0.046	0.600***	0.300***						
Continental	α^{co}	0.482***	0.422***	0.719***	0.359***						
Parameters in the inefficiency term (u_{it})											
Sigma	σ_u	2.064	1.411***	0.047***	0.045***	0.292	0.149***	0.029***	0.041***	0.063***	0.048***
EEGI	β^{EEGI}		-1.054***		-1.062***		-0.638***		-0.561***		-0.360**
Parameters in the random error term (v_{it})											
Sigma	σ_v	0.132***	0.154***	0.043***	0.028***	0.024***	0.023***	0.042***	0.042***	0.033***	0.014***
Parameters in the compound error (ε_{it})											
Sigma	$\sigma_\varepsilon = \sigma_v + \sigma_u$	2.196***	1.565***	0.090***	0.073***	0.315**	0.172**	0.069***	0.083***	0.096***	0.062***
Lambda	$\lambda = \sigma_v/\sigma_u$	15.627***	9.168***	1.095***	1.613***	12.042***	6.478***	0.73***	0.98***	1.892***	3.429***
Model statistics											
Observations		456	456	456	456	456	456	456	456	456	456
Cross-section		29	29	29	29	29	29	29	29	29	29

BC95: Battese and Coelli, (1995); TRE: True Random Effects (Greene 2005a); TFE: True Fixed Effects (Greene 2005b); MMSLE: Marginal Maximum Simulated Likelihood Estimator (Belotti and Ilardi 2018); MMLE: Marginal Maximum Likelihood Estimator (Chen et al. 2014); PDE: Pairwise Difference Estimator (Belotti and Ilardi 2018). (1): The model does not include the EEGI in the inefficiency term; (2): The model includes the EEGI in the inefficiency term. The MMLE model does not allow the variation of u_{it} with respect to any variable, while in the PDE model it is a requirement. Since PDE is an extension of MMLE, we set together the results of these two models. Fixed effects variables (i.e., land area and climate dummies) are excluded from (true) fixed effects models (Filippini et al. 2014).
*, **, *** denotes 10%, 5% and 1% significance level, respectively.

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To analyze the impact of the EEGI on energy inefficiency levels, we look at the second column of each model in Table 13. In all cases, the estimated β coefficient for EEGI is negative and significant at 1%. Therefore, improvements in energy governance are associated with less inefficiency (or greater efficiency). The estimated β ranges from -0.36 in PDE to -1.062 in TRE. To provide a better quantitative assessment of the effect of EEGI on EE, we show estimated results for the elasticity around the average level of EEGI, approximated by $\beta x EEGI$. Thus, given the average level of EEGI (2.54), the EE-EEGI elasticity ranges from 0.92 in PDE to 2.7 in TRE: an increase of 10% in the EEGI (i.e., 0.4 points) around its average value can produce an increment of EE between 9.20% and 27%, depending on the model estimated. As discussed below, we consider PDE estimates as the most reliable to analyze the impact of the EEGI on EE. In any case, these estimated results show the importance of adequate energy governance to promote the efficient use of energy.[39]

However, it is worth noting that the point estimates of β and resultant elasticities are very different across the different models. On the one hand, we have that BC95 and TRE models, which do not include true fixed effects, seems to be over-estimating the effect of EEGI on EE. As commented in Section 2, unobserved heterogeneity can bias estimates in these models precisely because of the omission of fixed effects. The estimation for the TFE model is -0.638 and the resultant elasticity 1.62. However, TFE estimates can be affected by the incidental parameters problem, and the MMLE, MMSLE and PDE models are able to correct it. While this issue does not affect the estimation of regressors in

[39] As mentioned in Section 2, since BC95 only admits the truncated-normal distribution for the inefficiency parameter, all remaining models draw on this distribution for comparative purposes. Assuming other distributions commonly accepted (e.g., half-normal or exponential) provides similar results. The frontier and inefficiency coefficients are very similar in terms of magnitude and significance, and the correlation between the estimated EE (Section 3.3.) is very high for TFE and TRE, close to 0.99 in both cases. MMLE, MMSLE and PDE offer similar results, although the variation in EE is slightly higher (the correlation is close to 0.90).

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Equation 1, it may generate biased estimates of σ_u, β and EE. As a consequence, the effect of EEGI on EE is lower than that estimated with the TFE model. Specifically, the β estimated for the MMSLE is -0.561 (an elasticity of 1.42), and -0.36 for PDE (an elasticity of 0.92). In this line, we find significant differences in the estimation of inefficiency parameters between TFE and MMLE, MMSLE and PDE. While the estimates of σ_v are similar in all fixed effect models, the estimation of σ_u is significantly smaller for MMLE, MMSLE and PDE models than for the TFE (the estimation of λ is also smaller for MMSLE and PDE), which is an indicative that these models are correcting the incidental parameters problem of TFE.[40]

In line with other works in the field, our results reveal that energy governance can play a crucial role in order to improve EE in the OECD. Establishing comparisons with these works is a complicated task, since the studies available to date do not develop a comprehensive assessment on the effect of energy governance on EE, and they are limited to the evaluation of a specific policy or a set of measures. However, important points in common can be identified, which are enhanced by the results of our work. For instance, the β coefficient estimated for most of the measures that Filippini et al. (2014) consider in their study is around the interval 0.10-0.20. Only the financial measures are proven to perform a high impact on EE, which varies according to the different specifications. In contrast, the lowest coefficient that we find for our energy governance measure is 0.36 (PDE), and even practically 1.10 in the least conservative case (TRE), which actually indicates a much greater effect than the one deduced from the aforementioned work.

[40] Models like MMLE/PDE, although they perform much better than the original TFE approach, could still provide relatively high EE estimates. A transient and persistent analysis on EE, like that conducted in Filippini & Hunt (2016), may shed some light on this concern. However, this paper aims to assess the role of energy governance on energy efficiency, rather than examining the level of EE itself. Therefore, the estimation of these models is beyond the scope of this paper, and it remains pending for future research.

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These findings suggest that previous literature may have underestimated the impact of energy governance on EE. From our estimates, it is also derived that in those countries accounting with a low EEGI score, improvements in energy governance may lead to truly significant increases in EE

To sum up, the fixed effects estimators provide more consistent results in our application. Among them, the PDE model is the one that offers the best convergence properties, as well as more conservative estimates of the effect of energy governance on EE. Therefore, the PDE model is the specification used as a reference in the following sections, although we also show results for the BC95 and TRE models for comparative purposes (the results of the remaining models are available upon request).

Main results of this section are supported by several extensions conducted in Appendix 2, which give more reliability to our results. We first show that similar insights emerge from using a simple regression approach with EI. Second, the results are robust to considering alternative time-varying measures of EEGI (EEGI interacted with both international oil prices and the average value of the World Bank's WGI –see Appendix 2.B). Finally, we analyze that the potentially endogeneity problem of the regressors in the demand function and in the inefficiency term (Equations 1 and 4) is not a serious concern in our application (see Appendix 2.C).

3.3. Energy efficiency estimates: cross-country and time dimension estimates

We show EE resultant from the models estimated above. For each country-year, we recover the estimation of u_{it} and EE_{it} from Equation 3. To simplify the exposition of results, we focus on estimates of our preferred fixed effect models (MMLE without EEGI and PDE with EEGI). For comparative purposes, we present also the results of BC95

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and TRE. Results from TFE and MMSLE are very similar to those from MMLE/PDE.

Table 2.A.1 in Appendix 2.A shows the estimated mean values of EE between 2000 and 2015 for each country, as well as their position in the ranking. The Spearman rank-correlation coefficient between pairwise EE estimates when the EEGI is not considered in the model is relatively low (the average for the three comparisons is 0.22): positive correlations are found between MMLE and TRE (0.54) and BC95 and TRE (0.13), but the correlation between BC95 and MMLE is almost zero (0.02). The introduction of the EEGI makes the EE estimates more similar between the different models (the average for the three comparisons in 0.58): the rank-correlation is 0.67 between PDE and TRE, 0.27 between BC95 and TRE, and 0.79 between BC95 and PDE. [41]

Figure 5a, 5b and 5c show the yearly of the EE averages between 2000 and 2015 for MMLE/PDE, BC95 and TRE models. Each figure shows two lines: line 1 does not include the EEGI, and line 2 includes the EEGI in the estimation of EE. When the EEGI is not considered, the estimated average EE is 95% for MMLE and 95.4% for TRE. These estimates are almost 10% higher than the EE obtained with BC95. However, when including the EEGI in BC95, the estimated average efficiency increases by 5% (going, on average, from 86% to 91%). At the same time, the efficiency estimated with TFE and TRE decreases around 0.3% and 2.2%, respectively, which points to the existence of a time-invariant inefficiency component in our data (see Section 2).[42] Therefore, we show again that the inclusion of the EEGI in the model reduces the variations between the

[41] If columns 1 and 2 within each model are compared, MMLE/PDE provides the highest Spearman rank correlation (0.70), while this correlation is somewhat lower for BC95 and TRE (around 0.5), which is consistent with the magnitude of their β coefficients.

[42] These percentages simply represent average changes. We find that in some cases the efficiency is reduced by as much as 4.3% (e.g., Estonia), in other countries the reduction is lower, around 2% (e.g., Greece) and in some others the reduction is null (e.g., Australia).

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estimates of the different models. Consequently, it seems that the EEGI contributes to diminishing the effect of the unobserved heterogeneity bias that affects the TRE and, especially, the BC95 model. In addition, it also contributes to partially capture the time-invariant inefficiency of the countries.

Looking at the average yearly evolution of the EE for our set of 29 OECD countries between 2000 and 2015, it is observed that in all the models (including lines 1 and 2), the average change in the estimated EE between 2000 and 2015 is positive (i.e., EE shows an upward trend). However, there are important cyclical movements in the time series. We focus on the estimation of our preferred fixed effect models MMLE/PDE to analyze these movements. The economic crisis of 2008 marks a turning point: the average growth of EE between 2000 and 2008 is positive (0.4%), while the average change between 2009 and 2015 is negative (-0.3%). A closer inspection of Figure 5a reveals that the reduction of EE between 2009 and 2015 is lower in lines 2 (when EEGI is included in the model) than in lines 1. This result may be an indicative that energy governance could play an important role to cushion the negative impact of the crisis on EE in OECD.

To end this sub-section, Figure 6a, 6b and 6c show the scatter plots between the EEGI and the average EE estimates by country for the three models considered above. The scatter plots allow to illustrate, in a very simple way, the existing association between energy governance and EE throughout our sample of countries. The most relevant comparison here is that corresponding to the EE estimates stemming from the model including the EEGI. In all cases, we have a positive and highly significant cross-country correlation between EEGI and average EE.[43] Although these scatter plots do not

[43] In the BC95 and TRE models, it is verified that some observations, although they do not constitute outliers, are far from the average trend of the sample. This is the case of Switzerland in BC95 and Estonia in TRE (countries marked in the point clouds).

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necessarily show a causal relationship, they do reinforce our results from the previous section. For example, looking at Figure 6a (i.e., PDE model), in this cross-country comparison, countries with lower levels of EEGI shows an average EE below 95%, while countries with the highest levels of EEGI shows EE clearly above 95%. These differences are even higher if we look at results for BC95 and TRE models.

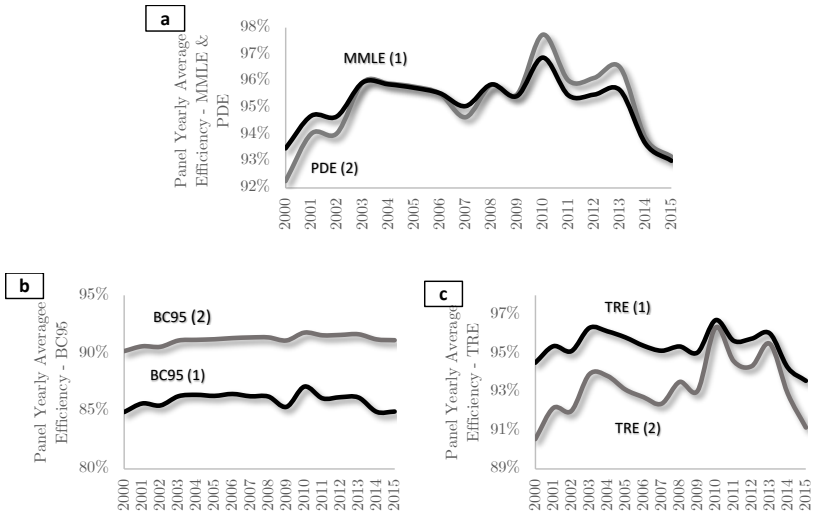


Figure 5. Evolution of energy efficiency (2000-2015) and the role of energy governance. Figure 5a draws on MMLE/PDE, Figure 5b is based on BC95, and Figure 5c, on TRE.

MMLE: Marginal Maximum Likelihood Estimator; PDE: Pairwise Difference Estimator; BC95: Battese and Coelli (1995); TRE: True Random Effects
(1): The model does not include the EEGI in the inefficiency term; (2): The model includes the EEGI in the inefficiency term

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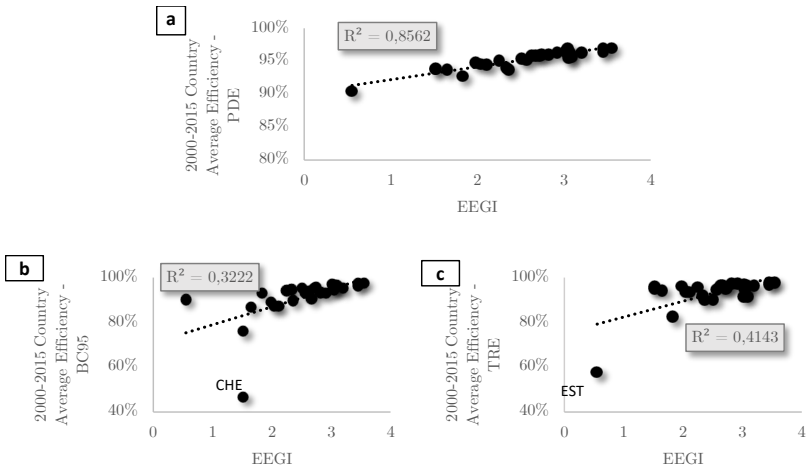


Figure 6. Energy efficiency and energy governance. Figure 6a draws on PDE, Figure 6b is based on BC95 and Figure 6c, on TRE.

PDE: Pairwise Difference Estimator; BC95: Battese and Coelli (1995); TRE: True Random Effects; EEGI: Energy Efficiency Governance Index.

4. The role of energy governance on the effectiveness of energy policies

Estimated results in the previous section show the importance of an adequate energy governance to promote the efficient use of energy. Improving the score of the EEGI depends on the deficiencies existing in each country. It is the set of available policies and the way in which they interact what really allows to strengthen the quality of energy governance. To delve into this analysis, in this section we estimate the energy demand function (Equation 1) and inefficiency equation (Equation 4) for each indicator used in the construction of the EEGI. To simplify the exposition of results, we show the estimates of the PDE, which is our preferred SFA alternative.[44]

[44] Qualitatively, results for the alternative fixed effects models are similar, and results are available upon request. Moreover, according to our previous discussion, the PDE offers the more conservative and robust effect of the EEGI on EE. Our results in this section can therefore be interpreted as a lower bound on the impact of the different EEGI indicators on EE.

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Table 14 collects the results of this analysis. Columns 1 to 8 show the estimates of the demand function by considering individually each indicator included in the EEGI, while, for illustrative purposes, in column 9 we include all indicators simultaneously. However, this latter model may lead to serious collinearity problems, so we prefer the individual analyses. In general, the coefficients and significance of the explanatory variables included in the energy demand function are very similar to those indicated in Table 13.

Looking at each indicator individually, we show that Strategies and Action Plans (S&A, column 2), Implementing Agencies (IA, column 3) and SE (Stakeholder engagement, column 4) are individually non-significant. The β coefficients of the remaining indicators are negative, and they are significant at 1% level for Public-Private Sector Co-operation (PPSC, column 6), Evaluation (column 7) and Targets (column 8), and at 10% for Laws and Decrees (L&D, column 1) and Role of Energy Providers (REP, column 5).[45] As expected, the estimated coefficients for each indicator vary notoriously, from -0.328 for Targets (significant), to 0.089 for IA (non-significant). In spite of that, the estimated average values of the EE (close to 0.95), the standard deviation of EE (0.04), and the standard deviations of inefficiency and random error terms are very similar in all cases. When including all indicators simultaneously (column 9), REP, PPSC, Evaluation and Targets coefficients are negative, but only those for Evaluation and Targets are significant (1% and 5% levels). However, the four coefficients are jointly significant (this result is common when explicative variables are highly correlated).

[45] Recall the association between the type of energy policies and each indicator exposed in Chapter 1. L&D includes measures related to regulatory aspects (e.g., building codes, appliance labeling and standards, decrees); S&A is related to all the country's energy plans; IA considers the establishment of energy agencies, their legal support and the plans they promote; SE examines the measures that promote the participation of the agents of the sector in the elaboration of energy policies; REP evaluates all policies involving energy providers; PPSC encompasses all policies that advocate (in its various forms) for cooperation between the public and private sectors; Evaluation refers to the measures of evaluation and monitoring of the development of policies and their results and, finally, the Targets indicator is related to all the measures that establish energy objectives, but in a quantified and achievable manner.

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Table 14. Demand function and inefficiency estimates for the different indicators included in EEGI. Pairwise Difference Estimator (PDE, Belotti and Ilardi 2018).

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Parameters of the demand function										
Energy prices (p_{it})	α^{p}	-0.049*	-0.057*	-0.042	-0.058**	-0.054*	-0.047*	-0.062**	-0.063**	-0.040
GDP (y_{it})	α^{y}	0.615***	0.633***	0.626***	0.643***	0.641***	0.678***	0.674***	0.64***	0.681***
Population (pop_{it})	α^{pop}	0.634***	0.575***	0.597***	0.586***	0.548***	0.491***	0.673***	0.661***	0.657***
Industrial share (ISH_{it})	α^{I}	0.001	0.001	0.001	0.001	0.001	0.005	0.001	-0.002	-0.001
Service share (SSH_{it})	α^{S}	-0.005	-0.005	-0.004	-0.005	-0.005	-0.001	-0.005	-0.007*	-0.004
Urban. rate (UR_{it})	α^{UR}	0.007**	0.006*	0.006**	0.006*	0.006**	0.005*	0.008***	0.006**	0.007***
Time trend (D_t)	δ^{t}	-0.014***	-0.014***	-0.014***	-0.014***	-0.014***	-0.015***	-0.015***	-0.015***	-0.017***
Parameters in the inefficiency term (u_{it})										
Sigma	σ_u	0.049***	0.049***	0.050***	0.050***	0.049***	0.049***	0.047***	0.047***	0.044***
L&D	$\beta^{L\&D}$	-0.163*								0.039
S&A	$\beta^{S\&A}$		-0.119							0.149
IA	β^{IA}			0.089						0.283*
SE	β^{SE}				-0.074					0.068
REP	β^{REP}					-0.229*				-0.271
PPSC	β^{PPSC}						-0.302***			-0.199
Evaluation	β^{Eva}							-0.223***		-0.153*
Targets	β^{Tar}								-0.328***	-0.357**
Parameters in the random error term (v_{it})										
Sigma	σ_v	0.013***	0.012***	0.011***	0.012***	0.012***	0.013***	0.016***	0.016***	0.021***
Parameters in the compound error (ε_{it})										
Sigma	$\sigma_\varepsilon = \sigma_v + \sigma_u$	0.062***	0.061***	0.051***	0.062***	0.061***	0.062***	0.063***	0.063***	0.065***
Lambda	$\lambda = \sigma_v/\sigma_u$	3.769***	4.083***	5.000***	4.167***	4.083***	3.769***	2.938***	2.938***	2.095***
Model statistics										
Observations		456	456	456	456	456	456	456	456	456
Cross-section		29	29	29	29	29	29	29	29	29
Average EE		0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.96	0.96
Std. Dev. EE		0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Min. EE		0.75	0.75	0.74	0.75	0.76	0.72	0.74	0.76	0.74
Max. EE		0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.98	0.99

Country specific dummies are not reported in the table. In all cases, the estimated model includes the EEGI in the inefficiency term. *L&D*: Laws and Decrees; *S&A*: Strategic and Action Plans; *IA*: Implementing energy efficiency Agencies; *SE*: Stakeholder Engagement; *REP*: Role of Energy Providers; *PPSC*: Public-private Sector Co-operation.
*, **, *** denotes 10%, 5% and 1% significance level, respectively.

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Looking at the individual analyses (columns 1-8), we show the estimated elasticity for the most significant indicators (PPSC, Evaluation, Targets, L&D and REP) evaluated at the mean of each indicator. The indicators L&D and REP show the lowest impact on EE, with elasticities close to 0.41 and 0.46%, respectively. That is, improving the L&D indicator by 10% (i.e., 0.4 points) would lead to an increase in EE close to 4.1%, and around to 4.6% in the case of REP. The indicators PPSC and Evaluation show a higher elasticity, close to 0.59 in the first case and to 0.66 in the second one. Finally, Targets is the indicator that accounts the strongest effect on EE. Its elasticity is 0.99, which means that increasing Targets by 10% would lead to an increase in EE close to 9.90%. Therefore, the establishment of quantifiable, achievable objectives, and the imposition of control and evaluation mechanisms are key aspects to improve EE in our set of countries. The establishment of public-private co-operations, the role of energy providers in the development of efficiency programs, as well as the establishment of proper legal basis also play a significant but less pronounced role on improving efficiency.

The meaning of increasing the score of any indicator (or that of the EEGI) depends on the country under study. For instance, in Estonia, the inclusion of two or three additional targets (e.g., to reduce emissions, penetration of renewables and building codes) could increase the score of the Targets indicator between 1 and 2 points. Based previous estimations, this could lead to an efficiency improvement of 25%. In the case of Canada, for instance, the Evaluation indicator is poorly scored (2 points), since the detected evaluation mechanisms were rather scarce. Increasing these mechanisms to cover 50% of the promoted plans, for example, could increase the score of the Evaluation indicator by 1 point. According to our estimates, this measure could improve EE by around 16.5%.

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We have two (a priori) controversial results that are worth mentioning. Although, in both cases, an in-depth analysis of these potential controversies is beyond the scope of this paper.[46] The first one is about the L&D indicator, whose coefficient is negative and significant in column 1, but it turns positive and non-significant in column 9. Regarding the latter results, it could be the case that an extensive regulatory framework could cause high levels of bureaucracy and administrative barriers that lead to the abandonment of investment decisions in EE (Hepbasli and Ozalp 2003; Sardianou 2008).[47]

The second controversial result is the positive sign (and significant at 5%) of IA in column 9 (it is positive but non-significant in column 3). This result points out that energy agencies do not contribute to improve the EE level of the countries. This fact could be due to the following reasons. First, our indicator only measures the existence of national agencies and their scope of operation. However, there are different types of government agencies, some more independent than others, some of them sharing other energy policy tasks (Delina, 2012) . Moreover, in other cases, coordination is handled by other types of institutions, ranging from public-private collaboration to the participation of non-governmental organizations. Thus, the correct implementation of this type of measures is not necessarily related to the formal existence of national agencies. Second, the IA indicator has the lowest (positive) correlation, just 0.10 (non-significant), with the Evaluation indicator. In other words, what may be relevant to improve EE is the establishment of strict procedures for energy policy evaluation and monitoring.

[46] The non-significance of S&A may be indicating that what is really important to improve EE is the implementation of specific measures, so the effect of this indicator could be reflected by L&D, Evaluation and Targets. Similarly, the non-significance of SE could also be due to the correlation of this indicator with the indicators REP, PPSC and L&D.

[47] In addition, the implementation of building codes and labeling codes for appliances or vehicles, which are included in the L&D indicator, accompanied by other programs that promote the acquisition of this kind of assets (through subsidies or discounts, among others), may give rise to a rebound effect in energy consumption due to acquisition and use of more energy efficient assets and loss energy efficiency (Lekve Bjelle, Steen-Olsen, and Wood 2018; Sun 2018).

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The results presented in this section are in line with those of Pereira & Pereira Da Silva (2017), who provide a descriptive evaluation about the effect of energy governance on the effectiveness of EE policies. However, they differ from the conclusions of some other works. For instance, Filippini et al. (2014) detected that financial incentives and performance standards play an important role in improving EE; Saussay et al. (2012) concludes that building codes are established to have a significant effect on the improvement of EE; and Park (2015) indicates that informative measures and the participation of citizens in the elaboration of policies are the most important aspects for improving EE. The reason behind these differences may be the fact that these authors evaluate a specific type of policy, ignoring other aspects such as the established objectives or the evaluation of their fulfillment. A detailed analysis of these aspects goes beyond the scope of this paper.

5. Conclusions and final remarks

Drawing upon the Energy Efficiency Governance Index (EEGI) built in Barrera-Santana et al. (2020), this work develops different SFA approaches in order to demonstrate that the EEGI is positively and significantly correlated with the EE levels in the OECD. Indeed, a change of 10% in the average EEGI score could raise EE by around 9.20% in the PDE approach, and up to 27% in TRE. The indicators Targets, Evaluation, the Role of Energy Providers and Public-private Co-operations seem to be the most relevant drivers of EE improvements. In addition, energy governance could have also played an important role to cushion the negative impact of the 2008 crisis on EE in OECD.

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Important implications for energy policy are derived from these results. First, coherent governance on EE requires a definition of national interests. Thus, Laws and Decrees should include specification of the country's overall EE perspective, their objectives and the institutions responsible for implementing the policy. Second, the reporting and evaluation of the EE initiatives and programs are one of the most effective policies to improve a country's EE level. Thirdly, regulatory rules should create incentives for energy providers to participate in EE initiatives. For instance, EE programs impact utility revenues and costs. These impacts mean that the energy sector regulator is in the position of promoting or blocking some EE initiatives carried out by the electric utility. Finally, EE governance should be established on the context of the country where it is located and, at the same time, taking into account together all the elements that make up a good EE governance. EE governance has a multidimensional character so that the compliance of anyone component increases the probability that another one to be satisfied.

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Appendix 2

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2.A. Estimated energy efficiency from SFA models

In this Appendix, we show the estimated mean values of EE between 2000 and 2015 for each country, as well as their position in the ranking. The first column in each model considers the specification without the EEGI, while the second one includes the EEGI in the estimation of EE. The bottom of the table presents the descriptive statistics of the EE for the entire sample of countries. Maim comments to this table are in the main text of the paper.

As mentioned in the main text, the TFE and TRE models proposed by Greene (2005a and 2005b) tend to overestimate the underlying level of EE. The MMLE/PDE model is a variant of the original TFE model, as explained in Belotti & Illardi (2018). Therefore, although this alternative solves the incidental parameter problem in TFE, due to its econometric foundation this approach could still provide relatively high EE estimates.

In fact, according to our results, the efficiencies estimated in MMLE/PDE, although lower than those corresponding to the TFE model, are still high. However, these estimates are in line with those found in seminar papers of the field. For instance, Filippini et al. (2014) assess the efficiency for a sample of EU-27 member states between 1996 and 2009. Such a sample should provide a similar result to the one generated by our sample. Indeed, the efficiency in the TFE model estimated by these authors is 0.94, very close to the 0.953 that we find. Another paper showing high EE estimates is P.K. Adom et al. (2018) work, who find the EE estimates from TFE mainly ranging from 0.85 to 0.95 for African countries. It could be expected that the efficiency level of African countries is worse than that of OECD countries. However, the efficiency results are actually comparable (in terms of magnitude) to those that we find, which clearly confirms that EE estimates from SFA

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models are always subject of discussion, regardless of the model used to calculate them. This conclusion supports our key statement, which is that the main aim of this paper is to assess the role of energy governance on EE, rather than to examine the level of efficiency itself. Even in this case, as already mentioned, our results reveal that considering the EEGI in the estimation helps to improve the accuracy and variability of the efficiency results.

From this outcome, we can conclude that, although models like MMLE and PDE can improve the performance of conventional approaches like TFE, they still provide relatively high EE estimates. At least, for a homogeneous sample of OECD countries in a period such as between 2000 and 2015. Since this is the first time that this kind of models is applied in the energy field, further research is needed in order to identify how models like PDE or MMLE may condition the EE estimates in other circumstances and contexts. In this vein, measuring persistent and transient EE, as in Filippini & Hunt (2016), could provide the first step to shed some light on this issue, which is a relevant extension to our analysis.

Another concern derived from our results is the limited between-country variability shown by the EE estimates of the MMLE model. The average scores range from 0.942 in the Slovak Republic to 0.955 in several other countries (e.g., Canada, France or Germany). Nevertheless, the estimates for the entire panel range from 0.79 to 0.99, with a standard deviation close to 3%, which indicates that the variability of the results is greater than what might appear at first glance. Moreover, this concern is partially overcome when the EEGI is introduced in the model (see PDE's column in Table 2.A.1.). The resulting average scores range now from 0.90 in Estonia to 0.97 in countries like Canada or Germany.

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In the remaining models, this concern is not relevant. For instance, in the case of the TRE model, when the EEGI is not considered, the average country scores range from 0.90 in the Slovak Republic to 0.98 in Portugal, Germany and Japan. If the index is considered, average efficiencies range from 0.58 in Estonia to 0.98 in France and Germany, which seems more than a reasonable variability. Finally, in the case of BC95, we find the highest variability range, with average scores from 0.47 in Switzerland to 0.96 in the USA without the EEGI, and between 0.87 in Greece to 0.98 in Germany when the EEGI is included in the estimation procedure.

When we compare our results with those found in the literature, the findings resonate with the idea that our results show an acceptable between-country variability. For instance, if we take the seminal work of Filippini and Hund (2011) as a reference, we can see that the country average results for the pooled model they develop range from 0.85 in Luxembourg to 0.94 in Switzerland. For this alternative, the minimum and maximum values found are 0.76 and 0.95, respectively, being the mean 0.89 and the standard deviation 0.03. In their case of the TRE model, the authors find a minimum country average score of 0.805 in Korea and a maximum of 0.94 in Switzerland. In addition, the maximum and minimum EE estimates registered for the panel are 0.65 and 0.99, being the average close to 0.92 and the standard deviation to 0.075

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Table 2.A.1. Energy Efficiency and EEGI: score and ranking by countries under alternative models.

Country	Code	BC95 (1) Level	BC95 (1) Rank	BC95 (2) Level	BC95 (2) Rank	MMLE/PDE (1) Level	MMLE/PDE (1) Rank	MMLE/PDE (2) Level	MMLE/PDE (2) Rank	TRE (1) Level	TRE (1) Rank	TRE (2) Level	TRE (2) Rank
Australia	AUS	0.712	28	0.907	21	0.954	6	0.959	12	0.967	9	0.965	8
Austria	AUT	0.817	24	0.871	26	0.951	22	0.945	21	0.940	22	0.938	21
Belgium	BEL	0.925	8	0.956	7	0.954	10	0.960	11	0.969	6	0.955	14
Canada	CAN	0.932	6	0.966	5	0.955	2	0.970	2	0.966	10	0.951	16
Czech Republic	CZE	0.927	7	0.953	9	0.953	14	0.958	14	0.973	4	0.950	18
Denmark	DNK	0.781	27	0.962	6	0.952	20	0.964	5	0.946	21	0.968	6
Estonia	EST	0.937	3	0.902	22	0.944	28	0.905	29	0.928	26	0.578	29
Finland	FIN	0.933	5	0.952	10	0.952	19	0.954	17	0.961	16	0.901	26
France	FRA	0.912	13	0.973	2	0.955	1	0.970	1	0.938	24	0.978	2
Germany	DEU	0.922	11	0.976	1	0.955	4	0.970	3	0.975	2	0.979	1
Greece	GRC	0.863	18	0.867	27	0.953	18	0.937	26	0.951	19	0.941	20
Hungary	HUN	0.841	19	0.933	17	0.954	5	0.960	10	0.951	20	0.973	4
Ireland	IRL	0.873	15	0.929	20	0.950	23	0.952	18	0.929	25	0.947	19
Italy	ITA	0.894	14	0.956	8	0.953	15	0.963	9	0.960	17	0.967	7
Japan	JPN	0.825	21	0.932	18	0.954	11	0.963	8	0.975	3	0.974	3
Korea	KOR	0.933	4	0.946	13	0.946	26	0.941	23	0.965	11	0.920	23
Mexico	MEX	0.786	26	0.760	28	0.953	17	0.938	24	0.922	28	0.951	17
Netherlands	NLD	0.924	9	0.942	15	0.954	12	0.951	19	0.938	23	0.957	13
New Zealand	NZL	0.924	10	0.967	4	0.951	21	0.956	15	0.963	12	0.916	24
Norway	NOR	0.822	23	0.897	23	0.944	27	0.937	27	0.923	27	0.900	27
Poland	POL	0.870	16	0.890	24	0.955	3	0.948	20	0.968	7	0.961	11
Portugal	PRT	0.914	12	0.941	16	0.954	8	0.958	13	0.978	1	0.962	9
Slovak Republic	SVK	0.938	2	0.932	19	0.942	29	0.927	28	0.903	29	0.825	28
Spain	ESP	0.868	17	0.949	12	0.954	9	0.963	7	0.962	24	0.971	5
Sweden	SWE	0.814	25	0.951	11	0.953	16	0.963	6	0.962	25	0.962	10
Switzerland	CHE	0.472	29	0.467	29	0.954	13	0.938	25	0.968	8	0.958	12
Turkey	TUR	0.839	20	0.872	25	0.948	24	0.944	22	0.963	13	0.936	22
United Kingdom	GBR	0.823	22	0.946	14	0.947	25	0.954	16	0.952	18	0.953	15
United States	USA	0.956	1	0.972	3	0.954	7	0.965	4	0.969	5	0.914	25
Average		0.860		0.912		0.950		0.953		0.954		0.932	
Std Dev		0.098		0.098		0.026		0.039		0.035		0.093	
Min.		0.447		0.443		0.790		0.750		0.745		0.681	
Max		0.960		0.977		0.993		0.999		0.995		0.988	
Cases		456		456		456		456		456		456	

BC95: Battese and Coelli (1995); MMLE: Marginal Maximum Likelihood Estimator; PDE: Pairwise Difference Estimator; TRE: True Random Effects. (1): The model does not include the EEGI in the inefficiency term; (2): The model includes the EEGI in the inefficiency term. The results by country represent the average of each state in the period 2000-2015. The statistics at the bottom of the table do not refer to country averages, but to the entire data panel

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2.B. A time-varying measure of energy efficiency governance in the SFA

Following the robustness assessment conducted in Chapter 1, we use the two the time-varying instrument defined in such chapter (i.e., the $EEGIOil_{it}$) in order to assess the implications of using a time-varying index into the SFA. We extend upon this analysis by constructing a new time-varying instrument resulting from the interaction between the EEGI and the time dimensions of the WGI ($EEGIWGI_{it} = EEGI_i x WGI_t$). We draw on our preferred SFA approach, that is the PDE model. Estimated results are shown in Table 2.B.1. For each alternative, the frontier coefficients are quite similar in terms of magnitude and significance to those presented in Table 13. The estimate of the λ parameter is also robust and significant at the 1% level. However, the most important result for our robustness analysis is that both $EEGIOil_{it}$ and $EEGIWGI_{it}$ account negative coefficients and significant at the 1% level. In addition, these coefficients are similar to those showed in Table 13 for the PDE model. Therefore, although these results correspond to a preliminary analysis, they should be understood as a first step to demonstrate that the positive effect of energy governance on EE persists even when the time dimension of the EEGI is taken into account. Future research may offer an in-depth analysis of this question using more appropriate methodologies for this purpose.

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Table 2.B.1. Results of the derived demand function with time-varying EEGI: Pairwise Difference Estimator (PDE, Belotti & Ilardi 2018).

Coefficient		(1)	(2)
Parameters of the demand function			
Energy prices (p_{it})	α^{p}	-0.119***	-0.051*
GDP (y_{it})	α^{y}	0.626***	0.657***
Population (pop_{it})	α^{pop}	0.577***	0.630***
Industrial share (ISH_{it})	α^{I}	0.001	-0.001
Service share (SSH_{it})	α^{S}	-0.004	-0.005
Urban. rate (UR_{it})	α^{UR}	0.005	0.006*
Time trend (D_t)	δ^{t}	-0.011***	-0.015***
Parameters in the inefficiency term (v_{it})			
Sigma	σ_u	0.048***	0.047***
$EEGIOil_{it}$	β^{EEGI_Oil}	-0.265***	--
$EEGIWGI_{it}$	β^{EEGI_WGI}	--	-0.287**
Parameters in the random error term (v_{it})			
Sigma	σ_v	0.015***	0.015***
Parameters in the compound error (ε_{it})			
Sigma	$\sigma_\varepsilon = \sigma_v + \sigma_u$	0.063***	0.062***
Lambda	$\lambda = \sigma_v/\sigma_u$	3.20***	3.133***
Model statistics			
Observations		453	428
Cross-section		29	29
Average EE		0.967	0.953
Std. Dev.		0.024	0.038
Min.		0.798	0.753
Max.		0.991	0.998

$EEGIOIL_{it}$: EEGI multiplied by ln-growth of international oil price series; *WGI:* World Governance Index; $EEGIWGI_{it}$: EEGI multiplied by yearly average WGI.
*, **, *** denotes 10%, 5% and 1% significance level, respectively.

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2.C. Extensions and robustness of the EEGI

In this Appendix, we carry out several extensions of the analysis conducted in Section 4.2. to provide robustness to our main result: energy governance is good for EE. We first use a regression approach with EI through Index Decomposition Analysis (IDA) to compare with the EE estimates stemming from the SFA. This exercise reinforces our results of Section 4 pointing out that EEGI positively affects EE. Second, using the methodology proposed by Karakaplan & Kutlu (2017), we analyze whether endogeneity of the regressors in the energy demand function and in the inefficiency term is not an important concern in our application (i.e., estimations are not bias for this reason). Since this latter analysis is usually disregarded in the SFA literature, it is a novel extension to our work.[48]

2.C.1. Energy intensity and energy governance

At the beginning of Section 3, we established the discussion about the deficiencies of using EI as a proxy of energy inefficiency. Nevertheless, EI is still a measure used to proxy energy inefficiency in many applications. In this section, we closely follow Metcalf (2008), who use a Fisher decomposition approach to decompose the changes of EI into two components: (i) efficiency, and (ii) activity. The first term refers to the changes in energy use per unit of economic activity, and the second one is related to the change in energy consumption due to the shift from energy intensive economic activities towards less intensive ones.[49] This approach allows also to construct a bottom-up measure of EI,

[48] See, for example, the seminal works of Filippini & Hunt (2011); Filippini et al. (2014) and other papers such as Price et al. (2017); Jiang et al. (2017); and Longo et al. (2020).

[49] The Fisher decomposition is an Index Decomposition Analysis (IDA) that starts by constructing Laspeyres and Paasche efficiency and activity indices. Laspeyres indices use a base period fixed weight, while the Paasche indices use an end period. Fisher's efficiency and activity indices are then constructed from the square root of the product of the Laspeyres and Passche indices, which provides a perfect decomposition of an aggregate EI index into economic activity and efficiency

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which is a "reconstructed" EI index that weights the different components (efficiency and activity) of the original EI.[50]

The decomposition requires to define economic sectors and to find suitable measures of energy consumption and economic activity for each of them, which strongly depend on data availability.[51] We conduct the decompositions for our set of OECD countries using data from 1995 to 2015, taking into account four economic sectors: residential, commercial, industrial, and agriculture, forestry and fishing.[52] On the one hand, information on energy use is extracted from the IEA's World Energy Balances Database (2018). On the other hand, we use data on the gross value added of each sector as economic activity measure (Metcalf 2008). This data has been taken from the World Bank's World Development Indicators Database.

Table 2.C.1 collects the main results of the Fisher decomposition of EI for our sample of 29 OECD countries in the period between 2000 and 2015. Columns 1 and 2 show the results of the efficiency and activity components of EI, respectively, and column 3 provides the results of the bottom-up EI. For illustrative purposes, the table includes the average levels and growth rates of energy consumption and GDP between 2000 and 2015. Figure 2.C.1 shows the average yearly evolution of the two components and the bottom-up IE.

with no residual (Fisher 1921).

[50] The bottom-up EI is calculated as the product of the Laspeyres and Passche activity and efficiency indices. This indicator represents a perfect decomposition of the aggregate EI, so its use is preferred to conventional measure of EI (Fisher 1921; Metcalf 2008).

[51] An additional difficulty to correctly conduct a Fisher decomposition, which also arises in other decomposition approaches, is that the energy demand by sectors must add the total energy demand in the economy, what is usually not possible with data availability (Boyd & Roop 2004).

[52] The models presented in this paper assess the period 2000-2015. However, when decomposing EI, we expand the reference year from 2000 to 1995 for several reasons. First, 1995 is the first year for which we have information for all the countries in the sample. Second, starting in 1995 (i.e., the index takes value of 100 in 1995, and not in 2000) allows us to have some heterogeneity (between countries) for the efficiency and activity components in 2000. Thus, we are able to take advantage of the full data set for 2000-2015.

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Appendix 2

The two components of EI (efficiency and activity) show high variability between countries. For example, the average value of the efficiency component is 0.79, but the mean score of the countries ranges from 0.50 in the case of Estonia to 1.03 for Spain and Italy. Likewise, the average value of the activity component ranges from 0.90 in Poland to 1.08 in Canada and Estonia, with an overall mean close to 0.98. Finally, the bottom-up EI accounts an average score of 0.77, ranging from 0.51 in Poland to 1.00 in Italy. At a first glance, the evolution of the EI is closely related with the efficiency component (see Figure 2.C.1). Indeed, the correlation between the efficiency component and the bottom-up EI is 0.974, which means that, in our sample, the efficiency component is responsible for almost all the variation experienced by EI. This result is supported by Metcalf (2008) and other works in the literature (Marrero & Ramos-Real 2013, among others). Therefore, as commented in Section 3, a basic decomposition approach for EI seems not to be able to correctly distinguishing between the activity and the efficiency components, at least in our sample and with our data availability (Alghandoor et al. 2008).[53]

In the second step of this analysis, we estimate a simplified regression version of the model estimated by Metcalf (2008), including country-fixed effects, the EEGI, climate dummies (Cold, Oceanic and Continental) and the GDP growth as explicative variables. Column 1 in the left panel of Table 2.C.2 shows a negative and significant effect for the EEGI on the efficiency component of EI. In columns 2 and 3 of Table 2.C.2, we consider a model using the controls proposed by Metcalf (2008), which include population, GDP and square GDP levels, investment-capital ratio (I/K) and capital-labor ratio (K/L), among others, and the estimated coefficient for the EEGI (and for the other variables)

[53] Probably, since the economic structure of OECD countries have changed relatively little between 2000 and 2015, and we do not have a broad classification of economic sectors in our data, our decomposition leads to a quite small activity component and, thus, to unreliable results (Zahur 2013; Grossi and Mussini 2017).

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does not experience a significant change.[54] In columns 4-6 of Table 2.C.2, we show the results for the bottom-up EI, and the preceding conclusions are still valid.[55]

Table 2.C.1. Main statistics for the components of energy intensity, bottom-up energy intensity, energy and GDP.

country	Efficiency (1995=100)	Activity (1995=100)	Bottom-up EI (1995=100)	TPEC (Mtoe)	ΔTPEC	GDP (BUSD)	ΔGDP
Australia	0.79	0.99	0.78	119.77	1.30%	884.47	2.95%
Austria	0.92	0.97	0.89	32.31	0.91%	340.49	1.35%
Belgium	0.82	0.98	0.80	56.68	-0.58%	420.20	1.39%
Canada	0.67	1.08	0.71	267.19	0.42%	1,327.26	1.94%
Czech Republic	0.62	1.00	0.62	43.85	0.16%	269.30	2.60%
Denmark	0.81	0.95	0.77	18.57	-0.97%	237.99	0.89%
Estonia	0.50	1.08	0.54	5.34	0.94%	29.33	3.29%
Finland	0.77	1.05	0.81	34.87	0.02%	201.70	1.12%
France	0.83	0.99	0.83	258.48	-0.14%	2,295.23	1.12%
Germany	0.87	0.96	0.84	326.75	-0.60%	3,171.23	1.12%
Greece	0.97	0.94	0.92	27.71	-1.04%	297.19	-0.19%
Hungary	0.70	1.02	0.72	25.71	0.06%	212.18	1.95%
Ireland	0.67	0.91	0.61	14.00	-0.27%	193.34	4.05%
Italy	1.03	0.97	1.00	171.59	-0.78%	2,071.93	0.00%
Japan	0.93	0.97	0.91	488.30	-1.24%	4,261.31	0.72%
Korea	0.79	0.98	0.77	229.41	2.47%	1,366.14	3.86%
Mexico	0.80	0.97	0.78	177.35	1.45%	1,676.09	2.19%
Netherlands	0.77	0.93	0.72	78.69	-0.14%	717.87	1.11%
New Zealand	0.85	0.93	0.79	18.00	1.25%	130.75	2.70%
Norway	0.81	0.98	0.79	28.64	0.83%	277.10	1.58%
Poland	0.57	0.90	0.51	94.44	0.45%	726.18	3.56%
Portugal	1.01	0.95	0.96	24.03	-0.75%	279.26	0.18%
Slovak Republic	0.51	1.07	0.54	17.72	-0.53%	120.48	4.00%
Spain	1.03	0.94	0.96	129.49	-0.16%	1,409.55	1.38%
Sweden	0.63	1.03	0.65	49.60	-0.30%	374.34	2.07%
Switzerland	0.84	0.96	0.81	25.97	-0.13%	394.43	1.72%
Turkey	0.94	1.00	0.95	97.39	3.52%	1,213.13	4.91%
United Kingdom	0.77	0.96	0.74	206.87	-1.40%	2,217.67	1.71%
United States	0.79	0.97	0.76	2,241.89	-0.25%	14,633.87	1.78%
Average	0.79	0.98	0.77	183.12	0.15%	1,439.66	1.97%
Std. Dev.	0.16	0.05	0.15	405.73	4.07%	2,691.16	3.11%
Min.	0.33	0.86	0.36	5.34	-19.19%	29.33	-15.92%
Max.	1.13	1.14	1.09	2,241.89	15.38%	14,633.87	23.33%

The average estimated coefficient between EEGI and EI and its efficiency component is close to -0.145, which means that increasing the EEGI by 1 point (about 25%) is

[54] In order to be consistent with the models described in Section 3, we use the GDP level and we control for the level of population. However, our results still remain valid if we instead use per capita GDP.

[55] The activity component is supposed to capture the changes in the level of efficiency due to variations in the economic structure of the countries. Therefore, since there is no theoretical foundation supporting the relationship between energy governance and the activity component of EI, we do not show the results corresponding to this relationship. In fact, as expected, the obtained results are misleading, since for some models the effect of governance is significantly positive and, for others, significantly negative.

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associated with a reduction of these energy measures by almost 0.145 points, which implies a reduction of almost 20% if we consider the average value of EI for the entire sample (0.77).

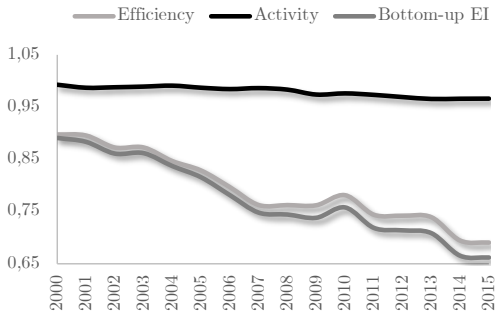


Figure 2.C.1. Average yearly evolution of EI and its efficiency and activity components.

Source: Own elaboration.

To conclude, we compare, for each country, the evolution of the EI (its bottom-up version) and the EE estimated using the SFA (PDE model). Depending on the sign of such correlation (over time), three groups of countries can be established (see Figure 2.C.2). Negative and significant correlations are obtained for the countries in the first group, with an average correlation of -0.60. These countries are Austria, Greece, Korea, Mexico, Norway and Turkey. The second group of countries shows positive and significant correlations, and it includes countries such as the Denmark, Germany, Ireland, Japan, Spain, Slovak Republic, the United Kingdom and the United States. The average correlation in this second group is 0.75. Finally, there is a group of countries where correlations are not individually significant, as it is the case of Australia, Belgium, Canada, Finland, Italy, New Zealand, Portugal and, Sweden, among others. These results are in line with the usual findings of the literature of the field (Evans, Filippini, Hunt, et al. 2013; and Filippini & Hunt 2011; 2012; 2016).

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Table 2.C.2. The effect of energy governance on the efficiency component of energy intensity and bottom-up energy intensity.

	Parameter	EI_eff_{it}			Bottom-up EI		
		(1)	(2)	(3)	(4)	(5)	(6)
EEGI	β^{EEGI}	-0.16***	-0.16***	-0.16***	-0.18***	-0.11***	-0.10***
Δy_{it}	$\beta^{\Delta y}$	0.32**			0.49***		
y_{it}	β^{y}		-0.37***	-0.46***		-0.40**	-0.60***
y_{it}^2	β^{y^2}			0.01			0.02**
p_{it}	β^{p}		-0.04	-0.04		-0.05**	-0.05**
K/L_{it}	$\beta^{K/L}$		0.01	0.01		0.08*	0.11***
I/K_{it}	$\beta^{I/K}$		-0.04*	-0.04		0.03	0.04*
pop_{it}	β^{pop}		0.18**	0.15*		0.14*	0.09
D_t	δ^{D}		-0.01***	-0.01***		-0.01***	-0.01***
$cold_i$	β^{c}	-0.18***	-0.86***	-0.85***	-0.23***	-1.09***	-1.06***
$oceanic_i$	β^{o}	-0.02	-0.43***	-0.39***	-0.02	-0.52***	-0.43***
$continental_i$	β^{co}	-0.06**	-0.61***	-0.58**	-0.05*	-0.78***	-0.72***

EI_ eff: Efficiency component of energy intensity; *EEGI:* Energy Efficiency Governance Index; Δy*:* ln-growth GDP; *y:* ln-GDP*;* y^2*:* squared ln-GDP; *p:* ln-Energy prices*; K/L:* Capital-labor ratio; *I/K*: Investment-Capital ratio*; pop:* ln-population; *D:* Time trend*; cold:* Cold climate dummy*; oceanic:* Oceanic climate dummy*; continental: continental* climate dummy.

If we analyze the two groups with significant correlations, we can see that the higher the EEGI is, the more negative (or less positive) is the correlation between EI and EE. Therefore, EI (and its efficiency component) is a better proxy of energy inefficiency in countries with better energy governance. This result contributes to explain, at least partially, the different sign and magnitude of the correlations found between EI and EE estimates from SFA in this and other studies in the field.

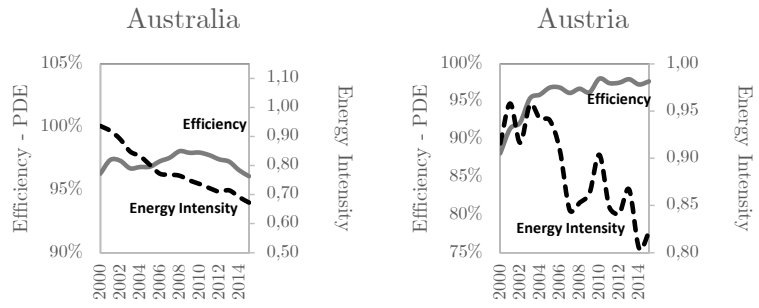


Figure 2.C.2. Energy efficiency versus (bottom-up) energy intensity by countries in the period 2000-2015.

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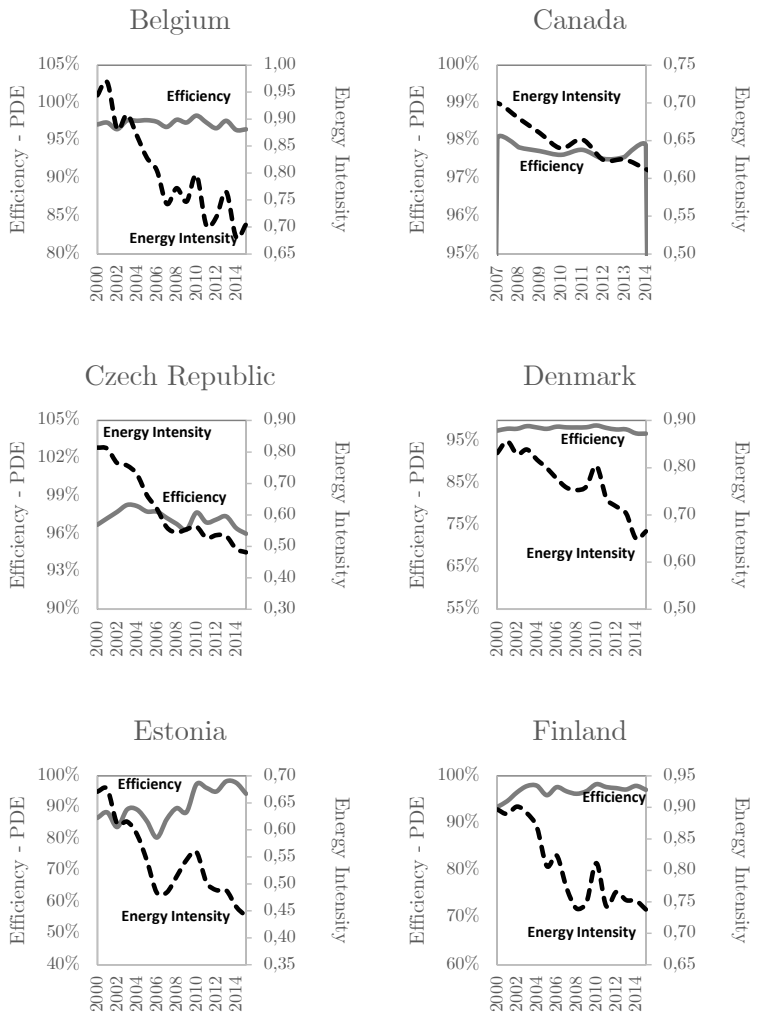


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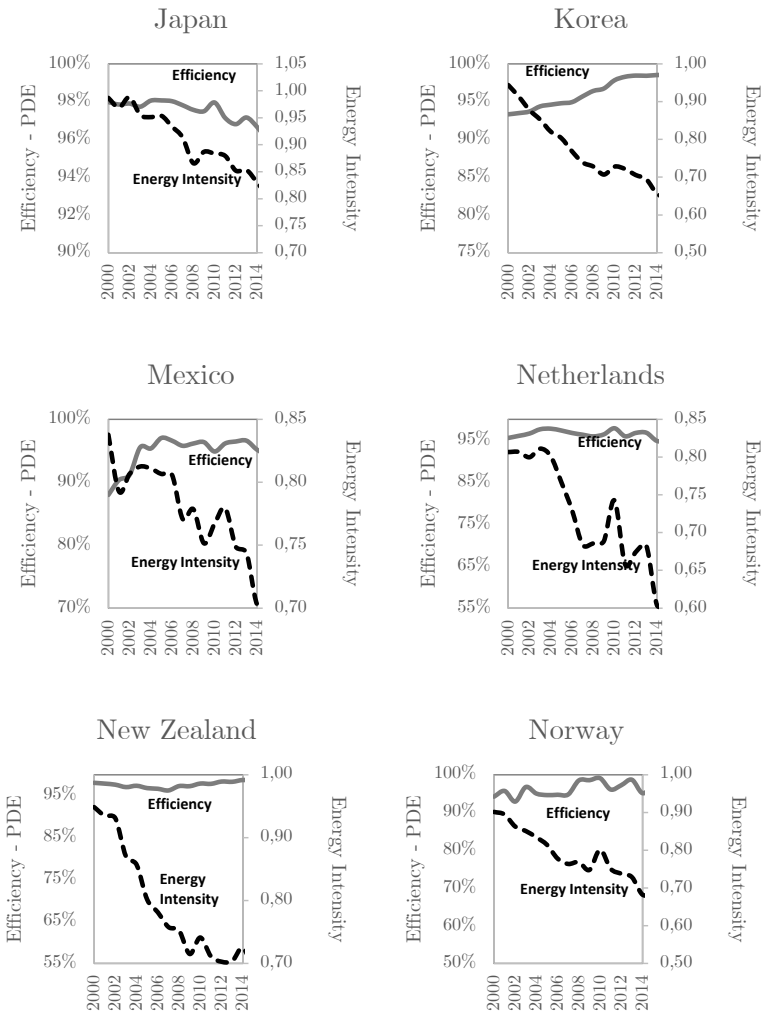


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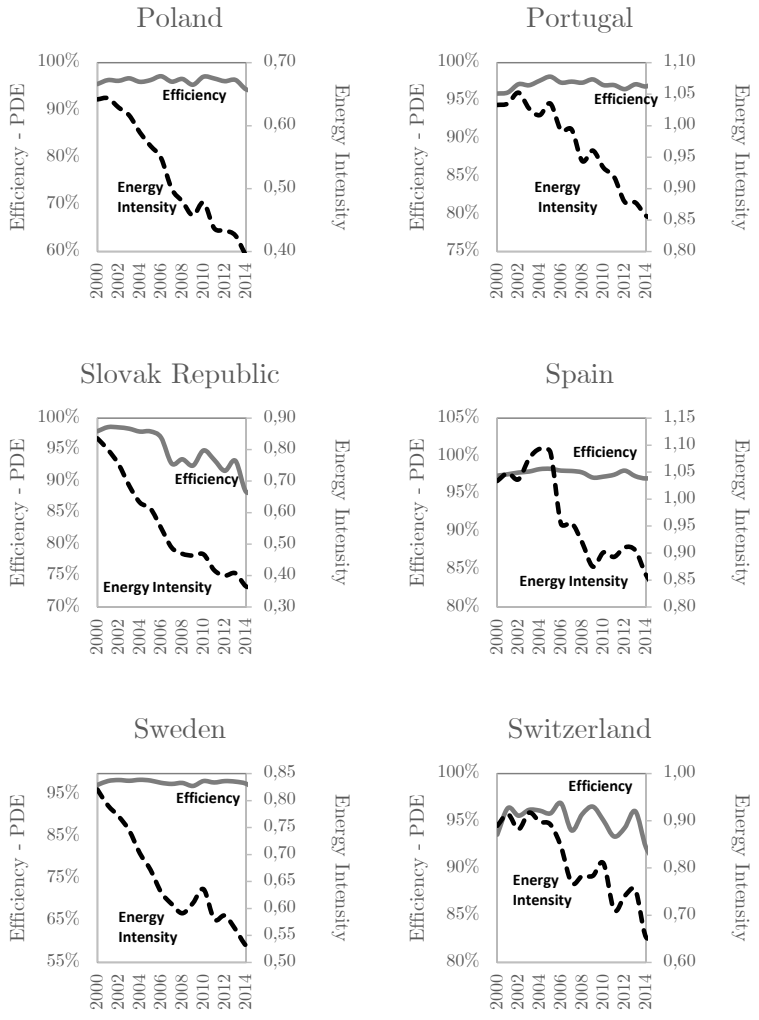


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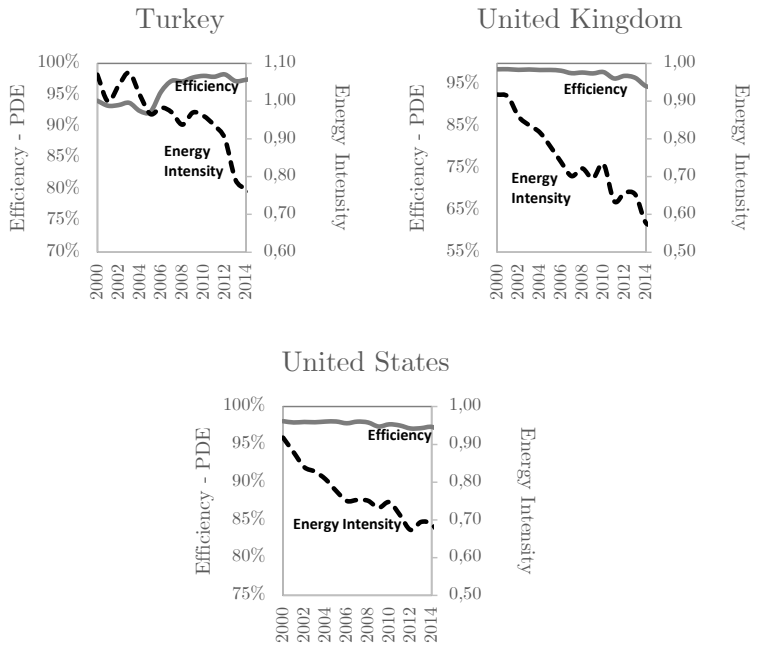


Figure 2.C.2. Continued.

2.C.2. Endogeneity analysis

The SFA framework is derived on basic principles of the microeconomic theory, which imposes a one-way relationship from any explanatory factor (considered as exogenous) to energy consumption (Equation 1) and energy inefficiency (Equation 4). Because of this theoretical foundation, endogeneity is hardly analyzed in the SFA context (see Filippini & Hunt 2011; 2015, among many others).[56]

However, when using macroeconomic panel data, endogeneity of the regressors may be a concern, which could lead to biased estimates.[57] Addressing the problem of

[56] In addition, it is also difficult to account for endogeneity in SFA models owing to there is no commonly accepted approach (see Filippini and Zhang 2016 for a detailed discussion).

[57] We acknowledge an anonymous referee for suggesting us this analysis.

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endogeneity usually requires a suitable Instrumental Variable (IV) approach. At the same time, the IV methodology could reduce the misspecification error in the model and, thus, the possible omitted variable bias (Kaufmann et al. 1999; Stern 2012; Wong, Chia, & Chang 2013). Nevertheless, due to the special nature of the error term in SFA, this task is relatively more complex compared to standard regression models (Karakaplan & Kutlu 2017). Precisely, this latter paper overcomes this difficulty and is able to analyze the potential endogeneity issue in the frontier regressors and in the inefficiency equation.

Roughly speaking, the procedure proposed by Karakaplan & Kutlu (2017) works in three steps. First, a frontier in which all variables are taken as exogenous is estimated. Second, a new frontier is estimated taking endogeneity into account. This latter frontier includes a correction term for bias (what these authors call the ŋ term) that depends on the parameters affecting the inefficiency and the random error term. Finally, the results of both models are compared using an ŋ endogeneity test, which relies on similar ideas to the standard Durbin-Wu-Hausman test for endogeneity. Here, rejecting the null indicates that there is endogeneity problems in the model, while not rejecting the null implies the contrary. Said in other words, not rejecting the null implies that the IV correction is not necessary and the efficiency should be estimated by traditional frontier methods, as the ones used in Section 4.[58]

According to our specification, the variables that, a priori, could generate endogeneity problems are energy prices, GDP, population and EEGI. We conduct the ŋ endogeneity

[58] There are other suitable alternatives to handle endogeneity in SFA (Gronberg et al. 2015; Tran & Tsionas 2015; Griffiths & Hajargasht 2016). However, the methodologies proposed in these works differ remarkably from the SFA methods presented in our main text. Furthermore, it also present additional advantages. First, this approach enables considering heteroskedasticity in either component of the composed error term (i.e., in both v_{it} and u_{it}). Second, the model can deal with both the endogeneity due to frontier regressors and that due to inefficiency determinants. Finally, the ŋ endogeneity test proposed by Karakaplan & Kutlu (2017) allow us to assess in a straightforward way if endogeneity is present in our models.

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test on several combinations of these variables in order to examine endogeneity (Karakaplan and Kutlu 2017). To this aim, and due to the absence of suitable external instruments (as it is common in the literature), we use lagged levels (from one up to three lags) of the growth rates of the instrumented variables, as in Griffiths & Hajargasht 2016; Guan, Kumbhakar, Myers, & Lansink 2009; Levinsohn & Petrin 2003, among others.

The results can be seen in Table 9 In columns from (1) to (3) the model analyzes the endogeneity associated with the *EEGI*, the GDP and the energy prices, respectively. In column (4), we combine the *EEGI* and GDP, while in column (5) we do the same with energy prices. In column (6), we consider these three variables can be endogenous simultaneously. Finally, in column (6), we further extend our analysis assessing the endogeneity associated when GDP, population and urbanization rate are jointly taken into account. The instruments used in Table 9 are the 2-years lags of the growth rate of each potential endogenous variable (results for 1 and 3-year lags are available upon request). The F-statistic tests, which measures the strength of the corresponding instruments to the instrumented variable (an indicative of its weakness as instruments) are also provided in this table.

In all cases, we find that the test fails to reject the null hypothesis, with p-values ranging from 0.116 to 0.963. Also, all instruments used are significant at the 1% level, accounting a F-statistic greater than or closer to 10 in all cases, which indicates that the instruments are not weak in our case.[59] Results of all these tests are summarized in Table 9. Therefore, the results of this section reveal that endogeneity is not an important

[59] Only those instruments related to GDP provide a F-statistic lower than 10 when they are considered together with the instruments corresponding to energy consumption and energy governance. However, the Stock-Yogo values indicate that the maximum possible bias is low and assumable. In fact, the consideration that the F-statistic should be higher than the threshold of 10 is merely a rule of thumb (Brueckner and Lederman 2018). Thus, we use the Stock & Yogo (2005) approach and their critical values, which express the weakness in terms of the size of the IV bias, since it is rather a more reasonably and comprehensive approach.

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concern in our models. As a consequence, we can assert that the results of the specifications described in Section 3 and presented in Section 4 are not biased (at least, for this potential problem), and that there is no need to control for endogeneity.

Table 2.C.3. Analysis of endogeneity in SFA models.

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
ENDOGENOUS VARIABLES	p_{it}	✓			✓		✓	
	y_{it}		✓			✓	✓	✓
	pop_{it}							✓
	UR_{it}							✓
	$EEGI_{it}^{oil}$			✓	✓	✓	✓	
Instruments (2-year lag)		$\Delta price_{it}$	Δy_{it}	$EEGI_{it}^{oil}$	$\Delta price_{it}$ $EEGI_{it}^{oil}$	Δy_{it} $EEGI_{it}^{oil}$	$\Delta price_{it}$ Δy_{it} $EEGI_{it}^{oil}$	Δy_{it} Δpop_{it} ΔUR_{it}
F-statistic (H0: weak identification)		19.46 (0.000)	14.34 (0.000)	23.39 (0.000)	26.79 (0.000) 11.25 (0.000)	7.75 (0.000) 10 (0.000)	11.04 (0.000) 5.24 (0.002) 10.96 (0.000)	10.24 (0.000) 11.99 (0.000) 11.04 (0.000)
N endogeneity test	p-value (H0: the variable(s) is (are) exogenous)	(0.333)	(0.123)	(0.963)	(0.149)	(0.116)	(0.135)	(0.170)

Variables: *p:* ln-Energy prices*; y:* ln-GDP*; pop:* ln-Population*; UR:* Urbanization Rate*;* $EEGI_{it}^{oil}$: EEGI multiplied by ln-growth of international oil price series. Instruments (2-year lags): $\Delta price_{it}$: ln-growth of energy prices; Δy_{it}: ln-growth of GDP; Δpop_{it}: ln-growth of population; ΔUR_{it}: ln-growth of urbanization rate. P-values for F-statistics and endogeneity test are reported in parentheses

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Chapter 3

A two-stage optimization framework for long-term energy planning in island power systems

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1. Introduction

Energy policy in recent years has brought the decarbonization of economies sharply into focus, and this change in direction has important implications for energy generation and consumption. Given that electricity production is one of the main drivers of global CO_2 emissions (accounting for almost 20% of the total) action in the electricity sector is key to achieving the goal of decarbonization (IEA, 2019). Thus, in the coming decades, Renewable Energy Systems (RES) will play a crucial role in reducing CO_2 emissions and in cutting generation costs. However, the relatively unpredictable nature of renewable resources may hamper the deployment of these systems and make it difficult to meet the energy targets proposed.

Spatial disaggregation, energy storage systems (ESS), interconnections, and electric vehicles (EV) providing vehicle-to-grid (V2G) services are key factors in the attempts to respond to this situation. Two main questions arise in this regard: (i) what is the optimal capacity that should be installed for each technology, and (ii) how should this capacity be dispatched in order to minimize generation costs and CO_2 emissions? Capacity- and transmission-expansion planning models allow both questions to be answered simultaneously. In this context, the works of Boffino et al. (2019) and Liu et al. (2018a) provide interesting approaches that optimize electricity generation, storage, and transmission investment over a long planning horizon. More specifically, Boffino et al. (2019) proposes a two-stage model in which the first step is dedicated to solving the capacity problem, and the second one focuses on the system's hourly commitment and dispatch over a set of representative operating days.

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A common aspect of these studies and other related literature is that they focus almost exclusively on the analysis of continental systems (see Lund et al., 2015; Madzharov et al., 2014; Sigrist et al., 2017; Sioshansi et al., 2009). However, it is island power systems that most urgently require the development of models of this type because they tend to produce far higher generation costs and carbon emission rates than their continental counterparts. The reasons for this are the cost of fuel transportation, lower generation efficiencies, and very strict specifications with regard to system reserves in order to guarantee frequency and voltage stability (Lobato et al., 2017).

This paper adds to the existing literature by combining and expanding models developed for continental power systems and applying them to the island domain. We adapt the two-stage capacity- and transmission-expansion model proposed by Boffino et al. (2019) to the case of island power systems in order to provide guidance for long-term planning decisions. We focus on reducing generation and emission costs, and implicitly on maximizing RES penetration. Our approach uses representative operating weeks, which provide a better reflection of day-to-day ESS operation than day-based simulations. Further, it implicitly captures short-term and small-scale uncertainties such as variability in load and renewable supply (Nahmmacher et al., 2016). The concerns outlined here are especially relevant in the case of island power systems, but they have gone virtually unnoticed so far.

To the best of our knowledge, our study is the first to propose a capacity- and transmission-expansion model for island power systems combining thermal generation (steam turbines (ST), diesel engines (DE), gas turbines (GT), and combined cycles (CC)); RES (wind, photovoltaics (PV), biogas and mini-hydro); ESS (both battery energy storages (BES) and pumped-hydro energy storage (PHES)); V2G services, and

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AC/HVDC interconnections. In addition, quite unusually in the literature, we incorporate commitment and energy capacity decisions for energy-storage units (Arbabzadeh et al., 2019). We also model EVs' charging cycles by allowing them to be co-optimized with the commitment and dispatch of the power system so that they reflect the impact of hour-t generation costs on energy demand (Chandrashekar et al., 2017; Sioshansi & Denholm, 2009). Mobility patterns across the nodes of the system are also implemented, thus allowing an accurate assessment of the role of EV as distributed ESS and capacity reserves. Finally, we extend the constraints on interconnections presented in (Lobato et al., 2017) by modeling power flows between the interconnected nodes.

The potential benefits of our model are shown via a case study of the Canary archipelago in Spain,[60] in which we assess a total of 19 cases. In 15 of them, we examine the technologies mentioned first individually and then together, to understand how each one affects power generation and the synergies that can arise from their joint use. Finally, we examine four additional cases and conduct a sensitivity analysis of the effect of carbon emission pricing on generation costs and RES penetration. This analysis is particularly relevant today, given that electricity costs in the Canary Islands (and throughout Europe) have skyrocketed as a result of the increase in the price of CO_2 emissions, going from an average cost of 24.75 €/Tm in 2020 to 48.98 €/Tm in 2021. This trend does not seem to be reversing in the short term.

From the socio-economic perspective, the Canary Islands represent an interesting setting for the study because they are the EU's largest outermost region in terms of both

[60] As explained in Section 4, the Canary archipelago comprises seven main islands. Tenerife and Gran Canaria are the largest in terms of total and peak energy demand, followed by Fuerteventura and Lanzarote, which are regarded as medium-sized islands. Finally, there are three more small to medium islands: La Palma, La Gomera and El Hierro. Today there are only six electrical systems, since Fuerteventura and Lanzarote were interconnected by a submarine cable in 2005.

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economic growth and electricity consumption. Generation costs on the islands may be up to 10 times higher than on the mainland (OMIE, 2017). From the technical perspective, the archipelago is also of particular interest because Spanish regulations do not allow RES, ESS or EV to provide the system with capacity reserves (Real Decreto 738/2015). In the short term, the Transport System Operator (TSO) tries to overcome this problem by promoting the development of interconnections, but has done little to assess the impact of other alternatives. In the long run, however, the inclusion of ESS and EV in the system's power reserves is inevitable if the European decarbonization objectives are to be met in island regions. Therefore, by including these technologies in the reserves and combining them with interconnections, this study should shed some light on the path that the Canary Islands and other European island power systems might follow in order to meet their energy targets.

The present study contributes to the literature in several significant ways. From a theoretical perspective, it responds to the need for complex capacity-expansion planning models for island power systems. In addition, our model provides a reliable approach to ESS operation by paying due attention to small-scale uncertainties in RES generation and load variability. It also assesses the intraday capabilities of V2G services as a power reserve in island systems. From an empirical perspective, our approach helps to assess the TSO's transmission-expansion policy and the consequences of an upward trend in CO_2 prices in the Canaries. Our model can be easily extended to other island regions, and so the results may be of great interest to the readership.

The remainder of the paper proceeds as follows. Section 2 summarizes the most important literature on the matter, paying special attention to research related to the Canary Islands. Section 3 presents the methodological approach, while the case-study is

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detailed in Section 4. The results are presented in Section 5. Finally, Section 6 draws the main conclusions.

2. Capacity- and transmission-expansion models: A review for island power systems

The capacity- and transmission-expansion planning is a crucial process taking into account multiple aspects and various parameters of the examined power system in order to optimally satisfy de future electricity demand. Accordingly, given the appreciable differences in the characteristics of continental and island systems, it is necessary to specifically develop capacity-expansion models for the latter (Georgiou et al., 2011).

One really distinctive aspect is that island systems are much more vulnerable to important technical issues such as variations in grid frequency and voltage. This leads to the guarantee and safety requirements (i.e., the power reserve criteria of the system) differing significantly. On the one hand, in terms of the magnitude of the reserves, while the total of them in a continental grid can account for 10% of generation, in island systems this percentage may increase up to 200% (see Section 3). Obviously, this circumstance has a strong impact on system modeling. On the other hand, the need for special reserve criteria arises. In the case of the Canary Islands, for example, this includes the requirement to ensure a reserve capacity 1.5 times higher than the power delivered by the turbine of a combined cycle, covering 100% of the increase in demand between one period and the next, the impediment to RES from providing power reserves, or the provision of a sufficiently large reserve capable of supplying the energy received through any interconnection. These aspects are not common in the case of continental systems.

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Likewise, island systems are also characterized by a more pronounced environmental sensitivity, which makes the assessment of CO2 emissions derived from electricity production more necessary and relevant than in the case of continental systems. Faced with such peculiar reserve criteria and the intensive use of fossil fuels for electricity generation, it is necessary to correctly identify the extent to which technologies such as ESS or EV can contribute to reducing these emissions.

However, the literature on the development of capacity- and transmission-expansion models for island regions is quite scarce. In fact, the studies available focus mainly on the development of models to optimize the commitment and dispatch of the system; significantly, they leave aside decisions regarding capacity and transmission investment. These studies frequently examine the use of technologies like ESS, EV, and interconnections. For the most part, they assess the impact of these technologies on issues like costs and/or emissions individually, but a thorough evaluation of the combination of these technologies might induce important changes in investment and operation decisions (Ramos-Real et al., 2018). The lack of an analysis of this kind constitutes an important gap which needs to be properly addressed by new research.

Regarding the implementation of ESS in island models, the consideration of PHES is likely to be the most recurrent alternative in the literature. Several studies have sought to optimize the operation of PHES, many of them focused on the Canaries. Bueno & Carta (2005) presented a model that performed a techno-economic analysis of a wind-powered PHES that was later applied to the island of El Hierro (Bueno & Carta, 2005b), and proposed similar models in (Bueno & Carta, 2006; Portero et al., 2015). However, in terms of increasing RES penetration, the results are disappointing. In addition, the authors do not provide an accurate representation of the day-to-day operation of ESS,

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since they neglect important concerns like unit commitment constraints for PHES, the strict reserve criteria of the system, or the analysis of the depletion of ESS during the operation period (Liu et al., 2018b; Nahmmacher et al., 2016).

Studies assessing the capability of V2G services to provide system power reserves in island regions are limited, though some of them have also focused on the Canary Islands. Ramírez-Díaz et al. (2015) and Ramirez-Diaz et al. (2016) analyzed the value of EV as distributed energy-storage capacity in the islands of La Palma and Tenerife. However, the authors do not consider important aspects that could strongly affect their results such as the representation of nodes along the power grid or the implementation of EV mobility routes between nodes. The consideration of these issues may induce important changes in the operation of generators, storage units, and V2G services according to factors like demand and generation levels in the node they are connected to and in nearby nodes, or the capacity limits of transmission lines. This latter issue is especially important in systems characterized by centralized generation and weak power grids, as is the case in the Canary Islands. Similarly, Colmenar-Santos et al. (2017) investigated the charging/discharging patterns for EV to facilitate their penetration in Tenerife's power system. However, they did not model system reserves or other important concerns like the costs incurred by battery cycling, and EV mobility patterns across the nodes of the power grid. By not modeling these aspects, these studies may misjudge the role of V2G services as distributed ESS and power reserves.

Finally, the literature on island interconnections is divided into two groups: island-to-mainland, and island-to-island. The first category mainly comprises studies that analyze the role of interconnections in increasing RES share and in reducing generation costs, for instance, in the Greek power sector (Georgiou et al., 2011; Kalampalikas & Pilavachi,

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2010; Kapsali et al., 2016; Koltsaklis et al., 2015, 2016; Voumvoulakis et al., 2012). The literature in the second category is much more scarce. Lobato et al. (2017) focused on the Spanish islands Lanzarote and Fuerteventura in order to study the economic value of island-to-island interconnections, while Ramos-Real et al. (2018) compared the costs and emissions of island power systems operating in isolation thanks to a high penetration of ESS, and other island systems operating through one interconnection. While Lobato et al. (2017) assessed only the role of interconnectors, Ramos-Real et al. (2018) took into account their combination with other technologies like BES and PHES; nevertheless, their approach represents a considerable simplification of the dispatch and commitment of the real Canary power system.

3. The model

The model presented in this work follows the approach proposed by Boffino et al. (2019), who in turn draw on the work of Liu et al. (2018a), in order to propose a two-stage capacity- and transmission-expansion model. This model is intended to assist in making long-term energy planning decisions. The first step of the model solves the capacity problem, while the second stage captures the operating conditions. The model assumes that there is no initial generation or storage capacity installed on the reference year, saving from those transmission lines and systems that are currently installed.

3.1. Model notation

3.1.1. Indices

c Index of thermal generation units.

g Index of renewable generation units.

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s	Index of stand-alone energy-storage units.
e	Index of EV fleets.
l	Index of existing and candidate transmission lines (including interconnectors).
n	Index of power system nodes.
i	Index of island.
o	Index of operating conditions.
ref	Index of reference node.
t	Index of time periods within an operating condition.

The indices $c, g,$ and s will account for all thermal, renewable and energy-storage technologies considered in the case-study (see Sections 1 and 4 for further details). The only ESS currently available in the archipelago is a PHES located at the island of El Hierro. However, BES are also considered in the model due to their growing interest as a complement to electricity generation. Although unit commitment decisions are only modeled for PHES, for the sake of simplicity both systems (PHES and BES) are denoted by the index s. Finally, the fleets of EV are based on Plug-in Hybrid Electric Vehicles (PHEV), as in Sioshansi & Denholm (2009).

3.1.2. Sets

Ω_n^C	Set of thermal units located at node n.
Ω_n^G	Set of renewable units located at node n.
Ω_n^S	Set of stand-alone energy-storage units located at node n.
Ω_n^E	Set of EV fleets located at node n
Ω^{L+}	Set of candidate transmission lines.
$\varsigma^r(l)$	Receiving-end node of transmission line l.

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$\varsigma^s(l)$ Sending-end node of transmission line l.

Following Boffino et al. (2019), we divide the transmission lines into existing and candidate lines. Both of them are divided in two categories: (i) AC and (ii) HVDC. Power flows are modeled differently in each kind of lines. While AC transmissions are represented using a linear approximation of Kirchhoff's laws, HVDC lines are modeled using a pipeline assumption, whereby power flows can be directed along each line (Boffino et al., 2019). Since all current and planned inland transmission lines are of the AC type (Red Eléctrica de España, 2015), HVDC candidate lines are only considered for interconnections.

3.1.3. Parameters

I_c^C Investment cost of thermal unit c [€/MW].

I_g^G Investment cost of renewable unit g [€/MW].

I_s^S Investment cost of stand-alone energy-storage unit s [€/MW].

I_l^L Investment cost of candidate transmission line l [M€].

$I^{C,max}$ Investment budget for building thermal units [€].

$I^{G,max}$ Investment budget for building renewable units [€].

$I^{S,max}$ Investment budget for building stand-alone energy-storage units [€].

$I^{L,max}$ Investment budget for building candidate transmission line l [€].

$\bar{P}_c^{C,max}$ Maximum capacity of thermal unit c that can be built [MW].

$\bar{P}_g^{G,max}$ Maximum capacity of renewable unit g that can be built [MW].

$\bar{P}_s^{S,max}$ Maximum capacity of stand-alone energy-storage unit s that can be built [MW].

K_c^C Generation cost of thermal unit c [€/MWh].

$C_c^{C,Start\_Up}$ Start-up cost of thermal unit c [€/p.u.].

$C_c^{C,Shut\_down}$ Shutdown cost of thermal unit c [€/p.u.].

K_g^G Generation cost of renewable unit g [€/MWh].

K^D Load-shedding cost [€/MWh].

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$K_s^{S,T}$	Discharging cost of stand-alone energy-storage uni s [€/MWh].
$K_e^{E,T}$	Discharging cost of EV fleet e [€/MWh].
$\eta_s^{S,T}$	Discharging efficiency of stand-alone energy-storage unit s [p.u.].
$\eta_s^{S,P}$	Charging efficiency of stand-alone energy-storage unit s [p.u.].
$\eta_e^{E,T}$	Discharging efficiency of EV fleet e [p.u.].
$\eta_e^{E,P}$	Charging efficiency of EV fleet e [p.u.].
χ_{CO2}	Carbon-emissions price [€/t].
$\varepsilon_{c,CO2}$	Carbon emission rate of thermal unit c [t/MWh].
$\varepsilon_{g,CO2}$	Carbon emission rate of renewable unit g [t/MWh].
$p_c^{C,min}$	Minimum operating power of thermal unit c [MW].
$p_g^{G,min}$	Minimum operating power of renewable generator g [MW].
$f_{g,o,t}$	Hour-t capacity factor of renewable unit g in operating condition o [p.u.].
$R_c^{C,up}$	Maximum ramp-up of thermal unit c [MW].
$R_c^{C,down}$	Maximum ramp-down of thermal unit c [MW].
$R_g^{G,up}$	Maximum ramp-up of renewable unit g [MW].
$R_g^{G,down}$	Maximum ramp-down of renewable unit g [MW].
$\bar{c}_s$	Energy-storage capacity of stand-alone unit s [hours].
γ_s^{S,L_min}	Minimum State of Charge (SoC) of stand-alone energy-storage unit s [MWh].
$p_e^{E,max}$	Available V2G capacity of EV fleet e [MW].
ρ_e^{E,L_min}	Absolute minimum SoC of EV fleet e [MWh].
ρ_e^{E,L_max}	Maximum energy-storage capacity of EV fleet e [MWh].
$\rho_e^{E,L\_GridMin1}$	Minimum SoC of EV fleet e at departure time 1 [MWh].
$\rho_e^{E,L\_GridMin2}$	Minimum SoC of EV fleet e at departure time 2 [MWh].
$N_{e,o,t,}^{E,C}$	Hour-t energy consumption of EV fleet e in operating condition o [MWh]
$\emptyset_e^A$	Arrival times of EV fleet e [hour].
$\emptyset_e^D$	Departure times of EV fleet e [hour].
F_l^{max}	Capacity of transmission line l [MW].
$\theta_{ref,o,t}$	Hour-t phase angle at reference node in operating condition o [rad].

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M	A large fixed constant.
B_l	Susceptance of transmission line l [S].
$P_{n,o,t}^{D,max}$	Hour-t load at node n in operating condition o [MWh].
$P_{i,o,t}^{D,max}$	Hour-t load at island i in operating condition o [MWh].
ρ_o	Weight of operating condition o [weeks].

3.1.4. Decision variables

$p_c^{C,max}$	Capacity of thermal unit c that is built [MW].
$p_g^{G,max}$	Capacity of renewable unit g that is built [MW].
$p_s^{S,max}$	Capacity of stand-alone energy-storage unit s that is built [MW].
$p_{c,o,t}^{C}$	Hour-t production level of thermal unit c in operating condition o [MW].
$p_{g,o,t}^{G}$	Hour-t production level of renewable unit g in operating condition o [MW].
$p_{n,o,t}^{D}$	Hour-t load at node n that is shed in operating condition o [MW].
$\gamma_{s,o,t}^{S,T}$	Hour-t discharging rate of stand-alone energy-storage unit s in operating condition o [MW].
$\rho_{e,o,t}^{E,T}$	Hour-t discharging rate of EV fleet e in operating condition o [MW].
$\gamma_{s,o,t}^{S,P}$	Hour-t charging rate of stand-alone energy-storage unit s in operating condition o [MW].
$\rho_{e,o,t}^{E,P}$	Hour-t charging rate of EV fleet e in operating condition o [MW].
$p_{l,o,t}^{L}$	Hour-t power flow through transmission line l in operating condition o [MW].
$p_{i_{il-i},o,t}^{L}$	Hour-t power flow through transmission line (interconnector) l from island ii to island i in operating condition o [MW].
$r_{c,o,t}^{down}$	Hour-t spinning-down reserve capacity provided by thermal unit c in operating condition o [MW].
$r_{c,o,t}^{up}$	Hour-t spinning-up reserve capacity provided by thermal unit c in operating condition o [MW].
$w_{c,o,t}^{up}$	Hourt-t non-spinning-up reserve capacity provided by thermal unit c in operating condition o [MW].
$r_{g,o,t}^{down}$	Hour-t spinning-down reserve capacity provided by renewable unit g in operating condition o [MW].
$r_{g,o,t}^{up}$	Hour-t spinning-up reserve capacity provided by renewable unit g in operating condition o [MW].

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$w_{g,o,t}^{up}$ Hourt-t non-spinning-up reserve capacity provided by renewable unit g in operating condition o [MW].

$r_{s,o,t}^{down}$ Hour-t spinning-down reserve capacity provided by stand-alone energy-storage unit s in operating condition o [MW].

$r_{s,o,t}^{up}$ Hour-t spinning-up reserve capacity provided by stand-alone energy-storage unit s in operating condition o [MW].

$w_{s,o,t}^{up}$ Hourt-t non-spinning-up reserve capacity provided by stand-alone energy-storage unit s in operating condition o (only for PHES) [MW].

$\gamma_{s,o,t}^{S,L}$ Hour-t SoC of stand-alone energy-storage unit s in operating condition o [MWh].

$\rho_{e,o,t}^{E,L}$ Hour-t SoC of EV fleet e in operating condition o [MWh].

$r_{e,o,t}^{down}$ Hour-t spinning-down reserve capacity provided by EV fleet e in operating condition o [MW].

$r_{e,o,t}^{up}$ Hour-t spinning-up reserve capacity provided by EV fleet e in operating condition o [MW].

$\theta_{n,o,t}$ Hour-t phase angle at node n in operating condition o [rad].

3.1.5. Binary decision variables

x_l^L Binary variable that equals 1 if candidate transmission line is built; 0 otherwise.

$xc_{c,o,t}^C$ Binary variable that equals 1 if thermal unit c starts up at time t of operating condition o; 0 otherwise.

$xd_{c,o,t}^C$ Binary variable that equals 1 if thermal unit c shuts down at time t of operating condition o; 0 otherwise.

$\delta_{c,o,t}^C$ Binary variable that equals 1 if thermal unit c is connected at time t of operating condition o; 0 otherwise.

$xc_{s,o,t}^S$ Binary variable that equals 1 if stand-alone energy-storage unit s is charging at time t of operating condition o; 0 otherwise (only for PHES).

$xd_{s,o,t}^S$ Binary variable that equals 1 if stand-alone energy-storage unit s is discharging at time t of operating condition o; 0 otherwise (only for PHES).

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3.2. Model formulation

3.2.1. Target function

$$\begin{aligned}\min \sum_c I_c^C\, p_c^{C,max} + \sum_g I_g^G\, p_g^{G,max} + \sum_s I_s^S\, p_s^{S,max} + \sum_{l\in\Omega^{L+}} I_l^L\, x_l^L \\ + \sum_{o,t}\rho_o\left\{\sum_c\left[\left(K_c^C + \chi_{CO2}\varepsilon_{c,CO2}\right)p_{c,o,t}^{C} + C_c^{C,Start\_Up}\cdot xc_{c,o,t}^C + C_c^{C,Shut_{down}}\right.\right. \\ \left.\cdot\, xd_{c,o,t}^C\right] + \sum_g\left[\left(K_g^G + \chi_{CO2}\varepsilon_{g,CO2}\right)p_{g,o,t}^{G}\right] + \sum_t\left(K^D p_{n,o,t}^D\right) \\ \left.+ \sum_{ess}\left(K_s^{S,T}\gamma_{s,o,t}^{S,T}/\eta_s^{S,T}\right) + \sum_{EV}\left(K_e^{E,T}\rho_{e,o,t}^{E,T}/\eta_e^{E,T}\right)\right\}\end{aligned} \tag{1}$$

3.2.2. Constraints related to investment decisions

$$0 \le p_c^{C,max} \le \bar{P}_c^{C,max}, \forall\, c \tag{2}$$

$$0 \le p_g^{G,max} \le \bar{P}_g^{G,max}, \forall\, g \tag{3}$$

$$0 \le p_s^{S,max} \le \bar{P}_s^{S,max}, \forall\, s \tag{4}$$

$$\sum_c I_c^C\, p_c^{C,max} \le I^{C,max} \tag{5}$$

$$\sum_g I_g^G\, p_g^{G,max} \le I^{G,max} \tag{6}$$

$$\sum_s I_s^S\, p_s^{S,max} \le I^{S,max} \tag{7}$$

$$\sum_{l\in\Omega^{L+}} I_l^L\, x_l^L \le I^{L,max} \tag{8}$$

3.2.3. System's equilibrium

$$\begin{aligned}\sum_{c\epsilon\Omega_n^C} p_{c,o,t}^C + \sum_{g\epsilon\Omega_n^G} p_{g,o,t}^G + p_{n,o,t}^D + \sum_{s\epsilon\Omega_n^S}\left(\gamma_{s,o,t}^{S,T} - \gamma_{s,o,t}^{S,P}\right) + \sum_{e\epsilon\Omega_n^E}\left(\rho_{e,o,t}^{E,T} - \rho_{e,o,t}^{E,P}\right) + \sum_{l,\varsigma^r(l)=n} p_{l,o,t}^L \\ - \sum_{l,\varsigma^s(l)=n} p_{l,o,t}^L = P_{n,o,t}^{D,max}, \forall\, c,o,t\end{aligned} \tag{9}$$

3.2.4. Load-shedding cost

$$0 \le p_{n,o,t}^D \le P_{n,o,t}^{D,max}\ \forall\, n,o,t \tag{10}$$

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3.2.5. Generators

3.2.5.1. Thermal units

$$0 \le p^{C}_{c,o,t} \le p^{C,max}_{c}, \forall\, c,o,t \tag{11}$$

$$p^{C}_{c,o,t} - r^{down}_{c,o,t} \ge p^{C,min}_{c}\delta^{C}_{c,o,t}, \forall\, c,o,t \tag{12}$$

$$p^{C}_{c,o,t} + r^{up}_{c,o,t} \le p^{C,max}_{c}\delta^{C}_{c,o,t}\ \forall\, c,o,t \tag{13}$$

$$p^{C}_{c,o,t} + r^{up}_{c,o,t} + w^{up}_{c,o,t} \le p^{C,max}_{c}\ \forall\, c,o,t \tag{14}$$

$$0 \le r^{up}_{c,o,t} \le\ p^{C,max}_{c}\ \forall\, c,o,t \tag{15}$$

$$0 \le w^{up}_{c,o,t} \le\ p^{C,max}_{c}\ \forall\, c,o,t \tag{16}$$

$$0 \le r^{down}_{c,o,t} \le\ p^{C,max}_{c}\ \forall\, c,o,t \tag{17}$$

$$p^{C}_{c,o,t} - p^{C}_{c,o,t-1} + r^{up}_{c,o,t} + w^{up}_{c,o,t} \le R^{C,up}_{c}, \forall\, c,o,t \tag{18}$$

$$p^{C}_{c,o,t} - p^{C}_{c,o,t-1} - r^{down}_{c,o,t} \ge -R^{C,down}_{c}, \forall\, c,o,t \tag{19}$$

3.2.5.1. Renewable units

$$0 \le p^{G}_{g,o,t} \le p^{G,max}_{g} \cdot f_{g,o,t}, \forall\, g,o,t \tag{20}$$

$$r^{up}_{g,o,t} = 0\ \forall\, g,o,t \tag{21}$$

$$w^{up}_{g,o,t} = 0\ \forall\, g,o,t \tag{22}$$

$$0 \le r^{down}_{g,o,t} \le\ p^{G,max}_{g} \cdot f_{g,o,t}\ \forall\, g,o,t \tag{23}$$

$$p^{G}_{g,o,t} - r^{down}_{g,o,t} \ge p^{G,min}_{g} \cdot f_{g,t}, \forall\, g,o,t \tag{24}$$

$$p^{G}_{g,o,t} - p^{G}_{g,o,t-1} \le R^{G,up}_{g}, \forall\, g,o,t \tag{25}$$

$$p^{G}_{g,o,t} - p^{G}_{g,o,t-1} - r^{down}_{g,o,t} \ge -R^{G,down}_{g}, \forall\, g,o,t \tag{26}$$

3.2.6. Stand-alone energy storage

3.2.6.1. Batteries

$$0 \le \gamma^{S,P}_{s,o,t} \le p^{S,max}_{s}, \forall\, s,o,t \tag{27}$$

$$0 \le \frac{\gamma^{S,T}_{s,o,t}}{\eta^{S,T}_{s}} \le p^{S,max}_{s}, \forall\, s,o,t \tag{28}$$

$$\gamma^{S,L\_min}_{s} \le \gamma^{S,L}_{s,o,t} \le \bar{c}_{s} p^{S,max}_{s}, \forall\, s,o,t \tag{29}$$

$$\gamma^{S,L}_{s,o,t} = \gamma^{S,L}_{s,o,t,-1} + \gamma^{S,P}_{s,o,t}\eta^{S,P}_{s} - \gamma^{S,T}_{s,o,t}/\eta^{S,T}_{s}, \forall\, s,o,t > 0 \tag{30}$$

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$$\gamma_{s,o,t}^{S,L} \geq \gamma_{s,o,t}^{S,L} = 0.5 \cdot \bar{c}_s p_s^{S,max} \; \forall \, s, o, t = 0 \tag{31}$$

$$r_{s,o,t}^{up}/\eta_s^{S,T} \leq \gamma_{s,o,t}^{S,L} - \gamma_s^{S,L_{min}}, \forall \, s, o, t \tag{32}$$

$$\gamma_{s,o,t}^{S,T}/\eta_s^{S,T} + r_{s,o,t}^{up}/\eta_s^{S,T} \leq p_s^{S,max}, \forall \, s, o, t \tag{33}$$

$$r_{s,o,t}^{down} \leq \bar{c}_s p_s^{S,max} - \gamma_{s,o,t}^{S,L}, \forall \, s, o, t \tag{34}$$

$$\gamma_{s,o,t}^{S,P} + r_{s,o,t}^{down} \leq p_s^{S,max}, \forall \, s, o, t, \tag{35}$$

$$r_{s,o,t}^{up} \geq 0, \forall \, s, o, t \tag{36}$$

$$r_{s,o,t}^{down} \geq 0, \forall \, s, o, t \tag{37}$$

3.2.6.2. Pumped-hydro energy storage

$$0 \leq \gamma_{s,o,t}^{S,P} \leq p_s^{S,max} \cdot xc_{s,o,t}^{S}, \forall \, s, o, t \tag{38}$$

$$0 \leq \frac{\gamma_{s,o,t}^{S,T}}{\eta_s^{S,T}} \leq p_s^{S,max} \cdot xd_{s,o,t}^{S}, \forall \, s, o, t \tag{39}$$

$$\gamma_s^{S,L\_min} \leq \gamma_{s,o,t}^{S,L} \leq \bar{c}_s p_s^{S,max}, \forall \, s, o, t \tag{40}$$

$$\gamma_{s,o,t}^{S,L} = \gamma_{s,o,t,-1}^{S,L} + \gamma_{s,o,t}^{S,P}\eta_s^{S,P} - \gamma_{s,o,t}^{S,T}/\eta_s^{S,T}, \forall \, s, o, t > 0 \tag{41}$$

$$\gamma_{s,o,t}^{S,L} \geq \gamma_{s,o,t}^{S,L} = 0.5 \cdot \bar{c}_s p_s^{S,max} \; \forall \, s, o, t = 0 \tag{42}$$

$$r_{s,o,t}^{up}/\eta_s^{S,T} + w_{s,o,t}^{up}/\eta_s^{S,T} \leq \gamma_{s,o,t}^{S,L} - \gamma_s^{S,L_{min}}, \forall \, s, o, t \tag{43}$$

$$\gamma_{s,o,t}^{S,T}/\eta_s^{S,T} + r_{s,o,t}^{up}/\eta_s^{S,T} + w_{s,o,t}^{up}/\eta_s^{S,T} \leq p_s^{S,max}, \forall \, s, o, t \tag{44}$$

$$r_{s,o,t}^{down} \leq \bar{c}_s p_s^{S,max} - \gamma_{s,o,t}^{S,L}, \forall \, s, o, t \tag{45}$$

$$\gamma_{s,o,t}^{S,P} + r_{s,o,t}^{down} \leq p_s^{S,max}, \forall \, s, o, t, \tag{46}$$

$$r_{s,o,t}^{up} \geq 0, \forall \, s, o, t \tag{47}$$

$$r_{s,o,t}^{down} \geq 0, \forall \, s, o, t \tag{48}$$

$$w_{s,o,t}^{up} \geq 0, \forall \, s, o, t \tag{49}$$

3.2.7. Electric vehicles

$$0 \leq \rho_{e,o,t}^{E,P} \leq p_e^{E,max}, \forall \, e, o, t \tag{50}$$

$$0 \leq \rho_{e,o,t}^{E,T}/\eta_s^{S,T} \leq p_e^{E,max}, \forall \, e, o, t \tag{51}$$

$$\rho_{e,o,t}^{E,L} = \rho_{e,o,t,-1}^{E,L} + \rho_{e,o,t}^{E,P}\eta_e^{E,P} - \rho_{e,o,t}^{E,T}/\eta_e^{E,T} - N_{e,o,t,}^{E,C}, \forall \, e, o, t > 0 \tag{52}$$

$$\rho_{e,o,t}^{E,L\_min} \leq \rho_{e,o,t}^{E,L} \leq \rho_{e,o,t}^{E,L\_max}, \forall \, e, o, t \tag{53}$$

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$$\rho_{e,o,t}^{E,L} = 0.5 \cdot \rho_e^{E,L\_max}, \forall\, e, o, t = 0 \tag{54}$$

$$\rho_{e,o,t}^{E,L} \geq \rho_e^{E,L\_GridMin1}\ \forall\, e, o, t = D0 \tag{55}$$

$$\rho_{e,o,t}^{E,T} \geq \rho_e^{E,L\_GridMin2}\ \forall\, e, o, t = D1 \tag{56}$$

$$r_{e,o,t}^{up}/\eta_e^{E,T} \leq \rho_{e,o,t}^{E,L} - \rho_e^{E,L_{min}}, \forall\, e, o, t \tag{57}$$

$$\rho_{e,o,t}^{E,T}/\eta_e^{E,T} + r_{e,o,t}^{up}/\eta_e^{E,T} \leq p_e^{E,max}, \forall\, e, o, t \tag{58}$$

$$r_{e,o,t}^{down} \leq \bar{c}_e p_e^{E,max} - \rho_{e,o,t}^{E,L}, \forall\, e, o, t \tag{59}$$

$$\rho_{e,o,t}^{E,P} + r_{e,o,t}^{down} \leq p_e^{E,max}, \forall\, e, o, t \tag{60}$$

$$\rho_{e,o,t}^{E,P}, \rho_{e,o,t}^{E,T} = 0\ \forall\, e, o, t\ \notin [\emptyset_e^A, \emptyset_e^D] \tag{61}$$

$$r_{e,o,t}^{up}, r_{e,o,t}^{down} = 0\ \forall\, e, o, t\ \notin [\emptyset_e^A, \emptyset_e^D] \tag{62}$$

$$r_{e,o,t}^{up} \geq 0, \forall\, e, o, t \tag{63}$$

$$r_{e,o,t}^{down} \geq 0, \forall\, e, o, t \tag{64}$$

3.2.8. System's reserves

$$\sum_{c\in C, c\in I} r_{c,o,t}^{up} + \sum_{s\in S, s\in I} r_{s,o,t}^{up} + \sum_{e\in EV, e\in I} r_{e,o,t}^{up} \geq 0.50 \cdot p_{c\in I,o,t}^{C}, \forall\, o, t, i, c \in I, s \in I, e\ \in I \tag{65}$$

$$\sum_{c\in C, c\in I} r_{c,o,t}^{up} + \sum_{s\in S, s\in I} r_{s,o,t}^{up} + \sum_{e\in EV, e\in I} r_{e,o,t}^{up} \geq 0.50 \cdot p_{g\in I,o,t}^{G}, \forall\, o, t, i, g \in I, s \in I, e \in I \tag{66}$$

$$\sum_{c\in C, c\in I} (r_{c,o,t}^{up} + w_{c,o,t}^{up}) + \sum_{s\in S, s\in I} (r_{s,o,t}^{up} + w_{s,o,t}^{up}) + \sum_{e\in EV, e\in I} (r_{e,o,t}^{up}) \geq 2 \cdot p_{c\in I,o,t}^{C}, \forall\, o, t, i, c \in I, s \in I, e \in I \tag{67}$$

$$\sum_{c\in C, c\in I} (r_{c,o,t}^{up} + w_{c,o,t}^{up}) + \sum_{s\in S, s\in I} (r_{s,o,t}^{up} + w_{s,o,t}^{up}) + \sum_{e\in EV, e\in I} (r_{e,o,t}^{up}) \geq 2 \cdot p_{g\in I,o,t}^{G}, \forall\, o, t, i, c \in I, a, g \in I, e \in I \tag{68}$$

$$\sum_{c\in C, c\in I} (r_{c,o,t}^{up} + w_{c,o,t}^{up}) + \sum_{s\in S, s\in I} (r_{s,o,t}^{up} + w_{s,o,t}^{up}) + \sum_{e\in EV, e\in I} (r_{e,o,t}^{up}) \geq P_{i,o,t+1}^{D,max} - P_{i,o,t}^{D,max}, \forall o, c \in I, s \in I, e \in I, i, t \mid P_{i,o,t+1}^{D,max} > P_{i,o,t}^{D,max} \tag{69}$$

$$\sum_{c\in C, c\in I} (r_{c,o,t}^{up} + w_{c,o,t}^{up}) + \sum_{s\in S, s\in I} (r_{s,o,t}^{up} + w_{s,o,t}^{up}) + \sum_{e\in EV, e\in I} (r_{e,o,t}^{up}) \geq 1.5 \cdot p_{c\in I,o,t}^{C}, \forall\, o, i, s \in I, e \in I, c \mid GT\ (CC), t \mid P_{i,o,t+1}^{D,max} > P_{i,o,t}^{D,max} \tag{70}$$

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$$\sum_{c\in C,c\in I} r^{down}_{c,o,t} + \sum_{g\in G,g\in I} r^{down}_{g,o,t} + \sum_{s\in S,s\in I} r^{down}_{s,o,t} + \sum_{e\in EV,e\in I} r^{down}_{e,o,t} \geq 0.50 * p^{C}_{c\in I,o,t}, \forall\, o,t,i,c \in I,g \in I, s \in I, e \in I \tag{71}$$

$$\sum_{c\in C,c\in I} r^{down}_{c,o,t} + \sum_{g\in G,g\in I} r^{down}_{g,o,t} + \sum_{s\in S,s\in I} r^{down}_{s,o,t} + \sum_{e\in EV,e\in I} r^{down}_{e,o,t} \geq 0.50 * p^{G}_{g\in I,o,t}, \forall\, o,t,i,c \in I,g \in I, s \in I, e \in I \tag{72}$$

$$\sum_{c\in C,c\in i}(r^{up}_{c,t} + w^{up}_{c,t}) + \sum_{s\in S,s\in i}(r^{up}_{s,t} + w^{up}_{s,t}) + \sum_{e\in EV,e\in i}(r^{up}_{e,t}) \geq p^{L}_{ii-i,o,t} \quad \forall\, t,i,ii,c \in i,s \in i,e \in i \tag{73}$$

3.2.9. Transmission lines

3.2.9.1. Existing lines

$$-F^{max}_{l} \leq p^{L}_{l,o,t} \leq F^{max}_{l}, \forall\, l \notin \Omega^{L+}, o,t \tag{74}$$

$$p^{L}_{l,o,t} = B_l\left(\theta_{\zeta^s(l),o,t} - \theta_{\zeta^r(l),o,t}\right), \forall\, l \notin \Omega^{L+}, o,t \tag{75}$$

3.2.9.2. Candidate lines

$$-F^{max}_{l} \cdot x^{L}_{l} \leq p^{L}_{l,o,t} \leq F^{max}_{l} \cdot x^{L}_{l}, \forall\, l,o,t \tag{76}$$

$$-(1 - x^{L}_{l}) \cdot M \leq p^{L}_{l,o,t} - B_l\left(\theta_{\zeta^s(l),o,t} - \theta_{\zeta^r(l),o,t}\right) \leq (1 - x^{L}_{l}) \cdot M, \forall\, l \notin \Omega^{L+}, o,t \tag{77}$$

3.2.10. Nodes

$$-\pi \leq \theta_{n,o,t} \leq \pi, \forall\, n,o,t \tag{78}$$

$$\theta_{ref,o,t} = 0, \qquad \forall o,t \tag{79}$$

3.2.11. Binary variables

$$\delta^{C}_{c,t} - \delta^{C}_{c,t-1} = xc^{C}_{c,o,t} - xd^{C}_{c,o,t} \forall\, t,c \tag{80}$$

$$xc^{S}_{s,o,t} \leq (1 - xd^{S}_{s,o,t}) \tag{81}$$

$$\delta^{C}_{c,t}, xc^{C}_{c,o,t}, xd^{C}_{c,o,t}, xc^{S}_{s,o,t}, xd^{S}_{s,o,t}, x^{L}_{l} \in \{0,1\}, \forall c,s,l \in \Omega^{L+} \tag{82}$$

Equation (1) represents the objective function. It consists of two differentiated parts: one relative to the investment costs and the other one referred to the operation costs. Following Equation (83), investment cost parameters have been annualized in order to

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make them comparable to operation costs.[61]

$$\frac{i \cdot (1+i)^y}{(1+i)^y - 1} \tag{83}$$

where y is the assumed lifetime of the asset an i is the real interest rate.

Operating costs are computed on an hourly basis for each week of operation. These costs refer, basically, to the production of energy with (conventional and renewable) generators, and to the discharging activities of EV and stand-alone ESS (both BES and PHES). The costs associated with curtailed energy are also considered. Finally, carbon emission costs are present only in the set of sensitivity cases.

Model constraints are also of two types: (i) investment and (i) operation. Regarding the former, Equations (2)-(4) impose limits on capacity that can be built from conventional, RES and ESS units, respectively. No additional thermal capacity to the one currently installed in the Canary Islands can be built, since the model is intended to increase renewable penetration in island power systems, rather than the share of thermal technologies. Equations (5)-(8) establish an economic ceiling for spending on investment in technologies. To fully assess the potential of the model, the maximum expenditure is equal to the cost of the maximum capacity that could be installed for each technology in order not to limit technological penetration by economic reasons. Equation (8) demonstrates the binary nature of investment decisions in transmission lines.

[61] The objective function used in this paper slightly differs from the actual cost function defined by the law in the Canary Islands (Real Decreto 738/2015). The real function introduces parameters that are not broadly used in capacity-expansion models, like fix O&M costs, or fuel and logistic costs that are independent from O&M costs. In order to ensure that the model proposed in this paper is easily extensible to other island power systems, it has been preferred to use the classical approach provided in capacity-expansion models (Boffino et al., 2019; Conejo et al., 2016; Domínguez et al., 2015). The omission of these parameters implies that results described in Section 5 are quite conservative in terms of conventional generation costs and, consequently, in RES penetration compared to similar works (Ramos-Real et al., 2018; Lobato et al., 2017; Sigrist et al., 2013).

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Equation (9) represents the balance of the system in each hour and week of operation. Basically, for each node, the sum of the energy generated by all thermal and renewable units located at the said node, added to the discharges from ESS and EV, and also to the incoming –minus the outgoing– power that flows through the lines connected to the node, must be equal to the demand at that node plus de unsatisfied load. Desirably, this latter variable should equal zero. Equation (10) establishes the limit of curtailed load to be no greater than the nodal demand.

Equations (11)-(19) are related to the operation of thermal units. Equation (11) indicates that the power assigned to a generator cannot be greater than its net capacity. Equation (12) establishes the spinning-down reserve capacity that each generator can provide according to its minimum operating power. Equation (13) does the same for the spinning-up reserve. In these latter two constraints, unit commitment decisions are implemented by means of a binary variable. Equation (14) defines the limit of the non-spinning-up reserve capacity that a thermal unit may provide. Equation (15)-(17) establish the numerical limits of the spinning and non-spinning reserves. Finally, Equations (18) and (19) state maximum variations in power delivery depending on ramp limits and available capacity.

Equations (20)-(26) adapt Equations (11)-(19) for RES. Equation (20) establishes limits for power delivery taking into account net capacity and the hour-t capacity factor of the operating period. Equations (21) and (22) impose that RES cannot provide up reserves, following the Operational Procedure of the TSO (Real Decreto 738/2015; POSEIE, 2006).[62] However, they are allowed to provide spinning-down reserve capacity,

[62] Only geothermal and impoundment hydropower facilities can provide reserves, which are not available in the case-study.

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but limited by their capacity factor (Equations (23) and (24)). As explained below, constraints (21) and (22) account for a drastic relevance since they imply that renewable generation necessarily needs to be backed-up with thermal production, hampering the deployment or RES. Finally, Equations (25) and (26) imposes the maximum and minimum ramps for RES.

Constraints (27)-(37) are related to BES operation. They have been adapted from the works of Boffino et al. (2019); Drury et al. (2011); Sioshansi et al. (2009); Sioshansi & Denholm (2010). Equations (27) and (28) state that BES cannot be charged or discharged at hour-t with a power flow greater than their net power capacity. The terminals of the storage unit are considered the frontier of the system, so that the parameters $\gamma_{s,o,t}^{S,P}$ and $\gamma_{s,o,t}^{S,T}$ refer to the energy that reaches the battery (or PHES) terminals to be stored and the energy delivered to the grid, respectively.[63] Equation (29) imposes lower and upper limits to the SoC. Since full operating weeks are represented instead of days, it has been checked that the depletion of the store resources does not play a significant role, so the lower SoC limit has been set to 0 (Boffino et al., 2019; Graves et al., 1999). Equation (30) defines the change in the SoC of the storage unit between one period and the next. Equation (31) establishes that the SoC of BES is equal to half of the total capacity at the beginning of each operating condition (Boffino et al., 2019; Graves et al., 1999). Equation (32) and (34) establish the limits of the spinning-up and spinning-down reserves in terms of energy storage, while Equations (33) and (35) impose said limits as a function of the power of the system. Finally, Equations (36) and (37) exhort that reserves cannot be negative.

[63] Therefore, due to the effect of charging and discharging efficiencies lower than 100%, the energy truly charged is lower than that received at the terminals, while the energy discharged from the battery is greater than the one actually delivered to the grid

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Equations (38)-(49) replicate Equations (27)-(37), but for the case of PHES. The main difference is that this work extends the equations extracted from the aforementioned papers by introducing unit commitment decisions for PHES (see Equations (38) and (39)). In addition, due to their slower response rate compared with BES or EV, PHES are allowed to provide non-spinning-up reserves (see Equations (43) and (49)). This allow to better represent the day-to-day operation of the PHES unit and to better understand the role of ESS as power reserves.

Equations (50)-(64) defines the contribution of EV and V2G services to the power system. These constraints have been adapted from the works of Chandrashekar et al. (2017); and Sioshansi & Denholm (2009) and they are similar to those proposed for BES. The main difference is that the maximum V2G power is given by the sum of the battery capacities of every EV fleet, which is a parameter of the model, rather than a decision variable. Charging and discharging cycles (equations (50) and (51)), energy storage (equations (52)-(56)), and power reserves (equations (57)-(64)) are represented analogously to BES. However, EV can move from one node to another and, while doing so, they consume energy and cannot be charged or discharged, nor can they provide reserves (equations (61) and (62)). This approach enables accurately identifying the actual role of EV as distributed ESS and capacity reserves. Similarly, since each fleet makes a minimum of 2 daily trips, there are two departure times for which a minimum load requirement is imposed (70% and 30%, respectively). Finally, it is worth insisting on the fact that EVs' charging cycles are allowed to be co-ordinated and co-optimized with the commitment and dispatch of the power system so that they reflect the impact of hour-t generation costs on energy demand (Chandrashekar et al., 2017; Sioshansi & Denholm, 2009).

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Equations (65)-(73) impose the operating constraints on system reserves. For the reasons exposed above, reserve criteria for island power systems are much stricter than those corresponding to continental networks. The equations shown here have been adapted from the works of Lobato et al. (2017); Ramos-Real et al. (2018); Sigrist et al. (2017); Sigrist et al. (2013), drawing on the Operational Procedure of the TSO (Real Decreto 738/2015; POSEIE, 2006). First, spinning-up and spinning-down reserves must be at least 50% of the highest power assigned to a generator unit (Equations (65), (66), (71) and (72)). Second, the sum of the spinning-up reserve and the non-spinning-up reserve must be, at least, equal to 100% of the greater of the following quantities: (i) the highest power assigned to a generator, (ii) during a demand ramp-up, 1.5 times the power assigned to the gas turbine of a combined cycle (Equation (70)), and (iii) the growth foreseen in demand between period t and t+1 (Equation (69)). Third, the tertiary reserve should be, at least, 100% of the highest power assigned to a generator. It is equivalent to say that spinning- and non-spinning-up reserves must be equal to 200% of this quantity (Equations (67) and (68)).

Equation (73) defines reserve capacity requirements for every interconnection. This constraint has been adapted from Lobato et al. (2017); Sigrist et al. (2017); Sigrist et al. (2013) by establishing that the total up reserve capacity in an island must be equal to or greater than the power flow that the island receives through any interconnection. In this vein, Equations (74)-(77) define the power flow in existing and candidate lines. If the constant M is large enough, it forces the power in the unbuilt candidate lines to be zero (Equation (77)). Power flow is determined by the phase difference between sending and receiving nodes, which is a standardized technique (Conejo et al., 2016). In this vein, Equation (78) and (79) establish the limits of the phase angles.

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Finally, Equation (80)-(82) establish the operating conditions for binary variables. Equation (80) relates the startups and shutdowns of thermal generator with their operating state, while Equation (81) do the same for PHES systems. As it can be deduced, PHES cannot charge and discharge at the same time. Equation (82) imposes the value limits for the binary variables.

4. Case-study

This section describes, in this order, the case study carried out, the identification of representative operating weeks, and the simulated cases. Appendix 3 describes some other important aspects, such as the definition of EV driver profiles, and the distribution of energy demand by nodes, given that data on electricity consumption are available only at the aggregate island level.[64]

4.1. The current system

The model proposed in this paper is tested on the Canary Islands' power system. The archipelago comprises seven islands. Tenerife and Gran Canaria are the largest and have the most robust power systems, followed by Fuerteventura and Lanzarote. As these two latter islands are currently interconnected, there are only six electrical systems in total. El Hierro, La Gomera and La Palma can be considered minor islands in terms of the size of their grids.

The model comprises a total of 14 nodes. Given the small size of their electrical systems, La Gomera, El Hierro, and La Palma are considered as a single node. Gran

[64] Data on electricity demand is extracted from the TSO's database.

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Canaria, Fuerteventura and Lanzarote have two nodes each, one representing the northern area of the island and the other the southern area. Tenerife is the only island to include EV in the simulations, since for the other islands no information on mobility routes is available. In order to properly assess the role of EV as distributed ESS and power reserves, a total of five nodes are used for Tenerife: the island's two centralized generation points, and the three main population cores. Figure 7 illustrates the distribution of the nodes and the existing and planned interconnections, while Table 15 summarizes the main features of transmission lines and interconnections already built and those in preparation;[65] the interconnections planned by the TSO will link Gran Canaria to Fuerteventura-Lanzarote, and Tenerife to La Gomera. In order to assess the full potential of this technology, we also include two other technically feasible interconnections in the simulation (La Gomera-El Hierro and La Gomera-La Palma).

Table 16 summarizes the thermal capacity currently available in the Canary Islands, which serves as the upper limit for decisions regarding thermal power in the model. A total of 83 thermal generators and 2,291 MW are identified, divided into four technologies: ST, CC, DE, and GT (Gobierno de Canarias, 2018). CC have the highest installed capacity, but are only available in Tenerife and Gran Canaria. This table also indicates the average costs associated with each thermal technology and its emission rates (Gobierno de Canarias, 2018; Real Decreto 738/2015). Although the costs introduced in the model are unit-specific, for the sake of simplicity only average costs are shown. On

[65] Investment costs associated to transmission lines and AC interconnectors have been extracted from technical projects developed for the region by the TSO and some electricity distribution companies. As a result, investment costs for transmission lines ranges from 0.8 M€ for the cable connecting nodes 2 and 3 in Tenerife, up to 11 M€ for the line connecting nodes 10 and 11 in Fuerteventura. The costs for AC interconnections range from 24M€ (Tenerife-La Gomera) up to 75 M€ (Gran Canaria-Fuerteventura). Investment costs for HVDC interconnections have been extracted from the literature (Domínguez et al., 2015; Kapsali et al., 2016), which results in costs ranging from 45 M€ (Tenerife-La Gomera) up to 70 M€ (Gran Canaria-Fuerteventura).

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average, ST is the most economical technology in terms of operation costs, closely followed by CC; DE and GT are considerably more expensive. As for investment costs, GT is the cheapest, followed by DE. However, while some ST have lower investment costs than CC, others are more expensive, depending on factors like age and efficiency. It is important to bear this in mind in order to properly understand the results presented in Section 5. Finally, the emission rate of each technology is provided by the TSO. CC are the cleanest technology and GT the one that pollutes the most.



Figure 7. Distribution of nodes and installed, planned and proposed interconnections.

Table 17 indicates the net power available in 2017 from RES, broken down by technology. To date, only four have been deployed in the region: wind, PV, biogas and mini-hydro. The total capacity is slightly above 400 MW, although the contribution of the two latter technologies is negligible. The costs for RES are not directly available from official institutions, so they have been extracted from well-reputed sources found in the literature. Finally, the hour-t capacity factor of each technology is based on the actual capacity factors in the region in 2017.

Table 18 presents the only stand-alone energy-storage unit currently available in the Canary Islands: a PHES unit installed in El Hierro with a net power of 11 MW and

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approximately 10 hours of autonomy. Its costs are extracted from the study by Hallam & Contreras (2015), who carried out a thorough assessment of the installation's economic profitability. The costs for candidate PHES for other islands, and also for BES, are also presented in Table 18. Finally, Table 19 presents parameters relative to EV operation, mainly charging, discharging, and road efficiencies assumed in this work, and also operation costs associated with battery cycling (Zhou, Chengke; Qian et al., 2011). Mobility routes and trip distances, as explained in the Appendix section, are defined according to a report from the State Government in which car travel flows in Tenerife are investigated. Energy consumption for EV is estimated drawing on such distances and on the average road efficiency measured as kWh/km.

Table 15. Characteristics of AC transmission lines and AC/HVDC interconnectors.

Island	Nodes	Line	Type	Voltage [kV]	Power [MVA]	Status
Tenerife	0-1	Inland	AC	220	628	Built
Tenerife	0-4	Inland	AC	66	107	Built
Tenerife	1-2	Inland	AC	220	575	Built
Tenerife	1-3	Inland	AC	66	107	Built
Tenerife	1-4	Inland	AC	66	107	Built
Tenerife	2-3	Inland	AC	66	107	Built
Tenerife	3-4	Inland	AC	66	107	Built
Tenerife	0-4	Inland	AC	66	107	Planned
Tenerife	2-3	Inland	AC	220	575	Planned
Gran Canaria	8-9	Inland	AC	220	682	Built
Gran Canaria	8-9	Inland	AC	220	287	Planned
Fuerteventura	10-11	Inland	AC	66	53	Built
Fuerteventura	10-11	Inland	AC	132	321	Planned
Lanzarote	12-13	Inland	AC	66	53	Built
Lanzarote	12-13	Inland	AC	132	321	Planned
Tenerife-La Gomera	0-5	Interconnection	AC	66	106	Planned
Tenerife-Gran Canaria	1-9	Interconnection	AC	132	321	Proposed
Gran Canaria-Fuerteventura	9-10	Interconnection	AC	132	213	Planned
La Gomera-La Palma	5-6	Interconnection	AC	66	66	Proposed
La Gomera-El Hierro	5-7	Interconnection	AC	66	33	Proposed
Fuerteventura-Lanzarote	11-12	Interconnection	AC	66	66	Built
Tenerife-La Gomera	0-5	Interconnection	HVDC	150	50	Planned
Tenerife-Gran Canaria	1-9	Interconnection	HVDC	150	200	Proposed
Gran Canaria-Fuerteventura	9-10	Interconnection	HVDC	150	100	Planned
La Gomera-La Palma	5-6	Interconnection	HVDC	150	50	Proposed
La Gomera-El Hierro	5-7	Interconnection	HVDC	150	10	Proposed

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Table 16. Generation costs, net power and CO2 emissions for thermal capacity in the Canary Islands.

Technology	Net Power [MW]	Investment cost [M€/MW]	O&M cost [€/MWh]	CO_2 [t/MWh]	Source
ST	483	1.32	6.29	0.90	Real Decreto 738/2015
CC	865	1.09	18.16	0.60	
DE	466	1.18	34.55	0.65	
GT	478	0.50	30.66	1.12	
Total	2291	1.02	22.42	0.82	

Table 17. Generation costs and net power for RES capacity in the Canary Islands.

Technology	Net Power [MW]	Investment cost [M€/MW]	O&M cost [€/MWh]	Source
Wind	224.44	1.05	0	Lazard (2018)
PV	182.02	1.68	0	Lazard (2018)
Mini-hydro	1.92	0.91	1.24	EIA (2019); IRENA & ETSAP (2015)
Biogas	1.60	1.55	9.1	Lazard (2018)
Total	410	1.30	2.59	

Table 18. ESS in the Canary Islands: costs, efficiencies and available power.

Tech.	Island	Net Power [MW]	Invest. cost[1,2] [M€/MW]	Energy cost[3] [€/MWh]	O&M cost[1,2] [€/MWh]	Charging eff.[1,2,3] [%]	Discharging eff. [1,2,3] [%]
PHES	El Hierro	11.2	2.87	5000	5.86	0.84	0.82
PHES	Except El Hierro	-	0.44	5000	5.86	0.84	0.82
BES	All	-	0.4	150000	8	0.95	0.95

Sources: (1) Hallam & Contreras (2015); (2) Ramírez-Díaz et al. (2015); Ramirez-Diaz et al. (2016); (3): Arbabzadeh et al. (2019)

Table 19. Parameters for EV operation in the Canary Islands.

Tech.	Charging eff. [%][1,2]	Discharging eff. [%][1,2]	Road eff. [kwh/km][3,4]	Discharging costs[1] [€/MWh]	Battery Capacity [MW]	SoC min.	SoC min. (t0)	SoC min. (t1)
EV	0.86	0.86	0.25	40	0.04	0.25	0.7	0.3

Sources: (1) Zhou, Chengke, Qian et al. (2011); (2) Ramírez-Díaz et al. (2015); Ramirez-Diaz et al. (2016); (3) L. Sigrist et al. (2017); (4) Madzharov et al. (2014); t0: Departure time 1; t1: Departure time 2; SoC: State of Charge

4.2. Operating weeks

Simulation models such as the one developed in this work are characterized by high computational demand. Therefore, in many occasions it is not feasible to simulate a full year, being necessary to adopt some simplifications in order to make the model feasible

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in terms of time and computational resources.

One very common approach consists on using clustering techniques to reduce the length of energy demand data to a set of operating conditions. It is normally used 30 to 60 days in order to represent a full year. From a technical point of view, this method remarkably reduces the computational requirements of the model. However, certain documents in the scientific literature suggest that, depending on the features of the case-study, it could be more convenient to use operating weeks, rather than operating days. This is especially useful when interday or seasonal energy storage is an important condition of a capacity-expansion model (Liu et al., 2018b). In addition, operating weeks represent more accurately the behavior of storage units when several storage technologies are considered (Nahmmacher et al., 2016). Therefore, given the combination of BES, PHES and EV in this work, and the remarkable role of ESS' performance on island systems, this paper simulates operating weeks instead of operating days.

The clustering algorithm developed in this proposal is based on the works of Liu et al. (2018b) and Nahmmacher et al. (2016), but adapted to the case of operating weeks. In addition to taking into account energy demand, the least manageable renewable generation technologies are also considered (i.e., wind and photovoltaics). In this way, not only do operating weeks represent the energy demand variation, but also the generation conditions (Nahmmacher et al., 2016).

First, all variables should be expressed on the same scale before applying the clustering technique. To do this, a min-max function in which the data is normalized with respect to the maximum values is used according to the next expression:

$$X_{Nt} = \frac{(x_t - x_{min})}{(x_{max} - x_{min})}$$

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Where X_{Nt} represents a normalized data of demand, wind or photovoltaic generation at time t, while x_t, x_{min}, and x_{max} refer to the original values at time t, the minimum and the maximum of the data series, respectively.

The next step is to apply the clustering algorithm. According to Liu et al. (2018b), a hierarchical clustering technique has been chosen, since it allows solving some traditional problems of non-hierarchical algorithms, such as the case of K-means (see Liu et al., 2018b; Nahmmacher et al., 2016 for a more detailed discussion). The cost is a higher computational demand. On the one hand, the distance between observations is computed by means of the Euclidean distance. On the other hand, the distance between clusters is measured by a minmax type link that provides as a result the most representative observation of the cluster (i.e., the prototype), instead of the traditionally used centroid. This fact, combined with the used of operating weeks, allows to represent more accurately real generator-ramping constraints and energy storage conditions.

To determine the appropriate number of operational weeks, a multitude of simulations are developed in which different amounts of weeks are used to assess which one offers a better accuracy-computational cost ratio. Table 20 compares the results for 1 to 10 representative operating weeks with those corresponding to the full year (52 weeks) in a simplified version of the model. In this case, 6 operating weeks –42 days– seem to be the most reasonable option, since it shows a variation of less than 1% with respect to the total cost of the model for the whole year without requiring too many hardware resources. In fact, the computation time for 6 representative operating weeks is quite similar to alternatives with fewer weeks. At the same time, it is between 20% and 30% lower than for a greater number of weeks. The weeks selected are those indicated in Table 21.

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Table 20. Costs estimates according to the number of representative operating weeks selected.

	Number of operating weeks																			
Cost (M€)	52	10	9	8	7	6	5	4	3	2	1	Δ10	Δ9	Δ8	Δ7	Δ6	Δ5	Δ4	Δ3	Δ2	Δ1
Total	400.23	395.44	395.51	395.61	397.51	397.66	397.93	385.25	384.06	384.97	383.96	1.20%	1.18%	1.15%	0.68%	0.64%	0.57%	3.74%	4.04%	3.81%	4.07%
Operation	167.27	167.27	167.32	167.43	169.26	169.30	169.40	163.93	164.27	162.39	155.63	0.00%	0.03%	0.09%	1.19%	1.21%	1.27%	2.00%	1.79%	2.92%	6.06%
Investment	232.96	228.17	228.19	228.18	228.31	228.36	228.53	221.32	219.78	222.58	228.33	2.05%	2.05%	2.05%	1.99%	1.97%	1.90%	5.00%	5.66%	4.45%	1.99%

Δ: Percentage change with respect to the use of 52 operating weeks.

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Table 21. Representative weeks for 2017 in the Canary Islands.

Week ID	Week of the year	Dates
0	5	Feb 20 - Feb 26
1	13	May 22 - May 28
2	21	Jul 3 - Jul 9
3	28	Aug 28 - Sep 3
4	36	Oct 23 - Oct 29
5	47	Dec 25 - Dec 31

4.3. Cases

A total of 19 cases have been assessed. This high number reflects the interest of evaluating the individual role of each technology (RES, ESS, EV and AC/HVDC interconnections) and their joint use, and the development of sensitivity cases to analyze the impact of CO_2 prices on generation costs and RES penetration.

In the first case, known as the "Current Situation", the model is forced to build and operate all the generation and storage capacity available in 2017 in the Canary Islands. This case calibrates the model and serves as a benchmark. Then, a baseline case (E0) optimizes investment and operation decisions for the Current Situation. Cases E1 to E3 assess the independent role of additional RES, ESS (both BES and PHES) and V2G services respectively. Cases E0 to E3 give rise to two additional cases each, in which we assess the benefits of including additional transmission lines and interconnectors with the technologies mentioned. For instance, E1+AC and E1+DC consider additional RES like E1, but introduce AC and HVDC interconnectors respectively.[66] Specifically, E0+AC and E0+DC allow an assessment of the individual role of interconnectors in the system. Finally, E4+AC and E4+DC combine all the previous technologies in the same case.

Table 22 indicates the maximum power that can be built for thermal, renewable and

[66] Due to computational limitations AC and HVDC interconnections are assessed separately.

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energy-storage units by islands and nodes in each case. It also includes the available energy capacity for ESS. The two main islands, Tenerife and Gran Canaria, account for 80% of the total renewable capacity that can be built, while the smaller islands, La Palma, El Hierro and La Gomera, account for less than 6%. In 2017, the electricity demand in La Gomera and El Hierro was met by means of 15 DE. The only notable RES in these islands is the wind farm on El Hierro. In the case of La Palma, Fuerteventura and Lanzarote there are 29 DE and also five GT. RES capacity is higher than in La Gomera and El Hierro, wind being again the most widespread technology, followed by PV. Finally, Tenerife and Gran Canaria together have 10 DE, 8 ST, 12 GT, and 4 CC. The role of RES in these two latter islands is more significant, and in fact Tenerife has some mini-hydro and biogas capacity. The upper limit of RES and ESS capacity that can be built is based on the Energy Plan of the Canary Islands (Consejería de Industria, 2006): specifically, the candidate RES capacity is 3.8 times higher than the capacity available in 2017 in the archipelago.[67]

Finally, four sensitivity cases are also implemented: S1, S2, S3 and S4. These cases address the need to assess the impact of CO_2 emissions on both generation costs and RES deployment. As indicated in Table 23, emission costs in S1 are based on the actual CO_2 emission price from 2017, which was around 5.83 €/Tm. S2 draws on the price corresponding to 2020, 24.75 €/Tm. In the future, the normalization and day-to-day adoption of the CO_2 emissions market will probably push up the price of every emitted ton. In order to capture this effect, two additional cases, namely S3 and S4, are also proposed, in which the price of CO_2 is raised to 50 €/Tm and 100 €/Tm respectively.

[67] The available RES capacity is also 2.5 times higher than the RES power currently installed in the Canary Islands, so the conclusions of our study continue to be of great interest (Gobierno de Canarias, 2019).

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Table 22. Available capacity for thermal units, RES, and ESS by technology, node, and island.

Island	Tech.	Nodes	Net Power [MW]	Available Power [MW]	Available Capacity [MWh]
Tenerife	ST	0,1	223.04	223.04	-
	CC	0	432.30	432.30	-
	DE	0,1	66.55	66.55	-
	GT	0,1	194.12	194.12	-
	Wind	0,4	60.18	402.00	-
	PV	0,1,2,3,4	115.34	300.00	-
	Mini-hydro	4	1.12	6.20	-
	Biogas	0	1.60	43.00	-
	BES	0,1,2,3,4	-	200.00	2,000.00
	PHES	1,2,3,4	-	90.00	900.00
Gran Canaria	ST	8,9	259.60	259.60	-
	CC	8	433.10	433.10	-
	DE	9	66.55	66.55	-
	GT	8,9	147.00	147.00	-
	Wind	8,9	118.90	411.00	-
	PV	8,9	40.40	61.52	-
	Mini-hydro	8	-	1.00	-
	Biogas	8	-	40.00	-
	BES	8,9	-	200.00	2,000.00
	PHES	8,9	-	164.00	1,640.00
Fuerteventura	DE	11	96.28	96.28	-
	GT	11	62.89	62.89	-
	Wind	10,11	13.10	81.00	-
	PV	10,11	13.50	22.50	-
	Biogas	11	-	11.50	-
	BES	10,11	-	40.00	400.00
Lanzarote	DE	13	135.28	135.28	-
	GT	13	51.94	51.94	-
	Wind	12,13	13.40	81.00	-
	PV	12,13	8.10	22.50	-
	Biogas	13	2.10	11.50	-
	BES	12,13	-	40.00	400.00
La Palma	DE	6	74.84	74.84	-
	GT	6	21.60	21.60	-
	Wind	6	7.00	28.00	-
	PV	6	4.60	7.93	-
	Mini-hydro	6	0.80	6.40	-
	Biogas	6	-	3.00	-
	BES	6	-	40.00	400.00
	PHES	6	-	30.00	300.00
La Gomera	DE	5	14.90	14.90	-
	Wind	5	-	8.00	-
	PV	5	-	5.00	-
	BES	5	-	20.00	200.00
	PHES	5	-	15.00	150.00
El Hierro	DE	7	11.18	11.18	-
	Wind	7	11.50	14.00	-
	PV	7	-	2.00	-
	Biogas	7	-	0.50	-
	BES	7	-	10.00	100.00
	PHES	7	11.20	11.20	112.00
TOTAL			2,714.01	4,720.92	8,602.00

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Table 23. CO2 prices and reference years for sensitivity analysis.

Sensitivity case	CO2 price (€/Tm)	Reference year	Source
S1	5.83	2017	SENDECO$_2$
S2	24.75	2020	
S3	50	Projection	
S4	100	Projection	

5. Results

First, we present the results from cases E0-E3, including their variants with AC/HVDC interconnectors, and then we show the estimates for E4+AC and E4+DC. Finally, insights derived from the sensitivity analysis are described. Results are presented in terms of capacity built, generation mix and costs. To facilitate the understanding of this section, Table 24 shows a summary of such results. Although these figures will be broken down in the next pages, it can be anticipated that the highest penetration of RES (on both capacity and energy basis) is reached when a cost for CO_2 emissions is established. In contrast, the most economical cases are those in which ESS are installed intensively.

5.1. The current system

In this case the model is forced to build the same generation and storage capacity that was installed in the system in 2017. As a result, the overall costs and generation structure are quite similar to those corresponding to the real case. For instance, the simulated RES contribution is 9%, while the real share in 2017 was 8%. In addition, the generation structure for RES, displayed in Table 25, is quite similar to the real one. However, individual thermal units present an important difference, given that the contributions of ST and DE rise but that of GT falls. To some extent, this difference may be related to

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Table 24. Summary of results in terms of capacity built, energy share and costs.

		Current Sit.	E0	E1	E2	E3	E0+AC	E0+DC	E1+AC	E1+DC	E2+AC	E2+DC	E3+AC	E3+DC	E4+AC	E4+DC	S1	S2	S3	S4
Capacity [MW]	ST	482.6	423.4	306.1	409.6	409.6	413.2	403.6	412.5	416.3	404.2	424.4	417.9	406.0	417.1	410.2	482.6	482.6	482.6	482.6
	CC	865.4	596.4	638.6	337.6	556.4	612.1	648.7	606.9	641.2	382.9	413.9	550.1	596.3	398.8	336.1	865.4	865.4	865.4	865.4
	DE	465.6	366.5	331.4	203.5	342.9	339.5	296.5	332.4	275.0	206.7	145.1	342.5	293.3	177.3	199.6	465.6	465.6	465.6	465.6
	GT	477.6	469.9	458.6	357.8	417.6	475.3	476.1	476.1	477.6	357.8	357.3	415.5	412.1	350.9	354.8	477.6	477.6	477.6	477.6
	Total thermal	2,291.2	1,856.2	1,734.7	1,308.5	1,726.4	1,840.1	1,824.9	1,827.8	1,810.0	1,351.6	1,340.7	1,726.1	1,707.8	1,344.2	1,300.7	2,291.2	2,291.2	2,291.2	2,291.2
	Wind	223.9	18.9	160.0	13.7	21.0	22.0	18.5	34.1	12.1	14.8	15.4	22.6	18.5	42.9	36.0	1,025.0	1,025.0	1,025.0	1,025.0
	PV	182.0	1.3	20.0	0.0	0.0	0.0	0.0	2.0	4.1	0.0	0.0	0.0	0.0	4.8	1.4	426.5	426.5	426.5	426.5
	Mini-hydro	1.9	1.9	13.6	1.9	1.9	1.9	1.9	13.5	13.6	1.9	1.9	1.9	1.9	13.6	13.6	13.6	13.6	13.6	13.6
	Biogas	3.7	0.0	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	109.5	109.5	109.5	109.5
	Total RES	411.6	22.0	198.4	15.7	22.9	24.0	20.4	49.6	29.9	16.8	17.3	24.6	20.5	61.3	51.0	1,574.6	1,574.6	1,574.6	1,574.6
	T O T A L	2,702.7	1,878.2	1,933.1	1,324.1	1,749.3	1,864.1	1,845.3	1,877.4	1,839.9	1,368.4	1,358.0	1,750.7	1,728.3	1,405.5	1,351.7	3,865.8	3,865.8	3,865.8	3,865.8
Energy share [%]	ST	44.6%	40.0%	39.0%	39.5%	38.9%	39.2%	38.6%	39.1%	39.6%	39.0%	40.7%	39.4%	38.5%	40.0%	39.3%	36.3%	33.5%	4.3%	1.2%
	CC	22.9%	35.1%	36.2%	28.5%	35.6%	37.7%	43.4%	36.6%	42.3%	31.8%	36.4%	35.5%	42.6%	34.0%	28.6%	11.2%	12.3%	42.1%	44.6%
	DE	17.2%	17.6%	14.1%	15.9%	17.4%	16.7%	12.4%	16.0%	11.1%	16.1%	9.4%	17.4%	12.1%	11.6%	15.2%	14.6%	14.9%	14.8%	15.6%
	GT	6.2%	6.7%	5.2%	15.5%	7.4%	5.8%	5.0%	6.2%	4.6%	12.5%	13.0%	7.0%	6.1%	12.0%	14.6%	1.3%	0.5%	0.3%	0.0%
	Total thermal	90.9%	99.4%	94.4%	99.5%	99.3%	99.3%	99.4%	97.9%	97.7%	99.4%	99.4%	99.3%	99.4%	97.6%	97.7%	63.4%	61.3%	61.5%	61.4%
	Wind	6.0%	0.4%	4.2%	0.4%	0.5%	0.5%	0.4%	0.9%	1.2%	0.4%	0.4%	0.5%	0.4%	1.2%	1.1%	25.6%	25.9%	25.8%	25.9%
	PV	2.9%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	6.8%	6.9%	6.9%	6.9%
	Mini-hydro	0.2%	0.2%	1.1%	0.2%	0.2%	0.2%	0.2%	1.1%	1.1%	0.2%	0.2%	0.2%	0.2%	1.1%	1.1%	1.0%	1.1%	1.1%	1.1%
	Biogas	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.1%	4.9%	4.7%	4.6%
	Total RES	9.1%	0.6%	5.6%	0.5%	0.7%	0.7%	0.6%	2.1%	2.3%	0.6%	0.6%	0.7%	0.6%	2.4%	2.3%	36.6%	38.7%	38.5%	38.6%
	T O T A L	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Cost [M€]	Operation	122.2	149.6	132.9	151.3	146.5	142.6	142.4	139.6	136.8	147.3	141.8	145.4	144.3	141.5	147.5	111.2	200.5	310.7	497.0
	Investment	271.9	179.1	192.6	148.4	165.8	177.5	177.3	178.2	179.4	153.6	164.5	167.0	167.4	154.3	144.2	401.9	404.0	402.8	411.7
	T O T A L	394.1	328.7	325.5	299.7	312.3	320.2	319.6	317.8	316.2	301.0	306.3	312.4	311.8	295.8	291.7	513.1	604.5	713.6	908.7

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the use of an objective function that differs slightly from the real one. However, when the same parameters are considered in both functions, the differences found for overall generation costs – including investment and operation – are lower than 1%, which suggests that our model performs reliably and accurately.[68] In fact, GT are mainly installed in the islands where more economical generation alternatives are available (e.g., Tenerife and Gran Canaria). Therefore, this technology may be experiencing overuse in the real system.

Table 25. Real and simulated generation structure in the Canary Islands for the reference year (2017).

Technology	Type	2017 Share [%]	Simulated Share (Current Situation) [%]
ST	Thermal	31.00%	44.60%
CC	Thermal	25.00%	22.85%
DE	Thermal	3.42%	17.18%
GT	Thermal	33.00%	6.23%
Wind	RES	4.26%	5.98%
PV	RES	2.94%	2.91%
Mini-hydro	RES	0.03%	0.16%
Biogas	RES	0.10%	0.09%

5.2. The role of interconnectors (E0)

Figure 8A and 8B show the thermal and RES capacity that is built in E0, E0+AC and E0+DC. The optimization of investment decisions allows reductions of around 30% in the total capacity built and of 20% in thermal power compared to the Current Situation, which suggests that the actual system may be oversized. Variations across cases are very modest. In all cases, CC account for the highest capacity share (around 32%), followed by GT, ST and DE. As shown in the following cases, cases with a high demand for power reserves (e.g., with large RES penetration) show a higher CC capacity because the size of their units is large enough to provide ample power reserves. Regarding

[68] This outcome remains accurate when looking at individual islands (results available upon request).

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ST, the capacity available for those offering lower investment costs is fully used, while that of the expensive group of ST is adapted to the needs of the case (see Section 4). Similarly, GT show a higher capacity share than DE since they involve lower investment costs. However, as explained below, the final contribution of GT to the energy mix is limited due to their high operation costs.

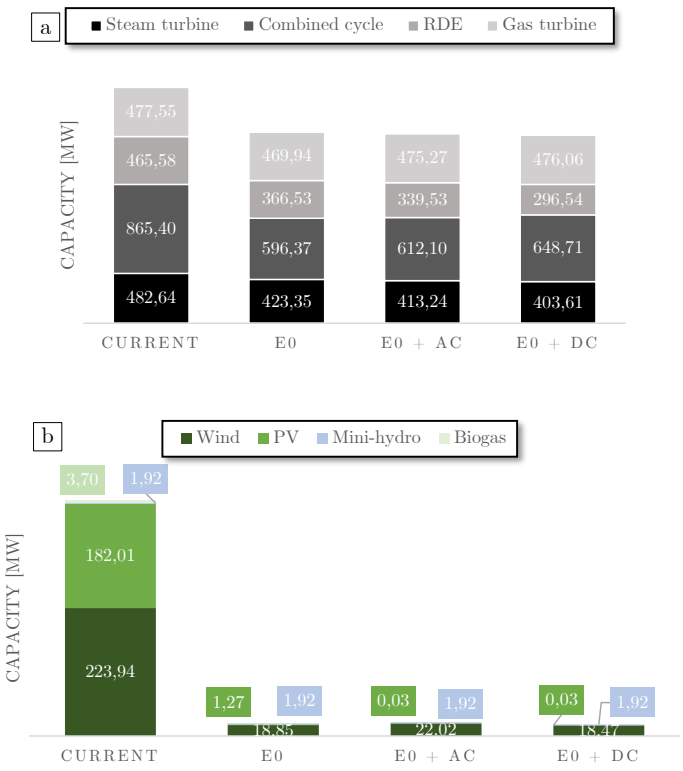


Figure 8. Thermal (a) and RES (b) capacity for cases E0, E0+AC and E0+DC.

The capacity built for RES in E0 and its variants is quite small, and much lower than that corresponding to the current system. Wind is the preferred alternative, but only around 20 MW are installed. PV is practically ignored since its capacity factor is small

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in the absence of energy-storage units. Biogas is excluded from the results due to its high investment and operation costs. Three reasons converge to produce this low RES penetration. First, emission costs are not included in this simulation, which leads to an underestimation of the benefits inherent in generating power with RES. Second, RES are forbidden by law to provide reserves to the system. This means that the RES capacity necessarily has to be backed up with additional investments in conventional systems (and thus additional operation costs). Third, the potential of renewable generators is limited by the technology's capacity factor over the course of the year.[69] Consistent with this result, the only ESS unit available for E0 and its variants – the PHES on the island of El Hierro – also undergoes a reduction in capacity, from 11.20 MW in the Current Situation to 4.83 MW in these alternatives.

As for interconnections and transmission lines, their potential is barely exploited. As shown in Table 26, only the AC interconnection between Tenerife-La Gomera and the transmission line between nodes 0 and 4 are built. In the case of HVDC interconnectors, the same line is also built, but the interconnection installed is between Gran Canaria and the Fuerteventura-Lanzarote system. This result supports the future plans of the TSO, which are intended to interconnect the islands Tenerife-La Gomera and Gran Canaria-Fuerteventura-Lanzarote.

The RES share meets the low expectations. Figure 9 shows that it ranges from 0.61% in E0+DC to 0.70% in E0+AC. Therefore, in the absence of CO_2 pricing, interconnections not only do not allow an increase in RES capacity, but they do not favor its participation

[69] Consider the following example. The average capacity factor for wind energy in the Canary Islands was 27% in 2017. This implies that, on average, in order to produce 1 MWh from wind it was necessary to install at least 3.70 MW of capacity. In addition, reserve criteria impose the need for two additional MW of thermal technologies as a backup, thus making a total power of 5.70 MW (and additional operation costs). If only thermal generation is installed instead, 3 MW would provide the same amount of energy and reserves. Consequently, the model decides to minimize the capacity built for RES. This situation is reversed when emission costs are included (see Section 5.7).

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in the energy mix either. As mentioned above, this is related (among other factors) to the system's strict reserve requirements. In contrast, interconnections favor a higher participation of CC in order to send cheap energy from the larger islands to the smaller ones.

Table 26. Transmission lines and AC/HVDC interconnectors built under every proposed case.

Transmission line	Node	Current	E0 + AC	E0 + DC	E1 + AC	E1 + DC	E2 + AC	E2 + DC	E3 + AC	E3 + DC	E4 + AC	E4 + DC
Inland	0-4		✓	✓		✓	✓					
Inland	2-3											
Inland	8-9										✓	
Inland	10-11											
Inland	12-13				✓				✓			
Interconnect.	0-5		✓		✓		✓	✓				
Interconnect.	1-9							✓				
Interconnect.	9-10			✓		✓		✓		✓	✓	
Interconnect.	5-6											
Interconnect.	5-7											
Interconnect.	11-12	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

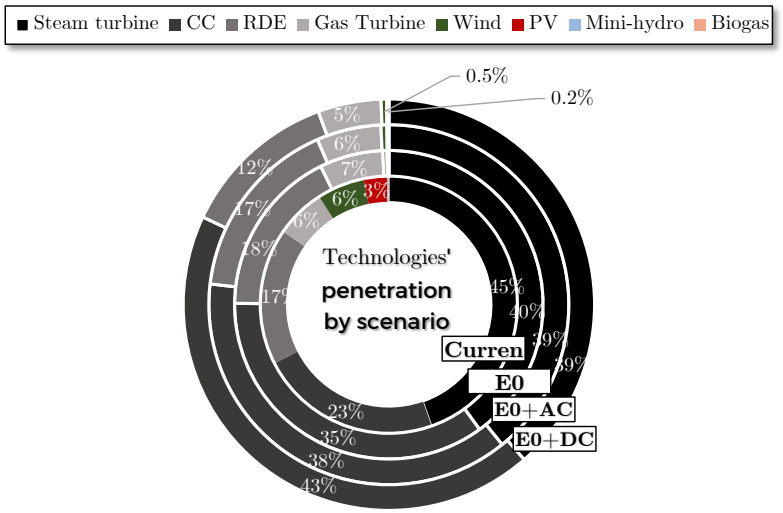


Figure 9. Contribution into the energy mix by technologies in E0, E0+AC and E0+DC.

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Finally, E0, E0+AC and E0+DC allow notable reductions in generation costs, mainly due to their great impact on investment decisions (see Figure 10). Specifically, while the simulated costs for the Current Situation are close to 400 M€, expenses in E0 are 329 M€, and approximately 2.5% lower in the cases of E0+AC and E0+DC, representing a saving close to 20%. A key conclusion derived from these results is that the main contribution of the interconnections proposed by the TSO is a modest improvement in generation costs. No significant differences between the use of AC or HVDC interconnectors have been found.

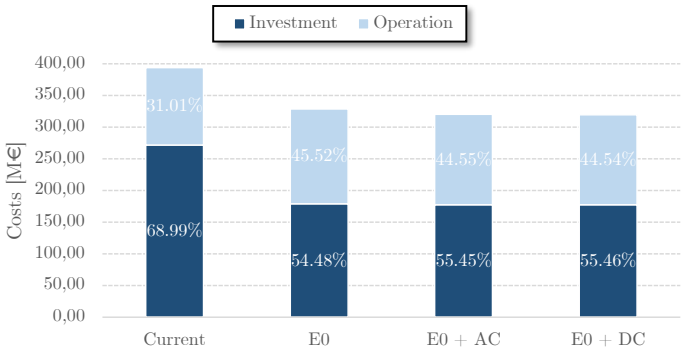


Figure 10. Generation costs by category in E0, E0+AC and E0+DC.

5.3. Additional renewable capacity (E1)

The additional RES capacity considered in E1 allows an increase in the penetration of these technologies with regard to E0. In general, the new installed capacity corresponds to an expansion of the RES that used up all the available power in the previous simulations.[70] However, the total capacity built – 200 MW – is still much lower than that

[70] This result may indicate that the location proposed by the regional energy plans for new RES generation may not be suitable. However, the locations available for RES in the Canary Islands are very limited due to the presence of large numbers of protected natural areas and other related concerns.

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of the Current Situation, for the reasons outlined above. Again, wind energy is the preferred alternative, accounting for 160 MW, followed by PV (20 MW), mini-hydro (14 MW) and, finally, biogas (4.83 MW). The high availability of mini-hydro leads to the depletion of its total available capacity. In contrast, the capacity built for thermal units in E1 decreases to 1735 MW (a reduction of almost 25%); CC are predominant, followed by GT, ST and DE.

Some important insights emerge when interconnections are included. Figure 11 shows that the RES capacity built in both cases is lower than that corresponding to E1. As in E0 cases, interconnections are built from Tenerife to La Gomera, and from Gran Canaria to Lanzarote-Fuerteventura (see Table 26). This circumstance contributes to increasing CC penetration in the larger islands in order to reduce operation costs in the smaller ones; this decreases both overall RES capacity and its contribution to the energy mix.

Figure 12 illustrates the ESS capacity built. In the case of E1, the only available unit is the PHES system in El Hierro. Since this island is not interconnected to any of the others, the estimated PHES capacity would be expected to be more or less constant. Indeed, it varies very little, from 4.61 MW in E1+DC to 6.30 MW in E1+AC. Likewise, all E1 cases provide the same optimal cost solution for the island of El Hierro, which is close to10 M€.

Consequently, the energy mix undergoes some changes, albeit modest (Figure 13). The RES energy share is increased with regard to E0 cases, although it is still lower than in the Current Situation. For E1, the new share is 5.6%, of which wind energy provides 4.22%, mini-hydro 1.08%, PV 0.31% and biogas a negligible 0.03%. Due to the increased participation of CC in E1+AC and E1+DC, the RES share for these two cases is even lower, close to 2%, but it presents a similar pattern. The share of thermal units is very

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similar to that found for E0 and the Current Situation.

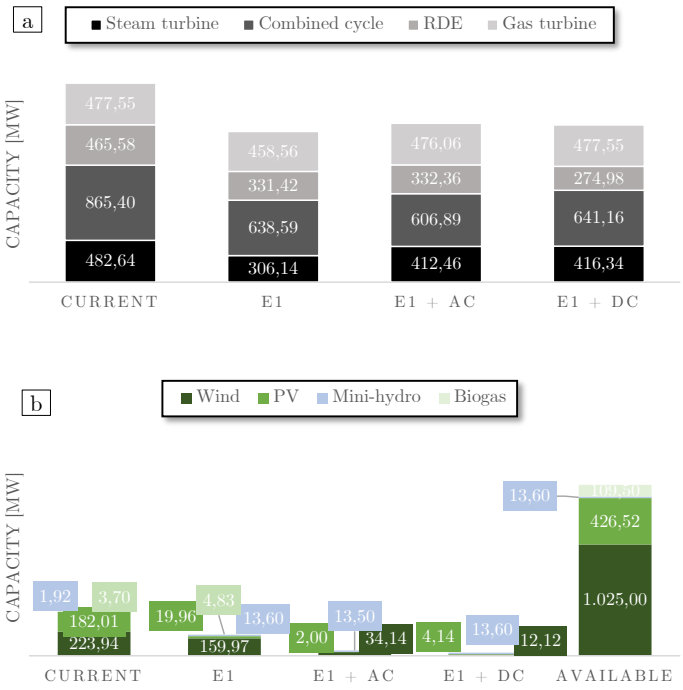


Figure 11. Thermal (a) and RES (b) capacity for cases E1, E1+AC and E1+DC.

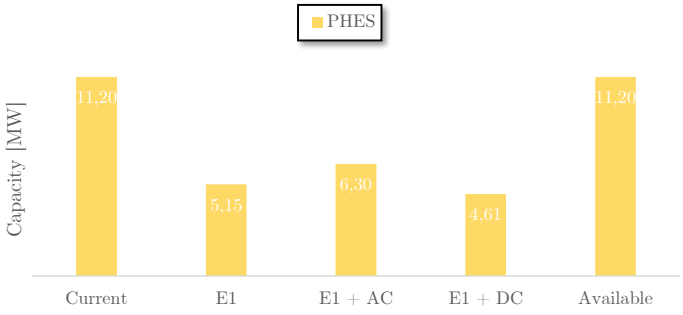


Figure 12. ESS capacity built in E1, E1+AC and E1+DC.

Figure 14 illustrates the structure of generation costs in E1 cases. The relatively large

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capacity of RES in E1 raises investment costs compared with E0, but these costs are still much lower than in the Current Situation. Operation costs are also lower than in E0. When interconnections are considered, the decreases in RES capacity contribute to reducing investment costs, while operation costs remain in a comparable range, thus reducing the overall generation costs. As in the case of E0, these savings represent approximately 2.5% of the total costs of E1.

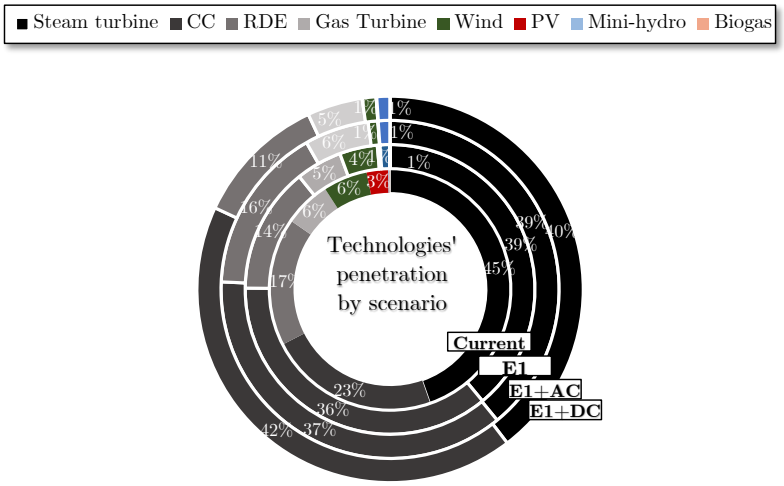


Figure 13. Contribution into the energy mix by technologies in E1, E1+AC and E1+DC.

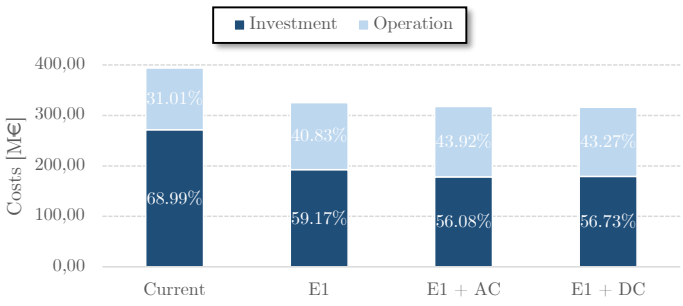


Figure 14. Generation costs by category in E1, E1+AC and E1+DC.

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5.4. Stand-alone energy-storage units (E2)

Figure 15 shows that the inclusion of ESS in the model helps to reduce the need for building capacity by almost 50% compared to the Current Situation. Thermal power is reduced by around 42%. The capacity installed is also lower than in E1 and its variants. The use of distributed ESS reduces the demand for large generators to provide power reserves, which in turn reduces the capacity built for CC. Even in this case, CC are the second most important thermal technology after ST. However, although ESS can help to partially overcome the problems associated with the availability of renewable resources and the need for power reserves, the contribution of RES (in terms of both capacity installed and energy produced) will only be relevant when the emission costs are included.

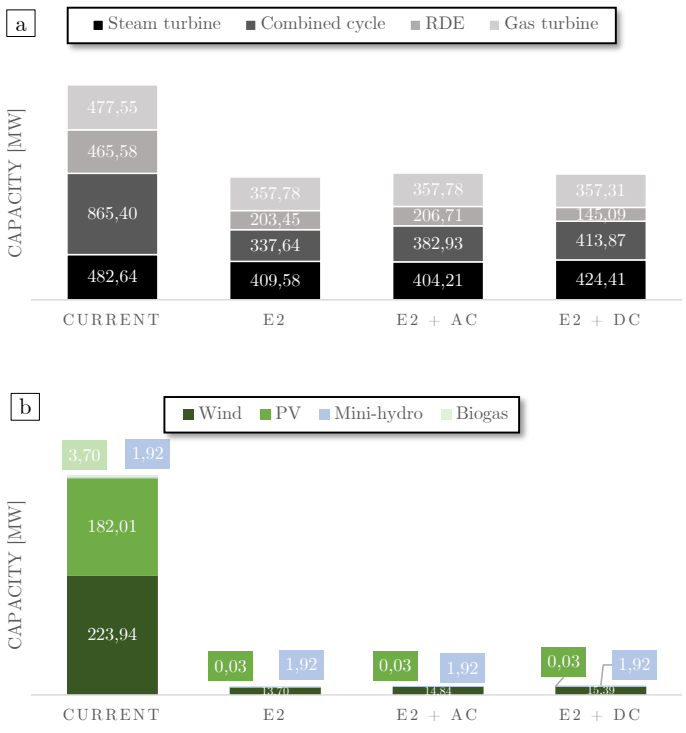


Figure 15. Thermal (a) and RES (b) capacity for cases E2, E2+AC and E2+DC.

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The key result of this case is that, of the alternatives considered so far, E2 and its variants require the least generation capacity to be built. This is due to the consideration of ESS for spinning and non-spinning reserves. The whole capacity for BES ranges from 237 MW in E2+AC up to around 292 MW in E2 and E2+AC, while the PHES capacity built rises to values between 290-300 MW. As shown in Figure 16, the ESS capacity across the cases is quite stable, with the exception of a slight fall in BES capacity in E2+AC, which is related to the interconnections and lines that are built in this case. In general, PHES is the preferred option because it has lower operating costs, but above all, lower energy capacity costs. This result differs from those of Ramos-Real et al. (2018), among others, and thus highlights the importance of modeling not only power (as many studies in the literature do) but also energy capacity.

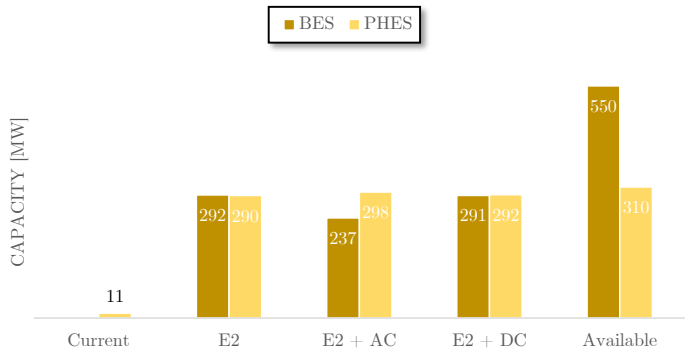


Figure 16. ESS capacity built in E2, E2+AC and E2+DC.

Table 26 shows that E2+DC is the case with the largest amount of interconnectors to be built, including those connecting Tenerife-La Gomera, and Gran Canaria-Fuerteventura-Lanzarote, and a third additional interconnection linking the two resulting systems (i.e., the five islands belong to a single system). In contrast, in the case of E2+AC only the interconnection Tenerife-La Gomera is built, and the already known line

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connecting nodes 0 and 4 in Tenerife. Nevertheless, the higher number of interconnectors built in E2+DC does not provide any further benefits in terms of cost savings or renewable penetration compared to E2 or E2+AC.

The energy share again shows a very low contribution of RES, below 1% (see Figure 17). However, in terms of costs, ESS meet the expectations. As displayed in Figure 18, the costs fall dramatically, from 394 M€ in the Current Situation to around 300 M€ in the new cases – a reduction of 25%. In addition, the use of ESS serves to balance the cost structure, since these cases provide very similar operation and investment costs. Nevertheless, the investment costs for E2+DC are slightly higher due to the increased number of HVDC interconnectors built in this case.

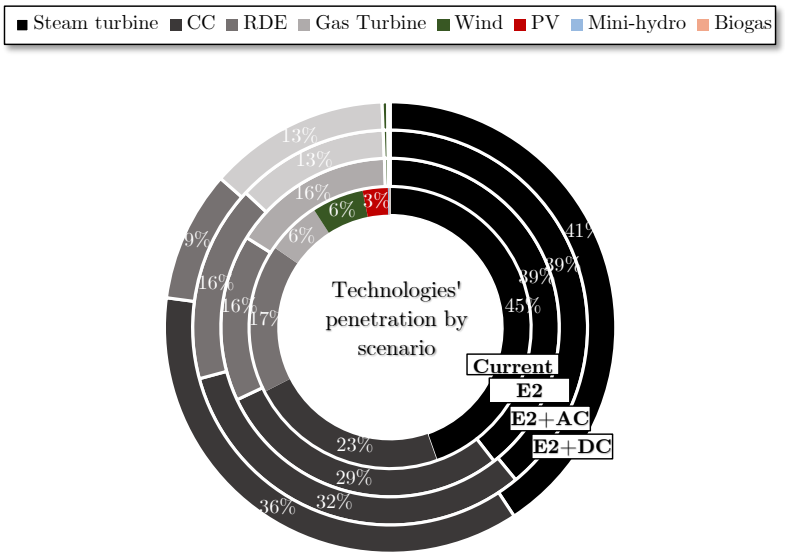


Figure 17. Contribution into the energy mix by technologies in E2, E2+AC and E2+DC.

Therefore, while ESS achieve notable reductions in cost in the need for capacity

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generation, issues like the availability of the renewable resources and the lack of CO_2 pricing still hamper the deployment of RES. Even when combined with AC and HVDC interconnectors, the contribution of RES remains unsatisfactory.

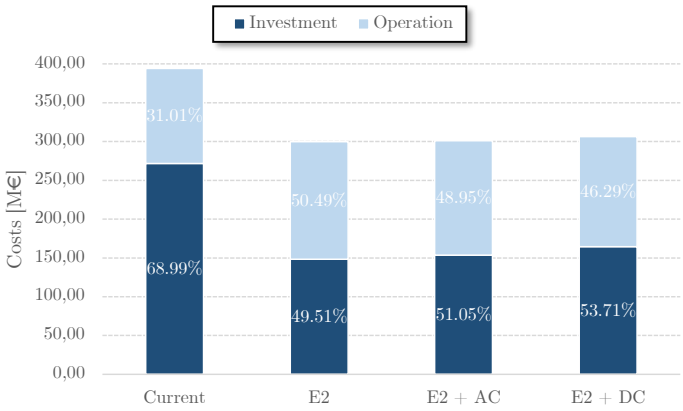


Figure 18. Generation costs by category in E2, E2+AC and E2+DC.

5.5 V2G capacity (E3)

Figure 19 shows that EV reduces the need for generation capacity to an intermediate point between the set of E2 and E1 cases, providing a total capacity close to 1750 MW in E3 and E3+A, and to 1730 MW in E3+DC. ST and CC are still the predominant technologies. In the case of RES, the capacity built is lower than in E1 or in the Current Situation, though slightly higher than in the E2 cases. This is largely because EV providing V2G services act like distributed ESS that not only offer mobile power reserves, but also have the ability to move energy from generation to consumption nodes. Finally, the capacity built for the only stand-alone energy-storage unit considered in this case – the PHES in El Hierro – follows the normal pattern described in cases E0 and E1.

Table 27 summarizes the energy delivered to the grid by the EV fleets. The differences

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observed in the table are associated with the changes inherent in the commitment and dispatch of the system implemented for each case. However, as indicated below, the total cost of the three models is almost identical (around 312 M€), suggesting that all the solutions may be considered as optimal. Figure 20 contributes to explaining this result by illustrating the behavior of EV in the case E3+AC. The first operating week has been taken as an example. Although the magnitude of the energy discharged differs between the cases, the pattern identified is the same: EV are charged during off-peak hours, and the excess energy is delivered to the grid during peak hours. In this first week, the amount of energy delivered to the grid is small. A similar situation can be observed in E3 and E3+DC. This result suggests that the key role of EV in E3 cases is that of providing mobile power reserves, rather than delivering power to the grid. This insight is at odds with those derived from the studies of Ramírez-Díaz et al. (2015) and Ramirez-Diaz et al. (2016), possibly due to the simplifications in the operation of the system in their models. For example, they do not consider nodes along the power grid nor mobility routes between nodes (see Section 2 for further details).

Table 27. Electricity delivered to the grid by EV providing V2G services.

Current	E3	E3 + AC	E3 + DC	E4 + AC	E4 + DC
-	23,530.00	23,530.00	23,530.00	23,530.00	23,530.00
-	48.00	48.00	48.00	48.00	48.00
-	155.30	155.30	155.30	155.30	155.30
-	2,411.49	2,548.48	4,907.50	0.00	0.00

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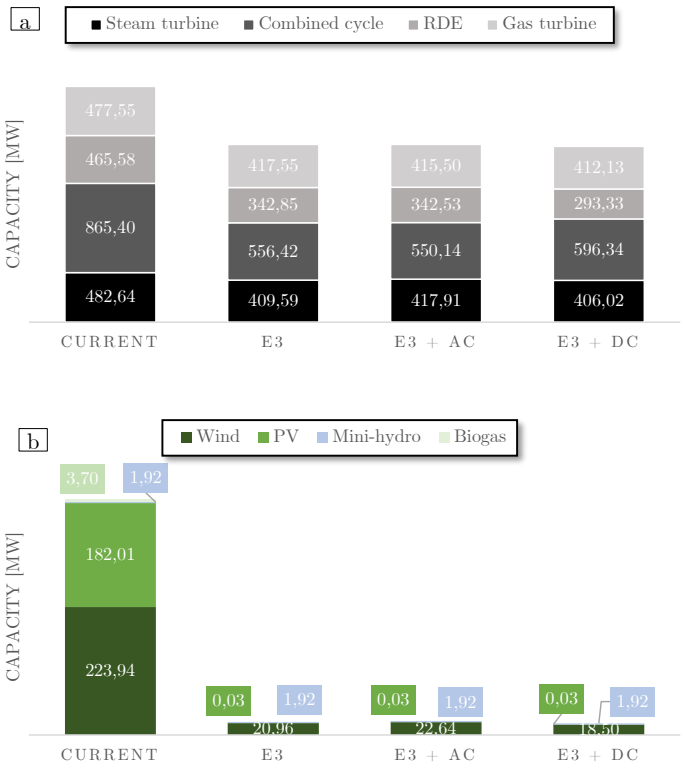


Figure 19. Thermal (a) and RES (b) capacity for cases E3, E3+AC and E3+DC.

Looking in detail at the interconnections and lines, E3+AC is the only case in which no interconnection is built. The most frequent decision so far was to build the interconnection between Tenerife-La Gomera and the transmission line connecting nodes 0 and 4 in Tenerife. Thanks to the role of EV in Tenerife, these investments are avoided. Instead, the model decides to increase the transmission capacity between nodes 12 and 13, in Lanzarote, by building a new line that reinforces the weak transmission system between Lanzarote and Fuerteventura. In E3+DC, no additional transmission lines are installed, but a HVDC interconnector is built between Gran Canaria and Fuerteventura-Lanzarote in order to reduce operation costs in this latter system.

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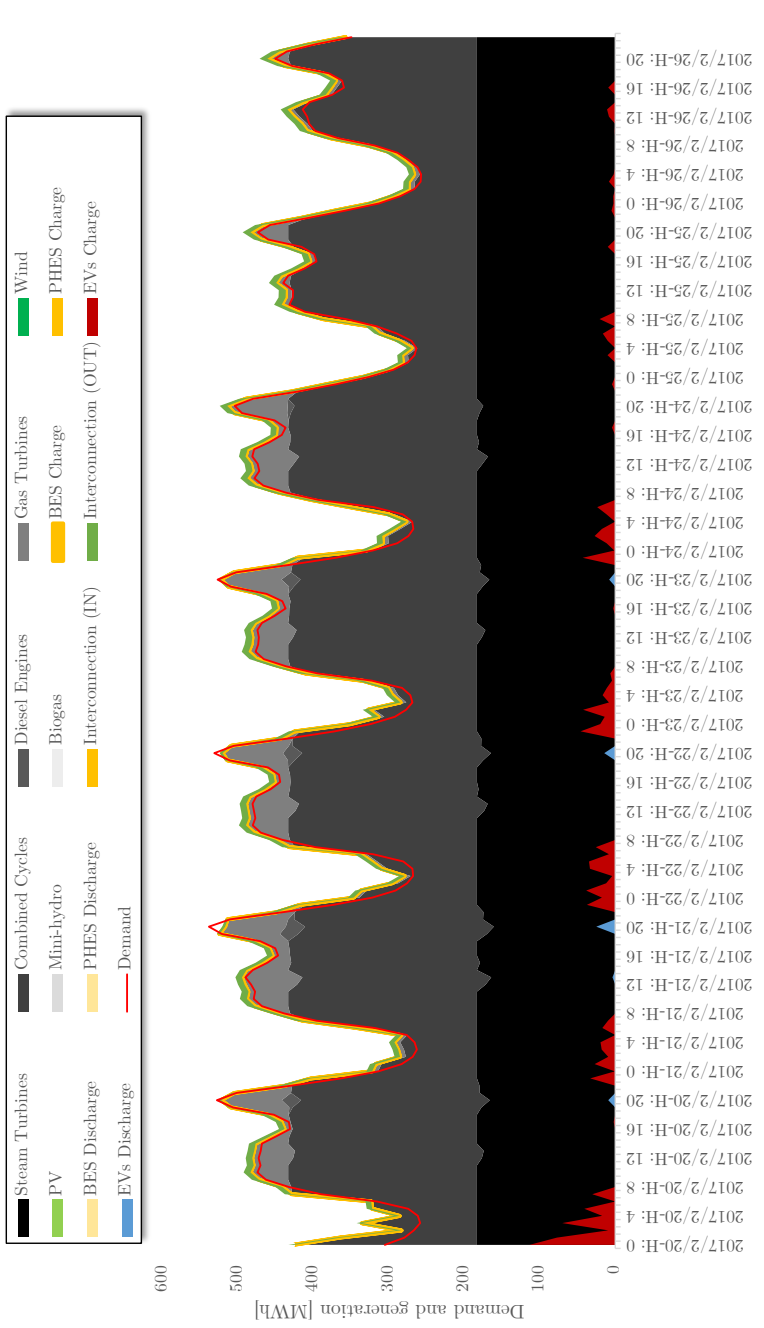


Figure 20. Behavior of the system during the first representative operating week in E3+AC.

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The share according to technologies indicates a very low participation of RES, below 1%, while the share corresponding to thermal technologies follows the same pattern seen so far. Figure 21 shows these results and Figure 22 the resulting costs. As expected, EV reduce the overall cost by almost 20% compared to the Current Situation. This cost is also lower than that of E1, by around 2%. However, E2 cases provide more economical results. Probably, if the proportion of EV was to increase, the costs would be closer to those provided by E2. In this regard, it is important to understand that V2G services provide capacity for reserves and storage whose costs are charged to the consumer (at the time the vehicle is purchased), and not to the system, which partially explains the reduction in (investment) costs.

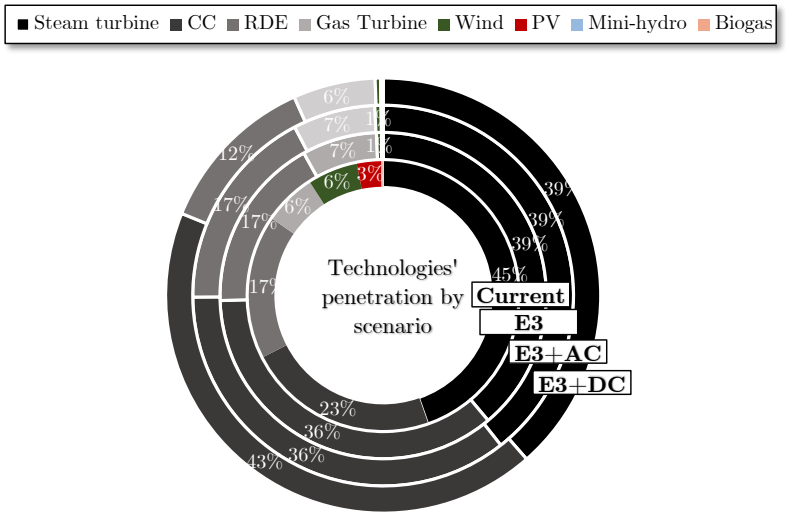


Figure 21. Contribution into the energy mix by technologies in E3, E3+AC and E3+DC.

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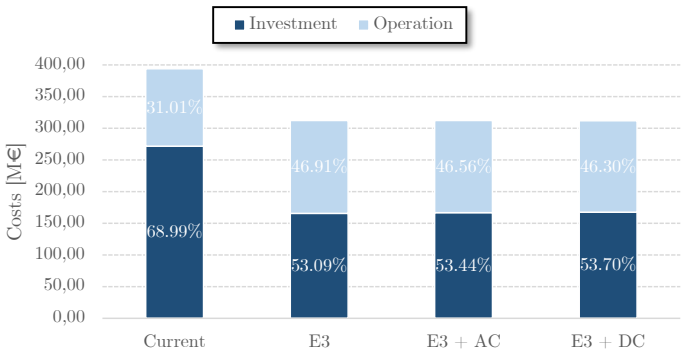


Figure 22. Generation costs by category in E3, E3+AC and E3+DC.

5.6. Combining all technologies (E4)

This case combines all the technologies analyzed above. Figure 23 shows that, as expected, E4+AC and E4+DC provide results similar to those found for E2, E2+AC and E2+DC. However, E4 cases provide the highest level of RES capacity seen so far in an interconnected case. Thus, the joint use of ESS, EV and interconnections helps to overcome partially the absence of CO_2 pricing, the variability of the renewable resources, and the high demand for power reserves. Nevertheless, as environmental constraints are not considered, the total RES capacity is still lower than that of the Current Situation.

Regarding ESS, the combination of EV with ESS reduces the need for storage units, as shown in Figure 24. Then, cases E4+AC and E4+DC are able to satisfy the same demand as E2 cases, but using less generation and storage capacity. In addition, as indicated in Table 27, EV do not provide electricity to the grid in E4 since they are mainly used to meet the reserve criteria. As a consequence of the combination of ESS and EV, the need for transmission lines and interconnections is also reduced. The only interconnection built is an AC interconnector between Gran Canaria and Fuerteventura-

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Lanzarote, as in previous cases (see Table 26).

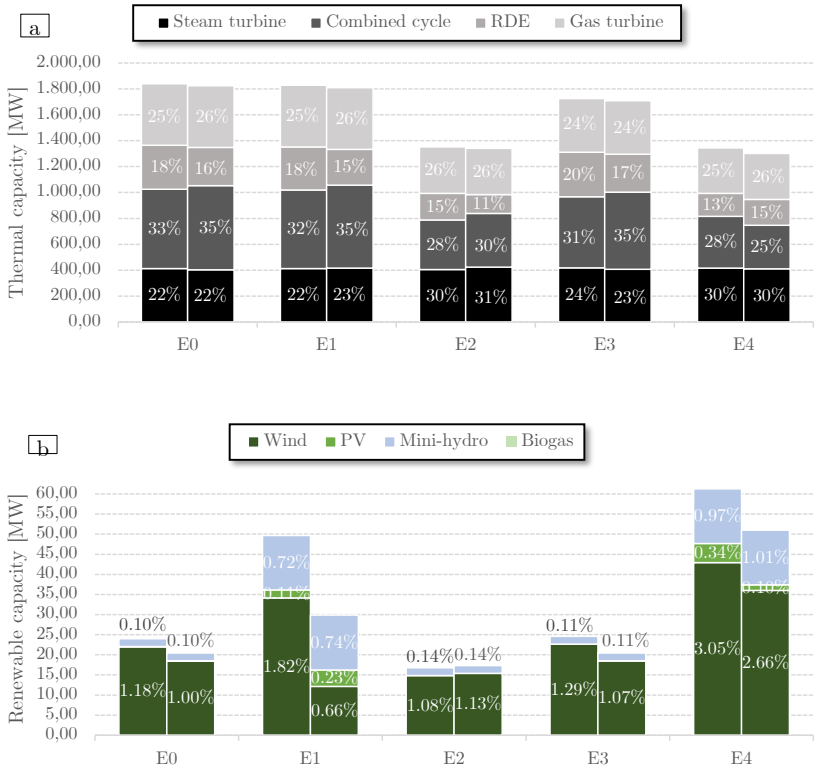


Figure 23. Thermal (a) and RES (b) capacity built for different alternatives. Left columns: AC cases. Righ columns: DC cases.

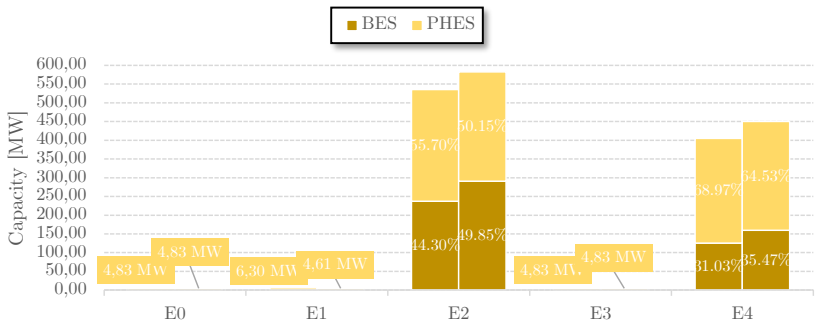


Figure 24. ESS capacity built for different alternatives. Left columns: AC cases. Righ columns: HVDC cases.

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Figure 25 illustrates the energy mix. E4 cases provide the second highest share for renewable energies (around 2.4%). As noted above, in the absence of environmental constraints, interconnectors are used to send cheap (thermal) energy from the larger islands to the smaller ones, which explains why the RES share in the E4 cases is lower than in E1. As a result, E4+AC and E4+DC provide the lowest costs of all the cases, falling below 300 M€ for the first time (see Figure 26). Specifically, E4+AC provides a cost of around 296 M€, and the cost for E4+DC is even lower, close to 292 M€. This represents a reduction of around 26% with regard to the current costs of the system, and of around 5% with regard to our previous best alternative (E2).

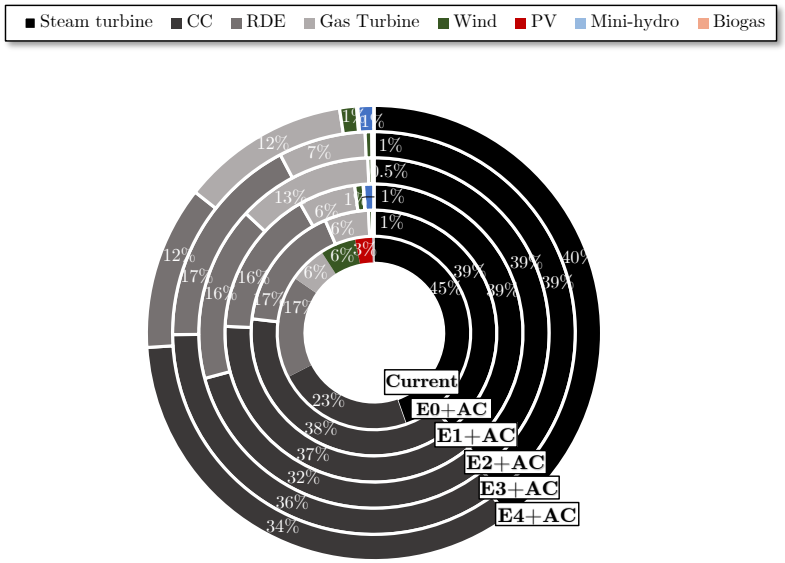


Figure 25. Contribution into the energy mix by technologies in the different alternatives proposed.

Even though the above cases provide notable reductions in terms of costs, RES do not

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meet the full potential of the renewable resources of the region, because of the system's strict reserve criteria and the absence of carbon price considerations. The following section addresses the role of CO_2 emission prices in the adoption of RES in the Canary Islands. However, assessing the optimal reserve requirements of the system requires a very different approach from the one proposed in this paper, and this should be the subject of future research.

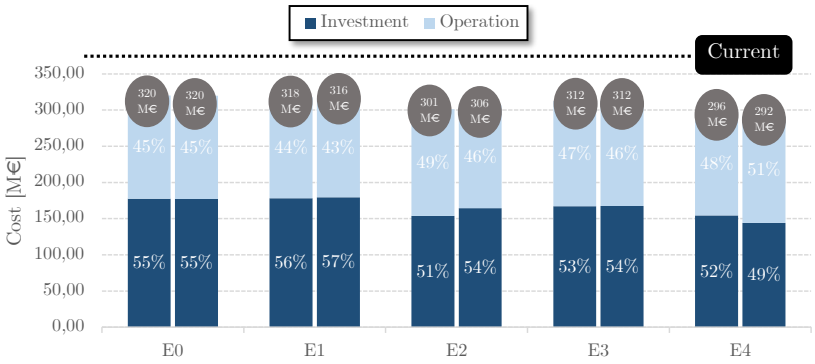


Figure 26. Generation costs by category in the different alternatives proposed.

5.7. Sensitivity analysis: The role of CO_2 emission costs

The results above demonstrate that the combination of ESS, EV, interconnections and additional RES capacity provides the most efficient way to reduce generation costs in island power systems. In this section, CO_2 emission costs are introduced into the simulation in order to identify any further economic and environmental benefits. Since no significant differences have been found between AC and HVDC alternatives so far, for the sake of simplicity the cases detailed in this section focus exclusively on the case of E4+AC.

Figure 27a shows the thermal capacity built and Figure 27b the RES capacity. From

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the highly reduced CO_2 price introduced in S1, the model adopts the whole RES capacity available: that is, 1757 MW. Since PV systems are distributed along the different nodes, the need for interconnections and transmission lines is reduced, as explained below. For the first time, S1 and S4 construct some biogas capacity in an interconnected case, due to the depletion of the power available from other RES technologies. In this regard, since renewable generation needs to be backed up with thermal units to fulfill the reserve requirements, all the available thermal capacity is also built. Then, the key point of this analysis is that when environmental constraints are taken into account, the model builds the current thermal capacity to meet reserve criteria, while the renewable capacity is 3.8 times higher in order to reduce operation costs.

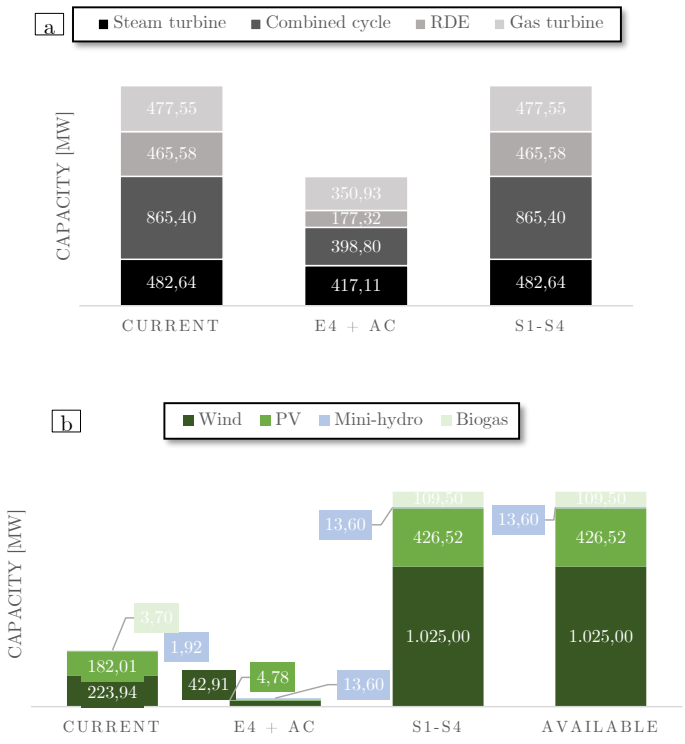


Figure 27. Thermal (a) and RES (b) capacity built under the sensitivity cases.

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Figure 28 compares the ESS capacity built in the current system, in E4+AC and the sensitivity cases. Unlike capacity generation, the storage capacity built is lower than in the previous cases. In fact, due to the increased contribution of (distributed) PV systems, the ESS capacity built in cases from S1 to S4 is lower than in E2 cases, but also lower than in E4+AC and E4+DC. Likewise, as RES penetration increases and emission costs are taken into account, no interconnector needs to be built, since it is much more economical to produce energy from distributed renewable resources and to store surpluses in PHES, BES and also in EV. As a consequence, cases S1-S4 support our previous conclusions regarding the role of interconnectors in sending cheap (thermal) energy from large to small islands.

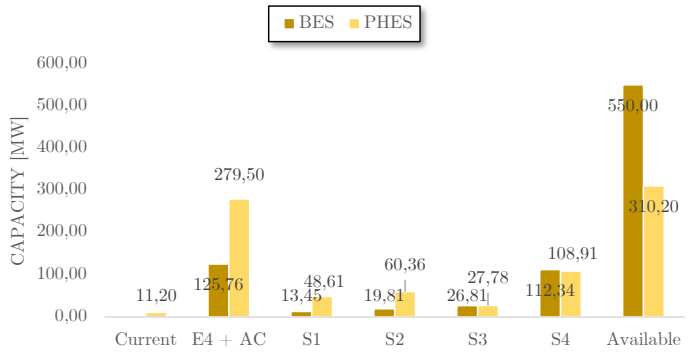


Figure 28. ESS capacity built under the sensitivity cases.

As a result of the new generation structure, the energy mix changes dramatically (see Figure 29). The share of RES increases from around 8% in the Current Situation and 2.42% in E4+AC up to 36.6% in S1 and between 38.6% and 38.9% in cases from S2 to S4 – the highest percentages found in this study. Wind energy provides, on average, 25.8% of the total energy generated, followed by PV, with a contribution of almost 7%, and finally, biogas and mini-hydro which account for 5.8% and 1.1% respectively.

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However, given the remaining available capacity for ESS, if additional RES power were considered, the model is likely to build at least some part of it, providing further benefits in terms of generation costs and renewable integration. Future work should use the model proposed in this paper to investigate this question further.

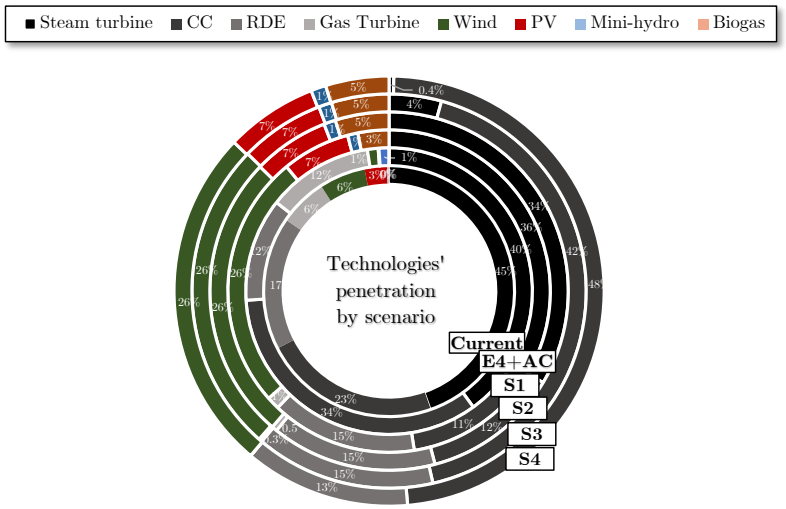


Figure 29. Contribution into the energy mix by technologies in the sensitivity cases.

Finally, generation costs for cases from S1 to S4 are higher than in the Current Situation (see Figure 30). On the one hand, operation costs in S2-S4 are quite high due to the consideration of significant CO_2 emission costs (S1 still provides lower operation costs than the Current Situation). On the other, as a direct consequence of the increased need for thermal back-up capacity for renewable generation, the investment costs are higher in S1-S4 than in the previous cases. It is worth mentioning that our results are more conservative in terms of RES penetration than those provided in Ramos-Real et al. (2018). This finding is related to several facts. First, due to the adaptation of the objective

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function to a broader context, our model is more conservative in terms of assumed costs of thermal technologies which diminishes the benefits of RES deployment. Second, our approach represents the operation of the actual system in a more realistic and accurate way by considering greater complexity in constraints related to power reserves and unit commitment decisions, among other aspects. As mentioned above, these considerations may hinder the development of RES.

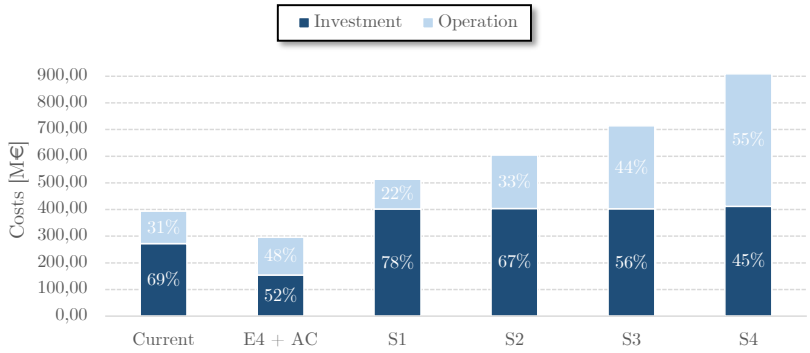


Figure 30. Generation costs by category in the sensitivity cases.

6. Conclusions

This paper presents a two-stage optimization model that can be used to assist in making long-term energy planning decisions for island power systems. Our proposal takes into account a wide set of technologies, such as RES, ESS (including BES and PHES), EV providing V2G services, and AC and HVDC interconnectors. The methodological approach uses representative operating weeks instead of operating days, which allows a better reflection of how ESS deal with small-scale uncertainties, variability in RES generation and load, and other considerations related to the day-to-day operation of this technology. We also model the role of EV as distributed storage units and power reserves

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in island regions.

We demonstrate the potential of our model via a case study of the Canary Islands. From the technical perspective, this Spanish archipelago is of great interest because it has very strict system reserve requirements in which neither RES, ESS nor EV are yet allowed to provide power reserves. Therefore, the Canary Islands offer an excellent opportunity to analyze these issues in advance for island regions and to assist in the energy planning process.

The benefits of the aforementioned technologies are assessed first individually and then combined through a set of 15 cases. The key finding is that in the absence of any policy mechanism that internalizes the social cost of carbon, thermal generation is the lowest-cost source of energy. This result is not new, but it is much more accentuated in the case of island power systems due to the strict criteria applied to power reserves. For instance, the maximum RES penetration found under this assumption is 2.5% and is achieved by combining additional RES capacity, ESS, V2G services and interconnections. This combination also provides a very small amount of power capacity to be built (around 1350 MW) and the lowest generation costs (292 M€) found in this study.

In general, CC are the preferred alternative when the demand for power reserve increases (e.g., in the case of high RES penetration). In all other situations, CC are displaced by ST with lower investment and operating costs. Among RES, the most prominent technology is wind power, reaching up to 1,025 MW. Our results on the adoption of ESS reveal the importance of correctly modeling this technology, not only in terms of their operation, but also in the consideration of both power and energy capacity costs. As a consequence, we obtain that PHES are the preferred alternative, due to their lower costs. In this study, V2G services are mainly found to provide power reserves.

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Finally, the use of interconnections should be assessed carefully. While they may bring down generation costs, in the absence of CO_2 pricing RES generation may be replaced with energy from CC in order to reduce the generation costs in the smaller islands.

Finally, we also propose four additional sensitivity cases in order to examine how rising CO_2 prices may affect generation costs and the demand for capacity reserves in island power systems. The immediate result is that the operation costs of thermal technologies are greatly increased, making it much more profitable to invest in RES. Consequently, we observe that the share of the production of clean energy comes close to 40%, almost regardless of the price of CO_2. Of course, generation costs are notably increased, since power production in the archipelago still relies mainly on thermal technologies. Nevertheless, this result is subject to the RES capacity considered in the simulations. Future studies should model an expansion of this capacity to analyze the penetration limits in the system.

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Appendix 3

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3.A. Energy demand and nodes

The electricity demand data has been extracted from the system operator's database (REE, 2021). The last year for which complete information is available is 2017. However, the data is aggregated at the island level, thus being necessary to establish a consistent criterion to distribute electricity demand in the islands with more than one node (i.e., Tenerife, Gran Canaria, Fuerteventura and Lanzarote).

Following previous works in this field (ITC, 2014), each node is assigned an electricity consumption proportional to the amount of population of the municipalities annexed to said node. To verify the validity of this assumption, it has been examined the correlation between the population series (ISTAC, 2021) and that of electricity consumption on the islands between 2000 and 2017. For the whole archipelago, Pearson's linear correlation coefficient is 0.91 and significant at the 1% level. Figure 3.A.1 illustrates this relationship. The correlation between both variables is really high up to 2012, when the economic crisis suffered at that time introduces greater variability in the series, although the positive relationship continues to be maintained.

Moreover, when this correlation is assessed by islands, the coefficients estimated are even higher, saving for the case of Gran Canaria. In Tenerife, Fuerteventura and Lanzarote this correlation is 0.94, 0.92 and 0.93 (all of them significant at the 1% level). In the case of Gran Canaria, the coefficient found is almost 0.80 (also significant at the 1% level). Thus, in view of these results, it seems that the distribution of the energy demand by nodes as a function of the municipal population is a reasonable approximation. Table 3.A.1 show the resulting electricity demand associated to every node.

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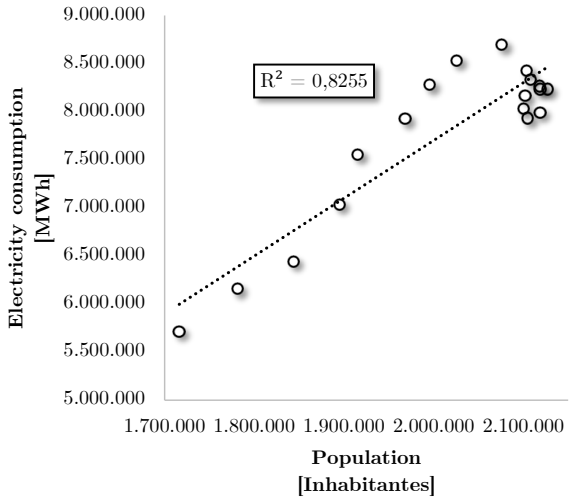


Figure 3.A.1. Correlation between electricity consumption and population in the Canary Islands.

Table 3.A.1. Share of electricity demand by nodes according to the population in near municipalities.

Island	Node	Share of island load [%]
Tenerife	0	0.28
	1	0.12
	2	0.23
	3	0.24
	4	0.13
Gran Canaria	8	0.26
	9	0.74
Fuerteventura	10	0.42
	11	0.58
Lanzarote	12	0.41
	13	0.59
La Palma	6	1.00
La Gomera	5	1.00
El Hierro	7	1.00

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3.B. Electric vehicles' mobility

One of the most difficult aspects to model correctly is the mobility patterns of EV fleets. The complexity of this task is even higher when the model considers the movement of EV from one node to another along the power grid. However, it is necessary to know at all times in what places EV are connected to the network in order to correctly determine their charging and discharging capacity, and the reserves they can provide to the system.

To attain this aim, our work draws on an official report from the State Government which analyzes the mobility patterns of passenger cars in Tenerife (Cabildo de Tenerife, 2017). The document identifies 10 different driver profiles that include job travels, medical reasons, shopping and leisure, among others. These driver profiles are particularly useful for determining the most frequent travel times of every kind of trip. In order to reduce the computational requirements of the model, some similar profiles have been grouped to define the EV fleets considered in this work. For instance, those related to accompaniment to school and accompaniment to other people.

In a similar way to how energy demand is distributed by nodes, the report defines a series of macrozones of origin and destination of car flows for every driver profile according to the population of every municipality. As some of these macrozones are included in a same node of the power grid, an average trip distance and standard deviation can be calculated for all travels and profiles between two given nodes. Then, the trip distance of an EV fleet traveling from node A to node B is derived from a normal distribution characterized by the corresponding average trip distance and standard deviation.

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Finally, combining the data on the location of transmission nodes and the driver profiles defined in the official report, this paper models EV routes in Tenerife and their interactions with the power grid. This includes the energy consumption of each EV fleet which is determined by means of the calculated travel distance and the assumed road efficiency. As a result, taking into account the mobility between nodes and the different profiles identified in the report, a total of 50 EV fleets have been used in this work (see Table 3.B.1 for further details). This clearly offers a reliable representation of the mobility criteria in Tenerife. The total number of EV considered is closed to 25,000 cars, which represents almost a 5% of Tenerife's car fleet (ISTAC, 2017).

Table 3.B.1. Operational characteristics of EV fleets.

ID	No. EV	Origin node	Dest. node	Avg. Distance [km]	Departure t0 [h]	Arrival t0 [h]	Departure t1 [h]	Arrival t1 [h]	V2G capacity [MW]
0	1,692	0	0	8.75	7	8	15	16	11.17
1	1,692	0	0	12.35	13	14	22	23	11.17
2	1,308	0	0	7.46	8	9	12	13	8.63
3	1,308	0	0	9.59	17	18	22	23	8.63
4	26	1	2	15.39	7	8	15	16	0.17
5	26	1	2	18.01	13	14	22	23	0.17
6	13	1	2	16.12	8	9	12	13	0.09
7	13	1	2	16.48	17	18	22	23	0.09
8	10	1	3	17.54	7	8	15	16	0.07
9	10	1	3	20.27	13	14	22	23	0.07
10	5	1	3	16.81	8	9	12	13	0.03
11	5	1	3	15.02	17	18	22	23	0.03
12	10	1	0	27.03	7	8	15	16	0.07
13	10	1	0	28.56	13	14	22	23	0.07
14	10	1	0	26.11	8	9	12	13	0.07
15	10	1	0	26.99	17	18	22	23	0.07
16	44	1	1	4.92	7	8	15	16	0.29
17	44	1	1	6.25	13	14	22	23	0.29
18	23	1	1	7.03	8	9	12	13	0.15
19	23	1	1	4.35	17	18	22	23	0.15
20	1,231	2	2	5.78	7	8	15	16	8.12
21	1,231	2	2	5.82	13	14	22	23	8.12
22	989	2	2	5.30	8	9	12	13	6.53
23	989	2	2	6.44	17	18	22	23	6.53
24	433	2	3	9.69	7	8	15	16	2.86
25	433	2	3	10.42	13	14	22	23	2.86
26	348	2	3	9.28	8	9	12	13	2.30
27	348	2	3	9.67	17	18	22	23	2.30
28	432	3	2	11.18	7	8	15	16	2.85
29	432	3	2	9.59	13	14	22	23	2.85

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Table 3.B.1. Continued.

ID	No. EV	Origin node	Dest. node	Avg. Distance [km]	Departure t0 [h]	Arrival t0 [h]	Departure t1 [h]	Arrival t1 [h]	V2G capacity [MW]
30	302	3	2	11.00	8	9	12	13	1.99
31	302	3	2	11.29	17	18	22	23	1.99
32	1,039	3	3	2.45	7	8	15	16	6.86
33	1,039	3	3	1.88	13	14	22	23	6.86
34	726	3	3	1.18	8	9	12	13	4.79
35	726	3	3	2.67	17	18	22	23	4.79
36	140	4	2	16.17	7	8	15	16	0.92
37	140	4	2	21.01	13	14	22	23	0.92
38	132	4	2	15.42	8	9	12	13	0.87
39	132	4	2	18.85	17	18	22	23	0.87
40	194	4	3	19.18	7	8	15	16	1.28
41	194	4	3	18.43	13	14	22	23	1.28
42	183	4	3	19.12	8	9	12	13	1.21
43	183	4	3	17.35	17	18	22	23	1.21
44	1,272	4	4	18.37	7	8	15	16	8.40
45	1,272	4	4	18.03	13	14	22	23	8.40
46	1,203	4	4	19.53	8	9	12	13	7.94
47	1,203	4	4	18.42	17	18	22	23	7.94

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CONCLUSIONS

In the current era, energy production and energy efficiency have proved to be some of the most influential factors on economic growth and key components in the abatement of CO_2 emissions. At the same time, income variations may induce important changes in energy use patterns, thus giving rise to a bidirectional causality that hinders the successful development and implementation of energy policies. Although many works in the literature have addressed this concern, the absence of proper quantitative metrics has prevented the use of the most appropriate methodologies, leading to contradictory results. As a consequence, there is no consensus on the way in which energy consumption and economic growth interact, the role that energy efficiency plays, or the identification of external instruments that can act as moderators of all these relationships.

This thesis is a multidisciplinary work that combines the most up-to-date methodologies in the fields of engineering and economics to respond to some of the main challenges posed by the literature in the field. Chapter 1 sheds some light on two of this concerns. First, we provide an unprecedented quantitative indicator on the quality of energy governance, which has been praised in the literature as one of the most relevant variables in the analysis of the energy-GDP nexus. The indicator reports information on the state of energy governance in 32 OECD countries between 2000 and 2015. Then, we draw on such indicator in order to break new ground in the understanding of the bidirectional relation between energy and GDP through an instrumental variable approach based on two-stage least squares. Important insights for policymaking are derived from our results.

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First, increasing energy governance quality by one standard deviation (around 32% over its average score) could reduce energy consumption growth by approximately 0.50%. Our work identifies specific ways to improve energy governance according to the context of every country. Second, we explore the channel that energy governance provides for the interaction between energy consumption and income growth. The elasticity between (energy-governance-driven) energy consumption and income growth is close to unity, which almost doubles that commonly found in the literature. For the other side of causality, we construct an adjusted income growth series, where the response of income to energy consumption is ruled-out. The resulting elasticity is negative (around -3.0), which is of opposite sign to the usual finding in the literature. Therefore, energy governance affects growth only through energy consumption, favoring a more efficient use of energy in the production process and, thus, fostering growth.

Chapter 2 adds to the existing literature by both contributing to the definition of a proper methodology to measure energy efficiency and assessing the impact of energy governance on such efficiency. The study draws on a panel dataset of 29 OECD countries between 2000 and 2015. To accomplish this purpose, we draw again on the governance index constructed in Chapter 1, demonstrating its remarkable scientific interest. We overcome some of the most common pitfalls found in the literature by implementing a stochastic frontier analysis instead of the classical energy intensity-based approach, whose validity has been widely questioned in the last decades. Our results suggest that increasing the average quality of energy governance by 10% could raise energy efficiency levels by around 9.20%, although this impact may be even higher according to different SFA models. Improvements in efficiency are strongly related to two key requirements: setting quantified and achievable targets, and carrying out an extensive evaluation of the

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results of energy policies.

Finally, Chapter 3 improves the understanding of how certain elements of energy governance can affect compliance with energy policies and their targets. We focus on the field of electricity generation, specifically in the case of isolated power systems such as that of the Spanish Canary archipelago. Our model determines the optimal mix of generation and transmission capacity required to satisfy energy demand at the lowest cost, while respecting the complex and strict technical and planning constraints inherent in island power systems. This is a novel approach that combines the use of thermal generation, renewable systems, electric vehicles providing vehicle-to-grid services, and AC and HVDC interconnectors. The results suggest that, in the absence of any mechanism to internalize the social cost of carbon, thermal generation is the lowest-cost source of energy. However, environmental considerations like the imposition of CO_2 fees highlight the benefits of renewable generation, and so the contribution of clean energies to the generation mix should be around 40% on an energy basis. The figures are far below the energy policy targets, demonstrating that an inadequate energy governance may compromise the success of energy policies due to imprecise targeting, regulatory barriers or other similar issues.

Finally, it is worth mentioning that, in addition to the present contributions made to the literature, this thesis breaks new ground for future research in the energy field, both from an economic and engineering perspective. In the first case, the construction of a time-varying energy governance index may be of great interest to improve the accuracy of the models conducted in this work and the scope of the conclusions drawn from them. In addition, the methodology proposed to construct our index may provide a source of inspiration to the elaboration of country-specific indicators that significantly improve the

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definition and development of energy policies. The instrumental variable provided in this work may be complemented with the analysis of other channels that affect the relationship between energy consumption and economic growth. Finally, our stochastic frontier estimates could be improved through the assessment of the effect of energy governance on transient and persistent efficiencies. From an engineering lens, the two-stage approach provided in Chapter 3 is easily extensible to other island systems, so it can be applied to different contexts and regions. Additional technologies, such as hydrogen store or geothermal energy, may be include to further generalize the results derived from our approach. Finally, the inclusion of time horizons for reinvestment in certain technologies would markedly increase the value of our contribution, giving rise to an almost definitive assistance tool for long-term energy planning in island systems.

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