A Multicriteria Assessment Approach to the Energy Trilemma

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ABSTRACT

The development of sustainable energy systems is pivotal in addressing climate change, but is also a complex and multifaceted task that should take into consideration a wide range of technological and socio-economic issues. The energy trilemma concept acknowledges this complexity and emphasizes the need to achieve a balance among three main dimensions: energy security, energy equity, and environmental sustainability. This study provides a systematic treatment of the energy trilemma at the country level. A novel multicriteria assessment framework is employed to evaluate the related performance of countries. Such an evaluation provides useful results for policy making, as it enables the examination of the status of each country and the challenges that it faces in achieving energy sustainability. The obtained empirical results are analyzed over time as well as considering the characteristics of the countries.

Keywords: Climate change, Energy policy, Energy trilemma, Multicriteria decision making

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1. INTRODUCTION

After the decisions of the COP21 meeting in December 2015, global energy policies shifted their focus towards achieving real progress on securing and managing energy. The need became apparent to align the acquisition and security of energy and economic development with the need to achieve environmental sustainability goals. Nonetheless, to implement this alignment is a challenging task. When the externality is a global one, it also requires international cooperation. Therefore, it is imperative to develop tools that will allow progress in attaining achievements consonant with goals and targets set forth by several worldwide organizations to be monitored and assessed.

Such an evaluation may provide useful results for policy making, enabling the examination of the status of each country and the internal and external challenges it faces in achieving energy and environmental sustainability and managing the acceptable trade-offs to meet future goals. The transition from a fossil fuel powered economy to a cleaner and more environmentally friendly one involves the consideration of several technological and socio-economic issues. In order to attain the goal of a sustainable society-economy, public awareness needs to be raised about the benefits of an energy transition and the opposing trends that should be managed. Kuzemko et al. (2016) present an

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analysis of such views on the role of governance for sustainable energy system change (socio-technical transitions).

At present, energy policies emphasize reducing the carbon footprint of energy. The roadmap to such an intermediate transition can be achieved in various alternative ways, such as extending the use of renewable sources, promoting practices that improve energy efficiency, controlling demand, and even, investing in less polluting fossil fuel technologies as well as some form of nuclear power. The adoption of such options and the effects that they have, depend on the microstructure of the economy, which differs from country to country. Böhringer and Bortolamedi (2015) highlight such differences, and identify the lack of a microeconomic foundation as a common problem in existing energy security indicators. The deficiencies become acute when these indicators are used as substitutes for economic cost-benefit analysis to provide guidance into energy security policies from a normative perspective. In addition, Ackerman and Munitz (2016) criticize existing climate economics models used in policy analysis such as DICE, PAGE, and FUND. For instance, they argue about the intensity, sensitivity and ambiguity of the net benefits of carbon fertilization proposed by the FUND model and its tendency to suggest that increased income per capita provides the ability to adapt to the marginal damages from CO_2 emissions. Pindyck (2013) also criticizes the development of integrated assessment models, on issues such as the choice of their functional form and the specification of their input parameters. In other works, Pindyck further argues that due to the long-term nature of policies related to environmental issues, the monetarization in present value-terms is very difficult (Pindyck, 2007; 2012). This is not only due to the deep uncertainties involved, but also due to the difficulty of specifying a proper social discount rate for societies whose members have differences in intertemporal preferences (Lawrance, 1991). Adopting a different economic perspective, Capros et al. (2016) examine the macroeconomic and sectoral effects of higher electricity and gas prices until 2050. They found that an increase in prices resulting from various scenarios (e.g., taxation, higher price markups, higher renewable production in the generation mix, etc.), has a negative impact on economic activity (as measured by gross domestic product-GDP) when compared to their baseline scenario of implementing all the European energy-related policies and achieving the 2020 objectives.

In contrast to the above strand of the literature that has focused on normative models of energy policies, another strand has followed more descriptive approaches. Such approaches provide important insights into specific characteristics and complementary dimensions of energy policies (Böhringer and Bortolamedi, 2015; Sovacool, 2013). Our view is that normative models and descriptive approaches are complementary rather than competitive. This enables the assessment of what has been achieved and the current status of the countries based on observed data and the combination of multiple indicators into composite (synthetic) indices. Assessing and monitoring the strengths and weakness of countries is an important part for making informed policy decisions, together with the examination of what *ought* to be done as specified on the grounds of normative rules and assumptions. Grigoroudis et al. (2015) compare three descriptive assessment models as energy sustainability barometers (ESI, SAFE, and EAPI).[1] Their results show notable differences in the rankings of countries produced by the different models. The ESI model ranks more highly rich countries with stable political systems, while the EAPI promotes countries that use nuclear energy as a low carbon fuel source, and SAFE favors countries with greater hydropower production in their energy mix (Phillis and Andriantiatsaholiniaina, 2001).

1. ESI: Energy Sustainability Index by the World Energy Council; SAFE: Sustainability Assessment by Fuzzy Evaluation; EAPI: Energy Architecture Performance Index by the World Economic Forum.

This study builds on the above context for characterizing the multidimensional nature of energy systems and policies, such as the energy trilemma framework of the World Energy Council, and introduces a methodology for aggregating disparate ordinal indicators in a panel of countries. Moreover, we introduce indicators related to the policy and regulatory framework, to research and development, as well as to innovation, as measures of key drivers for long-term improvements. The aggregation method introduced in this study is based on the observed choices of the countries across different dimensions of energy-related policies and to measured outcomes without the need to perform ambiguous data normalizations that distort the information embodied in the data. Furthermore, instead of using subjective weightings common to all countries, a data-driven process is employed, where the weights are derived from the data through an approach that is grounded on principles from the fields of production efficiency analysis. Thus, the proposed methodology combines normative and descriptive elements. On the one hand, the selection of the performance indicators and the specification of the evaluation model have normative grounds, whereas the derivation of the results (e.g., the weighting of the indicators) relies on the observed data of the counties. Finally, the approach introduced in this study allows both cross-sectional comparisons between countries and the comparison of the same country over time. To illustrate the applicability and the potentials of this analytical methodology, an empirical analysis is performed using up to date data for the OECD countries.

The rest of the paper is organized as follows. Section 2 discusses the energy trilemma concept, its main dimensions and alternative views in the literature. Section 3 describes the components of the proposed framework and the methodological approach used to construct an aggregate composite performance index using country-level data. Section 4 applies the proposed approach to data for the OECD countries. Finally, section 5 concludes the paper and discusses some possible future research directions.

2. THE CONCEPT OF THE ENERGY TRILEMMA AND ALTERNATIVE VIEWS

The energy trilemma concept focuses on the energy policy concerns of energy security, energy/environmental sustainability, and energy equity. These represent some of the possible tradeoffs, gains and losses in an economy.

The trilemma concept is clearly multidimensional, with each individual dimension contemporaneously affecting all other dimensions. For example, certain changes that promote sustainability, such as improving energy intensity and efficiency, also promote security by reducing energy dependency. Similarly, the diversification of energy sources using renewable energy sources, which are under the direct sovereign control of a country, promotes energy security as well as sustainability. Thus, it is rather difficult to provide a strict definition for each dimension and examine it in isolation of others. For instance, Ang et al. (2015) reviewed 104 papers and identified 83 energy security definitions.

Bearing in mind this difficulty, the following sections present the proposed measures in each dimension as well as some key findings from the relevant literature.

2.1 Energy Security

Although securing energy at an acceptable price and in an environmentally viable way is a key factor for sustainable development, the ability of individuals or larger groupings of people to afford the secured energy is not always achieved automatically or equally amongst the population.

Thus, a significant part of the literature on the concept of energy security follows a higher level of abstraction that usually interweaves energy sustainability and equity.

The Asian Pacific Energy Research Centre (APERC, 2007), for example, presented its 4 A's analysis of addressing energy security, considering resource *availability*, *accessibility* barriers (geopolitical, geographical and transportational, labor, technological etc.), environmental *acceptability* (implementation of technologies and investment in reducing CO_2 emissions), and investment cost *affordability* (to secure the necessary infrastructure to meet and manage future demand). Hughes (2009) used the concept of the 4 R's of energy security: (a) *reviewing* how energy is used, (b) *reducing* energy use through policies that aim to conserve energy where possible and promote energy efficiency, (c) *replacing* insecure sources with more secure ones, by diversifying either across sources in the energy mix or across suppliers, and (d) *restricting* new demand to secure sources.

Generally, the evaluation of energy related themes is context-dependent, which is a possible explanation for the diverse set of indicators that have been proposed in the literature. Kruyt et al. (2009) presented an overview of simple and aggregate indicators for energy security used in the TIMER model. They highlighted their elusive and contextual nature, especially for aggregated indicators as having *"the potential pitfall of hiding the underlying dynamics from sight"* (Kruyt et al., 2009, p. 2177), the problems arising from the weights associated with them, and the limitations of the models in terms of their ability to capture complex socio-economic, technological and geopolitical issues. Narula and Reddy (2015) also pointed out the inconsistency of findings when using indicators to evaluate and rank country performance, noting issues related to the selection of the indicators and the weighting methodologies. Cherp and Jewell (2011) pointed out the multidisciplinary nature of energy security, calling for an approach that considers perspectives such as the *sovereignty*, in terms of managing geopolitical issues; *robustness* in terms of protection and provision of physical systems tolerances to events; and *resilience* in terms of the identification and management of risks associated with the unpredictability of future events producing substantial economic effects. Their point is that the use of frameworks in energy security should be focused on national contexts as well as the "interactions between the Physical, the Political and the Economic" (Cherp & Jewell, 2011, p. 211).

Sovacool and Mukherjee (2011) provide a classification of 320 simple and 50 complex indicators in five dimensions, produced by interviews, surveys and literature reviews. The plethora of their metrics, albeit valuably informative, notwithstanding some valid points (Cherp, 2012), highlighted both the lack of actual data for many metrics as well as their overlaps and multidimensional character, depending on the conceptual views of the respondents. Winzer (2012) also highlighted the contextual and interweaving nature of energy security and its effects on sustainability. To separate the two concepts, energy security was defined as the "*continuity of energy supplies relative to demand*". Winzer, noted that energy security should be measured against the scope of the risks' impact, defined in terms of the continuity (price and availability) of commodities (oil, gas, electricity, etc.); service supply (heating, lighting, communication, transport, etc.); economic and social continuity; as well as welfare, in parallel to the concepts of *"affordability"* and *"acceptability"*. Winzer's approach is a systemic view of interconnected dependencies and this type of analysis is similar to the one of Hughes (2009), who noted that energy services and energy intensities should be *reviewed* by sector and as deeply as possible.

The review of Ang et al. (2015) defined seven energy security dimensions, namely: energy availability, infrastructure, energy prices, societal effects, as well as environment, governance, and energy efficiency. They also pointed out some robustness issues with regard to the creation of security indicators, given that using a compact set of indicators can lead to results that are sensitive to changes.

2.2 Sustainability

In the United Nations report “Our common future” it is stated that “*Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future*” (Brundtland, 1987, p. 39). However, sustainable development should not be solely viewed as a transformation of energy/resource constraints into policy objectives. Instead, it should further be viewed in the context of economic and energy efficiency to account for the attained welfare of current and future generations, all things considered. When examined in the context of energy policy, a particular threat to the welfare of future generations arises from the damages to global climates and the quality of life resulting from the accumulation of CO_2, and greenhouse gases (GHG) more generally, that accompany fossil fuel use.

Technological innovation has steadily improved energy efficiency so that less energy and CO_2 accompany the same output (GDP). It has also made investments in renewable sources less capital intensive (FS-UNEP, 2018; IRENA, 2018). Makridou et al. (2016) evaluated the energy efficiency of energy intensive industries across 23 EU countries between 2000 and 2009 and observed an overall improvement mainly caused by technological change. The results of their empirical analysis show that a diversified set of energy sources is associated with energy efficiency and demonstrate that sector and country characteristics should be considered when policy measurements are formulated. Within this context Jordaan et al. (2017) reviewed the financing mechanisms and investments from both industry and government in Canada, taking into account the international, federal and regional climate policies. They noted that, although Canadian emissions targets are consistently not realized, the country is a global leader in renewable and clean energy. Nevertheless, the authors argue that better communication of the financing mechanisms and policy incentives already in place as well as new complementary investment policies geared towards meeting the reduction targets, would increase the adoption of cleaner technologies.

Although the mix of clear policy signals and industry intentions drive the way for further energy reductions and efficiency improvement, their extent cannot be accurately determined a priori due to numerous reasons such as industrial scaling, financing requirements (e.g., capital expenditures), and time issues, among other. Sekulic et al. (2014) proposed a metric for measuring the margin for improvement between the actual energy used and the theoretical minimum needed for the same task, using an example from the automotive industry. As noted by the authors, this gap is indicative of “the margin space to be populated by a transformational technology” (Sekulic et al., 2014, p.38). However, whether it would be worthwhile to address this gap or not, depends on multiple sustainability goals and constraints, as well as energy efficiency considerations. Despite that, based on their results obtained from manufacturing processes, the authors argue that the technology factor may provide a more promising way of achieving energy savings than investment in gradual efficiency improvements using existing technologies.

In another view of this concept, Grossi and Mussini (2017) examined the inequality in energy intensity among the EU-28 countries, by considering a decomposition of inequality into energy transformation, final energy intensity, and their interactions. They found that countries with low energy intensity are more efficient in energy transformation and less energy intensive in end-use sectors than countries with high energy intensity, albeit having higher inequality in the energy transformation component. On the other hand, DeLlano-Paz et al. (2016) relied on modern portfolio theory to evaluate the three proposed EU 2030 goals of a minimum portfolio share of renewable efficiency improvement and CO_2 reduction. They concluded that the renewable energy share can be maximized by implementing a low CO_2 emissions policy.

In terms of sustainability, all GHG emissions, not just CO_2, need to be considered. In the Intergovernmental Panel on Climate Change (IPCC) 5th assessment report, it is calculated that from 1870 until 2011 we had already used about 65% of the carbon budget (total emissions) related to an increase of 2^{o}C in global temperature. Furthermore, the micro particle matter emitted by fossil fuels is directly responsible for life threatening diseases while the increasing use of unconventional fossil fuels, may produce other negative externalities (Jackson et al., 2014). It is important to note that the goal of promoting sustainability through the use of cleaner energy is directly compatible with strengthening energy security. The findings of Valdés Lucas et al. (2016) suggest that the EU's energy security strategy is the main driver of renewable energy deployment through the diversification of the energy mix and that the reduction of CO_2 emissions is an intended outcome.

2.3 Energy Equity

Energy equity, or inequality in the access to energy, are often discussed under the rubric of energy poverty or fuel poverty. The former usually expresses lack of access to energy due to poor infrastructure and, most importantly, high energy costs relative to the available income. Fuel poverty usually refers to the high burden of heating and other related energy expenses relative to household income (Boardman, 1991) or by the "low income high cost—LIHC" measure, which considers households that spend more than the median income level on fuel costs with the remainder placing them below a country's official poverty line (Hills, 2011). Li et al. (2016) provide an overview of the basic differences. The definition of fuel poverty is somewhat controversial (Moore, 2012) as its measurement can differ substantially depending on the context of the approach. It is affected by the available income and fuel prices, but also by the micro analysis of households' energy costs relative to the characteristics of the dwellings (e.g., indoor living temperature, the dwelling's size and location, its energy efficiency, the number of occupants and their age, local climate conditions, etc.).

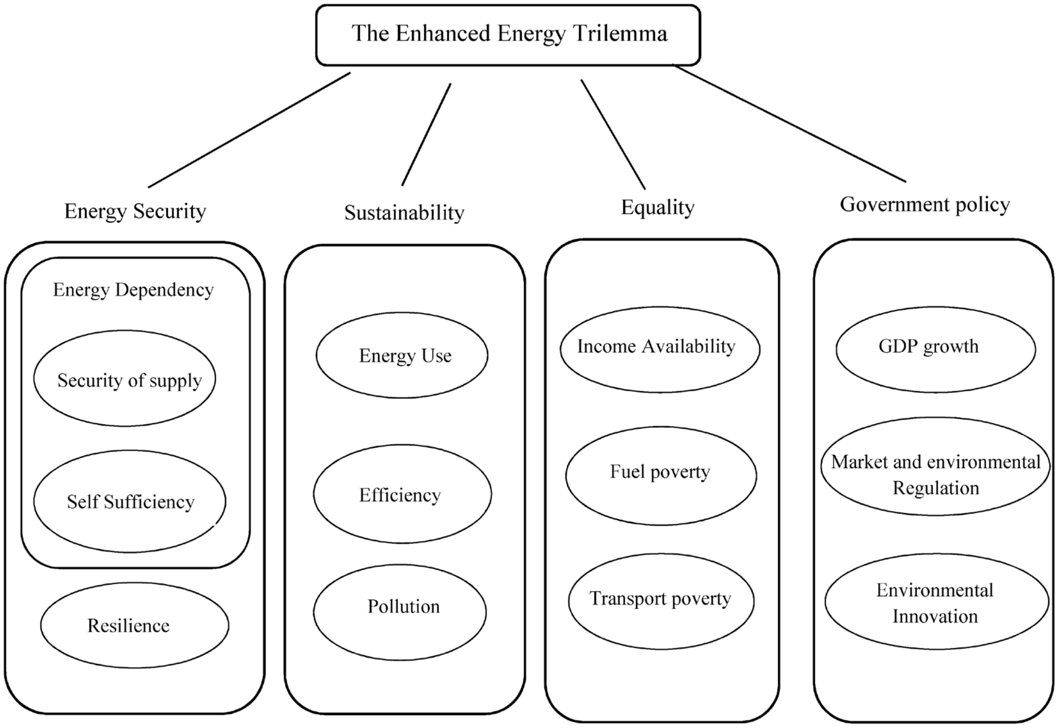
Furthermore, transport poverty and transport affordability are also relevant, as the need for mobility is directly related to employment opportunities and income creation and as such exacerbate inequality issues among the population. Mattioli et al. (2017) provide a comparison between the transport poverty/affordability and fuel poverty, presenting findings that suggest that households will reduce other costs in order to sustain mobility. Berry et al. (2016) also investigated the measurement of fuel poverty in the transport sector and highlighted the importance of considering the households' mobility needs and the way they adapt to rising transport prices.

3. METHODOLOGICAL FRAMEWORK

3.1 Conceptual framework

Our approach to the trilemma concept considers the effects that the outer environment (regional and global) may have on a country relative to its inner environment and economic structure, as illustrated in Figure 1. We consider the stages of acquiring, transforming, distributing, using, storing and planning for future energy needs and the affecting policies. We focus on policy tools and outcomes rather than conformity with normative rules. To this end, we have chosen indicators whose nature and information complement one another within and between dimensions. This en-

Figure 1: The enhanced trilemma framework



ables us to provide a macro view of the total measured outcome in each dimension and country's profile. Furthermore, we consider a fourth dimension to cover the outcome of policy decisions and the potential they create for long-term improvements.

Energy security is multidimensional and reflects not only the outer environment but also the inner one. It encompasses aspects of energy dependency, which reflect both the security of supply related to the outer environment a country faces and also the diversification of its energy supplies. Energy security also entails evaluating the distance from the energy source, the means of transportation, the relations with the transit countries (Misik, 2016) and a consideration of the county's intentions and ability to safeguard the flow of energy, politically and even through military strength.

Another part of the energy dependency theme is (self-)sufficiency, which involves evaluating the energy prices a country can afford, as well as the extent of volatility and spillovers that can be tolerated (Andriosopoulos et al., 2017; Metcalf, 2014; Zhang et al., 2017). The essence of energy security, however, is the extent of imports (non-sovereign energy sources) relative to a county's energy use, which expresses the bottom line of the energy dependency theme.

Resilience is associated with aspects such as: (a) the diversification of the energy mix especially in electricity production; (b) the microstructure of the economy's energy use (industry, utilities, heating, transport etc.); (c) the security of the infrastructure with regard to threats (both physical and cyber related, i.e. aging, automation etc.) and the ability of the system to tolerate the loss of one or more units; (d) the quality the of energy networks and their ability to cover short-term demand and long-term needs; and (e) the adoption of smart technologies to control decentralized production, prosumer management, pricing and the storage of energy.

The sustainability dimension encompasses the amount of energy used to produce a given output as well as the degree of substitution amongst the different energy sources going from fossil to renewable. It is important to account for improvements in measures of energy efficiency for both consumers and industrial users. When judging the environmental aspects of sustainability, all forms of emissions from energy use should be considered. A special case involves energy and emissions for space and water heating and electrical lighting and appliances, which account for a substantial share of the energy used by consumers. Household energy use for these purposes also has a direct relation with energy equality and fuel poverty.

The energy equality and fuel poverty dimension encapsulates mainly household access to energy services. The distribution of income is included in these measures as a means of revealing the socio-economic conditions in a country that could affect energy policy decisions regarding the cost of energy. An unequal disposable income distribution combined with a relatively high percentage of overall housing, electricity and heating living expenditures, increases social pressure and restricts consumer confidence and consumption, which are important to promote economic growth.

The addition of the government policy dimension enhances and extends the standard trilemma concept (Figure 1) through the consideration of measurements of environmental pressure and negative externalities on an economy's output. Policies in suggestive or applicable legislative form along with market regulation, should be considered when evaluating a country's position, since they have important implications for its economy, its willingness to implement sustainable technologies (change), and to increase competitiveness via technological innovation. However, more radical policies tend to have more profound effects, making them much harder to promote and implement. This dimension is complementary to the other dimensions and enables the examination of some fundamental policy aspects, which act as drivers for long-term improvements, in contrast to the standard security, sustainability, and equity indicators and metrics, which mainly represent the current status of a country.

The specific indicators of the above dimensions which will be described in the next sub-section are combined into a composite indicator measuring the performance of the countries according to the principles of the energy trilemma concept. The combined index summarizes the conflicting dimensions of the trilemma and the contextual environment of the countries, providing policy makers with an overall assessment of a country's current strengths and weaknesses, enabling the derivation of insights into the existing trade-offs. The results of such a composite indicator should be analyzed through a top-down approach. Since many different dimensions of information must be considered, one should first examine a country's overall performance and then explore how it is explained by the selected indicators to identify the strengths and weaknesses of the country over time and in comparison, to its peers.

Finally, it should be emphasized that security, sustainability, equality in purchasing energy, as well as government policy are affected by many factors that are out of a country's control. These include the geographical location and size of a country, local climate conditions, the availability of natural resources, and the conditions prevailing in the commodities markets, among others. The framework described above does not seek to control these external factors to derive a measure of pure energy policy performance. Instead, the aggregation of all dimensions into a composite index assesses the strengths and weakness of the countries, incorporating both the effects of internal policy decisions as well as external effects. Thus, the results represent a higher-level aggregation of the overall state of a country in relation to the existing outer environment as defined by the observed data for other countries.

Table 1: Selected Indicators

Security	Sustainability	Equality–Poverty	Government Policy
I_1: Energy imports, net (% of energy use)* (L)	I_6: Energy use (kg of oil equivalent) per $1,000 GDP (constant 2011 PPP) * (L)	I_{11}: Relative purchasing power of energy: *Percentage of Household electricity, gas and other fuels expenditure relative to median disposable income (%)***+ *(L)*	I_{15}: GDP adjustment for pollution abatement** (H)
I_2: Fossil fuel energy consumption (% of total)* (L)	I_7: CO_2 emissions (kg per PPP $ of GDP)* (L)	I_{12}: Relative purchasing power of transport fuel: *Median income divided by mean value of pump price for gasoline and diesel***+ (H)	I_{16}: Environmentally adjusted multifactor productivity growth (%)**(H)
I_3: Electric power transmission and distribution losses (% of output)* (L)	I_8: CO_2 emissions from electricity and heat production, total (% of total fuel combustion) * (L)	I_{13}: five-year geometric average of consumer prices energy, percentage change on the same period of the previous year (annual) **+ (L)	I_{17}: Aggregate ETCR (average electricity, gas) ** (L)
I_4: five-year geometric average of % change in energy use per capita*+ (L)	I_9: Total GHG (th.kgr) per capita** (L)	I_{14}: Gini (disposable income, post taxes and transfers) ** (L)	I_{18}: Environmental policy stringency** (H)
I_5: Herfindahl-Hirschman index of electricity mix*+ (L)	I_{10}: $PM_{2.5}$ air pollution, mean annual exposure (micrograms per cubic meter) * (L)		I_{19}: Environmentally related government R&D budget, % total government R&D** (H)
			I_{20}: Relative advantage in environment-related technology** (H)

Notes: *World Bank, **OECD, + Authors calculation, (L): Lower Values Better, (H): Higher Values Better.

3.2 Selection of indicators

Following our conceptual framework, we selected a total of 20 indicators, which are presented in Table 1. It should be noted that this framework and the selected indicators do not evaluate the economic efficiency of countries (i.e., the balancing of costs against the benefits of resource use). Instead, the focus is on the assessment of the countries' performance on the energy trilemma dimensions explained in the previous section.

For the security dimension, we focus on evaluating a country's sensitivity to a supply disruption by considering how much energy it imports, how resiliently it uses energy, while also considering the changes in energy use over time. Indicator I_1 refers to net energy imports as a percentage of the energy used. This metric along with I_2 expresses the dependency a country has on foreign energy supply that is outside its sovereign control. Indicator I_2 (fossil fuel energy consumption as percentage of total consumption) captures the effect that fossil fuels would have in case of a disruption of flow. Therefore, we view I_2 as an indication of the self-sufficiency sensitivity and potential. Indicator I_3 refers to electric power transmission and distribution losses as a percentage of output. This indicator is used as a proxy for the state of the infrastructure and its ability to serve the energy needs of all consumers as required. It should be noted that because our analysis focuses on OECD countries, access to electricity is not an important issue (it is close to 100% for all countries). Indicator I_4 (five-year geometric average of the percentage change in energy use per capita), provides an indication of the overall trend in energy use where increasing energy needs mean higher dependency and sensitivity to energy. I_5 is the Herfindahl-Hirschman index (HHI), which measures the diversification of the sources and technologies in the electricity mix. From a security of supply perspective, diversification is important since we are considering physical facilities that have both technical minimums but also technical maximus for energy they can supply. Thus, a loss of one or more units regardless of the technology and depending on the geographical dispersion of the production units, can be substituted by increasing other sources up to a given point. Hence more sources and a greater diversification of technologies is considered preferable, also keeping in mind the sovereignty factor.

For the sustainability dimension, consuming less energy to achieve a specific economic output denotes a smaller impact on the environment (either using fossil or renewable sources). We combine this notion with the evaluation of how much pollution is exerted for the formation of the GDP and we evaluate selected sectors of importance and the total environmental impact in terms of GHG gases. Indicator I_6, which measures energy use per GDP, represents the energy intensity of a country. Moreover, we examine the amount of CO_2 produced per GDP output (indicator I_7), which is a measure of carbon intensity that also acts as a proxy for the use of renewables and non-carbon intensive energy to produce output with less need for fossil fuels (either by reduced use of fossils or from improvements in efficiency).

The CO_2 that is emitted from electricity and heat production as a percentage of total fuel combustion (indicator I_8) complement the logic of the previous indicator, examining the shift from traditional uses of electrical energy to their expanding utilization and the evolution of the "electrification of everything" that is already under way. For example as e-mobility continues to phase out gasoline and diesel use in transport and as heating is shifted to technologies such as heat pumps (in conjunction with energy and heat conservation in buildings), the corresponding need for the equivalent energy will be shifted to the electricity networks and this metric is a good proxy to measure whether there is an actual improvement in terms of sustainability or not (i.e., an increase of CO_2 in this indicator could negate a decrease in CO_2 from transport).

We also use total GHG per capita (indicator I_9) to capture the impact on sustainability from all sources[2]. Because this is an aggregate CO_2 indicator it displays the overall outcome trend of emission impact and, as it is calculated on per capita basis, it provides a weighting scheme for country size. We account for air pollution using indicator I_{10} (mean annual $PM_{2.5}$ exposure; $PM_{2.5}$ is considered the most harmful among particulate matter pollutants[3]), thus covering an important aspect of livability conditions that relates to public health risks.

To evaluate energy equity-poverty, we calculated some relative purchasing power indicators. A country is evaluated more favorably when its households can acquire energy at a smaller fraction of their income and income is more equally distributed with less pressure from increasing prices.

Indicator I_{11} represents the percentage of a household's expenditure on electricity, gas and other fuels, relative to its median income. The former is complemented by the relative transport fuel purchasing power (indicator I_{12}), which compares the average gasoline and diesel prices to median income. Together, they express the possible tradeoffs a household faces between living quality and mobility. We also consider the five-year geometric average growth rate of consumer prices on energy (indicator I_{13}) to capture the price trends over time. Finally, the Gini index (indicator I_{14}) is used to provide an understanding of the relative distribution of income inside each country, thus enabling the consideration of the effect of energy policies on a country's income inequality, which has important implications for social stability and welfare. Several studies have shown that there

2. Data refer to total emissions of CO_2 (emissions from energy use and industrial processes, e.g. cement production), CH_4 (methane emissions from solid waste, livestock, mining of hard coal and lignite, rice paddies, agriculture and leaks from natural gas pipelines), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). Data exclude indirect CO_2.

3. For OECD countries, the average share of PM2.5 in PM10 exceeds 65%. Only in USA and Canada the share of PM2.5 is lower (~25%). Moreover, as noted in the 2013 report of WHO entitled "Health effects of particulate matter," PM2.5 is a

exists an association between energy-environmental policies and income inequality in several countries. Apergis (2015) using data for 32 OECD countries spanning the period 1998-2013 found that increasing renewable energy production has adverse effects on income inequality. Hübler (2017) further found that higher inequality is associated with reduced per capita CO_2 emissions and energy intensity. Khan & Heinecker (2018) showed that disparity affects energy consumption efficiency in a diametrically different manner in cities and nation states leading to a higher urban carbon footprint while increasing energy efficiency nationally. Jorgenson et al. (2017) analyzed United States state-level CO_2 emission and the income share of the top 10% as well as the Gini coefficient between 1997 and 2012. They found that emissions are positively associated with the top 10% income share, while the Gini coefficient had an inconsistent effect.

Government policy decisions at the regional and international level act as one set of drivers of change. Therefore, we evaluate as a separate dimension, the government policies and contextual performance of the countries related to GDP growth factors and the extent to which resources increase GDP rather than productivity gains. We also view market regulation and restrictions, technology push and support, as well as relative advances in technology, controlled for environmental performance.

Indicator I_{15} (GDP adjustment for pollution abatement) considers changes in pollution emissions and environmental quality and presents a positive or negative percentage adjustment of the GDP growth of each country[4]. Thus, it offers a monetization of the pollution impact[5]. Indicator I_{16} refers to the environmentally-adjusted multifactor productivity growth (EAMFP), which incorporates environmental services into productivity measurement and captures the economy-wide productivity growth. This indicator measures a country's ability to generate income while accounting for the consumption of natural resources and undesirable by-products (pollution). EAMFP is the share of growth that is not explained by the changes identified for labor, produced capital, and natural capital. The gap between the pollution-adjusted GDP and the environmentally-adjusted multifactor productivity represents the contribution of inputs to output growth. The larger the gap, the greater the contributions of labor, produced capital and natural capital to output growth. The smaller the gap, the more output growth depends on productivity gains (which is driven by technological improvements or efficiency gains).

Indicator I_{17} involves regulation in energy, transport and communications (ETCR) and summarizes the regulatory provisions in these fields. We use the average of the electricity and gas sector. The indicator is measured on a scale ranging from 0 to 6 with smaller values indicating a less restrictive (i.e., more positive) regulatory environment. The environmental policy stringency indicator I_{18} is used to define the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behavior (Botta and Koźluk, 2014). It ranges from 0 (not stringent) to 6 (highest degree of stringency). This indicator aggregates market-based policies (pollution taxes, trading schemes and feed-in tariffs) and non-market policies (emissions limits and R&D subsidies). It is considered that the higher it is the better, in accordance with the underlying

stronger risk factor than PM10 and it has been shown to be a robust indicator of risk associated with exposure to PM from diverse sources and in different environments (Lim et al., 2013).

4. A zero adjustment for pollution abatement means that a country had the same emissions as the previous year; in this case the pollution-adjusted economic growth is equal to GDP growth. Under the definition of the OECD "Growth adjustment for pollution abatement - measures to what extent a country's GDP growth should be corrected for pollution abatement efforts - adding what has been undervalued due to resources being diverted to pollution abatement or deducing the 'excess' growth which is generated at the expense of environmental quality".

5. In the current edition of OECD's database, pollution abatement is limited to eight types of air emissions—including greenhouse gases (CO_2, CH_4, N_2O) and air pollutants (NMVOC, SO_x, NO_x, CO, PM_{10}).

philosophy of this indicator, and the results reported by Botta and Koźluk (2014) that it is positively associated with GDP, negatively correlated with CO_2 emissions, and positively related with innovation in the energy sector.

Indicator I_{19} involves the environment-related government R&D budget (as a percentage of total government R&D), which includes, among others, research directed to the control of pollution and the development of facilities to measure, eliminate and prevent pollution. The relative advantage in environment-related technology index (I_{20}) represents the level of environmental innovation for a given country relative to the world average. An index equal to one means that a country innovates as much in "green" technologies as the rest of world. On the other hand, an index above one indicates a relative technological advantage (RTA), or specialization, in environment-related technologies compared to the world average. Thus, this indicator acts as a technological development proxy as it covers a wide range of patents that have direct and indirect effects on energy use and policy decisions.

3.3 Evaluation approach

3.3.1 Basic setting

The proposed benchmarking approach is based on concepts from the field of production efficiency analysis, namely the "benefit-of-the-doubt" (BoD) framework (Cherchye et al., 2007). BoD is a variant of data envelopment analysis (DEA), for constructing composite performance indicators to assess the relative performance of a set of comparable units (e.g., countries) in a benchmarking context. In contrast to the input/output scheme used in DEA, the BoD approach assumes a setting without inputs, where the outputs represent performance indicators describing the performance of the countries. Performance assessments in the BoD are derived in a data-driven context that requires minimum input from analysts and/or decision-makers.

Formally, let $\mathbf{x}_k = (x_{k1}, x_{k2}, \ldots, x_{kn})$ be the (row) data vector for a country k over n performance indicators (all in maximization form), and $\mathbf{w}_k = (w_{k1}, w_{k2}, \ldots, w_{kn})^\top$ a column vector with non-negative (unknown) weights of the indicators, representing trade-offs across the indicators. Assuming a linear weighted aggregation of the attributes of the form $\mathbf{x}_k\mathbf{w}_k$, the weights are defined so that the performance of country k relative to the best among a set $\mathcal{X} = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_m\}$ of m comparable peers is maximized (country k is assumed to belong in $\mathcal{X}$). This leads to a global performance index I_k defined as follows (Cherchye et al., 2007):

$$I_k^* = \max_{\mathbf{w}_k \in \mathcal{W}} \frac{\mathbf{x}_k \mathbf{w}_k}{\max_{\mathbf{x}_i \in \mathcal{X}} \mathbf{x}_i \mathbf{w}_k} \quad (1)$$

where, $\mathcal{W}$ is a set of user-defined weight restrictions for the attributes' weights. The resulting performance index ranges in [0, 1] with higher values indicating stronger performance.

At this point, it is worth elaborating on the underlying nature of some key aspects of the proposed methodological approach. The use of a linear function for the specification of the evaluation model implies some assumptions regarding the nature of the trade-offs (i.e., they are constant) and the preferential independence conditions among the indicators (i.e., interactions). The former issue, regarding the trade-offs which are assumed to be constant and independent of the attributes' levels, can be overcome by generalizing the linear sum to an additive value model of the form $F(\mathbf{x}) = \sum_j w_j f_j(x_j)$, where $f_j(x_j)$ represents the marginal value function of indicator j (for simplicity we drop the country indices here). The linear model is a special case of the additive one, if all marginal value functions are linear. In an additive model, the trade-offs are no longer constants in terms of the indicators' level. The proposed methodology can be easily extended to cover this case, either by assuming a specific parametric form for the marginal value functions or by estimating them directly from the data using the same data-driven scheme used to define the weights in the setting used in the paper (see, for instance, de Almeida and Dias, 2012). Such extensions, however, have some issues. On the one hand, it is hard to formulate a theoretical or empirical basis for the choice of a parametric form. On the other hand, deriving (non-linear) partial functions from the data, creates a lot of estimation problems, because the degrees of freedom may increase considerably, compared to the size and nature of the available data. Therefore, in this study we opted for a pure linear model to avoid complex modeling assumptions that would further create concerns about the estimations derived from the available data.

Regarding the preferential independence assumption of linear and additive evaluation models, it is worth noting that the consideration of a general non-linear evaluation model (e.g., a multi-linear value function that considers all possible interactions) poses two important difficulties. First, it is much less transparent and more difficult to use by policy makers. Second, it requires the specification of many parameters (there are $2^n - 1$ scaling constants, one for each interaction term), which makes such models practically unusable in evaluation problems involving many indicators. Therefore, we opted for a simpler model, which is easier to calibrate, understand, and deploy, in line with the arguments of Keeney and Raiffa (1993, pp. 289-299) and Keeney and Sicherman (1976) about the robustness of simple types of evaluation functions.

A third issue involves the use of country-specific weights for the indicators. Under a standard normative approach, one would expect the weights to be the same for all countries. Such a setting could be interpreted as assuming a social welfare function common to all countries. This assumption, however, appears rather strong and not very realistic (see, for instance, Fleurbaey and Tadenuma, 2014; Sen, 1976). The use of country-specific weights allows the consideration of the differences across countries (in terms of their policies and contextual environment), as represented through their observed performance on the chosen indicators.

The specification of the weights for composite indicators can be done through normative, data-driven or hybrid approaches (Decancq and Lugo, 2013; Nardo et al., 2008). The BoD framework follows a data-driven scheme, acknowledging that it is often impossible for stakeholders and policy makers to agree (*a priori*) on a commonly accepted set of normative weights, that would describe the policies a country *should* follow. Instead, in the BoD context, *a posteriori* weights are derived from the observed performance of the countries (Cherchye et al., 2004), such that every country is evaluated under its most favorable weights, in the spirit of the maximization formulation in equation (1). In the framework of the energy trilemma concept, a strong relative (observed) performance in a particular dimension is assumed to reveal either strong national policy priority on that dimension, and/or the existence of factors that provide a country with competitive advantages over others. Both these cases can be interpreted as arguments for supporting an overall positive evaluation. Nevertheless, poor performance on some dimensions could indicate possible risks. A common criticism of linear models and the above optimistic perspective is that such risks are not properly incorporated in the analysis. In this study we address this issue with the addition of a pessimistic perspective, which will be explained later.

A final remark that should be noted regarding performance index (1) and the principles of the BoD framework, is that the performance of the countries is assessed within a *relative* benchmarking context. More specifically, the evaluation is not expressed in absolute terms based on an ideal-normative profile (i.e., absolute best), which may be very difficult if not impossible to define.

Instead, the countries are benchmarked against an empirical Pareto frontier as defined by the data. In that regard, the observed best practices among the OECD countries in the sample define what is "optimal" under the current conditions. Therefore, the specification of a country's weights and its performance is not only done based on its own characteristics (observed data on the indicators), but also considering the characteristics of other countries. Under this setting, the success of a country depends on its own characteristics in relation to how other countries perform (i.e., how far a country's performance and achievements are from the observed best practices). Thus, it is reasonable to assume that the objectives of countries are set in accordance with the status of the international environment and the current status quo (technological, economic, and social). As the international environment changes, a country's objectives and priorities are adapted to the new technological and socio-economic conditions that emerge.

3.3.2 Min-max performance index under optimistic and pessimistic perspectives

An implicit assumption of the standard BoD performance index (1) is that all indicators are expressed on non-negative ratio scales. As a consequence, the resulting performance index is unit invariant, but not translation invariant (Pastor and Aparicio, 2015). This makes the handling of attributes having negative values as well as attributes in minimization form, non-trivial. Such situations commonly arise in applications related to environmental and energy systems, where attributes about energy consumption, emissions, environmental impacts, etc., represent undesirable effects that should be minimized. To overcome such difficulties, in this study we use a variant of the ratio index , following the approach of (de Almeida and Dias, 2012). To facilitate the presentation, without loss of generality, we shall assume that all attributes are scaled between 0 and 1, where 0 corresponds to the worst level and 1 to the best level for each attribute.[6] Moreover, we shall assume that $\mathbf{1w}=1$, i.e., the weights of the attributes sum up to 1. Based on this scheme, a min-max regret performance index can be derived instead of the ratio index in :

$$I_k^* = 1 + \max_{\mathbf{w}_k \in \mathcal{W}} \{\mathbf{x}_k \mathbf{w}_k - \max_{\mathbf{x}_i \in \mathcal{X}} \mathbf{x}_i \mathbf{w}_k\} = 1 - \min_{\mathbf{w}_k \in \mathcal{W}} \max_{\mathbf{x}_i \in \mathcal{X}} [(\mathbf{x}_i - \mathbf{x}_k)\mathbf{w}_k] \qquad (2)$$

If there exists a weighting vector $\mathbf{w}_k$ such that country k achieves the highest weighted performance score $\mathbf{x}_k \mathbf{w}_k$ among all others in the sample, then $I_l^* = 1$. The case $I_k^* < 1$, on the other hand, indicates there is at least one other country that outperforms country k irrespective of how the performance attributes are weighted. Thus, the lower is the I_k^* index, the higher is the performance difference between the best performing country and the one under consideration.

Deriving the value of I_k^* can be expressed as a linear programming problem. To simplify the exposition, we assume the most basic set $\mathcal{W}$ of admissible weights, which includes all non-negative weights that sum up to one, thus leading to the following formulation:

$$\begin{aligned} \min \quad & d \\ \text{subject to:} \quad & (\mathbf{x}_i - \mathbf{x}_k)\mathbf{w}_k - d \le 0, \quad i = 1, \ldots, m \\ & \mathbf{1w}_k = 1 \\ & \mathbf{w}_k \ge \mathbf{0}, d \in \mathbb{R} \end{aligned} \qquad (3)$$

6. An indicator j in maximization form (e.g., GDP growth) can be scaled in [0, 1] as $x_j' = (x_j - x_j^{\min}) / (x_j^{\max} - x_j^{\min})$, where $x_j^{\min}$ and $x_j^{\max}$ denote, respectively, the minimum and maximum values of the indicator in the sample. An indicator in minimization form (e.g., energy intensity) is re-scale as $x_j' = (x_j - x_j^{\max}) / (x_j^{\min} - x_j^{\max})$.

The decision variable d represents the maximum difference between the weighted performance score $\mathbf{x}_i\mathbf{w}_k$ of any country $i = 1, \ldots, m$ and the weighted performance score $\mathbf{x}_k\mathbf{w}_k$ of the country k under consideration. By definition $0 \le d \le 1$ because the set of competing units $\mathcal{X}$ includes country k and all performance scores range in [0, 1]. Thus, $I_k^* = 1 - d^*$, where d^* denotes the optimal value of d from the solution of the above linear program.

The min-max regret index I^* as defined in and estimated through the solution of problem , provides an optimistic point of view because it maximizes the performance of each country compared to the best of its peers. As noted earlier, this approach ignores problems that arise when a country has uneven performances across different indicators, particularly when there are indicators and dimensions where a country performs poorly. Adopting an optimistic perspective allows the specification of weights (trade-offs) that fully compensate a poor result in one dimension with others where a country performs better. To address such concerns, we augment the optimistic assessment with a pessimistic counterpart, which can be understood in the context of a Rawlsian perspective, by penalizing countries which perform poorly in some dimensions/indicators. In this case, the weights of the indicators for a country k are specified so that the performance of the country is minimized compared to the best of its peers:

$$I_{k*} = 1 + \min_{\mathbf{w}_k \in \mathcal{W}} \{\mathbf{x}_k\mathbf{w}_k - \max_{\mathbf{x}_i \in \mathcal{X}} \mathbf{x}_i\mathbf{w}_k\} = 1 + \min_{\mathbf{w}_k \in \mathcal{W}} \min_{\mathbf{x}_i \in \mathcal{X}} [(\mathbf{x}_k - \mathbf{x}_i)\mathbf{w}_k] \tag{4}$$

The interpretation of the pessimistic assessment I_{k*} is similar to the optimistic one I_k^* (i.e., $I_{k*} = 1$ if country k is the best among its peers and $I_{k*} < 1$, otherwise), with the only difference being that the pessimistic assessment is derived by emphasizing the weaknesses of the country under consideration. The estimation of I_{k*} can be formulated as a mixed-integer linear problem:

$$\begin{aligned} \min \quad & d \\ \text{subject to:} \quad & (\mathbf{x}_k - \mathbf{x}_i)\mathbf{w}_k - d - y_i \le 0, \quad i = 1, \ldots, m \\ & \mathbf{1y} = m - 1 \\ & \mathbf{1w}_k = 1 \\ & \mathbf{w}_k \ge \mathbf{0},\ \mathbf{y} \in \{0, 1\}, d \in \mathbb{R} \end{aligned} \tag{5}$$

where the binary variables $y_1, \ldots, y_m$ indicate whether a constraint $(\mathbf{x}_k - \mathbf{x}_i)\mathbf{w}_k \le d$ is active ($y_i = 0$) or not ($y_i = 1$) at the optimal solution. Constraint $\mathbf{1y} = m - 1$ ensures that only one constraint will be active to define the inner minimum in . Denoting by d^* the optimal objective function value of , the pessimistic performance index is obtained as $I_{k*} = 1 + d^*$.

The overall performance score for each country k is formulated as the average of the optimistic and pessimistic assessments, i.e., $I_k = (I_k^* + I_{k*}) / 2$, providing a balanced evaluation between the two extremes.

3.3.3 Weight restrictions

Both the optimistic and pessimistic peer assessments described above are flexible enough to define the weights of the performance attributes that maximize/minimize the performance of each country. However, without imposing some constraints on the possible trade-offs (weights) among the indicators, unrealistic results may be derived. For instance, under the optimistic setting where country-specific weights are optimized in relation to an empirical Pareto frontier, a country's overall performance will be equal to 1 if it outperforms the rest of the countries, even in a single indicator.

Even though this result complies with the concept of Pareto optimality,[7] it may be hard to justify from a practical (policy making) perspective. To address this shortcoming, additional information is required specifying reasonable ranges for the acceptable trade-offs. It is evident that this information requires either (approximate) normative assumptions, empirical estimates (e.g., from market data is available), or subjective judgments. Even though this adds some ambiguity, it is certainly more likely that policy-makers will agree on a "reasoned" consensus (even an informal one) rather than a unique set of weights (Sen, 1997).

In the context of BoD methodologies, weights restrictions can be defined on a country-specific basis or, following a more normative-like approach, for the whole set of data observations. The latter approach is followed in this study, given the lack of specific microeconomic information that would provide a solid basis for imposing country-specific value restrictions. More specifically, lower and upper bounds on the weights are introduced in the following general form:

$$\frac{\alpha}{n} \le w_{kj} \le \frac{\beta}{n}, \qquad j = 1, \dots, n \tag{6}$$

The parameters α and β are user-defined constants. The lower bound parameter $\alpha < 1$ ensures that at least $100\alpha\%$ of the total weight of the performance attributes will be distributed equally among all attributes (i.e., each attribute will have a weight of at least α / n). On the other hand, β defines an upper bound of β / n for the weights of all attributes, thus ensuring that the results are not heavily dependent on a single attribute. In the present analysis, we set $\alpha = 0.1$ and $\beta = 2$. The chosen lower bound parameter $\alpha = 0.1$ implies that at least 10% of the total will be assigned equally to all indicators. Thus, each one of the five security indicators will have a weight of at least 2% in assessing the energy security performance of the countries. Similarly, each one of the four equality-poverty indicators will have a minimum weight of 2.5% in the assessment involving the sustainability dimension. On the other hand, the upper bound threshold parameter $\beta = 2$ implies that the maximum performance that can be assigned to a country on its strongest/weakest dimension (depending on the optimistic/pessimistic evaluation) will not exceed $2 / n$. For instance, in the security dimension ($n = 5$ indicators) no indicator's partial contribution to the weighted total performance score of a country, can exceed 0.4, i.e., $w_{kj} x_{kj} \le 0.4$, for every country and indicator .

4. EMPIRICAL APPLICATION

4.1 Data description and performance indicators

Our sample consists of the 34 OECD countries[8] for the period between 2005 and 2015. This period encompasses both the financial crisis of 2007-2009 as well as the oil price rally and fall.

Looking at the basic data for the indicators described in section 3.2, in the security dimension, some countries (Australia, Canada, Mexico and Norway) are pure exporters of energy, some are in transition (Denmark and Estonia), while all others are pure importers. For importing countries there is a cluster of countries (Czech Republic, Iceland, Netherlands, New Zealand, Poland, Sweden, United Kingdom, and United States), whose imports are below 40% throughout the time period, while the rest of the countries rely much more on energy imports. Regarding fossil fuel energy consumption (indicator I_2), only three countries, namely Sweden, Estonia and Iceland, are

7. A country is Pareto efficient if it is not dominated by any other country.

8. Latvia is excluded from the analysis, as it became a member of OECD in 2016. Countries in alphabetical order unless otherwise mentioned.

below 40%. Mexico and Turkey have the highest distribution losses (indicator I_3), averaging more than 14% of output, followed by Hungary (approximately 10-12%). All other countries are below 10% with Estonia improving by 4% during the time period.

For the sustainability dimension, Iceland has been the most energy intensive country (indicator I_6) as its energy use to GDP increased by more than 170% during the period 2005-2011, followed a downward trend until 2015 (11% decrease compared to 2011). All other countries have achieved much lower (i.e., better) energy intensity levels, with significant improvements (in most cases) over time. Similar improvements were also observed in CO_2 intensity (indicator I_7). Estonia is the country with the highest CO_2 intensity and the largest CO_2 emissions from electricity and heat production (as percentage of the total fuel combustion; indicator I_8). On the other hand, Australia is the worst performer as far as the total GHG emissions per capita are concerned (I_9), followed by the United States, Canada, and Luxembourg.

In the energy equality dimension, the Slovak Republic, Mexico, Poland, Hungary, and the Czech Republic have the lowest relative purchasing power of energy (indicator I_{11}), as their households' expenditures on electricity, gas and other fuels exceeds 15% of the median disposable income. This percentage was consistently lower than 10% for Austria, Belgium, Denmark, France, Germany, Ireland, Israel, Luxembourg, Netherlands, Spain, Sweden, UK, and the USA, while Australia, Canada, Finland, Iceland, and Norway were even lower (less than 6%). On the other hand, transport fuel purchasing power (indicator I_{12}) was low for Chile, Czech Republic, Estonia, Greece, Hungary, Mexico, Poland Portugal, the Slovak Republic, and Turkey.

For the government policy dimension, Mexico, South Korea, Iceland, and Israel are the worst performance on market regulation (indicator I_{17}), whereas the USA, Germany, Spain, and the UK performed the best. Finally, with regard to environmental policy stringency (indicator I_{18}) most countries achieved intermediate results (between 1.5 and 4, with 6 being the best), whereas in terms of environmental R&D and related technologies (indicators I_{19}– I_{20}), New Zealand, Estonia, Denmark, and Chile were the top performers.

4.2 Results

Based on the conceptual framework described in section 3.1, four partial assessments and an overall (aggregate) assessment are derived using the methodology described in section 3.3. The analysis is based on a rolling window scheme (window analysis; Cooper et al., 2007), which allows the analysis of the dynamics of the countries' performance over time and the identification of trends. More specifically, the 11 years considered in the analysis are split into 9 rolling three-year periods, i.e., 2005-2007, 2006-2008, 2007-2009, up to 2013-2015. The data set corresponding to each window consists of 102 country-year observations (34 countries by three years). The evaluation procedure of section 3.1 is applied to each of these 9 data sets. Under this scheme, a country in year t is benchmarked up to three times against all cases included in different time windows, covering the time periods $[t-2, t]$, $[t-1, t+1]$, and $[t, t+2]$.

The annual averages (over all countries and time windows) for the overall performance index and its four components are summarized in Table 2. Scandinavian countries, like Sweden, Denmark, and Norway, together with France and Switzerland rank at the top of the list, whereas Mexico and Turkey stand out as the worst performers. Sweden ranks in the top two positions in terms of security and sustainability but performs just above average in the government policy dimension (contextual environment), due to its below average public investments in environmentally related R&D. Switzerland exhibits a similar pattern, with strong results in security, equity, and sustainability, but weak government policy performance. Similar to Sweden, Switzerland also performs poorly in terms of

Table 2: Average performance scores by country (ranks in parentheses)

	Sec.	Sust.	Eq.	Gov. policy	Overall
Australia	73.2 (17)	56.3 (31)	83.7 (6)	80.9 (8)	68.8 (22)
Austria	71.5 (21)	79.2 (11)	81.5 (8)	80.8 (9)	80.6 (8)
Belgium	74.7 (10)	74.4 (14)	77.8 (13)	78.4 (19)	77.1 (12)
Canada	74.8 (9)	62.6 (28)	89.9 (2)	83.9 (4)	78.1 (11)
Chile	68.4 (30)	73.8 (19)	48.2 (32)	75.5 (22)	57.6 (28)
Czech Republic	72.1 (20)	57.4 (30)	63.7 (25)	80.7 (10)	60.1 (27)
Denmark	77.8 (3)	80.8 (8)	84.6 (5)	83.8 (5)	88.6 (2)
Estonia	69.1 (26)	50.5 (34)	57.9 (28)	68.5 (30)	44.5 (31)
Finland	82.4 (1)	73.0 (21)	83.2 (7)	77.6 (21)	83.9 (6)
France	77.1 (6)	88.5 (3)	77.0 (15)	79.7 (13)	87.3 (4)
Germany	74.0 (15)	75.0 (13)	76.0 (16)	85.9 (2)	80.5 (9)
Greece	69.4 (25)	74.2 (16)	58.6 (27)	71.9 (25)	60.5 (26)
Hungary	68.8 (28)	74.2 (17)	56.3 (29)	81.5 (7)	65.6 (23)
Iceland	75.4 (8)	73.0 (22)	78.2 (12)	57.6 (33)	65.3 (24)
Ireland	68.8 (27)	83.0 (7)	75.8 (17)	68.7 (29)	71.2 (18)
Israel	68.6 (29)	64.7 (27)	66.3 (23)	59.1 (31)	52.0 (30)
Italy	70.9 (22)	80.4 (9)	70.9 (20)	81.5 (6)	75.9 (14)
Japan	72.7 (18)	73.9 (18)	77.5 (14)	77.7 (20)	75.5 (15)
Korea	69.7 (24)	51.5 (33)	69.9 (21)	73.5 (23)	54.6 (29)
Luxembourg	68.1 (31)	67.9 (26)	91.3 (1)	71.8 (26)	70.8 (20)
Mexico	60.7 (32)	71.1 (23)	36.8 (34)	53.7 (34)	32.4 (34)
Netherlands	70.7 (23)	74.3 (15)	79.2 (11)	78.6 (16)	74.7 (16)
New Zealand	74.5 (11)	77.5 (12)	73.5 (18)	72.7 (24)	74.6 (17)
Norway	74.1 (13)	84.5 (6)	88.8 (3)	79.1 (14)	87.5 (3)
Poland	59.3 (33)	56.3 (32)	51.3 (30)	78.4 (18)	44.2 (32)
Portugal	72.4 (19)	86.1 (4)	63.5 (26)	80.4 (11)	76.5 (13)
Slovak Republic	77.1 (5)	69.8 (24)	51.3 (31)	78.4 (17)	65.2 (25)
Slovenia	75.6 (7)	73.2 (20)	71.4 (19)	70.6 (27)	70.0 (21)
Spain	73.7 (16)	85.4 (5)	68.5 (22)	86.0 (1)	82.5 (7)
Sweden	81.1 (2)	92.1 (2)	81.1 (9)	79.9 (12)	92.4 (1)
Switzerland	77.1 (4)	95.5 (1)	86.1 (4)	70.2 (28)	87.1 (5)
Turkey	55.9 (34)	68.4 (25)	42.1 (33)	58.9 (32)	32.7 (33)
United Kingdom	74.1 (14)	79.8 (10)	65.7 (24)	84.7 (3)	78.1 (10)
United States	74.3 (12)	61.1 (29)	79.9 (10)	78.9 (15)	71.0 (19)

environmental public R&D investments. Moreover, its relative advantage in environment-related technologies is below average and its regulatory framework in the electricity and gas sectors creates a less competitive environment than other countries. Denmark has a robust performance across all dimensions, ranking consistently in the top 10. On the other hand, Norway's main strengths are sustainability and equity, whereas it ranks 13th in security, due to its low diversification of electricity production and its average performance in reducing energy use per capita. Finally, France achieves strong results in security and sustainability, but performs moderately in equity (due to increasing energy and fuel prices) and government policy. The worst performing countries (Mexico and Turkey) exhibit consistently poor performance in all dimensions of the analysis.

To obtain further insights into the differences between the countries in terms of their performance patterns, the average performances in the main dimensions together with the countries' overall performance scores were used to cluster the countries into homogeneous performance groups. To this end, the k-means clustering algorithm was used. Taking into consideration the characteristics of the clusters formed through the algorithm (e.g., their homogeneity and coherence), we decided to keep four groups of countries. The centroids of the clusters (mean performance scores) and the countries in each group are shown in Table 3. The first group consists of 12 European countries with the highest overall performance. The most distinguishing characteristics of this cluster is the high level

Table 3: Groups of countries and their performance patterns (average performance scores)

Group	Countries	Sec.	Sust.	Eq.	Policy	Overall
Top	Austria, Switzerland, Denmark, Finland, France, Germany, Italy, Norway, Portugal, Spain, Sweden, United Kingdom	75.5	83.4	77.2	80.8	83.4
Upper middle	Australia, Belgium, Canada, Iceland, Ireland, Japan, Luxembourg, Netherlands, New Zealand, Slovenia, United States	73.0	70.7	79.8	74.5	72.5
Lower middle	Chile, Czech Republic, Estonia, Greece, Hungary, Israel, Korea, Poland, Slovak Republic	69.2	63.6	58.2	74.2	56.0
Poor	Mexico, Turkey	58.3	69.8	39.5	56.3	32.6

of sustainability (the mean sustainability score is 83.4) and government policy performance (mean score 80.8). The second group consists of 11 countries, including 6 European countries as well as Canada, United States, Australia, New Zealand, and Japan. The overall performance of the countries in this group is lower than the one in the first cluster of countries (72.5 versus 83.4), mainly due to the lower sustainability performance of the second group (mean score 70.7), even though the mean equity score is higher than that of the first group. The third group consists of nine countries characterized by below average performance scores, mainly in terms of security, equity, and sustainability. Low equity is the main weakness of the countries in this cluster, as evident from the large difference between the mean equity score of this group and the ones of the two top groups (58.2 versus 77.2 and 79.8). The countries in this cluster are mostly eastern European countries (Czech Republic, Estonia, Hungary, Poland, Slovakia), together with Greece, Chile, Israel, and South Korea. Finally, the last group includes only Mexico and Turkey which exhibit significant differences from the rest of the countries, mainly in security, equity, and government policy performance.

Looking further into the relationships between the aggregate index and its components, Table 4 presents results about the existing correlations (Pearson's and Kendall's correlation coefficients). As expected, the overall ratings are strongly correlated with all partial assessments, thus verifying that all dimensions contribute significantly to the aggregate result. Regarding the correlations between the four components, it is evident that the security ratings are strongly correlated with the results derived for the other three dimensions, as both the linear (Pearson) and ordinal (Kendall) correlations are significant at least at the 10% level. On the other hand, the correlations between the other three dimensions are much weaker (in most cases insignificant at the 10% level). These results are indicative of the multi-faceted nature of energy security and its close connections with other aspects of energy policy. Sustainability, equity, as well as government policy performance have unique aspects that justify their consideration as separate dimensions in an integrated framework for energy policy decisions, such as the one considered in this study.

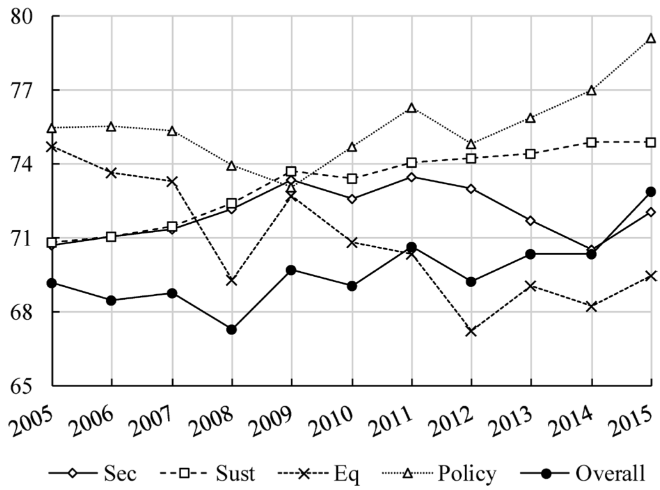
Finally, it is worth considering the dynamics and the trends of the benchmarking results during the period of the analysis. Figure 2, illustrates the results for the aggregate index and its four components. It is evident that the aggregate performance of the countries shows some improvement, particularly for the period after 2010. This improvement has been mainly driven by improvements in sustainability and government policies. The former increased almost steadily throughout the period of the analysis, whereas the component score regarding the contextual environment (government policy performance) improved after 2009. The security dimension improved up to 2011, followed by a decline in the later years due to an increase in energy imports. On the other hand, equity appears to raise the most notable challenges, displaying a decreasing trend due to increasing energy and fuel costs.

Table 4: Correlations between average performance scores (Pearson correlations above the diagonal, Kendall's correlations below the diagonal)

	Sec.	Sust.	Eq.	Policy	Overall
Sec.		0.41**	0.67***	0.48***	0.84***
Sust.	0.28**		0.26	0.18	0.66***
Eq.	0.43***	0.17		0.38**	0.79***
Policy	0.20*	0.22*	0.18		0.66***
Overall	0.53***	0.57***	0.50***	0.42***	

Notes: *** / ** / * Significant correlations at the 1 / 5 / 10% level.

Figure 2: Performance trends over time



5. CONCLUSIONS AND FUTURE RESEARCH

In this paper we considered the aspects describing the concept of energy trilemma in terms of energy security, sustainability, and equity. In contrast to similar existing frameworks, we considered an enhanced point of view adding a contextual dimension, which considers not only economic aspects, but also government policies about the functioning of the energy markets, and the promotion of innovations in energy and environmental technologies. The aggregation of the indicators in each dimension and the overall assessments were based on a model that relies on concepts from non-parametric productive efficiency analysis. Results were obtained for OECD countries during the period 2005-2015. Using a k-means algorithm we clustered the countries into four homogeneous performance groups. The top group is characterized by countries with high sustainability scores, and good policy responses, while the two middle groups have reduced sustainability and low equity respectively. The bottom group demonstrates significant differences, especially in security, equity and policy performance. The results of the proposed benchmarking and evaluation methodology show that Scandinavian countries tend to utilize a relatively balanced and more independent energy mix compared to other OECD countries. Energy sustainability has improved steadily during the period of the analysis, driven by the increasing use of clean energy technologies and improvements in energy efficiency. However, there is still work to be done in energy equity, as this dimension remains challenging. Overall there is improvement over time.

Of course, the aggregation of multiple conflicting dimensions covering very different socio-economic and technical aspects of energy policies, should always be viewed with caution. The philosophy of the framework presented in this work combines normative principles with descriptive analysis. Moreover, it is important to emphasize that composite indicators such as the one proposed, should be used in a top-down manner, to gain insights into the trade-offs across the combined dimensions that explain the top-level (aggregate) assessments. Otherwise, it is likely that the synthetic indicator will conceal important information embedded in the disaggregate data (Cherchye et al., 2004).

The identification of the strengths, weaknesses, and challenges in energy policies through a unified perspective that considers different dimensions will continue to be an active area of research. On the one hand, the analysis performed in this study could be extended to other countries, beyond OECD member states. The analysis of developing and under-developed countries poses several challenges, not only in terms of data availability and quality, but also regarding the conceptual framework, as such countries have very diverse characteristics, thus making direct comparisons much more involved.

Moreover, future research should focus on discovering the causal links between different dimensions, such as those considered in the framework proposed in this study. Such an analysis could determine the underlying drivers that describe the performance of the countries and define their long-term success. Also, an analysis of the relationship between economic efficiency and the energy trilemma concept and the related performance of the countries, could provide interesting insights for energy policy making.

Finally, analyzing pure policy performance is also an interesting area for future research. Indeed, one can identify many factors that are outside policy controls (size, geographical characteristics, local climate, etc.), which affect measurements such as the ones used in this study. The scope of the evaluation presented in this study was not to control for exogenous factors, but rather to formulate a global evaluation of the overall characteristics and status of the countries (i.e., incorporating both policy and external effects). In a second stage, the evaluation outputs should be examined in relation to the effects of exogenous factors, either by adjusting the input data for the indicators, or by regressing the evaluation results against exogenous factors.

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