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Review Article

Advancing the European energy transition based on environmental, economic and social justice

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ABSTRACT

Energy transition has implications not only for economic growth and social welfare but also for the planet. It is therefore important to provide a framework of quantifying how this transition might affect these aspects from a triple perspective. In this regard, an in-depth and critical analysis of the available reports, policy frameworks and initiatives on energy transition, under the sustainable and circular perspectives, has been developed. This manuscript provides a "know-how" framework to assist in decision making and to assess the effectiveness, gaps and future actions to be developed for an effective energy transition. It presents a set of indicators to assess the sustainable and circular potential of emerging technologies and renewable energy production schemes, focusing on the environmental, social and economic pillars. It also highlights the policies and initiatives that should be implemented to facilitate this transition, as well as analyzing a comparison between European countries on how to improve energy renewability in those with low scores in the energy transition indexes. This study provides a critical analysis of the implications on energy transition over environmental, social and economic sustainability, as well as on circularity. It provides a preselection of the most appropriate indicators (both quantitative and qualitative) to effectively analyze the transition. The outcomes of this study can help stakeholders, citizens and policy makers on where to focus to improve efficiency, renewability and technology development for a sustainable and circular energy transition.

1. Introduction

The transition from fossil to bio-based and renewable energy is key to mitigating environmental impacts, avoiding fossil resource depletion, promoting sustainability, fostering economic growth, and improving the health of communities (Obaideen et al., 2021; Pablo-Romero et al., 2022; Yang et al., 2021). Adopting renewable energies in the framework of a more sustainable, cleaner and resilient energy sector for the near future is not possible on the basis of individual and immediate actions but has to take into account the socio-economic context affected by the changes to be implemented (Jacques et al., 2023; Mamidi et al., 2021). At the European level, the transition to renewable energies is driven by several reasons, in which the need to reduce dependence on fossil fuels for energy production and the requirement to mitigate climate change and polluting emissions that could put the health of communities at risk, are the main driving forces (Fankhauser et al., 2021; Galimova et al., 2022; Krane and Idel, 2021). The proposed transition to renewables aims to diversify the energy mix in the European Union, improve energy security, and reduce the carbon footprint of the energy sector. All these objectives meet several of the Sustainable Development Goals. The main uncertainty is how we will get there. To this end, the EU has launched several policies and initiatives, most of which are described in the following sections. The energy transition can be beneficial, but also problematic when it comes to employment. The regions and social communities dependent on fossil-based sectors are the ones that will suffer unemployment, so we must think of corrective actions and strategies to ensure an equitable and just transition for the whole of society. To this end, Table 1 lists a series of key risk aspects and possible measures for action:

Regarding policies on energy transition, the European energy policy is made up of a series of measures aimed at achieving an integrated energy market, security of energy supply and sustainability of the energy sector: energy diversification, functionalization and efficiency, decarbonization and research on the energy transition. Despite the intense interest in the energy transition, there are certain challenges that need to be addressed to advance a more sustainable energy value chain: intermittency of some renewable resources (Abdalla et al., 2021; Kousksou et al., 2014; Worighi et al., 2019), economic implications (Jenniches, 2018; Pavloudakis et al., 2023; Schuetze and Hussein, 2023) and

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Nomenclature

ACER	European Agency for the Cooperation of the different National Energy Regulations
AT	Austria
BE	Belgium
BG	Bulgaria
CCUS	Carbon Capture, Utilization and Storage
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EAS	Energy Access and Security
EDG	Economic Growth and Development
EE	Estonia
EL	Greece
ENTSO	European Networks for the collaboration on the Transmission System Operators
ES	Environmental Sustainability
ES	Spain
ESS	Energy System Structure
ETI	Energy Transition Index
FI	Finland
FR	France
GHG	Greenhouse gases
HCCP	Human Capital and Consumer Participation
HR	Croatia
HU	Hungary
IE	Ireland
IPCC	Intergovernmental Panel on Climate Change
IT	Italy
LT	Lithuania
LU	Luxembourg
LV	Latvia
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
R&PC	Regulation and Political Commitment
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
SP	System Performance
TPI	Transition Performance Index
TR	Transition Readiness
VOCs	Volatile Organic Compounds

technological innovation (Impram et al., 2020; McPherson and Tahseen, 2018). Another aspect that is necessary for the energy transition are policies and regulatory frameworks, which must be consistent and must establish clear supportive and affordable financial mechanisms for investing in renewable energy (Daszkiewicz, 2020; Miller et al., 2015).

The objective of this manuscript is to analyze the energy transition in the European context under sustainable and circular perspectives by identifying a set of indicators, providing a robust framework to assess this transition. This is important because there is a lack of "know-how" to achieve a sustainable and circular energy transition, rather than a plethora of policy actions and recommendations, sometimes difficult to understand how to apply them at lower levels, such as in industrial production. In this study, an assessment of European energy sector data, including renewable energy production capacity, the leading technologies for renewable production, as well as analysis of the Energy Transition Index (ETI), seeking to identify the rationale for its different scores obtained per country, has also been assessed. It also offers a selection of "crucial" actions that should be developed to advance the energy transition and ensure long-term stability of the effects of decarbonization in the energy sector. The outcome of this manuscript could be considered useful for stakeholders, citizens and policy makers to promote and enhance a sustainable and circular energy transition, and where to focus on improving efficiency, renewability and technology development for environmental protection, economic growth and social consequences.

2. Methods

The development of this article has been based on the stages depicted on Fig. 1SM: a 1st stage based on the analysis of the manuscripts, policy frameworks and initiatives about sustainability on the energy sector, the 2nd stage on the integration of sustainability with circular economy, considering the identification of synergies, gaps and improved actions. 3rd stage is based on the search and selection of the appropriate indicators to measure energy transition from a sustainable and circular approach, followed by the analysis of country indicators on the framework of renewable energies and energy transition index (4th stage), to finalize with the identification of present gaps and future framework to ensure a green energy transition.

To perform the literature review, SCOPUS database has been used, considering as keywords "Energy transition AND Sustainability", "Energy transition AND social justice", "Energy transition AND Environment", "Energy transition AND policies", "Energy transition AND economic growth", "Energy transition AND circular economy" and "Energy transition AND circularity", considering the manuscripts from 2015 onwards. On the other hand, also directives, international reports, action plans, and European databases has been considered for providing the framework of the policies and the actual state of the European countries on energy transition. The data considered for the analysis, and for the development of graphs and figures, is the one more recent, in order to provide the most actual vision of the degree of development of energy transition.

2.1. Effect of energy transition within the sustainability perspective

The energy transition is more than an advance in the technological and political framework. The decision-making process on energy transition must be supported and verified by detailed analyses based on socio-economic and environmental criteria. Adequate management of renewable resources, a balance between different technologies and progressive adaptation to the new energy framework must be ensured in order to guarantee targets of foremost importance such as energy security, economic stability, growth and job creation. With this in mind, the analysis of the environmental, economic and social pillars is the focus of study in the following sections.

2.1.1. Environmental pillar

The transition to renewable energy sources, such as solar, wind, hydro and geothermal, is expected to significantly reduce GHG (Greenhouse gases) emissions. The burning of fossil fuels, mainly coal, oil and natural gas, are major contributors and drivers of climate change, and with the integration of renewables into the market value chain, these emissions are avoided, along with emissions of other air pollutants such as particulate matter and volatile organic compounds (). Renewable resources contribute to the decarbonization of the energy sector and can be confirmed by the data provided in Fig. 2SM, which depicts the GHG emissions avoided by the penetration of renewable

Table 1
Job risk and concerns on energy transition, including possible action measures.

Job risk/concerns	Action measures	Reference
Job displacement in the fossil-based sector	Collaboration between public and private partnerships to promote the creation of renewable energy job opportunities and enhancement of investments and public funds to support the renewable energy sectors	(Briggs et al., 2022; Du et al., 2023; Raghutla and Kolati, 2023)
Economic impact on society depending on fossil-based sector	To reduce the effect of economic growth on the high-dependency regions, the support of the implementation of new business, infrastructure and entrepreneurship collaboration is key. To promote this, incentives such as tax breaks, low-interest loans, investment grants, mentorship programs and enhancement of collaborative networks should be implemented and promoted.	(Rajagopal, 2023; Temmes et al., 2021)
Ensuring transitioning workforce	Training and education programs should be encouraged to provide the necessary skills to workers to be included in the renewable energy sector.	(Rorrer et al., 2023; Sun et al., 2023)
Regional disparities	The regional dependency on fossil resource is different for each region, thus energy transition is going to affect differently. In order to avoid the exacerbation of regional disparities, government and other partnerships should allocate funding and adequate funding amounts considering the regional dependence on fossil resources.	(Aghahosseini et al., 2023a; Antje et al., 2023; Lonergan et al., 2023)
Effect over society welfare	Implementation of policies to ensure job quality, fair wages and worker conditions on the renewable energy sector. Social community participation on decisions related with energy transition technologies should be taken into account.	(Aruta et al., 2023; García-García et al., 2022; Hanke et al., 2022)

resources in the energy mix of European countries. As could be seen, from 2010 to 2019, significant changes are observed, since in most countries the avoided emissions are two-fold higher. On the contrary, some regions, such as Austria, Hungary, Denmark, Estonia, Malta, Slovenia and Sweden, do not present better scenarios, but increase GHG emissions in the transport sector. Therefore, in order to boost the energy transition and move towards a decarbonized Europe, it is necessary to implement more renewable energies in the energy mix of the aforementioned countries.

On the other hand, it could be stated that the energy transition has both a direct and indirect impact on environmental quality. The "direct way" relies on the fact that increasing the share of renewable energy in the energy mix reduces emissions and fossil fuel consumption (Fig. 3SM), which has an immediate consequence in reduced dependence on coal or oil suppliers. As could be seen in Fig. 2, the avoidance of fossil fuels has led to a positive benefit in the regions of Denmark, Finland and Sweden. This statement is reinforced as, according to the Environmental Protection Agency, in Ireland, emissions decreased by 1.8 % given the reductions in the use of peat, oil and coal for electricity production in 2022, specifically in the case of CO_2 emissions, which were reduced from 348 g CO_2/kWh to 331 g CO_2/kWh. In addition, the research article developed by Rashedi et al. (2020) also shows how the reduction in fossil fuel use in the power sector has implied a reduction in life cycle impact categories from 2019 to 2020, with a decrease in impact score of 11–25 % in some of the impact categories.

But, even in a not so significant difference between 2010 and 2019, all EU countries have experienced a positive effect from the use of renewable resources. The "indirect way" is based on the fact that the energy transition could imply cascading effects on the overall economy, *e.g.*, it could change industrial processing, which implies reduced emissions and costs (*i.e.*, self-sufficient energy production), promote more sustainable actions in communities, *e.g.* by encouraging recycling and separation of waste generated in households and services, with a view on bioenergy production, and also to enable better land use.

Another important aspect of the interconnection between energy transition and environmental effects is related to the decentralization of energy systems (Brisbois, 2020; Kubli and Ulli-Beer, 2016). The implementation of decentralization systems reduces long-distance energy transportation, which implies improved grid resilience and more controlled management of energy resource demand. In addition, it promotes diversification of energy sources, as well as increase local involvement and awareness of communities for more sustainable and efficient renewable energy. As a result, it is expected that emissions related to energy production will be significantly reduced.

The integration of renewable energies makes it possible to include smaller-scale renewable energy installations, such as rooftop solar panels or small wind farms for residential areas. In this sense, energy self-sufficiency is achieved, even partially, and it is also beneficial that this type of system reduces transmission losses and the need for long-distance transportation, which also implies a reduction in GHG emissions. This fact could be seen in Fig. 1, as the share of renewable electricity has increased significantly from 2010 to 2020 in most EU regions, with Hungary, Slovakia and Slovenia showing the smallest difference. In order to increase their values, both policy and regulatory frameworks, together with international collaboration and cooperation, are thought to be crucial to increase the share of renewable resources in this sector (Drago and Gatto, 2022; Gielen et al., 2019; Tanil and Jurek, 2020). Implementing best practices in energy production, improving energy efficiency, facilitating the expansion of renewable energy, as well as the development of cross-border renewable energy projects are decisive actions to promote a more renewable electricity grid (Bartek-Lesi et al., 2023; Thaler and Hofmann, 2022).

Another sector that needs to make progress in the use of biofuels is transportation. It has been established that intense road transport not only has a notable contribution in GHGs but also influences respiratory and cardiovascular diseases, as well as increases noise pollution (Ara Aksoy et al., 2021; Requia et al., 2018; Xia et al., 2015). Taking this into account, the share of renewable resources in the transport sector has grown significantly in the last decades, as can be seen in Fig. 2. All EU countries have made efforts to switch from fossil fuels to renewable energies, with Austria being the only country with more or less constant values but in line with other EU countries. On the other hand, Sweden is the country that stands out, as its score rises to 31. The reason behind this increase in share is simply based on the incentives for the purchase of electric vehicles by governments and policy makers, as well as their technological advancements, given the improvements in electric battery technology and the implementation of a gross number of fast charging stations (Aghahosseini et al., 2023b; Mastoi et al., 2022). However, this situation differs among countries, where users of these types of vehicles are faced with much higher purchase costs and numerous limitations in battery recharging, which prevents the transition from becoming real. In the case of using biofuels such as bioethanol or biodiesel, this option provides greater diversification in fuel alternatives for the transportation sector for consumers.

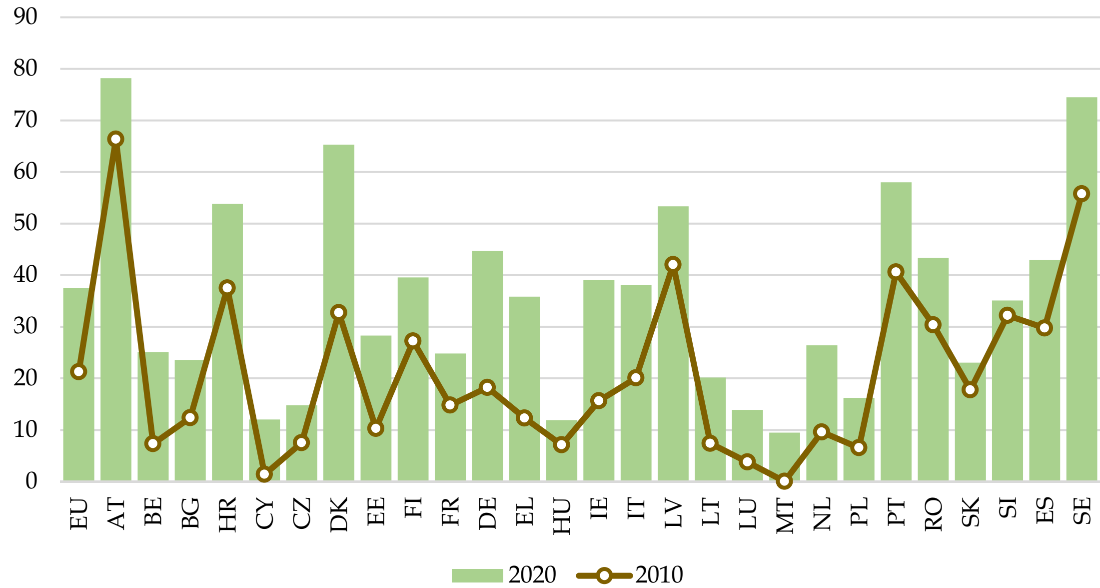

Fig. 1. Share of renewable resources in the electricity sector. Comparison between 2010 and 2020. Data source: European Commission. Acronyms: EU (European Union), AT (Austria), BE (Belgium), BG (Bulgaria), HR (Croatia), CY (Cyprus), CZ (Czech Republic), DK (Denmark), EE (Estonia), FI (Finland), FR (France), DE (Germany), EL (Greece), HU (Hungary), IE (Ireland), IT (Italy), LV (Latvia), LT (Lithuania), LU (Luxembourg), MT (Malta), NL (Netherlands), PL (Poland), PT (Portugal), RO (Romania), SK (Slovakia), SI (Slovenia), ES (Spain), SE (Sweden).

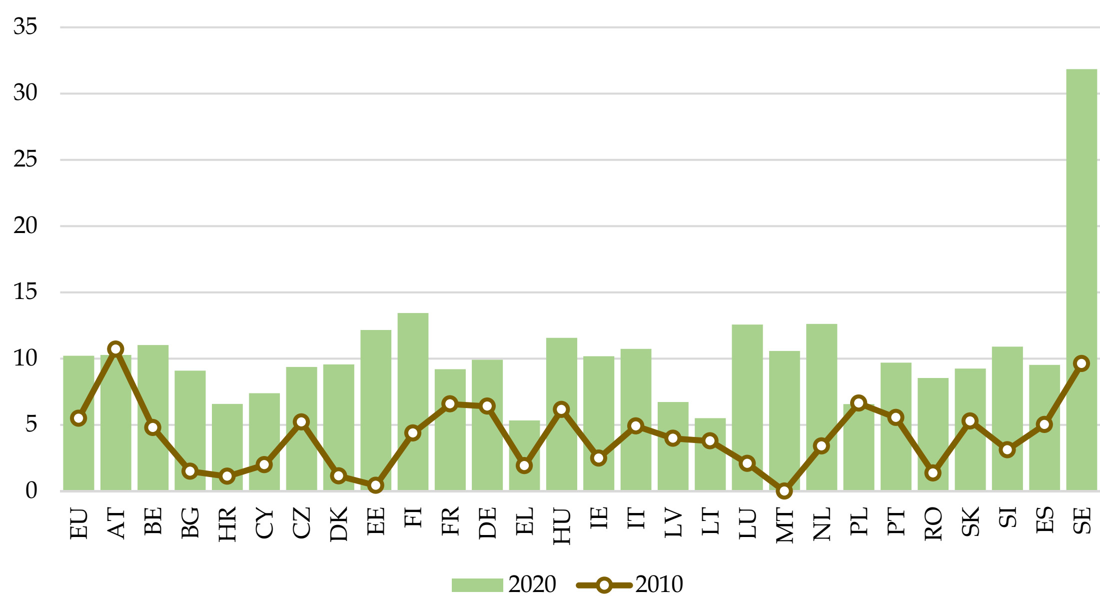

Fig. 2. Share of renewable resources in the transport sector. Comparison between 2010 and 2020. Data source: European Commission. Acronyms: EU (European Union), AT (Austria), BE (Belgium), BG (Bulgaria), HR (Croatia), CY (Cyprus), CZ (Czech Republic), DK (Denmark), EE (Estonia), FI (Finland), FR (France), DE (Germany), EL (Greece), HU (Hungary), IE (Ireland), IT (Italy), LV (Latvia), LT (Lithuania), LU (Luxembourg), MT (Malta), NL (Netherlands), PL (Poland), PT (Portugal), RO (Romania), SK (Slovakia), SI (Slovenia), ES (Spain), SE (Sweden).

2.1.2. Economic pillar

One of the major concerns for economic growth in the energy transition is population growth. Some research reports have discussed how this “reality” should be addressed to ensure sustainability in the energy transition, concluding that reducing energy demands should only be achieved by increasing the efficiency of technologies at all stages of the value chain. The benefits in the economic pillar on the optimization of energy production and use are clear, higher productivity, higher profits and lower costs, provided price volatility is controlled and the distribution infrastructure is robust and widespread. In fact, it has been reported that, by integrating these actions, an amount of 100 TWh of energy could be saved annually, with in turn also avoiding the emission of 30 million tons of CO_2 (Sousa and Soares, 2023). On the other hand, the aforementioned research also points out that an efficient and adequate energy mix, adapted to each European value chain and territory, is a key aspect to advance in more sustainable frameworks.

It has been reported that the energy transition could help the economic growth of communities, even in a greater way compared to conventional fossil-based energies, but always if this energy transition is framed in a reliable and consistent policy framework and aided by adequate investments (Ajmi and Inglesi-Lotz, 2020; Dogan et al., 2022; Khan et al., 2022). Along the same lines, the accessibility and affordability of this renewable energy must be guaranteed for the social community. This aspect is somehow quantified by reducing the proportion of income spent on fuel and electricity in each household. As could be seen in Fig. 3, from 2010 and 2015 in most countries the increase in consumption is higher compared to that from 2015 to 2020. For example, in the case of Malta consumption remains almost unchanged, as well as in the Netherlands, Luxembourg, France, Lithuania and Cyprus, and, in some countries, such as Denmark, Austria and Slovenia, the evolution of consumption has decreased in the last period, from 2015 to 2020. This could be an example of the increased awareness and consciousness about the promotion of energy efficiency and the adoption of new action plans to reduce energy consumption in households.

2.1.3. Social pillar

When analyzing the social effects of energy transition, the first thought is about what is called as "energy poverty". The lack of access to energy sources is also a public health, being more important on low-income populations, as it is related with serious health problems, including death. Renewable energies are expected to be potential strategies for improving energy affordability, reliability and sustainability, with reduced negative health effects (Jaiswal et al., 2022). Air quality is directly dependent on the pollution effects of the consumption of fossil resources for energy production. The transition to renewable energy could have a positive effect on the increase of air quality, thus reducing the health pitfalls that air pollution could entail (*i.e.*, respiratory and skin illness, moreover) (Henry et al., 2021). Besides the aforementioned issues, the research report developed by Pan et al. (2021) also concluded that energy poverty implies a significative negative effect over the health of society, increasing the death rate and reducing the life expectancy at birth (Pan et al., 2021; Banerjee et al., 2021). In the research report of Alharthi et al. (2022), in which an analysis of 20 Middle East and North Africa economies showed that, from 2000 to 2019, it has been demonstrated that the use of renewable resources implies a reduced concentration of PM2.5 and oxidized compounds on the atmosphere, thus diminishing the effects on health issues, mostly respiratory and skin illness (Alharthi et al., 2022).

Nearly one billion people in the world do not have safe access to energy, which not only limits their quality of life, but also implies that they have access to unsafe energy sources that can be the cause of important health effects, such as carbon monoxide poisoning. In addition to this, it is important to mention that there is still a high dependence on the self and unregulated use of coal and biomass as energy resources for cooking and heating the home, which is not only more insecure, but also less efficient in the use of these resources, which slows down to a certain extent the transition towards a more sustainable use of energy (Seddighi et al., 2023). Various policies and initiatives have contributed to the phase-out of coal, such as carbon pricing mechanisms, renewable energy targets and incentives (the inclusion of tariffs and tax credits on fossil resources has encouraged the deployment of renewable technologies), reduction or elimination of subsidies, environmental regulations and agreements (*e.g.*, the establishment of emission caps and the Paris Agreement), as well as societal awareness and support for climate action.

Another important aspect that relates society and energy transition is regarding with health effects of energy production and utilization systems. While the energy conversion entails about 755 of the total GHGs emissions, it is also the responsible of the 66 % of NOx and particular matter emissions, with important detrimental effects over the air quality, and thus affecting over the health of the communities as air pollution could enhance lung cancer, heart diseases and strokes, apart from respiratory effects given the inhalation of pollutants (Seddighi et al., 2023).

In this regard, the report developed by Yuan et al. (2022) has demonstrated that the application of energy policies for energy transition under a cooperative framework have a positive effect on the diminishment of related energy emissions, as CO_2, $PM_{2.5}$ (Particular matter), VOCs (Volatile Organic Compounds) and SO_2 (Yuan et al., 2022). In this future scenario the key indicators for energy transition that makes the difference are mostly related with the percentage of non-fossil fuels in primary energy consumption (increased by almost 10 % in comparison to the actual value), in the number of electric vehicles on the road (with an expected increase of 20 %) and also the coal consumption, that is maintained practically unaltered, even the population and the energy consumption is expected to increase substantially in the following years. Considering these aspects, Yuan et al. (2022) has observed that the major reduction of emissions are related with NOx and

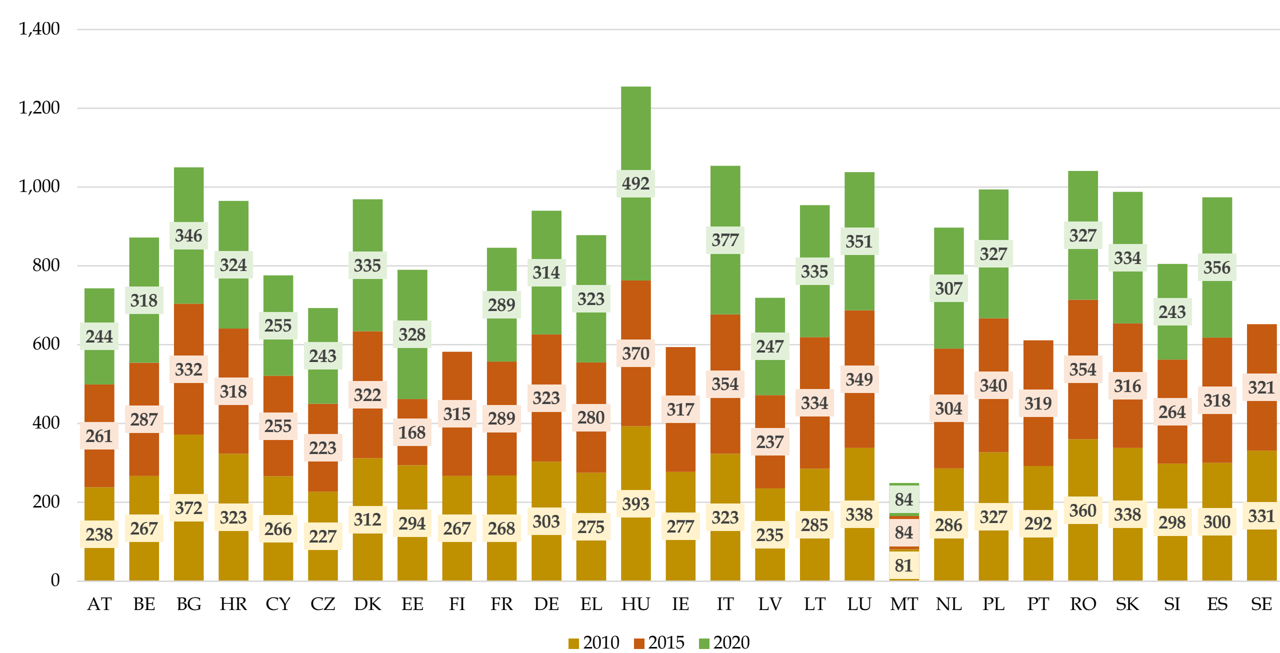

Fig. 3. Individual household consumption per year in electricity and other energy fuels, expressed in "per mille". Data source: Eurostat. Acronyms: AT (Austria), BE (Belgium), BG (Bulgaria), HR (Croatia), CY (Cyprus), CZ (Czech Republic), DK (Denmark), EE (Estonia), FI (Finland), FR (France), DE (Germany), EL (Greece), HU (Hungary), IE (Ireland), IT (Italy), LV (Latvia), LT (Lithuania), LU (Luxembourg), MT (Malta), NL (Netherlands), PL (Poland), PT (Portugal), RO (Romania), SK (Slovakia), SI (Slovenia), ES (Spain), SE (Sweden).

VOCs, with about a 20 % decrease for both cases (Yuan et al., 2022).

One of the main concerns when evaluating the potential scenarios for energy transition are related with the possible loss of employment, which could have important effects over both the social community but also to the local economy. At the moment, the fossil-based sector is employing about 13 million people in the world, corresponding to more than fifty million families being related (Singh and Singh, 2023). But the fact is that several jobs are being created in the scope of bioenergy, as it could be appreciated on Fig. 4, in which is being exemplified the number of actual jobs in the different renewable energy technologies and also per country of the European Union. Poland, France and Spain are the regions with the highest job creation in this sector, being the solar photovoltaic, for Poland and Spain, and the energy from solid biomass, for France, the ones with highest employment.

Regarding the responsibility of social communities on the energy transition and efforts for decarbonization, a recent research developed by Baur et al. (2022), based on the analysis of a survey about the social acceptance of the technological transition for renewable energy, has concluded that the public acceptance is positive, with percentages of acceptances that goes from 48 % to 58 % within a "rather positive attitude" and from 16 % to 37 % in the case of a "very positive acceptance" over 1247 respondents. With regard to the main concerns, both smell and noise pollution, together with some hazards to both environment and healthy issues, are the ones that stands out the most (Baur et al., 2022). Given this, efforts should be made to promote the dissemination and sharing of knowledge about renewable energy production facilities, so that the community is not reluctant to locate a renewable energy facility in an established and safe environment (Bragolusi and Righettini, 2022; Singh and Singh, 2023). This aspect should be worked on in the near future, as the social welfare of the energy transition needs to be ensured in order to promote the sustainability of the energy value chain.

Social acceptance is key, not only for the energy transition, but also for participation. For example, in the case of the use of solid urban waste as an energy resource, selective separation in its production, *i.e.*, in households and services, is essential. Without community participation and involvement, the renewable based technologies developed are of little value, so cooperation between the different actors in the value chain is essential. In this aspect, the elaboration of adequate regulations is key on the promotion of a faster social acceptance (Abreu Netto et al., 2023). Besides, those regulations should include aspects as the gender equality, labor, economic growth, *etc.*, given the fact that, as could be seen on Fig. 5, the gender employment gap, defined by the European Institute for Gender Equality as "the difference between the number of men and women employee in the range of 20 to 64 years", it still far away in what is considered as sustainable development. The energy transition should also be aware on diminishing these differences and going further a more equitable and fair employment.

2.2. Circularity and energy transition

The 2022 United Nations Climate Change Conference has discussed about the benefits of developing more circular systems in the energy transition. One of the principles of circularity is the integral use of the available resources, but also the search for cleaner process and thus cleaner energy (Patwa et al., 2021; Velenturf and Purnell, 2021). In this regard, this is directly related with the energy transition, as the renewable energy is significantly cleaner in comparison that the one coming from fossil resources. On the other hand, the European Union should not only be aware about energy transition, but also of the related consequences on natural reservoirs that it could have (Ferreira et al., 2022; Kong et al., 2022). For example, according to the US Department of Energy, in order to allow decarbonization on the United States, more than 3 terawatts of solar capacity will be needed, which is an increase on more than a 40 % in comparison to the actual capacity. This will imply the need to construct and install a significant number of solar planes, which are constructed using metals and minerals, such as copper, zinc or cadmium, so the demand of them is going to drastically increase on the following years, so its depletion could occur, just as happens with fossil resources. Those metals and minerals are known as "critical materials" and, according to the report developed by IRENA (International Renewable Energy Agency), about the critical materials for the energy

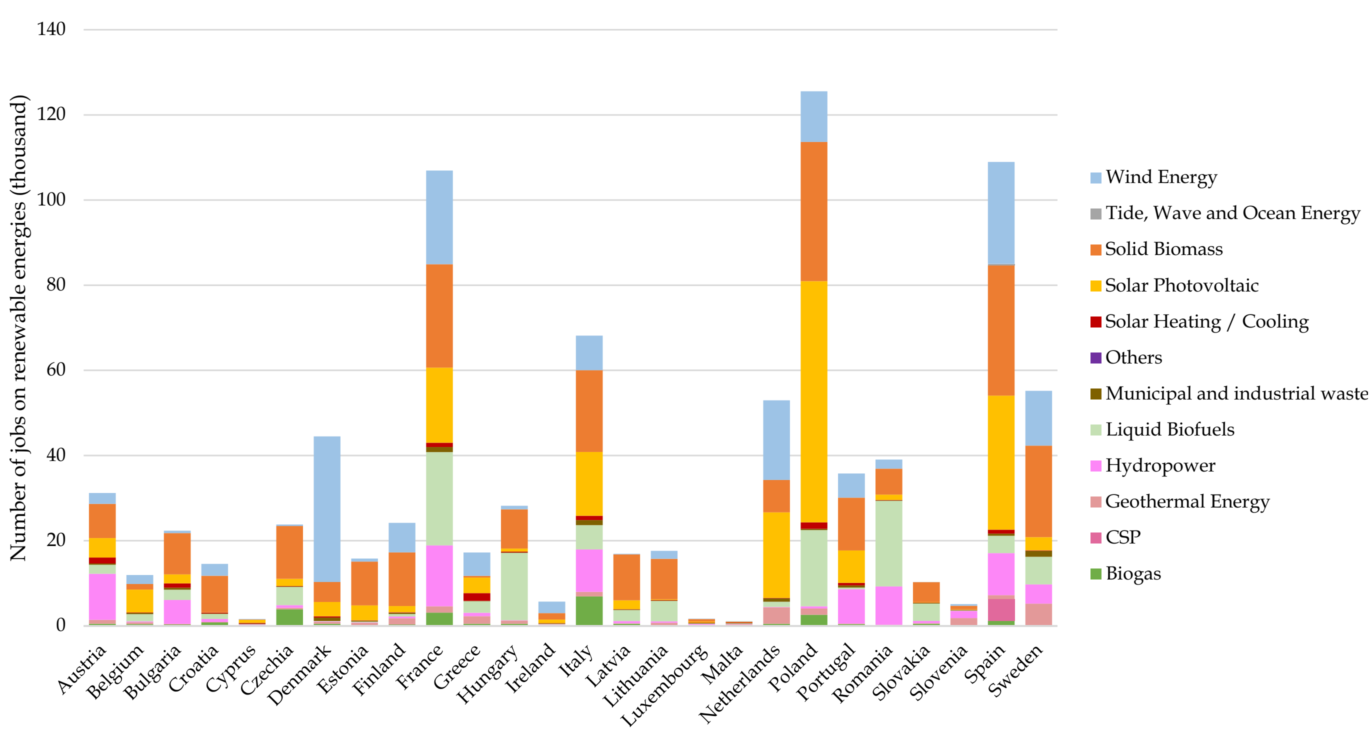

Fig. 4. Number of jobs on renewable energies on 2021, total value and per type of technology and country. Database: Renewable Energy and Jobs, report by IRENA (International Renewable Energy Agency) (2021).

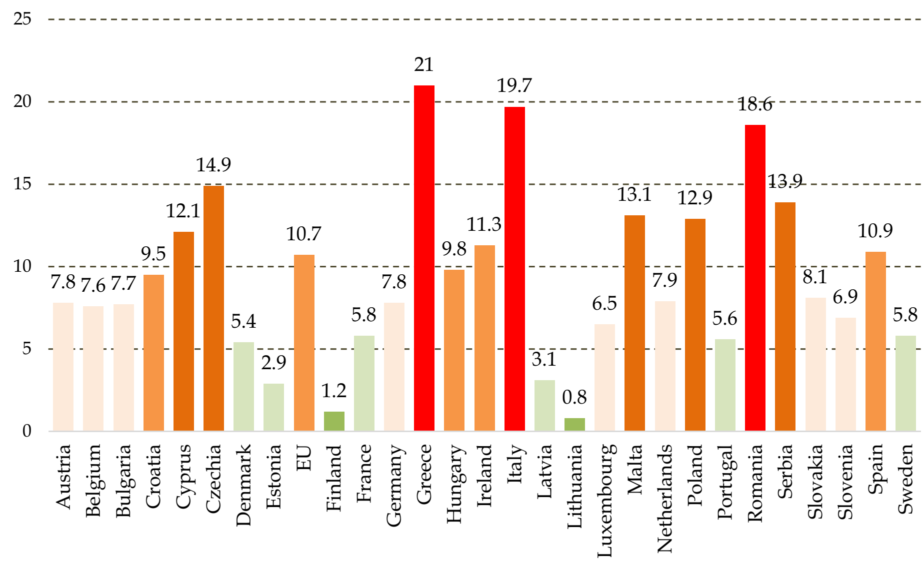

Fig. 5. Gender employment gap. Database: EIGE (European Institute for Gender Equality), available in https://eige.europa.eu/gender-statistics/dgs (2023).

transition, its projected demand for 2050, in comparison to the actual one (2020) is going to substantially increase for all the critical material types, being more noticeable for copper (from 30 Mt./year to an average of 60 Mt./year), nickel (from 2.54 Mt./year to 6.5 Mt./year), lithium (from 0.41 to an average of 3.5 Mt./year), cobalt (increasing from 0.14 to 0.55 Mt./year) and neodymium (10 times higher, from 0.03 to 0.3 Mt./year). The reason of such increase in based on the fact that critical materials are needed to construct a significant number of technologies needed for energy transition, such as solar panels, batteries, turbines or electrolyzers. For example, copper is used for the electricity grid cables and for solar energy panels, lithium is required for batteries for electric vehicles, dysprosium and/or neodymium are applied to the construction of turbines for wind energy and magnets for electric vehicles (Dolf Gielen et al., 2022; Liang et al., 2022; Månberger and Stenqvist, 2018).

On the other hand, it has been estimated that, by 2050, almost 78 million tons of decommissioned technology for solar panels is expected, which could entail a problem for its proper management (Bender and Atalay, 2021). So, anticipate actions should be developed before this could occur, the increase on the efficiency of the technology, as well as smart design, which enables to reuse the materials used in the obsolete solar panels, are essential actions to be considered from the early stage of design to ensure the sustainability of the sector. To illustrate the benefits of thinking on more “eco-design” and “smart design thinking” and its impact on energy efficiency and the associated economic costs and environmental profits, Table 2 is depicted. The data included on the table is the result of a report by the European Commission and, as it could be observed, both energy, economic and climates savings are achieved when more efficient designs are developed.

The development of circular strategies for recycling and reuse the materials required for the construction of renewable energy technologies will be essential (Morseletto, 2020; Norouzi et al., 2021; Velenturf and Purnell, 2021). Besides, this could also be beneficial under an economic and social perspective. Regarding economics, thinking about end-of-life strategies is going to reduce the associated costs of production, as the cost of virgin resources is going to significantly increase in the coming future (Bauwens et al., 2020; Söderholm, 2011; Takacs et al., 2022). From a social point of view, the creation of new jobs and the economic growth of the communities is also expected, given the need of developing new technologies to ensure the conservation of mineral and metals through their integral use and their longest preservation on the market value chain. This approach of decreasing the use of virgin materials by maximizing the use of the available resources is known as “sharing economy”: perhaps a material could no longer be used for solar panels production but could provide an alternative service or could be used in the construction of other technologies (Goddin, 2020). On Table 3 some of the most urgent resource risks and circular solutions are

Table 2
Economic, energy and environmental saves achieved by the implementation of eco-design on common services on households and services sectors. Database: *EU action on Eco-design and Energy labeling*, a Report from European Commission (2020).

	Economic/product save	Energy saves per year	Climate protection
Energy efficient lighting products	Around 30€/year/person	34 TWh of electricity	Prevent 7 million tons of CO_2 emitted per year
Air heating and cooling products	N/A	56.4 TWh of energy	Lower the CO_2 emissions by 9 million tons
Fridges and freezers	200 € per consumer over the lifetime	9.6 TWh of electricity	3.1 million tons of CO_2 not emitted
Vacuum cleaners	70 € over the lifetime of the product	20 TWh of electricity	Prevent 6 million tons of CO_2
Washing machines and washer-dryers	250 € saved in the product lifetime	5 TWh of electricity and 711 million m^3 of water	0.84 tons of CO_2 equivalent per years
Air conditioners	Bills reduction of 340 € on the product lifetime	11 TWh of electricity	5 million tons of CO_2 emissions avoided
Electronic displays	84 thousand tons of plastics recycled yearly	39 TWh of electricity yearly	Up to 13 million tons of CO_2 emissions
Cooking appliances	15 years with eco-efficient cooking appliances save up to 230 €	1 % of energy consumed annually in households is saved	2.7 million tons of CO_2 not emitted per year
Dishwashers	300 € saved on the lifetime of the product	2.1 TWh of electricity	0.7 metric tons of CO_2 equivalent avoided yearly
Water pumps	300 € saved on the lifetime of the product	Use of 3.3 TWh avoided of electricity	1.5 million tons of CO_2 not released yearly
Off mode, standby and networked standby devices	N/A	4 TWh of energy savings	Reduction on GHG emissions by 1.36 Mt. CO_2 eq per year

Table 3
Identification of resource risk and circular solutions for risk reduction.

Resource risk	Circular solution	Reference
Water scarcity	Development of new technologies and enhancement of the actual ones to promote water recycling and purification systems, thus reuse water for sustainable agricultural practices. Also, the promotion of sustainable and responsible use of water in industrial and service sectors could heal to reduce the risk on water availability.	(Hussain et al., 2019; Ingrao et al., 2023; Maeseele and Roux, 2021)
Energy dependence on fossil fuels	This risk is trying to be faced by the promotion of energy transition through the establishment of policies, action plans and legislation to reduce the dependence on fossil fuels. Research and enhancement of renewable energy, as wind, solar o hydropower, could reduce energy shortages and promote a sustainable energetic sector.	(McCauley and Pettigrew, 2023; Qadir et al., 2021)
Depletion of critical resources	The increase on the use of electronics, as well as some new technologies that requires these materials, as solar panels, have resulted in the rapid consumption of metals and minerals. Recycling and recovery strategies, and the promotion of responsible mining activities, could help on the avoidance of the depletion of mineral resources.	(Calvo and Valero, 2022; Watari et al., 2021)
Deforestation and land degradation	The implementation of sustainable practices on the agricultural and forestry, enhancement of reforestation and regenerative agricultural could be helpful on the restore and protection of land and forest areas.	(Giuntoli et al., 2022; Kauppi et al., 2022)
Food waste	Every year, supply chains suffer from large quantities of food waste. The implementation of resource recovery from food waste, its use for animal feed, if possible, as well as the inclusion of food waste reduction plans could be considered circular and effective actions.	(Chhandama et al., 2022; Trabold and Babbitt, 2018; Varjani et al., 2023)
Plastic pollution	The reduction of non-biodegradable plastics, as well as the increment on incentives for the research on new bio-based plastics, biodegradable, and recycling strategies, could be adequate to mitigate plastic pollution.	(Awogbemi and Von Kallon, 2023; Bauer et al., 2022; Tang, 2023)
Climate change	Some circular actions rely on carbon capture and storage technologies, the implementation of recovery strategies in value chains to avoid inadequately managed waste streams, and the transition to low-carbon technologies.	(Kamali Saraji and Streimikiene, 2023; Krishnan et al., 2023; Zhou et al., 2023)

being addressed:

3. Results and discussion

In this section the main goal is to identify the available and most appropriate criteria looking to evaluate, as effectively as possible, the energy transition. In this approach, the European Environmental Agency has created a guideline for the evaluation of the sustainability on energy transition, encompassing 4 social indicators, 16 economic and 10 environmental-based indicators. Regarding the social aspect, the main pillars of assessment are the evaluation of the equity and heath, being aware about the affordability, accessibility and safety of the energy transition and dependence. With respect to economic indicators, while the security on energy availability is also an aspect of awareness, the main focus is the evaluation of the use and production patterns, in which the productivity on production, the efficiency on the distribution, the type of end use as well as the energy prices are the main focus. Finally, when assessing the environmental pillar, the indicators are classified according to atmosphere, water and land, in which maintaining the quality of the environmental services, assessing the type of waste management and climate change are the main aspects considered.

Besides the EEA, other authors have also provided new approaches and indexes to measure energy transition, as the case of Lehtveer et al. (2021) who identified that the indicators to measure the energy transition in the European context could be divided into three main categories: resource indicators, focused on assessing the type of renewable resource used for energy production, as well as its management and environmental effects, transition rate indicators, based on evaluating the sustainability on the use of alternative technologies and its effects over the economics, environmental and society, and energy security indicators, in which the scoring of the dependency on energy is the main constraint (Lehtveer et al., 2021).

The research report developed by Lutz et al. (2015) also includes the use of certain indicators for measuring, in this case, the Germany energy transition (Lutz et al., 2015). Those authors have expand the scope of the analysis, considering also the three pillars of sustainability, but aggregating the indicators in six dimensions: use of the environment, encompassing the aspects of use of resources and maintenance of carbon sinks and ecosystem services, environmental quality of life, in which the effects on health and on social communities are evaluated, natural capital, not based on economic aspects but on resources availability, biodiversity and ecosystems quality and actual investments, green economy, in which the economic dimension is evaluated through the analysis of the interrelation between corporations, households and government, economic and social development, based on evaluating the labor market, trends in demand and consumption as well as finances, and policies, considering the institutional and political actions and measurements to promote the transition of greener economies.

The scope of the Oeko-Institut for the European Commission is slightly different in terms of measuring the effects of energy transition, more focused on the social and environmental justice, identifying as the main goals of the energy transition the reduction of inequalities on the distribution of benefits and environmental effects, promotion of financial savings and social participation, and awareness on how the transition affects over the economic growth and employment. Mostly all of the indicators used are framed on the objectives of the Sustainable Development Goals, and also considering other initiatives on the European Level.

On the other hand, some authors also encourage the use of the "Transition Performance Index (TPI)", a wide scoreboard that considers the encompass of economic, social, environmental and governance transition. It should be mentioned that, according to the database of the European Commission, the EU average score on energy transition amounts to 68.96, thus being classified as a "strong transition" according to the classification of the TPI, while the world average transition is below, 51.54, framed on the moderate transition level. Besides, as society is one of the most affected when talking about energy transition, in order to effectively assess the impacts over the social dimension, also the "Leave-no-one-behind" index could be interesting to be applied. It considers four dimensions on the social pillar: poverty, services, gender and income.

3.1. Criteria to be assessed for energy transition analysis

Bearing in mind the different approaches and indexes considered by the aforementioned organizations and researchers, Tables 4, 5, 6 and 7 are provided, encompassing the most important ones in order to effectively assess the adequacy of energy transition on the promotion of a more sustainable and circular energy sector. The classification of the indicators has been based on the three pillars of sustainability: environment, economics and society, as well as governance, as it has been demonstrated that the support from policies, financial investments and regulations is key on the effectiveness of energy transition.

3.2. The present and future framework

The EU has made a significant commitment to the integration of renewables into the energy mix of European regions, setting targets and policies and action plans to accelerate the transition to a low-carbon economy. For example, the Renewable Energy Directive implements the target of achieving at least a 32 % share of renewables by 2030, and also promotes the development of individual national targets to advance the energy transition. Forecasts on employment opportunities depend on specific scenarios, value chains and regions, but several potential trends could be identified. In sectors related to the energy transition, namely the renewable energy sector (*i.e.*, solar, wind and hydropower), energy efficiency technologies (including the retrofit and construction sector, as buildings need to be adapted to reduce energy needs) and the transportation sector (*i.e.*, electric vehicles), employment opportunities are expected to increase, encompassing technicians, installers, engineers, designers, researchers and auditors. On the other hand, sectors related to non-renewable resources, such as fossil fuel industries or nuclear energy, may experience a decline in employment opportunities, given the decrease in demand for these types of energy resources and the shift to cleaner energy systems.

The EU has also worked on including financial support, investments in renewable projects and portfolio standards in the form of policy measures, which could also help further efforts by stakeholders and entrepreneurs to work on new technologies for renewable energy production. In this sense, as could be seen in Figs. 4SM and 5SM, progress has been made in renewable energy production. As could be seen in Fig. 4SM, the increase of renewable electricity generation in the European context is remarkable, while in the 2000s the total annual amount only reached around about $1.45{\cdot}10^6$ GWh, by early 2020 this value has increased to more than $3{\cdot}10^6$ GWh, being twice as high. Regarding the percentage increase, it could be observed that in most years, the improvement was proportional, with the only exception of the transition from 2002 to 2003 and from 2010 to 2011, where a reduction in renewable electricity production was detected. On the other hand, Fig. 4SM also provides the type of technology for electricity production, where significant variations are also observed between 2000 and 2020. While the presence of wind and solar power is almost negligible, in 2020 the sum of solar and wind related technologies is more than double compared to hydropower, which is the most prominent energy for the early 2000s. The rationale behind these lower costs is also given the technological advances ease of grid integration and incentives and subsidies. Solar and wind energy technologies have rapidly improved their efficiency and thus their cost-effectiveness, thanks to improvements in panel design, turbine technologies and storage solutions. Those storage solutions and the improve on the integration of these type of energies on the grid has enhanced the reliability and attractiveness of solar and wind technologies.

Table 4
Environmental indicators to be assessed in order to quantify energy transition. Database: Oeko-Institute, Lehtveer et al., 2021, Lutz et al., 2015.

Avoidance of climate change.	Biodiversity protection.	Resources quality.	Waste production and management.
E1. *Qualitative assessment of GHG emissions in ton per capita* ***E.2.*** *Score of the carbon footprint of the renewables energies production (ton CO_2 eq. per kWh of energy produced)*	***E3.*** *Percentage of protected areas in comparison with total use areas for energy production.* ***E4.*** *Effect on bioenergy production over biodiversity (i.e., number of species lost or being affected)*	***E5.*** *Air quality* ***E5.1.*** *Quantification of the ambient concentration of air pollutants in urban areas* ***E5.2*** *Amount of pollutants emissions from energy production* ***E6.*** *Water quality* ***E6.1.*** *Discharges of pollutants on water from energy production* ***E6.2*** *Evaluation of water productivity (i.e., volume of water used per kWh of energy produced or amount of water recycled to the process)* ***E7.*** *Soil quality and land protection* ***E7.1.*** *Use of fertilizers per area of crop lands for energy production* ***E7.2*** *Measurement of soil are affected by acidification.* ***E7.3*** *Hectares of land used for energy crops and comparison to agricultural areas to food sector.* ***E7.4*** *Rate of deforestation associated with the energy sector.* ***E7.5*** *Amount of carbon sink areas per hectare of land used for energy production.* ***E8.*** *Appropriate use of resources* ***E8.1.*** *Mass of critical materials used for the technologies needed for bioenergy production (i.e., solar panels)* ***E8.2.*** *Measurement of the quantity of materials being recycled (i.e., kg of materials reused per kg of residues produced)* ***E8.3.*** *Resources productivity on energy production (i.e., number of resources required per kWh of energy produced)*	***E9.*** *Amount of waste per kWh of energy produced.* ***E10.*** *Ratio between amount of waste appropriately managed and the total waste generated.* ***E11.*** *Total amount of waste sent to landfilling from the energy sector.* ***E12.*** *Mass of radioactive residues per kWh of energy produced.*

Table 5
Economic indicators to be assessed in order to quantify energy transition. Database: Oeko-Institute, Lehtveer et al., 2021, Lutz et al., 2015.

Use, production and efficiency.	Natural capital investment.	Renewable energy.	Energy prices.
***EC1**. Use and productivity.* ***EC1.1.** Amount of energy used per capita.* ***EC1.2.** Amount of energy required per unit of Gross Domestic Product (GPD).* ***EC1.3.** Efficiency on renewable energy conversion and distribution.*	***EC2**. Amount of economic resources used on the conservation of land used for energy production.* ***EC3**. Investments on green corridors for biotope networking.* ***EC4**. Amount of energy required per unit of Gross Domestic Product (GPD).*	***EC5**. Production.* ***EC5.1.** Ratio resources-to production, calculated by the amount of renewable resources required per kWh of electricity produced.* ***EC5.2.** Ratio reserves-to production, calculated by the intensity on reserves depletion per kWh of electricity produced.* ***EC6**. Use.* ***EC6.1.** Energy intensity on the productive sectors: primary (agriculture, farming, etc.), secondary (industrial processing) and tertiary (services and commercial sectors).* ***EC6.2.** Ratio between renewable energy and total energy used in the **EC6.1** sectors.* ***EC6.3.** Households energy intensity in terms of total kWh required per year.* ***EC6.4.** Renewable energy demand from the transport sectors, both passengers and freight travels.*	***EC7**. Price of renewable energy by type and by sector, considering with and without taxes and subsidies.* ***EC8**. Difference percentage on the price between non-renewable and renewable energies.*

On the other hand, liquid biofuels and biogas have also experienced an increase over the years, but not as remarkable as in the case of solar and wind energy. Besides, the comparison of renewable with conventional fossil-based production is shown in Fig. 5SM. As could be seen, although significant improvements in the share of renewables have been achieved over the years, especially since 2010, there is still a challenge to be faced to go towards decarbonization, as the average share of renewables in the electricity mix in European regions still does not reach 50 %. The use of coal and peat has been significantly reduced from the 2000s to 2020, as these are resources that involve the emission of high level of GHGs and other air pollutants when burned for energy production and, to be aligned with the Paris Agreement targets and ensure the health of communities, there has been an urgent need for their reduction. In this context, both national and EU governments have implemented phase-out plans and carbon pricing mechanisms to discourage the consumption of coal and peat for energy production. In addition, it has been reported that the reduction in the use of these non-renewable resources also increases energy security by reducing dependence on their suppliers, which is an essential aspect when assessing an

Table 6
Social indicators to be assessed in order to quantify energy transition. Database: Oeko-Institute, Lehtveer et al., 2021, Lutz et al., 2015.

Energy security.	Social awareness.	Health and safety.	Other aspects.
***S1**. Net energy imports per total primary energy supply.* ***S2**. Stocks on critical materials for energy production and it comparison with its demand (i.e., ton of critical materials per ton needed for solar panels production)* ***S3**. Net energy imports per total primary energy supply.* ***S4**. Energy accessibility to all households enhanced by energy transition (i.e., comparison between energy accessibility before and after energy transition).* ***S5**. Energy affordability on households and services sector enhanced by energy transition (i.e., comparison between incomes spent of fossil resources before and after energy transition).*	***S6**. Healthy life expectancy at birth (years) increased by energy transition.* ***S7**. Employment rate between 20 and 64 years on energy transition sectors in comparison to total employment rate in all sectors.* ***S8**. Gender equality in the energy transition sectors, and related ones.* ***S9**. Fair salaries on the energy transition sector (i. e., % of non-remunerated time per total worked time).* ***S10**. How energy transition has helped on reducing public debt (i.e., comparison between debt to GDP ratio before and after energy transition).*	***S12**. Number of accidents derived from the renewable energy production.* ***S13**. Reduction on health effects and illness derived from pollution from energy production.*	***S14**. Scoring of the amount of people suffering about extreme poverty and material deprivation, in relation with the energy sector.* ***S15**. Measurement of energy inequalities and effective protection of the fundamental labor rights in the energy sector.* ***S16**. Evaluation of how the energy transition could help on the accessibility and quality of energy services.*

Table 7
Governance indicators to be assessed in order to quantify energy transition. Database: Oeko-Institute, Lehtveer et al., 2021, Lutz et al., 2015.

Policies on renewable energy.	Funding.	Institutional framework.	Stakeholder engagement.
***G1**. Number of policy measures for a green economy based on renewable energies.* ***G2**. Percentage of reduction on the subsides that does not enhance the promotion of renewable energy transition.* ***G3**. Enhancement of policies on environmental taxation and tradable permits on energy sector.*	***G4**. Number of policy measures for a green economy based on renewable energies.* ***G5**. Total funding received for the development of renewable energy production processes.* ***G6**. Promotion of research for energy transition based on economic incentives.* ***G7**. Environmental awareness programs to promote the energy transition.*	***G8**. Evaluation of the tools used for promoting an effective coordination for enhancing energy transition.* ***G9**. Transparency framework with respect to energy security, energy accessibility, social development and economic growth as a result of energy transition.*	***G10**. Proposition and implementation of measures to promote the involvement of experts and stakeholders in the energy transition.*

efficient energy transition (Belaïd and Zrelli, 2019; De Rosa et al., 2022; Hughes, 2009). Apart from the share of renewables in the energy mix, another important aspect to be assessed to ensure the sustainability of the energy transition is the potential of each European region to install a renewable energy facility. For example, regions with the longest sunshine hours are the most promising for the installation of solar photovoltaic panels, while the windiest regions will be preferred for the installation of wind turbines. In this context, the following figures show the average theoretical potential of PV power production (kWh/m^2/day) (data for 2023) (Fig. 6SM, A) and the average eolic power density (W/m^2) (Fig. 6SM, B) (data for 2021) per region. As can be seen, in the case of solar energy, the Spanish and Portuguese regions seem to have the highest potential for this type of technology, while in the case of wind energy, northern countries, such as Norway or the United Kingdom, are expected to be more efficient in terms of production capacity.

The Energy Transition Index (ETI), a tool used by the World Economic Forum, could be useful to assess and evaluate the progress made by European countries in the transition to a low-carbon energy system, taking into account environmental, social and economic dimensions. This tool could be useful to know where to focus to increase the transition and to highlight the strengths of each country, as well as its main areas for improvement. It also allows for cross-country comparisons, which could also be considered as a driving force for advancing the energy transition. Several indicators and databases are used to assess this index, some of which are energy capacity and efficiency, climate change, existing subsidies, policies and regulatory frameworks, carbon intensity, policies, energy security, human capital, technology investment and economic growth. Each indicator is weighted according to its relative importance, and a final composite index is obtained for each country level, which is then incorporated into the global ranking.

In this context, Table 8 depicts both the global ranking and the energy index of the European Union countries. As could be seen, the best European country in terms of energy transition is Sweden, achieving a value of 78.6, 2.2 points above Denmark, the second best ranked European region. The difference between Sweden and the country with the lowest score, Poland, amounts to 20.9 points, but it is worth mentioning that this country has experienced a significant change in the index since 2012, higher compared to other countries with a higher transition index, such as Cyprus, Romania, Italy, Portugal, Germany, the Netherlands and even Denmark, with the third position.

On the other hand, the indexes referring to best (Sweden, Fig. 6), average (Belgium, Fig. 7) and worst country (Poland, Fig. 8) have been deeply analyzed, considering the most important parameters to be calculated to obtain the final value of the index. The main categories of parameters are the following: system performance and transition readiness, where in system performance both economic growth, safety and environmental issues are evaluated, when evaluating transition readiness, the main focus is on investments, energy system organization, governance, regulations, among others.

In the case of Sweden, Fig. 6, all parameters needed to analyze the final energy transition index, both system performance and transition readiness, achieved individual scores above the regional and global average, except for the Energy System Structure (ESS) and Regulation and Political Commitment (R&PC) sub-indices, where the values are on the borderline compared to the global and regional averages, respectively. On the other hand, the value that stands out the most is the Environmental Sustainability (ES) sub-index, as it has the largest difference between the regional and global average values and that of the country. In general, the sub-indexes related to the system performance (SP) category obtain better scores compared to the transition readiness (TR) category.

Moving towards the country with an average index value (Belgium, Fig. 7), the scores obtained are significantly different from those of the top-ranked country. In most of the sub-indexes the country does not achieve a sufficient score to be above the regional average value, being in this case the SP sub-category the worst performer, with the Economic Growth and Development (EDG) and Energy Access and Security (EAS) sub-categories being the sub-indexes that are far from the average. On the other hand, with respect to the TR subcategory, in four of the sub-indices, the values obtained are in line or even better when compared to both regional and global average scores. However, in the case of the human capital and consumer participation (HCCP) and energy system structure (ESS) sub-indices, the values obtained are below average, so further improvements are needed.

Similar values are obtained when examining the case of the worst ranked country at the EU level (Poland, Fig. 8), where, contrary to the previous case, the most disadvantaged subcategory in this case is TR, especially in the ESS sub-index, where the value obtained is significantly lower than the regional and world average, by more than 50 %. In the case of HCCP, the score achieved is also below the regional average, although at the limit of the global one, similar to the case of the R&PC sub-index, but in this case with a smaller difference. With respect to the other category, SP, it is the ES sub-index where the greatest improvement is needed, as it does not reach the averages, while in the case of EGD Poland is very close to the regional and global averages. Finally, the

Table 8
Energy transition index for the European Union countries. Database: "Fostering Effective Energy Transition" a report by World Economic Forum (2022). Color code: best index (green), average value (yellow), worst index (red), higher increase on the index value (grey highlight on table cell).

Global ranking	Country	2021	Change since 2012	Global ranking	Country	2021	Change since 2012	Global ranking	Country	2021	Change since 2012
1	Sweden	78.6	1.29	16	Estonia	68.6	2.42	38	Romania	64.3	0.88
3	Denmark	76.8	0.9	17	Spain	68.3	2.42	40	Luxembourg	63.9	2.25
5	Austria	75.2	1.37	18	Germany	68.3	0.18	41	Malta	63.8	5.20
6	Finland	73.2	2.88	19	Portugal	68.2	1.89	43	Slovakia	63.1	3.02
9	France	71	1.74	20	Belgium	67	2.65	45	Czech Republic	62.5	2.06
11	Netherlands	70.9	0.87	23	Croatia	66.6	3.46	51	Cyprus	60.5	0.72
12	Latvia	70.7	2.49	27	Italy	66.1	3.22	54	Greece	60	4.87
14	Ireland	68.8	2.12	31	Slovenia	65.6	3.58	58	Bulgaria	58.6	4.38
15	Lithuania	68.7	5.3	32	Hungary	65.4	5.92	62	Poland	57.7	3.39

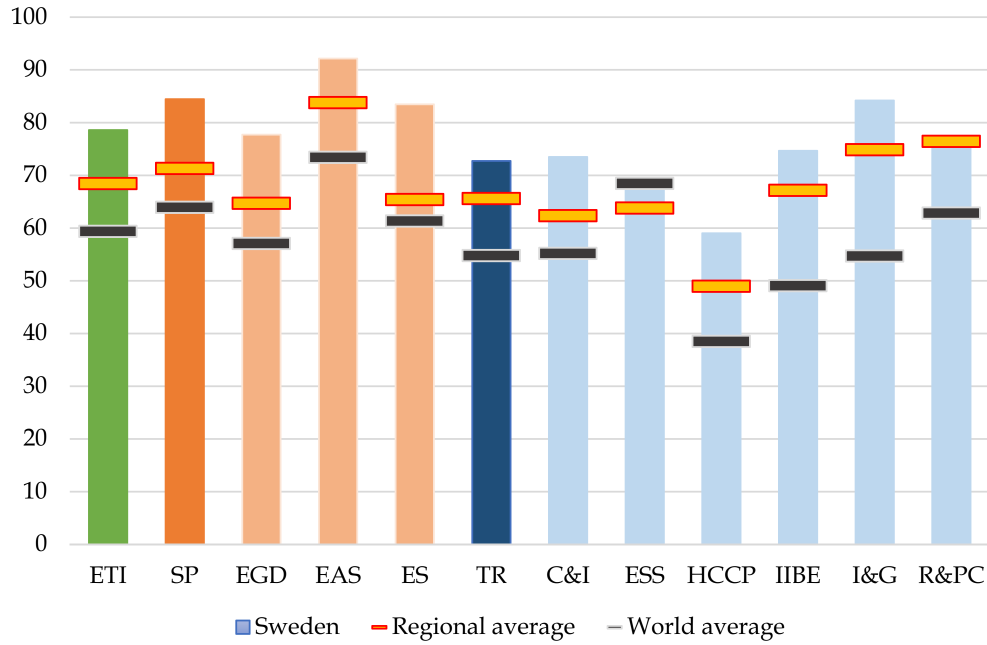

Fig. 6. Energy transition index and the most important parameters for its calculation. The vertical bars represent the values for Sweden country, the horizontal bars in yellow/orange the regional average values and the black/grey the world average energy transition indexes for each parameter. Acronyms: ETI (Energy Transition Index), SP (System Performance), EGD (Economic growth and development), EAS (Energy access and security), ES (Environmental sustainability), TR (Transition readiness), C&I (Capital and investment), ESS (Energy system structure), HCCP (Human capital and consumer participation), IIBE (Infrastructure and innovative business environment), I&G (Institution and governance), R&PC (Regulation and political commitment).

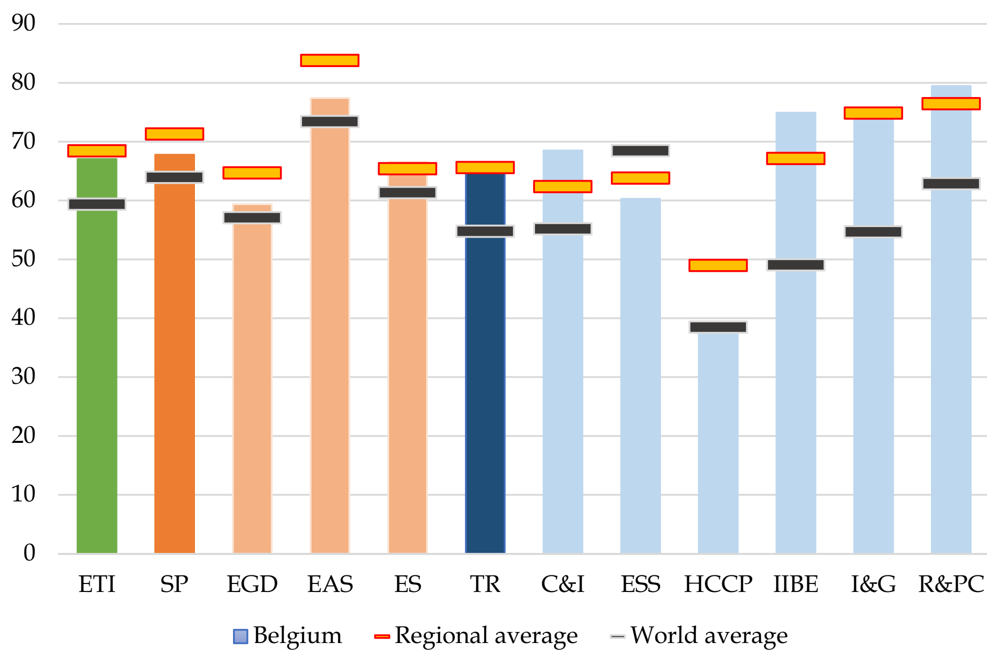

Fig. 7. Energy transition index and the most important parameters for its calculation. The vertical bars represent the values for Belgium country, the horizontal bars in yellow/orange the regional average values and the black/grey the world average energy transition indexes for each parameter. Acronyms: ETI (Energy Transition Index), SP (System Performance), EGD (Economic growth and development), EAS (Energy access and security), ES (Environmental sustainability), TR (Transition readiness), C&I (Capital and investment), ESS (Energy system structure), HCCP (Human capital and consumer participation), IIBE (Infrastructure and innovative business environment), I&G (Institution and governance), R&PC (Regulation and political commitment).

biggest difference when comparing the three profiles is in the final score of the Energy Transition Index, since while the other two scenarios are above the averages and therefore more efficient in terms of energy transition compared to the average trend, in the latter case the score obtained is lower, although not by a very significant percentage.

As a general discussion it could be stated that the use of the Energy Efficiency Index, together with the analysis of the sub-categories and sub-indices required for its calculation, is an efficient tool to be aware of where to focus efforts, policies and action plans to promote a greater energy transition in the region. In this sense, future directions for advancing fossil-based energies and ensuring long-term stability of decarbonization effects that could be considered "crucial" could be the

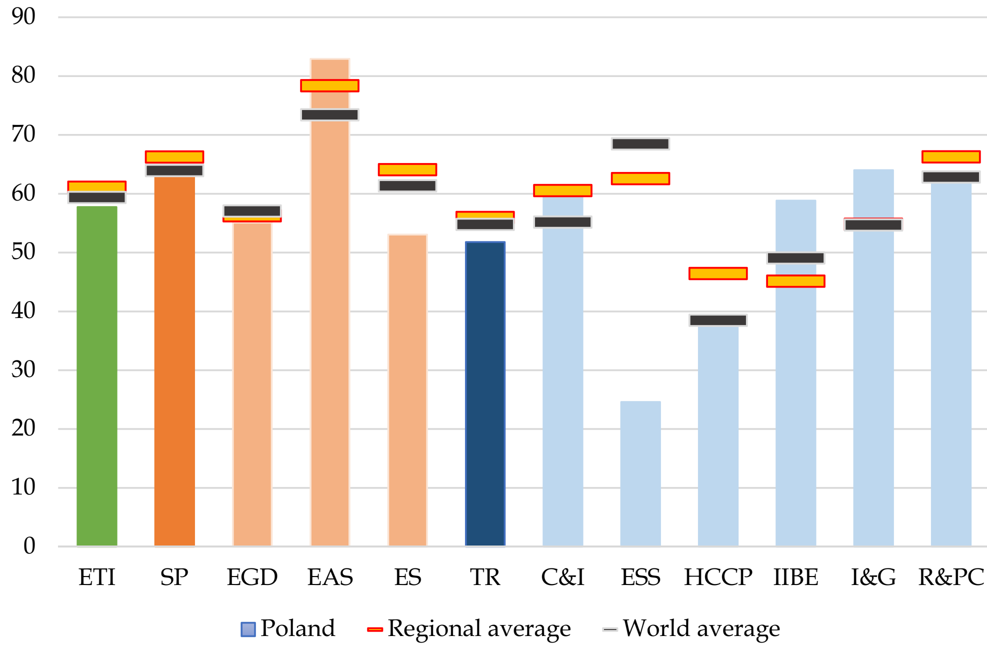

Fig. 8. Energy transition index and the most important parameters for its calculation. The vertical bars represent the values for Polish country, the horizontal bars in yellow/orange the regional average values and the black/grey the world average energy transition indexes for each parameter. Acronyms: ETI (Energy Transition Index), SP (System Performance), EGD (Economic growth and development), EAS (Energy access and security), ES (Environmental sustainability), TR (Transition readiness), C&I (Capital and investment), ESS (Energy system structure), HCCP (Human capital and consumer participation), IIBE (Infrastructure and innovative business environment), I&G (Institution and governance), R&PC (Regulation and political commitment).

following:

1. Improving investment, policy incentives and financing in projects on renewable resources and CCUS (Carbon Capture, Utilization and Storage) technologies. Those are key players in the decarbonization of the European Union, but for their further development, their cost-effectiveness must be ensured through adequate support from stakeholders, policies and also the social community.
2. Adaptation of traditional technologies to make them less harmful to the environment. For example, in the case of natural gas, the implementation of CCUS could provide a lower carbon energy resource. To achieve this advantage, constant monitoring and the development of appropriate regulations are required to ensure an effective reduction of emissions and a “more sustainable” fossil-based energy source.
3. Promotion of alternative renewable technologies instead of solar and wind, as they showed the highest percentage share at the European level. The increase in population has ended up with a huge amount of municipal waste, which could be further valorized for energy purposes instead of being sent to landfills, which are highly unsustainable. The biomethane produced by its valorization could replace fossil natural gas and, at the same time, promote a triple benefit: better waste management, avoidance of landfills and their associated environmental impacts, and cleaner energy.
4. Ensuring economic growth and the well-being of social communities with energy transition. Although the main objective for moving away from fossil resources is the environmental pillar of sustainability, the other two are also equally important. The support of social communities is essential for increasing the value of renewable resources, as well as for the efficient and conscious use of energy. To this end, the energy transition must promote economic growth and job creation in the energy sector and must provide a healthier planet to avoid common health problems related to climate change, such as cardiovascular and respiratory diseases. In addition, the transparency and reliability of energy transition action plans must be safeguarded. Most of the problems related to transparency in the energy transition relate to the lack of data availability, accountability and information sharing. These problems could lead to greenwashing, which provides biased information on the environmental benefits of products and processes. Lack of access to data implies significant challenges in the decision-making process by stakeholders and local communities on energy transition strategies. Transparency issues also affect traceability, making it certainly impossible to be accurate and reliable and could also have a major impact on reporting and monitoring activities.
5. Creation of strong policy frameworks and carbon pricing taxes to promote incentives to reduce emissions and accelerate the transition to a cleaner energy sector. A financial incentive should also be created for companies, at least in the “first gross installation”, to promote a higher share of renewables in the energy mix and reduce related emissions. Some economic incentives that could be identified are the tax credits, to reduce the installation cost of renewable energy technologies, deductions, to enhance investment, feed-in-tariffs, which entails a guaranteed payment for those who produce electricity using renewable technologies, net metering, to sell the excess renewable electricity to the grid, adaptation of standards, green bonds, to enhance the development of projects for the adoption of renewable energies, financial aids from the governments, carbon pricing, to incentive the adoption of renewable energies given its lower costs in comparison to the fossil-based ones, and acceleration of depreciation, promoted by the governments and interested stakeholders and entrepreneurs.
6. Increase energy efficiency and ensure energy security for all social communities. Some of the priorities to improve energy efficiency are the implementation of digitalization in the technologies, and the integration of monitoring and optimization systems in the framework of Industry 4.0, could effectively increase the energy efficiency (Shabalov et al., 2021). In addition, another important issue in the efficiency of energy sector is on its storage, which is considered as a critical aspect for a green transition (OECD, 2019). These aspects are key to reducing demand and dependence on fossil fuels, as well as awareness of the avoidance of metal and mineral depletion for

building renewable technologies. Intelligent design and end-of-life strategies must be consciously carried out when implementing new technologies, seeking to avoid the uncontrollable use of resources as happened with fossil fuels.

7. Be mindful of the three pillars of sustainability and the European Commission's Circular Economy Action Plan when evaluating renewable energy and technologies. Promoting clean energy means adapting the new energy sector to the principles of sustainable development and circularity. It is necessary to demonstrate environmental, social and economic benefits, as well as to avoid underutilization of available resources, even if they are renewable. In addition, the SDGs must also be considered, especially in terms of food security, as some of the renewable energies are produced through the use of crops, and energy security, to promote their access to all of society, including marginalized areas. These aspects are not as well fulfilled in the concepts of sustainability and circularity but are equally important. Policies should prioritize renewable and infrastructure investment projects in marginal areas, for example by expanding the electricity grid, providing smaller grids to localize power generation, or promoting emerging off-grid strategies. In addition, policymakers could also improve and promote financial incentives for low-income communities, such as facilitating the purchase of solar panels or electric vehicles.

An important issue that should be critical and deeply analyzed is the relationship between energy transition and geopolitical risks, as going further renewability on energy could have an important effect on global policies and international collaborations. The reliance of some countries on fossil fuel imports could imply international conflicts and issues on energy supply and access to resources, that should be treated carefully to avoid energy disruptions. Besides, the transition could also affect over the "dominance" of certain regions in the global energy market, causing a reduction on the dominant position of energy-exporting regions over the energy-importing ones, thus being a possible way of conflict given the effects on economic growth of the exporting regions. Moving forward renewable energy should also ensure the absence of economic disparities between European countries, as well as it should guarantee that all the regions are having the appropriate infrastructure development (*i.e.* electric grids) to implement non-fossil based energy resources. Another important fact is the establishment of new alliances between European countries, with the ones having a higher potentiality on the production of renewable energies (*i.e.* coastal regions are able to produce hydropower energy, windy regions for wind energy, so climate has an effect on the capacity of production). Given this geopolitical risk issues, Europe should carefully analyze how this energy transition is being developed in order to reduce the aforementioned risk and to ensure that the energy sector is stable and safe in the future coming.

Social communities are a crucial on the decision-making of the political actions and policy actions, in order to ensure that decisions on energy transition are taken consciously, with deliberation, appropriate authorization and a collaborative between all stakeholders (Rogge and Reichardt, 2016). The alignment of social communities, together with the aggregation of all internal and external actors of the society, could enhance the transition and provide innovative solutions to promote renewability and reduction on the dependence of fossil resources, moving for a green and inclusive economy (United Nations, 2021). Besides, it is important to consider a multi-level policy coordination in order to avoid differences between regions, as inclusiveness on energy access should be something to be avoided in this energy transition (Berka et al., 2020). On the other hand, governments and stakeholders should recognized the limits on the adaptation to renewable energy resources, bearing in mind the economic capacity of the regions, and also enhance the consciousness of social communities on energy savings (Villalba-Eguiluz et al., 2023). Energy transition should be sustainable and solidary, in which social aggregation is considered as efficient to meet the requirements of green economy and to promote an ecological transition (D'amato and Korhonen, 2021).

Besides, it could be stated that the present manuscript entails an evident role in advancing on SDG12 "Responsible Consumption and Production", as it provides guidance and a selection of indicators to measure how the energy transition could have an effect on environmental protection, social welfare, economic growth and thus ensure responsible energy consumption and production. Within the scope of the sub-target 12.2 "Resource efficiency and circular economy", the report provides the circularity approach and the assessment of critical materials in the transition to renewable energy, for the target 12.4 "Environmental impact reduction", the GHG emissions avoided by the energy transition have been analyzed. In the case of sub-target 12.5 about "Social inclusion and equitable access", 16 indicators have been selected to measure social sustainability, while discussing energy poverty and access to energy by social communities, as well as the importance of their inclusion in energy-related decision-making processes, also contributing to the sub-target 12.6 "Sustainable Development integration".

Regarding the limitation of the study, it is important to note that data availability and transparency are key in the analysis of energy transition strategies and technologies, since a limitation found in the analysis is related to difficulties in data collection for the evaluation of sustainability and circularity indicators, two perspectives that should go hand in hand to ensure an effective energy transition. To this end, in a future framework, accessibility to data should be promoted.

4. Conclusions

The analysis presented in this article concerning the impact of the energy transition on the pillars of sustainability and material circularity has shown that, compared to previous periods of this energy transition, the environmental, economic and social benefits are highly plausible. The energy transition contributes to an improvement in the quality of the environment, enables economic growth and implies an enhancement in the quality of life of social communities, as long as the priorities and needs, but also the balance between these three pillars, are taken into account. The development and implementation of integrated policies that enhance the achievement of sustainability in the energy sector could be useful, such as those that set clear emission reduction targets, policy actions to promote the creation of green jobs, and effective policy grants to enhance sustainable energy education in social communities. In addition, a collaborative attitude between policy makers and stakeholders would be effective in addressing trade-offs and synergies in the energy sector.

On the other hand, this manuscript has also shown the need for political initiatives, financial support, and the easing of the promotion and certification of new energy production models. Governments should participate in the energy transition in forms of subsides for renewable energy projects, in the development of supportive and collaborative regulations for the energy sector, as well as in the implementation of tax incentives for renewable technologies. Those must also avoid the mistakes of the past, such as the depletion of fossil resources due to their intensive use, which cannot happen now with the so-called critical materials for the energy transition. Policies should promote and foster stakeholders' collaboration, considering the integration of industries, social communities and academia in the decision-making process for the implementation of renewable technologies. Also, policies should develop new management strategies for avoiding the depletion of renewable resources, as by the implementation of recycling programs or the enhancement of the diversification of resources.

In general, it can be concluded that the energy transition is positive and beneficial, but only if it complies with the standards and requirements of sustainability and circularity. The creation of a regulatory framework to promote the cooperation and implementation of sustainability and circularity standards will be desirable, also including the possibility of achieving economic incentives to the technological performances that embrace sustainable practices.

CRediT authorship contribution statement

A.A.: Methodology, Formal analysis, Investigation, Writing-original draft, Writing-review & editing. G.F.: Supervision, Writing-review & edition. MT.M.: Supervision, Writing-review & editing.

Declaration of competing interest

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

Data availability

Not applicable.

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Appendix A. Supplementary data

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