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The impact of education on the Energy Trilemma Index: A sustainable innovativeness perspective for resilient energy systems

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ABSTRACT

This study investigates the association between the Energy Trilemma Index (ETI) (which measures secure, affordable, and sustainable energy) and a country's level of education from a sustainable innovativeness perspective. We analyze if school life expectancy (SLE) and the students' predispositions towards STEM degrees (science, technology, engineering or mathematics) can stimulate the creation of sustainable and resilient energy systems. We perform a regression analysis based on data from 118 countries, and we employ both an ordinary least squares (OLS) regression and a robust-to-outliers MM-estimator. The statistical investigation reveals that the higher the school life expectancy, the higher the ETI. By contrast, we find no significant association between the ETI and the percentage of STEM graduates. So what matters in energy sustainability is the number of persons who decide to continue tertiary studies rather than their attitudes towards studying scientific subjects. This research paper contributes to the literature on renewable energy, circular economy (CE), sustainable innovation, and knowledge management by demonstrating how education can aid in implementing energy systems that adhere to the triple bottom-line approach (society, economy, and environment). Thus, sustainable and resilient energy systems can be spurred by not only environmental and economic variables but also social ones. Therefore, the traditional approach of the CE for achieving sustainable development should be substituted by alternative CE approaches that consider social variables. From the managerial standpoint, a high SLE can foster resilient energy systems through the creation of ad hoc policies, the birth of new companies connected to the renewable energy sector, and new organizational forms of energy management handled directly by citizens.

1. Introduction

In a globalized world where the demand for resources becomes unrelenting because of population growth, energy consumption is continuously increasing [1]. For this reason, the need arises for clean energy, which will not irreversibly affect the environment with CO_2 emissions but will help instead to avoid the devastating effects of climate change [2]. The new circular economy model oriented on cautious production and consumption through waste reduction and natural ecosystem management is one of the leading advocates of renewable energy generation [3]. Indeed, according to Vence and Pereira [4], one of the CE's main pillars is expanding the businesses related to eco-innovation, where renewable energies play a central role. Nonetheless, the CE concept has some limitations. Environmental limits include the thermodynamic law and the rebound effect [5]. Second, we shall also consider socioeconomic constraints: Schroeder et al. [6] have shown that CE practices have no relevant connections with most of the 17 sustainable development goals (SDGs). In this regard, Genovese and Pansera [7] point out that most CE studies use a technocratic and apolitical approach, ignoring social implications. For these reasons, CEs should include additional aspects related to social variables. Because of the different geopolitical pressures caused by the recent Russian/Ukrainian conflict, the availability of safe and economically resilient energy systems is necessary to avoid an economic crisis [8]. Therefore, different environmental, economic, and social problems arise when energy sources are analysed. For this reason, in the present paper, we consider it more appropriate to

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analyse a composite indicator that considers all these elements, instead of only environmental variables, using the framework of sustainable innovativeness. This framework encompasses the triple bottom-line approach and focuses on economic, social, and environmental aspects [9]. One of the most relevant indicators that summarize all the above aspects is the Energy Trilemma Index.

The Energy Trilemma Index characterizes an energy system from a sustainability standpoint rather than a classical circular economy lens since it considers energy security, equity, and environmental sustainability [10]). Following this perspective, alternative approaches to the CE are being developed that include factors beyond environmental protection in the sustainable development framework [11]. Since the ETI appears to be one of the most significant indicators for understanding sustainable and resilient energy systems, several studies have focused on determining the key drivers of his indicator [12]. Previous research has found a link between environmental and economic indicators and the ETI. Researchers have shown that the ETI correlates with environmental sustainability, economic growth, and other economic variables such as patents by origin and the ease of starting a business [13–14] (Melnyk et al., 2020). However, social factors influencing this indicator have not been analysed in detail, so the present paper aims to fill this gap. Previous studies have shown that education plays a vital role in creating sustainable innovations in the energy sector from different points of view. First, education for sustainability is a concept that strives to provide higher education students with the skills and knowledge needed to make the transition to a more sustainable business model [15]. Indeed, environmental sustainability education allows students to improve their skills by identifying the complexities of environmental challenges and teaching them critical-thinking skills with environmental methods [16]. Second, developing renewable energy-related technologies, such as those connected to solar hydrogen, necessitates establishing education programs need to teach technical and scientific personnel to be at the forefront of fast-emerging sustainable and resilient energy systems [17]. As a result, the new education system should assist practitioners in assessing competing technologies in terms of the economic, social, and environmental perspectives [18]. Third, new organizational forms of energy management, where people actively take part in energy management, are gaining popularity because of their resilience in terms of sustainable innovativeness (Adefarati et al., 2019). To implement responsible and sustainable innovations, the ongoing transition of the energy system towards decentralized, digital, sustainable, and cooperative energy systems needs educational programs that foster social, economic, and environmental knowledge [17]. Microgrid systems, in particular, are becoming increasingly popular on university campuses seeking reliable and cost-effective energy solutions due to their economic, environmental, and technical benefits [19]. Instead, in developing countries, particularly in rural areas, where people experience massive power outages, education plays a fundamental role in implementing microgrid energy systems to overcome this problem [20]. Hence, the primary goal of our study is to understand if the level of education and the propensity toward scientific subjects can impact the creation of sustainable and resilient energy systems. Therefore, we want to determine whether a high specialization of workers and a population with a high amount of education can favor the development of sustainable and resilient energy systems. Precisely, we investigate if years of schooling and the attitude of students towards STEM subjects positively correlate with the ETI. With these premises to assess the implementation of sustainable and resilient energy systems from a perspective of sustainable innovativeness, our study aims to answer the following research question: Are the educational level and the predisposition toward STEM subjects positively correlated with the ETI?

The contributions of this paper are twofold. First, we contribute to the literature on renewable energy and sustainable innovativeness by investigating if education plays a central role in implementing renewable energy systems. Second, from a managerial standpoint, our research aims to understand if a higher level of education and predisposition towards STEM subjects can stimulate the development of sustainable and resilient energy systems, new companies producing renewable energy, and alternative organizational forms for energy production and management.

The remainder of the paper is organized as follows: In the next section, we provide a literature review discussing the impact of education on sustainable innovativeness and the resilience of energy systems, and thus on the ETI. Section 3 shows the statistical methodology on which our investigation relies, and we introduce the empirical setting and the variables employed. In Section 4, we present the results of the empirical analysis. Then, in Section 5, we discuss the implications of our study. Finally, in Section 6, we draw some conclusions and outline research limitations and future directions.

2. Literature review and hypothesis development

2.1. The connection between education, the ETI, and sustainable innovativeness

Creating sustainable innovations is necessary to achieve sustainable development goals. For this reason, organizations that want to spur sustainable innovations must integrate economic, environmental, and social responsibilities with a holistic view of business ethics and, in operational terms, with the triple bottom line approach [9].

Education has always played a leading role in implementing sustainable innovations. The international community at the UN Conference on Environment and Development in Rio de Janeiro in 1992 pointed out the importance of education in achieving sustainable development. The leaders announced that “education is a decisive factor of change to a better, sustainable, and safe future” [21]. For this reason, our society needs innovative professionals that spur educational institutions to seek ways to foster sustainable innovation competencies among their students and thus meet the social demand for sustainable products [22]. Behind all sustainable businesses, the individuals’ capacity to innovate and to use interdisciplinary competencies for innovation is the lifeblood of these kinds of companies and organizations [23]. Indeed, high education levels improve knowledge management processes, which increase sustainable innovativeness and sustainable corporate performance at the environmental, economic, and social levels [24]. The main goal must be training future professionals to help create new sustainable innovations. As a result, the number of higher education programs in the sustainable development sector is increasing, with the responsibility of providing the next generation of leaders with the knowledge and skills that encourage sustainable innovation [25]. Universities can increase knowledge creation and collaboration processes among stakeholders by establishing collaborations and specialized works [26]. Higher education programs not strictly related to sustainable development can also stimulate the creation of sustainable innovations [27]. For example, following the human capital theory and previous empirical studies, Rashid [28] assumed that entrepreneurship education and training (EET) directly correlates with the creation of sustainable innovations. Indeed, to achieve sustainable innovative processes, higher education managers, executives, and practitioners need to focus on institutional culture, trust, and communication channels [29]. The adoption of sustainable innovations depends not only on specific education but also on the general education of the population, which influences customers' preferences towards sustainable innovations by stimulating demand and the emergence of new businesses [30].

Witek and Kuźniar [31] found a link between education and sustainable product consumption. Higher knowledge is typically associated with higher education levels, which translates into certain purchasing patterns. Higher education promotes a broader understanding of social processes, a more sensible approach to resource use and management in the home, and purchase decisions that prioritize environmentally and socially friendly products and sustainable innovations.

For these reasons, the educational system has become significant in the sustainability sector. Skilled workers are formed in higher education systems that produce graduates ready to work with almost no need for company-specific training. This process mainly involves traditional skills, such as math, and soft skills, such as teamwork, and information processing [32].

Given these considerations, it is necessary to understand whether education influences the energy sector in terms of sustainable innovativeness (as we will explore in the following sections). In this respect, the ETI appears to be an appropriate and representative indicator to measure sustainable innovativeness in the energy sector [10].

Previous literature has established that the ETI can be profitably used as an indicator of sustainable energy, being the landmark resource to guide policymakers to find solutions for sustainable and resilient energy systems [33]. To help countries determine their level of energy sustainability, the World Energy Council (WEC) annually publishes a report based on the ETI [13].

Based on the ETI, a wide range of innovative programs have been developed to reduce energy costs and support the transition to low-carbon energy [34]. Indeed, the ETI has already been used as an indicator for helping public and private decision-makers in their mission of adopting policies that promote the use of clean, affordable, and secure energy [10]. For example, in Indonesia, the Energy Trilemma Index helps to cope with one of the most challenging difficulties faced by all countries of the world, the contradictory needs of energy security, climate change mitigation, and (especially in developing nations) energy poverty [35].

Moreover, the Energy Trilemma Index measures energy security, fostering the creation of new techniques and solutions that consider the scalar, material, distributional, and political characteristics of energy systems [12]. For instance, in the United States, the ETI has fostered the implementation of innovative electric systems and grid policies, which, besides increasing economic growth, have enhanced the degree of energy security and respect for the environment. The result was the creation of smart grids, which support the development of a sustainable and resilient energy system [36]. Therefore, according to Khan et al. [14], the ETI measures the strength of a country's energy system from the environmental, social, and economic points of view, following the triple bottom-line approach of sustainable innovations. More specifically, the ETI measures three aggregate indicators of an efficient energy system.

1. Energy security: the country's capacity to satisfy current and future energy demands, its resilience, and its energy infrastructure reliability. This indicator is closely related to the social aspect. It aims to understand whether energy is available without interruptions for a specific country's present and future population [37].
2. Energy equity: the country's capacity to provide inexpensive, dependable, and sufficient energy for business and home usage. This indicator is closely related to the economic aspects. It evaluates the present and future energy costs and, therefore, the possibility for enterprises to have low-cost energy that lowers production costs [38].
3. Energy sustainability: the country's capacity to react to climate changes and address environmental sustainability by transforming energy infrastructures to low or zero carbon, thereby reducing carbon dioxide (CO2) emissions to tolerable levels. This variable is closely related to the environmental aspects. The energy sustainability index aims to understand the amount of present and future total to predict the environmental impacts of energy use within a country [39].

For these reasons, the ETI follows a sustainable innovativeness approach according to the triple bottom line (society, economy, and environment). Therefore, we will use the ETI as a proxy of the sustainable innovativeness of the energy sector in correlation to education to understand if education plays a role in implementing sustainable and resilient energy systems.

2.2. Study hypothesis: Education and the Energy Trilemma Index

2.2.1. School life expectancy and ETI

Previous literature has highlighted that the predisposition of a population to study longer influences energy environmental sustainability and energy security [40–41]. Higher education is associated with a more substantial moral commitment to sustainability, a more pronounced willingness to protect the environment, and a sense of responsibility for long-term sustainable development [42]. For this reason, universities are now endowed with the third mission, being engaged in teaching and research activities that contribute to solving societal and economic problems [43]. In this respect, a significant connection has been detected between university support systems that provide sustainability courses and the degree of success achieved by energy sustainability projects [44] because low educational attainment and university research and development may negatively impact energy quality [45].

As a result, we can state that education has a substantial role in minimizing the deterioration of the environment because of its influence on energy resource. Consequently, the role of education in accomplishing SDG targets may be critical. Therefore, education should be regarded as one of the most relevant factors in green energy development [46].

Education enhances the use of biomasses, one of the most dependable energy resources in the rural areas of the developing world. In regions with higher education levels, biomass-processing techniques for producing energy are more efficient and less impactful from an environmental standpoint [45]. Generally, countries with many sustainable degrees, classes, and programs to improve energy management and production of carbon-free energy have a higher energy quality system [47]. According to Romero-Rodríguez et al. [48], massive open online courses (MOOCs) are associated with implementing sustainable energy systems.

Furthermore, new business outcomes can support radical and incremental sustainable innovations [49]. Previous studies have investigated the correlation between education levels and new models of energy security from a radical innovation perspective [50]. According to Sovacool [51], people with a university degree consider education a critical value that stimulates the active participation of citizens in energy-management issues. Adhikari and Shrestha [52] demonstrate that higher education institutions bring civic value to companies and organizations by enhancing intellectual capital and creating knowledge. In doing so, they encourage multidisciplinary teaching, learning, and research methods that contribute to society. Therefore, they not only promote the creation of knowledge to improve the profitability of business processes, but they also contribute to achieving sustainable development goals by creating practices that increase organizations' socio-environmental impacts.

In particular, education can support new organizational forms which ensure participation and transparency in energy production or management where citizens have a role in the decision-making and promoting of social education on energy security. In addition, highly educated individuals are more concerned with independent energy generation and the use of up-to-date technology in the energy system. By contrast, those who do not have a higher degree are more concerned with energy prices [53].

For these reasons, we propose testing the following research hypothesis:

H_1: the Energy Trilemma Index is positively associated with school life expectancy.

2.2.2. The relationship between STEM and the ETI

Energy quality is a transdisciplinary topic covered in a variety of educational subjects. More specifically, the concept of energy is central and transversal to several fields [54]. Energy is a subject taught in chemistry, biology, earth science, and physics and is related to other scientific concepts. When instructors introduce the notion of energy to their students, it becomes the cornerstone of their knowledge, facilitating their comprehension in higher school grades. Students also see real-world energy applications, and studying STEM disciplines enhances their problem-solving skills [55].

A high level of specialization in scientific subjects increases the skills of workers who, being more competent, give the companies a competitive advantage both in terms of profitability and propensity toward sustainable innovation processes [56]. In addition, STEM education is viewed as a tool for better addressing the energy source demand in a postindustrial, low-carbon future and for releasing us from drudgery by creating high amounts of knowledge-intensive labor [57]. STEM also refers to an integrated educational approach to understanding our era's challenging issues, such as energy sustainability. For example, according to Karwowski et al. [58], long-term STEM education and workforce development may improve management, leadership, and creative (innovation) skills in smart city sustainable-energy programs. Indeed, by providing a thorough understanding of energy resilience, STEM studies can support society by developing practices and technologies to face the energy crisis better and to make energy systems more resilient. In addition, scholars have also shown that the attitude of teachers towards renewable energy resources is positively associated with the intentions of students to pursue a career in the energy sector [59].

Several examples of school projects for increasing the awareness of energy quality are implemented in different STEM classes in various countries. We recall two examples: In northern Iowa, several high schools and middle schools have collaborated to strengthen students' mathematics and scientific skill sets, showing the link between fundamental mathematics, physics, engineering technologies, and the renewable energy sector. In such a project, students have been stimulated to develop professional skills under the mentoring of different professionals. Hence, students have been divided into different teams, programs, and classes related to different careers in energy efficiency, security, and renewable energy [60].

In Africa, the University of Bristol is teaching STEM subjects that promote sustainable development, focusing on renewable energies and their potential impact on the economy and environment. This academic institution uses global forums to highlight the advantages that renewable energy sources offer for development, especially at the tertiary level. Through the Working to Advance STEM Education for African Women (WAAW) Foundation, this university aims to increase the number of African girls studying STEM disciplines. More specifically, camps for girls are organized in Nigeria and Kenya to encourage them to pursue STEM careers. Lectures, experiments, games, and computer programming are among the activities that the girls participate in during camp. Importantly, these activities strongly emphasize problem-solving in the African context, with a particular focus on renewable and safe energy systems [61].

Upon all the above connections between STEM subjects and the issues of energy security and environmental sustainability, we test the following hypothesis:

H_2: The Energy Trilemma Index is positively associated with the fraction of persons with a STEM degree compared to the total number of graduates.

2.3. Research design

Fig. 1 shows the model we use to test H_1 and H_2. As mentioned before, the model focuses on social aspects of education to investigate if they are associated with the Energy Trilemma Index. Specifically, the two hypotheses aim to assess the impact of the school life expectancy and the predisposition of students to choose STEM university programs on the ETI. We also include suitable control variables consistent with previous literature.

3. Empirical analysis

3.1. Research context

To test hypotheses H_1 and H_2, we use a linear regression approach, which allows us to assess whether the number of years spent at school and the percentage of persons (relative to the total number of university graduates) with a STEM degree are associated with the Energy Trilemma Index. We use countries as statistical units, and we perform a comprehensive analysis based on countries all over the world. Specifically, we take the data for the Energy Trilemma Index (dependent variable) from the World Energy Council website, which reports data for 127 countries worldwide (see https://trilemma.worldenergy.org/). For the independent and control variables, we take the data from the online database Global Innovation Index, which reports data relative to countries whose number ranges from 127 to 133, depending on the year (see https://www.globalinnovationindex.org/analysis-indicator). We

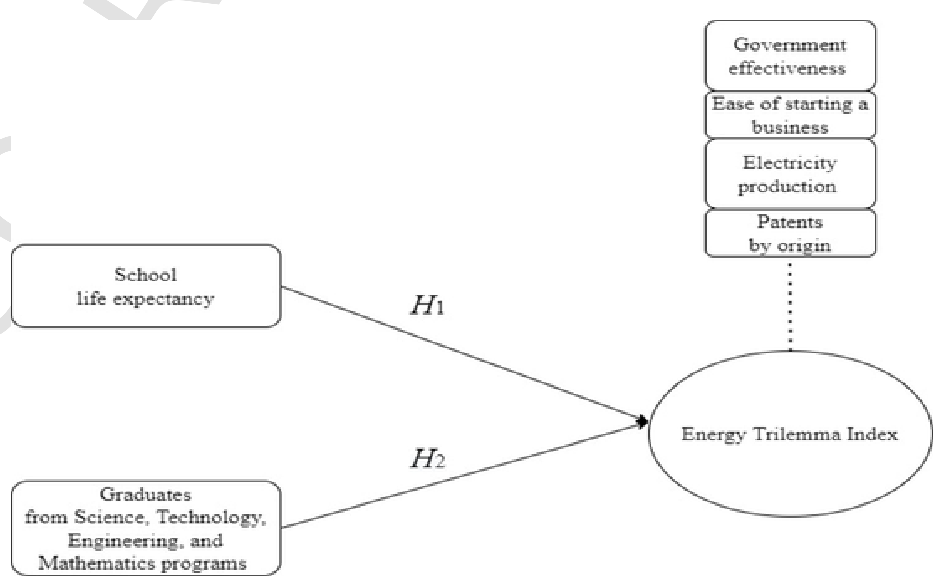

Fig. 1. Research design: Authors' elaboration.

matched the two datasets considering only the countries common to both. For some countries, data are incomplete; therefore, we exclude them, ending up with 118 statistical units. The data values for the Energy Trilemma Index are available for the year 2021 (and are contained in the 2021 annual report). In contrast, for all the remaining variables, the Global Innovation Index reports data for the time interval of 2015–2019. However, for some variables, data from some years are missing. Thus, for each country and for each independent and control variable, we take the average of the values reported by the Global Innovation Index dataset over the whole interval of 2015–2019, excluding the years for which data are unavailable.

3.2. Data and variables

3.2.1. Dependent variable

ETI: Energy Trilemma Index

We set the Energy Trilemma Index (ETI) as the dependent variable. As already mentioned, this index is a composite index of the energy security of a country (resilience of the energy system), the energy equity of a country (access to energy), and energy sustainability (decarbonized energy generation).

Source: Online database from the World Energy Council website (2021).

(https://trilemma.worldenergy.org/).

3.2.2. Independent variables

1. *SLE: School Life Expectancy*

It is the primary-to-tertiary education school life expectancy for all students i.e., the total number of years that a person of school-entry age may be expected to spend at school. Higher values indicate that students are more likely to spend more years at school, having a higher overall retention rate inside the education system. We note that the expected number of years does not always correspond to the number of grades completed because of grade repetition.

Source: Online database of Global Innovation Index (GII) (2015–2019) (https://www.globalinnovationindex.org/analysis-indicator).

2. *STEM %: Percentage of graduates in science and engineering*

It is the proportion of tertiary-level graduates in statistics, engineering, technology and information, mathematics, natural sciences, manufacturing, and construction as a fraction of all tertiary-level students.

Source: Online database of Global Innovation Index (GII) (2015–2019).

(https://www.globalinnovationindex.org/analysis-indicator).

3.2.3. Control variables

1. *GEI: Government Effectiveness Index*

It measures the perception of the value of public services, the value of civil service as well as its independence from political pressures, the performance of policymaking and implementation, and the reputation of a government's commitment to such policies. More specifically, the GEI is a composite index of five indicators: voice and accountability, political stability, regulatory quality, the rule of law, and control of corruption. Scores are standardized between −2.5 and 2.5. We include government effectiveness since it can have a direct effect on the Energy Trilemma Index [10].

Source: Online database of Global Innovation Index (GII) (2015–2019) (https://www.globalinnovationindex.org/analysis-indicator).

2. *EOSAB: Ease of Starting a Business*

It ranks economies based on the ease of starting a business. It is computed by considering all the procedures officially required or commonly undertaken in practice for an entrepreneur to establish and formally begin operating a commercial and industrial business, including the cost and time to finish such procedures and the paid-in minimum capital requirement. Scores are standardized between 0 and 100. We include the ease of starting a business since it may positively affect economic growth, which may be positively associated with the Energy Trilemma Index [14].

Source: Online database of Global Innovation Index (GII) (2015–2019) (https://www.globalinnovationindex.org/analysis-indicator).

3. *GEO: Electricity production relative to the population*

It is the electricity generated, estimated at the terminals of all alternator sets, divided by the country's population. It includes generation from geothermal, solar, wind, tidal, wave energy, combustible renewables, waste, hydropower, coal, oil, gas, and nuclear power. Production covers both the output of facilities built primarily to generate electricity and the production of heat and power systems. GEO is measured in GWh per million people. According to Al Asbahi et al. [13], the electricity output may positively influence the ETI. The amount of energy per capita positively correlates with a country's energy security and energy access.

Source: Online database of Global Innovation Index (GII) (2015–2019).

(https://www.globalinnovationindex.org/analysis-indicator).

4. *PPPGDP: Patents by origin*

It is the number of resident applications submitted at a specific regional or national patent office divided by the gross domestic product (in billions of PPP). Resident patent applications are those submitted with an IP office for and on behalf of the first applicant's native country. For example, an application submitted with the European Patent Office (EPO) by an applicant residing in one of the EPO's member countries, such as Germany, is considered a resident application for that country (Germany). The number of patents may positively correlate with the Energy Trilemma Index (Melnyk et al., 2020). For this reason, we include PPPGDP among our control variables.

Source: Online database of Global Innovation Index (GII) (2015–2019).

(https://www.globalinnovationindex.org/analysis-indicator).

3.3. Statistical analysis

Table 1 shows all the variables and data employed. The results in all the following tables have been obtained using this dataset.

Table 2 reports descriptive statistics for all variables. As we may see, the ETI, STEM %, and EOSAB show a low statistical variability, as the variation coefficient (ratio between the standard deviation and the mean) is lower than one-third. In contrast, the variability is higher for the GEI, GEO, and PPPGDP. In particular, the GEI has a variation coefficient higher than two, the maximum of the GEO is higher than ten times its mean, and the maximum of the PPPGDP is higher than twenty times its mean.

In Table 3, we show the Pearson's correlations among all the variables, which measure the association between all pairs of variables. Specifically, the ETI shows a strong and positive correlation with SLE (0.7961) and the GEI (0.7715). Thus, we may expect to find a positive and strong relationship between the ETI and school life expectancy, as well as a strong relationship between the ETI and government effectiveness.

Moreover, the high and significant correlations between the Energy Trilemma Index and all the other variables justify the choice of the following regression model, in which we test the impact of all the independent and control variables on the energy trilemma index:

$$ETI = \beta_0 + \beta_1 SLE + \beta_2 STEM\% + \beta_3 GEI + \beta_4 EOSAB + \beta_5 GEO + \beta_6 PPPGDP + \varepsilon \quad (1)$$

First, we check that model 1 is free of multicollinearity issues by computing the Variance Inflation Factors (VIFs) for every regressor.

Table 1
Dataset and Variables.

Variables	Meaning	Countries analyzed	Years
ETI (Dependent variable)	The composite index of energy quality (energy security + energy equity + energy sustainability)	118 countries worldwide	2021
SLE (Independent variable)	Number of years that a person is expected to spend at school by country	118 countries worldwide	Average in the time interval from 2015 to 2019
STEM % (Independent variable)	The portion of graduates in statistics, engineering, technology, math, natural science, manufacturing, and construction as a fraction of the total graduates	118 countries worldwide	Average in the time interval from 2015 to 2019
GEI (Control variable)	Composite index of five indicators of government effectiveness: voice and accountability, political stability, regulatory quality, rule of law, and control of corruption.	118 countries worldwide	Average in the time interval from 2015 to 2019
EOSAB (Control variable)	Ease of starting a business	118 countries worldwide	Average in the time interval from 2015 to 2019
GEO (Control variable)	Quantity of energy produced by country divided for the population	118 countries worldwide	Average in the time interval from 2015 to 2019
PPPGDP (Control variable)	Number of patents divided by the gross domestic product	118 countries worldwide	Average in the time interval from 2015 to 2019

Table 2
Descriptive statistics.

Variable	Mean	St. Dev	Min	Max
ETI	63.9195	12.7528	27.8	84.2
SLE	14.3910	2.84880	5.98	21.6
STEM%	22.2968	7.0238	9.5	45.78
GEI	0.3297	0.8760	−1.18	2.22
EOSAB	86.3398	8.4684	53	100
GEO	5175.757	6760.127	25.74	56186.84
PPPGDP	3.9542	10.1100	0.033	80.04

The VIFs obtained are extremely low (the highest one is equal to 2.74, and the mean VIF is 1.71), indicating no multicollinearity problems.

4. Results

We test the significance of the regression coefficients in (1) based on the Huber-White robust standard error estimation, corrected for heteroskedasticity [62–63]. The results of the regression model are reported in Table 4. As we may see, the overall regression is statistically relevant, as the F-statistics is significant at 99 %. In addition, the R^2 value close to 0.7 indicates that model 1 explains a high fraction of the variance of the energy trilemma index.

As reported in Table 4, the coefficient of SLE is positive and highly significant (at the 99 % level), which indicates that the Energy Trilemma Index tends to be higher in countries with a high school life expectancy. This result was somehow expected, based on the high correlation coefficient between the ETI and SLE (0.7961) reported in Table 3.

In contrast, the ETI is not associated with the percentage of persons with STEM degrees as the coefficient of STEM % is not significant. Finally, among the control variables, the Government Efficiency Index (GEI) is the only one showing a significant association with the Energy Trilemma Index.

As is well-known, the OLS estimator, which we used to compute the regression model coefficients (1), is extremely sensitive to outliers. However, since the 118 countries on which the statistical analysis is focused are heterogeneous, the employed dataset contains outliers, as we can infer from Table 2. For example, the PPPGPD variable also takes values higher than 20 times its mean (the mean and the maximum of PPPGPD are equal to 3.9542 and 80.04, respectively). Therefore, to check if the results obtained using the OLS estimator are robust against extreme tail values, we again estimate the regression model (1) using a robust-to-outliers estimator. Specifically, following a common approach, we employ the so-called MM-estimator proposed by Yohai [64], with relative efficiency (versus the least squares estimator under Gaussian errors) equal to 95 % (see also [65;66], Chapter 10). Such an estimator has a breakdown point of 0.5, i.e. it can handle up to as many outliers as 50 % of the whole dataset. Thus, it is very robust to extreme values (the OLS estimator has a breakdown point equal to 0). The obtained results, which we report in Table 5, corroborate our previous findings: The coefficient of SLE is still positive and highly significant (at the 99 % level), which confirms that the Energy Trilemma Index is higher in countries with high school life expectancy. Moreover, we find no association between the ETI and the percentage of persons with STEM degrees. Again, we note that the Government Efficiency Index (GEI) is the only control variable associated significantly with the Energy Trilemma Index (see Table 6).

5. Research implications and contributions

5.1. Discussion of the results

The primary purpose of this paper is to investigate how education impacts sustainable and resilient energy systems. This paper aims to examine the impact of SLE and STEM % on the ETI. Specifically, based on a regression analysis focusing on 118 world countries, we study the relationship between the ETI and SLE (hypothesis H_1) and between the ETI and the fraction of STEM graduates relative to the total number of persons holding a university degree (hypothesis H_2).

Table 3
Pearson’s Correlations, *, **, and *** denote significance at the 90%, 95%, and 99% levels, respectively.

	ETI	*SLE*	*STEM%*	*GEI*	*EOSAB*	*GEO*	*PPPGDP*
ETI Prod	1						
SLE	0.7961***	1					
STEM%	0.2716***	0.2444**	1				
GEI	0.7715***	0.7340***	0.2194**	1			
EOSAB Work	0.4566***	0.5298****	0.1685**	0.5579***	1		
GEO	0.4391***	0.4680****	0.0864	0.5089***	0.3033***	1	
PPPGDP Work	0.2803***	0.2488**	0.1473	0.3607***	0.1767*	0.1837*	1

Table 4
Regression Results Obtained Using the OLS Estimator, *** denote significance at the 99% level. The absence of asterisks indicates that the coefficient is not significant at the 90% level.

Variable	β
Constant	34.1688***
SLE	2.2619***
STEM%	0.1132
GEI	5.8428***
EOSAB	−0.07977
GEO	4.43E-06
PPPGDP	0.006095
F-stat	39.41***
R^2	0.7156
Adjusted R^2	0.6977

Table 5
Regression results using an MM-estimator with 95% relative efficiency, *** denote significance at the 99% level. The absence of asterisks indicates that the coefficient is not significant at the 90% level.

Variable	β
Constant	26.6793***
SLE	2.2667***
STEM%	0.0989
GEI	4.9123***
EOSAB	0.0260
GEO	−3.88E-05
PPPGDP	−0.002340
Wald χ^2	165.64***
Pseudo R^2	0.5787

Table 6
Hypotheses Tested.

Hypothesis	Evidence
H_1: The Energy Trilemma Index is positively associated with the school life expectancy	**Accepted**
H_2: The Energy Trilemma Index is positively associated with the fraction of persons with a STEM degree compared to the total number of graduates	**Rejected**

The ETI has received growing interest in the literature because it is a complex indicator that combines all dimensions of sustainability (environment, economy, and social) [10,13–14] (Melnyk et al., 2020). As shown in Table 4 and Table 5, the results of our empirical investigation show that the SLE is strongly and positively associated with the ETI. By contrast, we find no significant association between the ETI and the percentage of STEM graduates, suggesting that what impacts energy sustainability is a country's education level rather than the population's predisposition to study STEM disciplines.

Our analysis increases the knowledge regarding the impact of education on sustainable and resilient energy systems. We acknowledge that previous literature has shown that a high education level favors the growth of new companies in the renewable energy sector and the use of more effective energy-management systems in industrial production [67–68]. Nevertheless, these findings do not consider two essential aspects. First, studies on sustainable energy do not consider the impact of education from the sustainable innovativeness perspective. Instead, we believe it is interesting to show the importance of education in creating sustainable energy systems and assess its impact on sustainable energy systems, also by comparing it with other social and environmental variables. Since we demonstrated that a high education level impacts more than other variables, we can say that governments should intervene by investing heavily in the education sector if they wish to foster the growth of resilient and sustainable energy systems. Second, our results suggest that SLE has a significant effect on creating new organizational forms of energy production by fostering innovative processes of energy management. As a result, education not only stimulates the birth of new renewable energy enterprises and improves the environmental efficiency of manufacturing processes, but also promotes the emergence of energy communities, off-grid systems, and new organizational forms that empower individuals, encouraging new social and innovative businesses in the energy sector. Because we performed a statistical analysis at the country level, our paper examines the education of both energy professionals and citizens. The latter play a key role in the fostering the growth of resilient energy systems through the development of new innovative forms of energy management. Moreover, high educational levels play a role in preferences consumption since people with higher education have a greater sensitivity towards environmental issues [69–70]. Additionally, our results confirm that the positive association between the ETI and SLE reflects the behavior of environmentally responsible companies. Indeed, to implement processes and solutions targeted at high levels of energy quality and sustainability, these firms tend to hire skilled employees and employees with advanced degrees [71]. Companies that produce energy from sustainable sources hire highly educated workers, and they also need them to build and run safe and secure energy systems, like smart grids, whose complexity calls for skilled workers [36,45]. Therefore, our paper brings two principal contributions to the literature about energy sustainability, sustainable innovations, and the ETI. First, as already noticed, unlike previous research focusing on economic variables related to the ETI, we analyze the social dimension of education. Furthermore, we highlight that SLE has a higher effect than other drivers on creating sustainable and resilient energy systems. Indeed, according to our analysis, the SLE positively impacts the ETI, whereas the ease of starting a new business and the number of patents do not. This point is crucial. To foster the birth of sustainable and resilient energy systems, investing in education is more effective than providing funds that stimulate the creation of new businesses [72]. Thus, our analysis suggests that organizations must invest in education or hire highly educated people if their goal is to develop sustainable innovations that aim to create sustainable and resilient energy systems [73]. Additionally, from a more general perspective, our study shows that education can favor the creation of energy organizations oriented to social and environmental purposes and not just economic aspects. Among the variables considered, the ones showing a significant association with the ETI, and having a high correlation between themselves, are the SLE and GEI. This finding might reflect the interaction between highly educated people and institutions. Indeed, persons with a high university degree might influence institutions by pressuring them to develop policies consistent with their principles, which go beyond the purely economic aspect. Thus, education and proactive policies can promote the development of sustainable and resilient energy systems through the birth of new companies in the renewable energy sector and citizen participation in new forms of energy management, such as energy communities or smart grids [74].

5.2. Theoretical contributions

From a theoretical perspective, our study contributes to the existing literature by addressing the need for a more comprehensive explanation of the variables that affect sustainable and resilient energy systems. This study is also original as it shows that education can influence the quality of energy systems more than economic variables. Our investigation assesses education's role in influencing the ETI based on a perspective of sustainable innovativeness, emphasizing the relevance of SLE in creating sustainable and resilient energy systems. For this reason, this paper contributes to the literature on sustainable innovation in the energy sector. Interestingly, among SLE and STEM %, only SLE has a (positive) correlation with the ETI indicates that the population's knowledge and awareness can affect the development of sustainable and resilient energy systems more than the predisposition of people toward certain types of careers. Therefore, governments that want to stimulate sustainable innovations should invest in education instead of just offering incentives aimed at creating innovative companies in the energy sector [75]. In addition, our study provides a twofold contribution to the literature on knowledge management in the energy sector. First, a high level of education stimulates companies to adopt safe and renewable energy sources. Managers and employees with a higher education degree are more aware of the issues concerning the use of fossil fuels. As a result, higher education encourages processes of change by producing new knowledge that workers accept and support [76]. Second, people with higher education, who are more aware of the harmful environmental effects and geopolitical issues related to the use of fossil fuels, help organizations develop decentralized energy systems. For this reason, in countries with a higher education rate, these organizations are becoming more and more numerous. Through new forms of cooperation and organization, citizens create innovative energy systems characterized by a free exchange of energy and information according to the principle of open innovation [77].

Additionally, our study contributes to the theoretical literature on responsible innovations. Indeed, to create sustainable and resilient energy systems, as said before, it is necessary to build alternative solutions for energy management, such as off-grid systems or energy communities, where citizens go from being mere consumers to producers and consumers of energy at the same time [78–79]. These energy systems require *people with* transversal, technical, organizational, and financial skills to produce and manage energy efficiently, so their members are usually persons with a high level of education [80]. Usually, responsible innovations do not have economic growth as a primary and direct objective. On the contrary, their goal is to treat energy as a common good that can be redistributed equally among the participants in the community by promoting a decentralized and nonhierarchical model of the use of energy sources, following the principles of responsible innovation. For this reason, education plays a leading role in creating innovative forms that follow the principles of responsible innovation with a view to sustainability in the energy sector [81].

5.3. Management and policy implications

First, our study confirms that a high level of education allows companies to have a greater possibility of drawing on quality human capital and developing new technologies and innovations needed for implementing sustainable and resilient energy systems [82]. Second, the positive association between SLE and the Energy Trilemma Index indicates that highly educated persons often care for energy safety and sustainability. In contrast, low-educated persons prioritize other aspects, such as energy prices [53]. Thus, entrepreneurs who plan to install new plants for producing and selling safe and sustainable energy should also pay attention to the education level of the population they serve. These two implications are relevant from the management point of view regarding both company competitiveness and market outlets. Companies in countries with a higher education rate can select workers who are more specialized, thus increasing the competitiveness of companies [83]. Furthermore, in countries with a higher schooling rate, energy consumption is headed toward more renewable forms [46]. For this reason, it is essential at an entrepreneurial level to invest in advanced training programs both within companies to increase productivity and externally through awareness programs to push the population towards sustainable models of energy consumption [51]. Third, a high level of education is a stimulus to creating new organizational and entrepreneurial energy management models. New organizational forms of energy resource management, such as energy communities, are currently being implemented to make energy systems more sustainable. To be optimized, these systems require that the persons who use them have a high level of knowledge since each network member is personally responsible for the consumption and exchange of energy with all the other members [84]. A similar consideration also holds for off-grid systems in developing countries, which must be constructed in rural areas with no national electricity grid. Indeed, creating and managing these energy production systems is complex and requires a high level of education [85]. Finally, a high level of education is related to an institution's high level of quality, which positively correlates with the ETI. For this reason, this study brings an important policy implication. A high level of education stimulates institutions to create ad hoc policies that can favor the spread of sustainable and resilient energy systems. For example, a high SLE can promote policies that limit the use of specific energy sources [86] or that foster the creation of new organizational forms of energy management such as energy communities [87].

6. Conclusions, research Limitations, and future directions

As already mentioned, our investigation is original and thus opens the scene for future studies on the relationship between education, energy sustainability, and responsible innovations. Specifically, our study aims to show how SLE affects managers, workers, and the population regarding the implementation of sustainable and resilient energy systems. As a result, education broadens the opportunities for firms to use renewable energy sources by upgrading manufacturing processes with a focus on sustainability. This process can foster the development of new decentralized organizational forms with better management of energy sources through active citizenship. Nonetheless, our research has some limitations. Because we have adopted a quantitative and empirical approach, we have not focused on a theoretical analysis of why a higher level of education is associated with a higher ETI. Therefore, it would be interesting to deepen these issues in more detail. Moreover, the time interval of our analysis is limited. Indeed, we computed the ETI indicator based on data for the year 2021 and obtained the other variables by averaging data over the time interval from 2015 to 2019. If new (additional) data become available, it would be desirable to extend the present study by conducting a broader temporal analysis. In addition, our investigation considers the population as a whole. Other studies could adopt a different perspective, focusing on single individuals and considering age, sex, and other personal characteristics. Finally, we conducted a global analysis. It would also be necessary to extend the analysis by analyzing the different parts of the world separately to understand where education plays a more relevant role in stimulating the creation of sustainable and resilient energy systems. Future research could also go beyond the scope of this study by investigating the impact of other variables related to education, such as expenditure on education or the number of women with advanced degrees, making a bridge with the existing literature [46,88]. Furthermore, our analysis could also be extended by considering variables belonging to other dimensions, such as a quality technological infrastructure supporting a quality energy system [89]. Finally, our study does not analyze the influence that specific university careers may have on implementing and creating sustainable and resilient energy systems. So, future investigations are needed to determine the professional courses that countries should implement to stimulate the creation of organizations concerned with developing sustainable and resilient energy systems. However, we also remark that several of the future extensions suggested above would require data that, up to now, are not publicly available (at least to the best of our knowledge).

Uncited references

[90,91,92].

CRediT authorship contribution statement

Simone Gibellato : Conceptualization, Writing – original draft, Project administration, Data curation. **Luca Vincenzo Ballestra**

: Conceptualization, Methodology, Writing – review & editing. **Fabio Fiano :** Supervision, Writing – review & editing. **Domenico Graziano :** Supervision, Writing – review & editing. **Gian Luca Gregori :** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the data are freely available on the websites reported in the paper

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