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Eco-environmental, and social impacts of producing electricity with various renewable energy sources

Rima Aridi, Mona Aridi, Marie-Lise Pannier, Thierry Lemenand ^{*} 

Univ Angers, LARIS, SFR MATHSTIC, F-49000, Angers, France

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ABSTRACT

The shift towards renewable energy is crucial for mitigating climate change and reducing dependency on fossil fuels. Exploring the diverse impacts of renewable energy sources is essential to guide future investments and policies. This study comprehensively compares five different renewable energy sources—solar, wind, biomass, hydropower, and pumped storage—used to produce electricity, focusing on their economic, environmental, and social impacts. Economic evaluations are conducted using the Levelized Cost of Energy (LCOE), revealing values of approximately 0.048, 0.030, 0.065, 0.045, and 0.085 €/kWh for the respective sources. Environmental impacts are assessed using the OpenLCA software, which evaluates ten midpoint impact categories that culminate in three endpoint damages: human health, ecosystem health, and natural resources. Accordingly, the Environmental Cost Indicator (ECI) was calculated, with results indicating values of around 0.0104, 0.0045, 0.0019, 0.0004, and 0.0180 €/kWh. Additionally, the social impacts these renewable energy sources are considered, highlighting the broader implications of their adoption. This comprehensive analysis provides a detailed understanding of the trade-offs involved in choosing different renewable energy sources, aiming to support sustainable energy transition strategies.

1. Introduction

In an era where global interconnectedness is rapidly increasing, the demand for enhanced human welfare, improved health, and expanded energy-related services is more critical than ever. Despite the unchanging physical shape of the Earth, our global society is undergoing significant transformations [1,2]. Energy resources play a crucial role in meeting basic human needs such as illumination, food preparation, spatial comfort, activities, and communication, as well as supporting creative and industrial processes across all civilizations [3].

According to the 2022 statistical analyses by Our World in Data, approximately 70 % of global energy sources are derived from burning fossil fuels [4]. This reliance on fossil fuels, while providing the majority of our energy, has serious environmental consequences. The combustion of fossil fuels releases substantial amounts of carbon dioxide (CO₂) into the atmosphere, contributing significantly to climate change and ecological degradation over the past 150 years [5]. The environmental impact of these emissions has reached problematic levels, necessitating urgent action to mitigate their effects [6,7].

The dominance of fossil fuels in our energy systems poses a challenge to both economic and environmental sustainability. This scenario underscores the need for developing new, accessible, environmentally safe, sustainable, and ecologically sound energy sources [8–10]. Transitioning to cleaner and more sustainable energy sources is imperative to curb global warming and protect our ecosystem. Despite the rapid growth of renewable energy, it remains insufficient to completely replace carbon-intensive energy sources in the near term. Fossil fuels are expected to continue playing a significant role in the world's energy balance for many years, even as oil production faces potential declines [11].

Fortunately, the universe offers a diverse array of renewable green energy sources [12]. However, the consumption of non-renewable energy sources still surpasses that of renewable ones. With rising global environmental awareness, the share of renewable energy increased to 29 % in 2018 [13]. Commonly used renewable energy sources include solar, wind, hydro, and geothermal energy, which are illustrated in Fig. 1. Transitioning to these sources is crucial for achieving a sustainable and environmentally friendly energy future.

Electricity plays a crucial role in daily life, and its price has

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* Corresponding author.

E-mail address: thierry.lemenand@univ-angers.fr (T. Lemenand).

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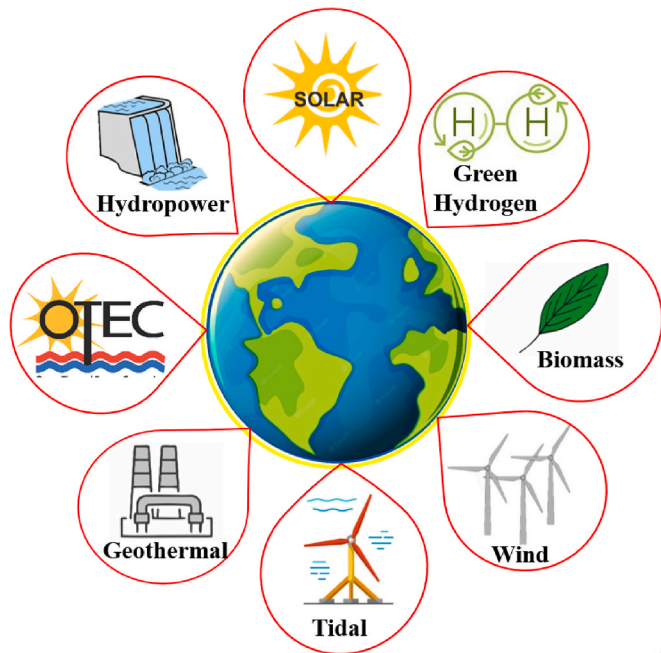


Fig. 1. Various renewable energy sources.

significant economic implications. While low electricity prices can boost purchasing power and competitiveness, high prices can drive the transition to cleaner energy and improved energy efficiency [14]. The International Energy Agency (IEA) and the European Commission (EC) work together to reform energy supply and demand by introducing alternative energy sources. The liberalization of electricity markets, particularly in the 1990s, improved efficiency, fostered competition, and benefited consumers, although government oversight remains essential. In the European Union (EU), electricity market liberalization was largely completed by 2014, with some countries seeing decreased prices, while retail electricity prices increased due to higher fuel costs and CO₂ emission-related expenses. The rise in renewable energy sources has contributed to these price increases, although wholesale prices have generally dropped. Technological advancements and further cost reductions in renewable energy could potentially lower electricity prices in the future. Full market liberalization increases competition, and EU policies supporting renewable energy aim to meet emission reduction targets set by the Kyoto Protocol and the Paris Agreement [15]. The Kyoto Protocol, adopted in 1997, set binding emissions targets for developed countries, while the Paris Agreement, approved in 2015 by 195 countries, focuses on global commitments to reduce greenhouse gas emissions by 2030 [16]. The shift to renewable energy is crucial for achieving global climate goals, including reducing CO₂ intensity by 96 % by 2050 [15,17].

In this study, a comparison on five renewable energy sources of production of electricity is carried out. The selected sources to produce electricity are solar, wind, biomass, hydropower, and pumped storage. The environmental impact of these sources was chosen as they were the only sources presented in the database for the same country. The sources are taken in Switzerland (CH) as there is a wide variety of renewable energy integration, according to Statista in 2023 [18], 88 % of Switzerland's electricity is from renewable energy sources [19]. Besides, all the data are obtained from the same database "Ecoinvent", which is developed in CH with data available for many countries. As for the economic and social impacts, the values are globally and not restricted to a specific country. To gauge the system's effectiveness, it is vital to examine three key areas: economic, environmental, and social [20]. These pillars are fundamental to sustainable development, aiming for minimal impact across all fronts [21].

This study's novelty lies in its comprehensive comparison of five different renewable heating sources under identical parametric conditions and for the same application, benchmarked against electricity-based fossil fuels. In addition, the study provides an in-depth analysis of the economic, environmental, and social impacts of each heating source, offering a holistic evaluation. Unique to this study is the use of OpenLCA software for environmental impact assessment across ten midpoint impact categories, culminating in three endpoint damages: human health, ecosystem health, and natural resources. Moreover, this research incorporates a detailed social impact analysis, which is often overlooked in similar studies, providing a broader perspective on the implications of adopting various renewable energy sources. This multifaceted approach aims to support sustainable energy transition strategies by presenting a comprehensive understanding of the trade-offs involved. Furthermore, a detailed investigation was conducted on electricity consumption from renewable energy sources and total electricity consumption across different countries.

2. Economic study

The Levelized Cost of Electricity (LCOE) for renewable energy sources such as solar, wind, hydropower, biomass, and pumped storage is influenced by several key factors. Capital costs, including initial investment for infrastructure and technology improvements, significantly impact LCOE. Operating and maintenance costs vary across technologies, affecting long-term expenses. The capacity factor, determined by the actual energy output relative to potential output, hinges on resource availability like sunlight, wind, and water flow. Financing costs, influenced by interest rates and financing structures, also play a crucial role. The project's lifetime, with longer-lasting systems spreading costs over more years, reduces LCOE. Government policies, including subsidies, tax incentives, and regulations, can lower costs and improve economic viability. Additionally, efficient energy storage and grid integration are essential for managing intermittency and ensuring reliability, impacting overall costs. Environmental and social factors, such as environmental impact and public acceptance, further shape the economic landscape for renewable energy projects.

The Levelized Cost of Electricity (LCOE) for renewable energy sources has experienced significant changes in recent years, marked by a notable decrease in costs and an increase in efficiency. This shift can be attributed to the substantial investment in research and development, leading to significant improvements in renewable energy technologies. Fig. 2 shows the variation of LCOE for different renewable energy sources in the last 12 years.

Over the past ten years, the fossil fuel price was between 0.05 and

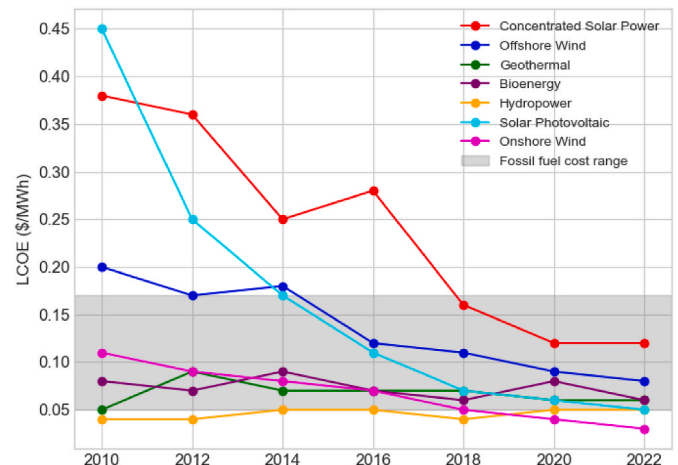


Fig. 2. Variation of LCOE of different renewable energy sources reproduced based on data from [22–24].

0.17 \$/kWh, now exposing the vulnerabilities of countries reliant on fossil fuels for power generation. Even before the 2022 fossil fuel crisis, renewables were already economically outcompeting fossil fuels. In 2021, new renewable energy capacities significantly underpriced new fossil fuel plants and, in many cases, existing ones as well.

Since 2010, solar photovoltaic (PV) technology has experienced dramatic cost reductions. The global weighted-average Levelized Cost of Electricity (LCOE) for newly commissioned utility-scale solar PV projects fell from 0.445 \$/kWh in 2010 to 0.049 \$/kWh in 2022, an 89 % decrease, primarily driven by a 90 % drop in module prices.

Onshore wind projects saw the global weighted-average cost of electricity decrease by 69 %, from 0.107 \$/kWh in 2010 to 0.033 \$/kWh in 2022. This was due to lower wind turbine costs and improved capacity factors. Offshore wind projects saw a 59 % reduction in LCOE, from 0.197 \$/kWh in 2010 to 0.081 \$/kWh in 2022.

Concentrating Solar Power (CSP) deployment has been slower, with less than 0.1 GW added in 2022, bringing the total to 6.5 GW. The LCOE for CSP dropped by 69 %, from 0.38 \$/kWh in 2010 to 0.118 \$/kWh in 2022.

Bioenergy's LCOE decreased by 13 % in 2022 to 0.061 \$/kWh, 25 % lower than in 2010.

Geothermal LCOE fell by 22 % from 2021 to 2022, reaching 0.056 \$/kWh.

New hydropower projects saw their LCOE rise by 47 % from 0.042 \$/kWh in 2010 to 0.061 \$/kWh in 2022, but costs remained lower than the cheapest new fossil fuel options despite significant cost overruns in some projects.

Renewable energy sources have become cheaper than finite sources of electricity due to several factors. Firstly, despite their high initial price, the intensive research and development held over improving these technologies provided highly efficient, yet affordable output compared to previous state. For instance, solar technology found a niche in supplying electricity for satellites like the Vanguard 1 in 1958, creating a demand even at high costs. As noticed from Fig. 2, the LCOE of solar PV undergone a drastic reduction that exceeds 10 times its cost within 12 years. Besides, as production increased, the price of solar modules declined due to learning-by-doing, leading to a virtuous cycle of increasing demand and falling prices. This positive feedback loop has propelled solar technology forward since its early days in outer space as shown in Fig. 3. Furthermore, according to Det Norske Veritas (DNV), formerly DNV GL, an international accredited registrar and classification society headquartered in Høvik, Norway [25], the average LCOE of solar PV is expected to fall by at least 40 % by 2050, with individual projects falling by as much as 60 % relative to today's average cost. With its high cost-learning rates (26 % at module level per doubling of capacity, declining to 17 % in 2050), solar PV will be the cheapest source of new

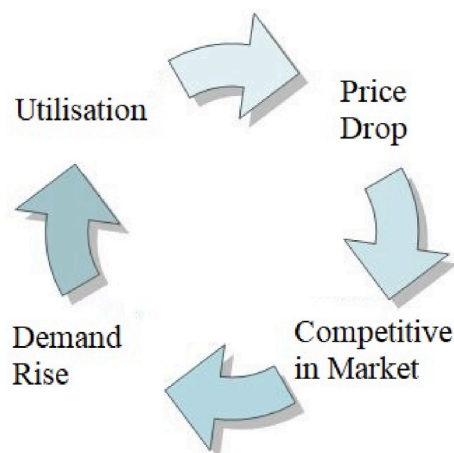


Fig. 3. The cycle of price and demand.

electricity globally by a considerable margin, despite its lower capacity factors relative to other variable renewable energy sources. By 2050, 23 PWh/yr of solar electricity will be generated worldwide.

Future trends in LCOE for renewables are poised to benefit from ongoing technological advancements and economies of scale. Innovations in solar panels, wind turbines, and energy storage solutions are expected to enhance efficiency and reduce costs. As renewable energy deployment increases, economies of scale will drive down costs through mass production and improved supply chains. Strengthening climate policies and international agreements aimed at reducing carbon emissions will continue to support renewable investments, potentially lowering LCOE by reducing financial risks and increasing regulatory support. Grid modernization efforts, including smart grid technologies, will facilitate higher integration of renewable energy, reducing costs associated with grid compatibility and improving overall economic feasibility. These trends collectively indicate a promising future for the cost-effectiveness of renewable energy sources.

In this section, we focus on economic study, specifically analyzing five renewable energy sources: solar, wind, biomass, hydropower, and pumped storage. Fig. 4 presents the levelized cost of electricity (LCOE), which denotes the break-even distribution price of generated energy throughout the system's lifespan. The cost of one kWh for solar, wind, biomass, and hydropower are extracted from Statista in 2021 per kWh [10], for the pumped storage the price is sourced from a published article [26].

It is noticed that the pumped storage has the highest LCOE, this could be attributed to the reason for integrating different systems. This integration demands increased maintenance, monitoring efforts, and pumping requirements, especially during energy shortages. On the other side, the wind source has the lowest LCOE, due to the significant improvements in wind energy technology that employ turbines with high efficiency and lower cost. Hydropower is also one of the cheapest renewable energy sources due to its simplicity in design and installation, however, it requires monitoring according to the season and the flow of water current. When comparing the studied renewable energy sources to fossil fuel, it is evident that electricity generated from fossil fuel tends to incur higher costs. This is largely attributed to the ongoing efforts directed towards reducing the cost of renewable energy sources. Despite the high initial cost of renewable energy, however, in the long run the cost is paid off and this is presented in the lower LCOE.

3. Environmental study

The Environmental Life Cycle Assessment (ELCA) method is commonly used to evaluate a product's environmental impact across its lifecycle. It estimates how each product affects the environment from inception to disposal, considering emissions and associated costs reflecting potential harm. Here, we assess the environmental effects of solar, wind, biomass, hydropower, and pumped storage. Each source emits specific pollutants with varying environmental consequences [27, 28].

Fig. 5 demonstrates the processes studied in the LCA of any type of product or process in two manners: (1) cradle to grave, which means studying the LCA from the first beginning till dumping or recycling the product, (2) cradle to gate, which means studying the LCA of the product from the creation till delivering it to the user that means after this stage the impact of the product use is not considered in the study. As noticed, each process has emissions to air, water, and soil that differ from one application to another. In this study, we conduct ELCA for the five energy sources to evaluate their environmental effects from cradle to grave, utilizing OpenLCA 1.10.3 and the Ecoinvent database v2.0 for a case study in Switzerland (CH) [29].

In this section, we will look at the life cycle assessment of each kind of renewable energy, where throughout the course of each process, byproducts mainly gases are released into the atmosphere (air and soil). These byproducts may have a negative impact on the environment. They

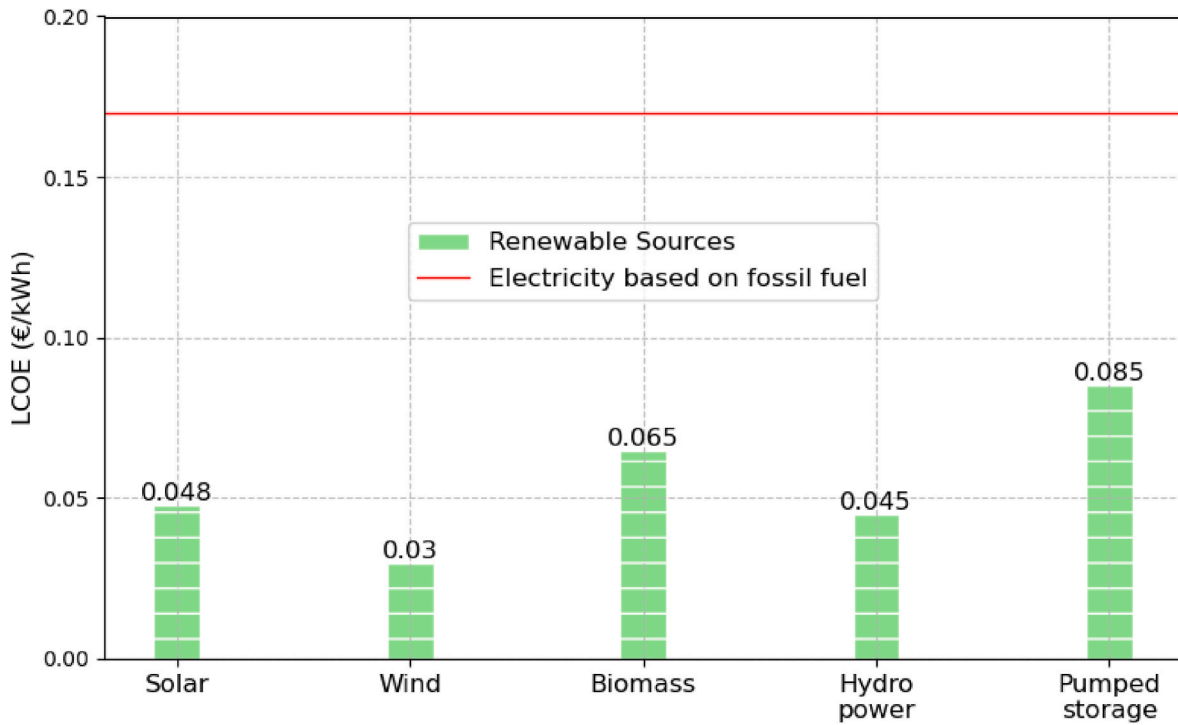


Fig. 4. Price of different renewable sources compared with LCOE of electricity-based fossil fuel.

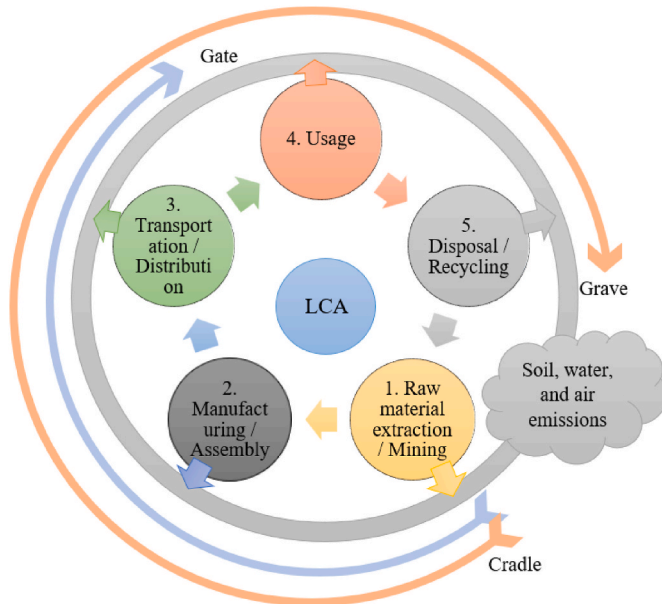


Fig. 5. Life cycle of using the heating source from cradle to grave.

differ from one operation to another, and each kind has a distinctive adverse impact. Consequently, the effects of each kind are evaluated, and measured in carbon dioxide equivalents (CO₂-eq), and the expense according to the Environmental Cost Indicator (ECI) is computed to evaluate all various indicators. This LCA classifies the implications of the groups into three sectors: (1) ecosystem health or abiotic environment influence and ecotoxicity impacts, which focus on the environment's overall impact, (2) human health, which deals with the environment's impact on people's health, and (3) natural resources or resource availability, which deals with the elements scarcity and natural assets [27, 30].

Fig. 6 shows the Environment Cost Indicator (ECI), which is a tool

used to assess the environmental impact of products or processes. It quantifies the total ecological costs incurred throughout their life cycle, encompassing resource use, emissions, and other environmental pressures. The midpoint impact category identifies specific environmental stressors, while prices ($Price_i$) reflect the monetary value of these impacts. Causes of ECI include activities like energy consumption and waste generation, contributing to overall environmental degradation. The endpoint of ECI analysis represented by damage to human health, ecosystem health and natural resources, reveals the ultimate environmental consequences, guiding efforts towards sustainability and informed decision-making [26].

Fig. 7 illustrates a radar chart depicting ten impact categories attributed to the five distinct energy sources studied in this paper. Each energy source exhibits varying degrees of impact across these categories, highlighting their individual environmental footprints. Notably, pumped storage emerges with the highest impacts across most categories. Conversely, solar and wind energy demonstrate elevated impact levels in human toxicity, while biomass stands out for its significant contribution to eutrophication, among others.

For instance, pumped storage has the highest impact in GWP100, ozone layer, photochemical oxidation, acidification potential, marine and freshwater ecotoxicity. On the other side, wind energy has the highest impact on human and terrestrial ecotoxicity, while biomass has the highest impact on the eutrophication. All the values are obtained from the software OpenLCA through Ecoinvent database.

Fig. 8 shows the impact ($Impact_i$) of producing 1 kWh of electric energy from the five renewable energy sources using the ECI, calculated for each energy source, with each impact category having a different coefficient that combines all relevant environmental impacts into a single result of environmental costs, which is equivalent to the environmental cost of the product.

The ECI presented for each source is calculated by multiplying the impact values ($Impact_i$) of each of the ten categories shown in Fig. 7, by their corresponding prices ($Price_i$) listed in Fig. 6. The sum of the prices across all categories constitutes the ECI, presented in the following equation:

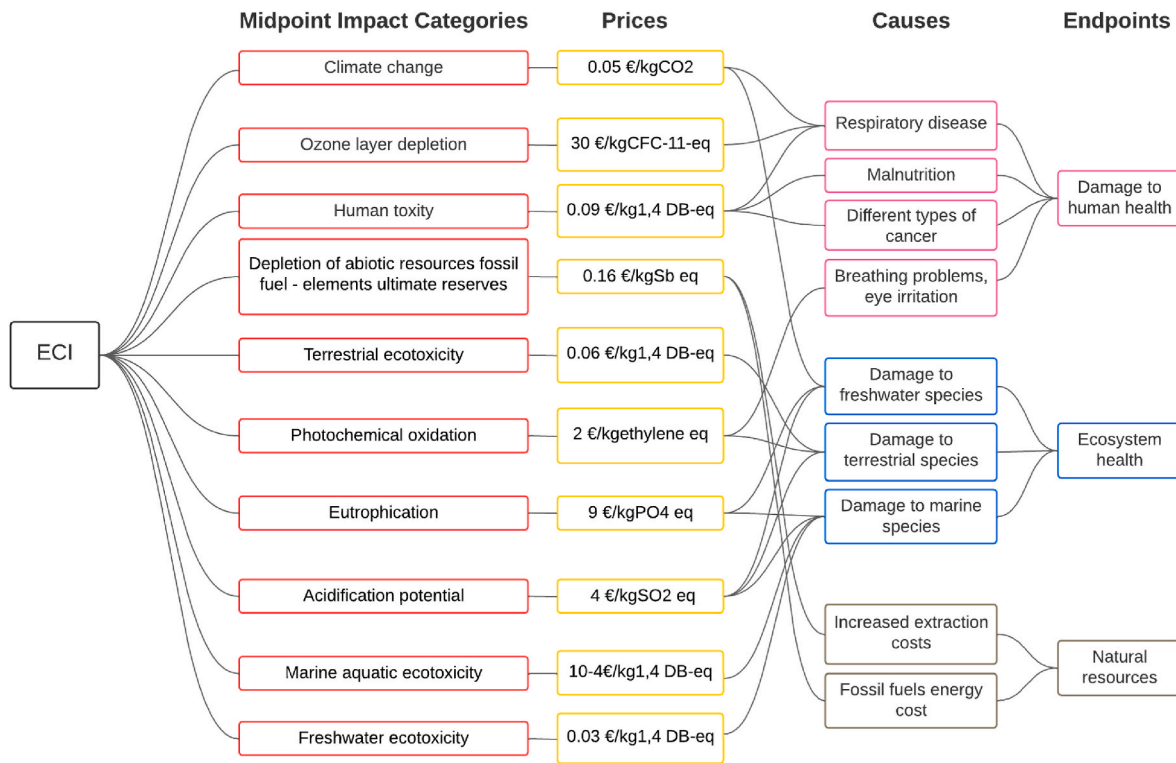


Fig. 6. Impact categories for categorization at midpoint and endpoint levels.

$$ECI = \sum_{i=1}^{i=10} Price_i \cdot Impact_i$$

It is observed that hydropower has the lowest ECI of 0.00036 €/kWh, which exhibits the smallest area on the radar chart as shown in Fig. 7, whereas pumped storage has the largest ECI of 0.0180 €/kWh, as plotted with a large area on the chart of Fig. 7. This may be due to the hydro-power process's ease of use, which involves using potential energy to rotate the pump's wheel to produce an efficient amount of energy from flow, hence, it has a high energy density.

On the other hand, the ECIs of 0.0104, 0.0045, and 0.00187 €/kWh are corresponding to solar, wind, and biomass respectively, which they rely to a high extent on the land use to compete with crops for arable lands. It is important to note that the environmental impact of each energy type can vary from one country or region to another. This variation is influenced by factors such as climate conditions, district geology, materials used, and the power generation methods employed.

The environmental costs associated with renewable energy sources remain notably lower when compared with those of electricity generated from fossil fuels. For instance, the cost of fossil fuel-based electricity surpasses that of solar, wind, biomass, hydropower, and pumped storage by factors of more than 3.5, 7.5, 18, 94, and 1.8 respectively. Such stark differentials underscore the viability and sustainability of renewable energy, advocating for a transition towards greener alternatives as a means to mitigate emissions and foster environmental stewardship.

4. Social impact

Studying social impact is as important as studying environmental and economic impacts, where we cannot live in a good society without having a healthy environment and vice versa [29]. Thus, for a process of product to be sustainable it should fulfil the three pillars of a healthy environment that are presented by a sustainable process: ecology, economic, and social impacts as shown in Fig. 9.

Reaching sustainability requires the involvement of the three

mentioned factors, if one factor is missing then sustainability cannot be attained. For instance, the method is considered tolerable when its processes respect the ecology and society, whereas the method is viable when its processes are economically feasible and eco-friendly. However, the method is equitable when its processes are profitable and respect society. The intersection of the three pillars results in a sustainable method [26].

Social benefits from renewable energy include consumers with eco-friendly thinking, technical advancements, potential for employment, and healthy society. Encouraging shifting towards renewable energy has also enhanced positive environmental outcomes, such as a reduction in CO₂ and increased public knowledge of climate change, resulting in giving the populace a clean, healthy atmosphere. Implementing renewable energy systems is challenging since they are susceptible to regional climatic and environmental factors. As a result, they need a high level of awareness and expertise, broadening the scope of research for scientists. The use of renewable energy raises people's knowledge of environmental issues, which strengthens the notion that the environment must be protected [29].

Although biomass is a renewable resource with numerous benefits, including waste reduction, abundance, and dependability, it is not always healthy or clean, it depends on the manner of conversion, which is classified into four categories: combustion of organic substances to generate heat, thermochemical transformation to produce gaseous, liquid, and solid fuels, chemical conversion to supply liquid fuels, and biological digestion to produce gaseous and liquid fuels [31]. In this study, biological digestion is mainly studied.

The first three forms of biomass primarily involve burning materials at high temperatures, leading to significant greenhouse gas emissions and negative environmental impacts. In contrast, the fourth type, biogas, utilizes fermentation to convert wastes into fuel, offering fewer drawbacks since it does not involve burning or heating materials. Additionally, the fermentation process produces gas, and the resulting wastes can be used as biofertilizers for crops, which are environmentally friendly compared to chemical fertilizers that contribute to soil and air

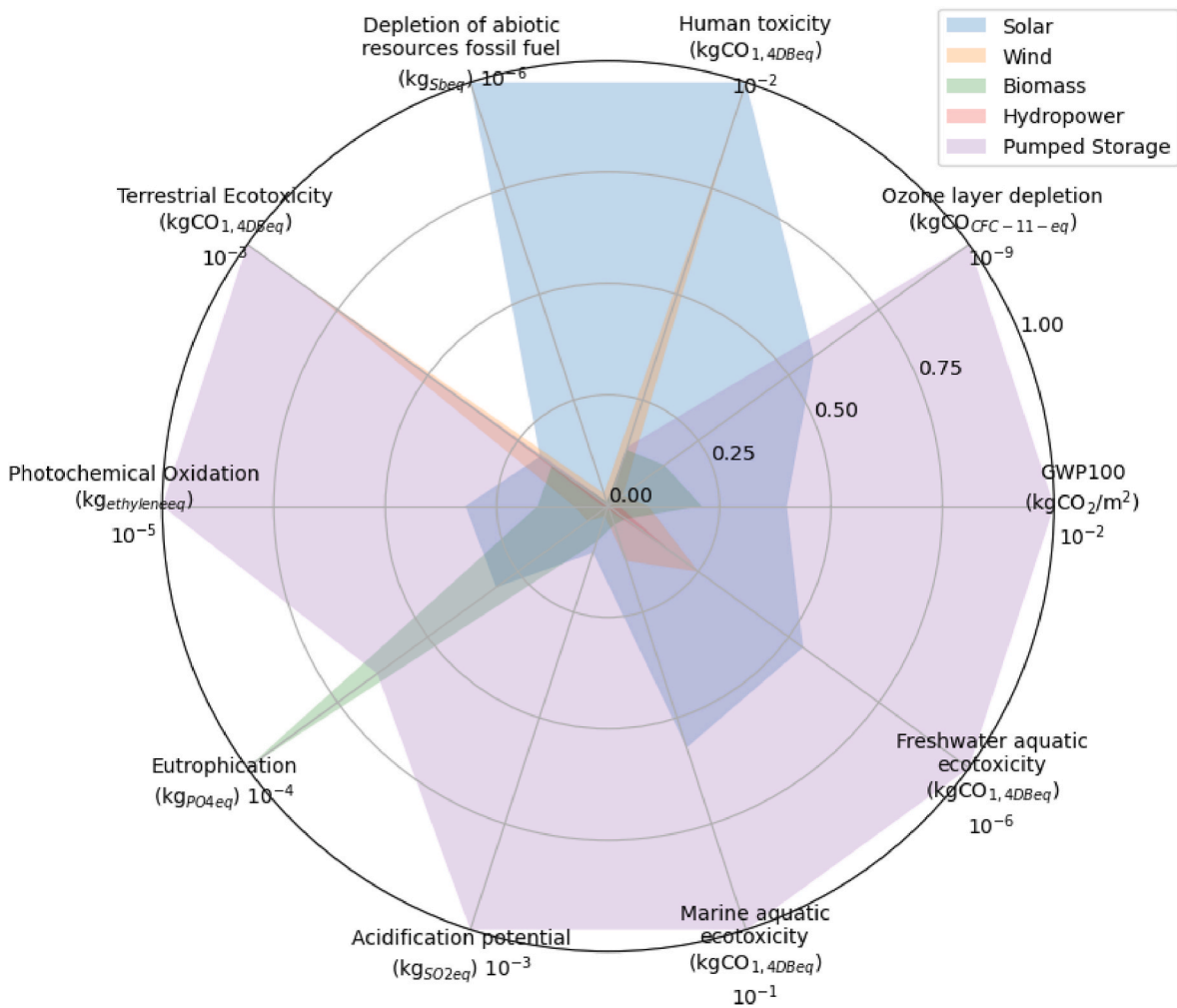


Fig. 7. Radar chart of the impact categories for each energy source.

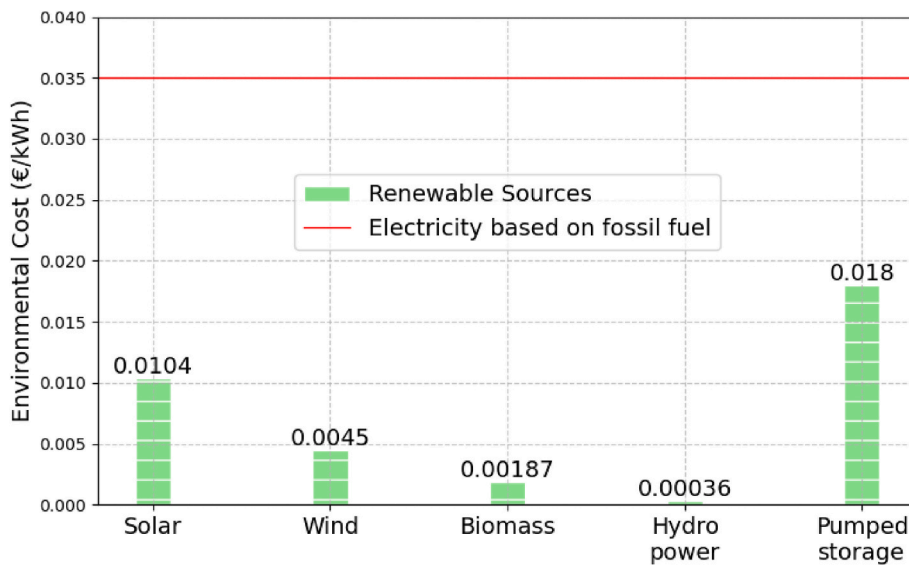


Fig. 8. Environmental impact analysis of production of electricity from different sources compared to electricity-based fossil fuel.

pollution.

Solar panels are frequently installed on building roofs, expanding job opportunities in PV system production and assembly. According to the

International Renewable Energy Agency (IRENA) [32], the renewable energy sector experienced significant job growth, with the number of jobs reaching 12.7 million in 2021 and surpassing 13.7 million in 2022

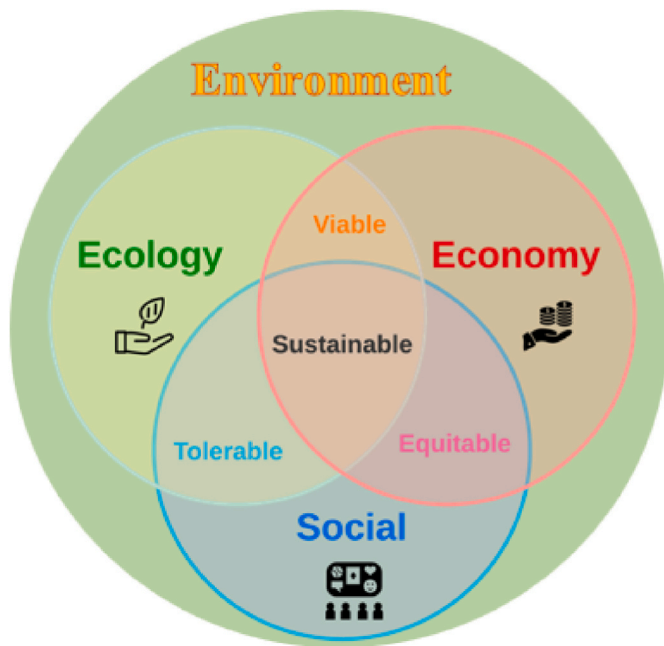


Fig. 9. The three pillars of healthy environment.

as presented in Fig. 10. This upward trend underscores the increasing importance of renewable energy in the global economy and highlights its potential to drive employment opportunities as the world transitions toward sustainable energy sources. This encourages regional development to minimize energy-based nonrenewable sources and shift more towards renewable sources. The expense of installation and continuous maintenance for solar systems are their greatest drawback, however, in the long run, solar systems are feasible as shown previously [33]. Initiatives involving biomass energy have significantly increased local employment and promoting rural development. These power plants offer a wide range of employment opportunities in biomass production and preparation as well as plant construction, management, and

maintenance. Natural water resources in these regions are also questioned for their capacity to regulate plant emissions, especially if the plant uses the source of water as a heat sink [26].

The main sociopolitical issue with hydropower projects is displacement of local populations, despite their significant economic benefits and job creation. However, they often disrupt natural landscapes. Wind energy plants offer job opportunities, particularly for engineers, but they can be noisy and pose risks to birds, leading to noise and visual pollution concerns. Geothermal energy projects bring societal benefits such as improved education, living standards, and reduced healthcare issues for local communities [27,34].

Quantitative Social Lifecycle Assessment (SLCA) is a methodology, which focuses on evaluating the social impacts associated with the life cycle of a product, service, or system. It encompasses various aspects such as Human Rights, Working Conditions, Health and Safety, Cultural Heritage, Governance, and Socio-economic Repercussions.

Each of these main indicators comprises several sub-indicators tailored to the specific objectives of the study, making SLCA a more complex and sometimes subjective process compared to LCA. The complexity arises because social impacts are often qualitative and context-dependent, requiring detailed data and nuanced interpretation.

Despite these challenges, SLCA is becoming more robust with the development of specialized databases. One such resource is the PSILCA (Product Social Impact Life Cycle Assessment) database, available at psilca website [35]. This database provides comprehensive data to support the calculation of social indicators, thereby improving the accuracy and reliability of SLCA studies.

By integrating these social aspects into lifecycle assessment, SLCA helps organizations and policymakers understand and mitigate the social implications of their decisions, promoting more socially responsible and sustainable practices.

5. Electricity-driven renewable energy consumption across different countries

In this section, the global consumption of renewable energy is explored, highlighting the variations across different countries. Energy consumption varies significantly from one nation to another due to

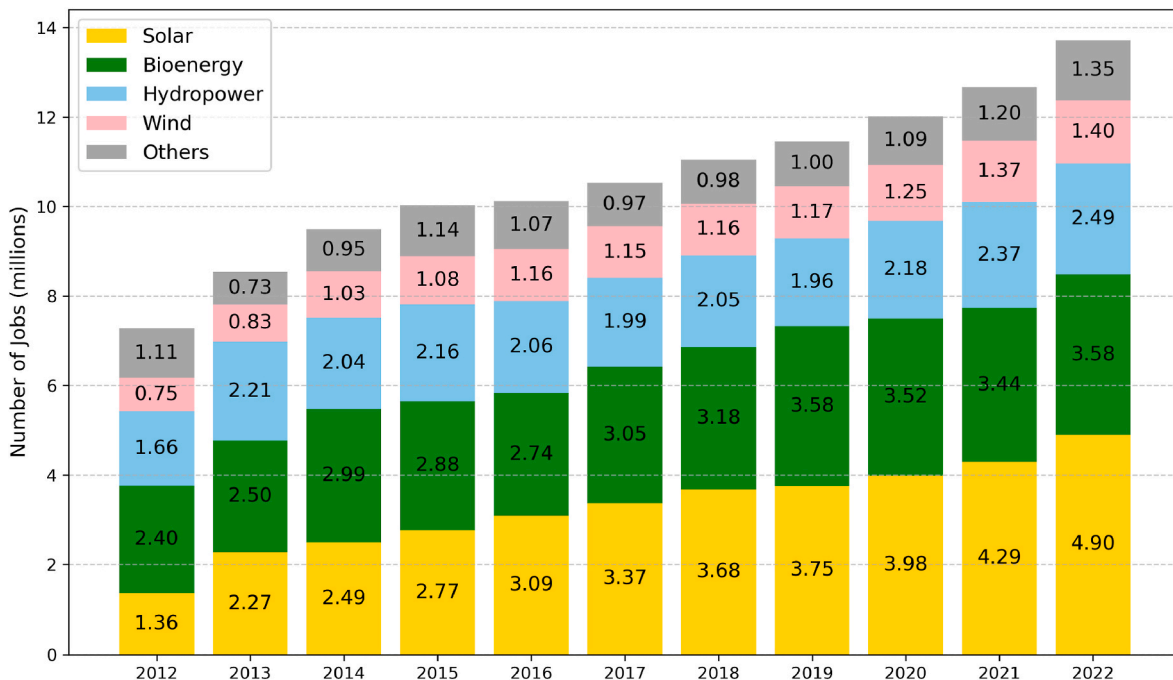


Fig. 10. Evolution of global renewable energy employment by technology, 2012–2022 based on data from [32].

factors such as population size, geographic area, and per capita consumption. Historically, reliance on renewable energy sources was relatively low, but in recent years, there has been a substantial increase. For example, in 1999, global electricity generation from renewable energy was roughly half of what it is in 2023 [36].

Fig. 11 illustrates the total electricity consumption and the share of primary energy consumption from renewable sources, comparing world average renewable energy consumption in 2023 and 2016. In 2023, 12 countries surpassed 30.24 % in renewable energy consumption, exceeding the global average. This shift towards green energy is driven by various initiatives, including the Paris Agreement, which encourages countries to reduce their carbon footprints and invest in sustainable energy sources. Consequently, many nations are increasingly adopting renewable energy technologies to meet their energy demands while minimizing environmental impact [37,38].

Moreover, Fig. 11 shows that the reliance on renewable energy has increased significantly since the Paris Agreement adopted in 2016. Countries such as China, India, Brazil, France, Germany, Mexico, Indonesia, Turkey, UK, Australia, Spain, Vietnam, Italy, South Korea, Egypt, and Sweden have made notable improvements in their percentage of renewable energy consumption. Others have either increased their share by less than 1 % or maintained the same percentage. On a global scale, the reliance on renewable energy rose from 23.75 % in 2016 to 30.24 % in 2023, marking an increase of almost 7 % over seven years. This trend underscores the growing commitment of nations worldwide to transition towards cleaner, more sustainable energy sources [4,39].

The choice of renewable energy sources is highly dependent on geographical and climatic factors, that is why the electricity mix, the combination of different energy sources used to generate electricity, varies significantly from one region to another. For instance, many European countries have successfully integrated a high percentage of wind energy into their electricity mix, significantly lowering their carbon footprints. Australia, benefiting from abundant sunshine, has increasingly shifted towards solar power, making it a cornerstone of its renewable energy strategy. In contrast, Brazil's extensive river systems

make hydropower the predominant renewable energy source, providing a substantial portion of the country's electricity [4,39].

The electricity mix plays a crucial role in a country's energy strategy, allowing for a tailored approach that maximizes the efficiency and sustainability of energy production. A diverse electricity mix can enhance energy security, reduce greenhouse gas emissions, and increase resilience against price volatility and supply disruptions. Countries with a higher share of renewables in their electricity mix are better positioned to meet their environmental goals and reduce their dependence on fossil fuels [15].

By diversifying their electricity mix, countries can leverage their unique geographical and climatic advantages to optimize energy production and storage. This approach not only supports the global transition to renewable energy but also ensures a stable and sustainable energy supply for the future. Countries that strategically integrate renewables into their electricity mix are better positioned to meet their environmental goals and provide a reliable energy supply for the future.

6. Conclusion

This research has conducted a comparative study between different renewable energy sources to study the economic, environmental, and social impact of producing electricity in Switzerland. The five types of energy sources were solar, wind, biomass, hydropower, and pumped storage. Different conclusions were obtained in this study, which are classified into three categories.

6.1. Economic

The initial investment in renewable energy systems is high, however, in the long run, they are economical as they run through free sources of energy.

The LCOE ranked by increasing order of cost is 0.030, 0.045, 0.048, 0.065, and 0.085 €/kWh for wind, hydropower, solar, biomass, and pumped storage, respectively.

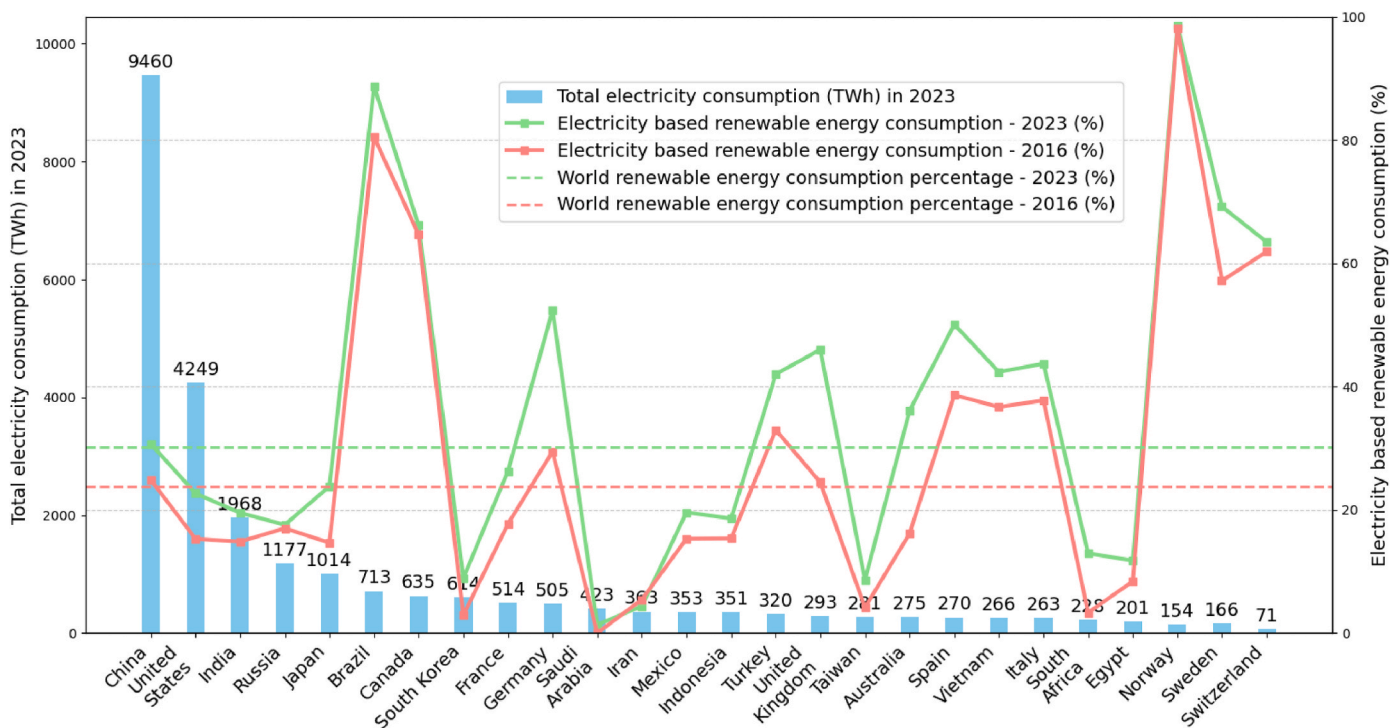


Fig. 11. Total electricity consumption and renewables include electricity production from hydropower, solar, wind, biomass and waste, geothermal, wave, and tidal [4,39].

6.2. Environmental

The environmental impact of the five different types of energy input was studied, and the results show that hydropower has the lowest environmental impact, however, pumped storage has the highest environmental impact.

The environmental cost ranked by increasing order of cost is 0.00036, 0.00187, 0.0045, 0.0104, and 0.0180 €/kWh for hydropower, biomass, wind, solar, and pumped storage, respectively.

6.3. Social

While renewable sources of energy generally have low environmental impacts, promoting a healthier environment and cleaner society, they do come with specific drawbacks associated with the type of source used. These drawbacks may include issues such as noise, bird strikes, high temperatures, and others. On the other side, along with the environmental advantages, renewable energy technologies have several social advantages as well such as raising the awareness of society to the idea of protecting the environment, providing job opportunities that require high and medium levels of education, which encourage the governments to focus on education.

Quantifying social impact is challenging, yet one promising approach is the integration of social life cycle assessment (SLCA) into future studies. SLCA offers a structured method to evaluate the social implications of products or processes throughout their life cycle, providing valuable insights into their societal effects.

Results indicate that since the adoption of the Paris Agreement in 2016, the global share of electricity production from renewable energy has increased by approximately 7 %. This upward trend continues as major countries, including China, increasingly rely on renewable energy to meet their growing electricity demands. China, along with other large economies, is making a significant shift towards renewable energy sources, further driving the global transition to cleaner energy.

7. Recommendations

In this work, diverse perspectives have arisen, enriching our understanding of complex issues, and fostering a more comprehensive and inclusive approach to problem-solving.

- o Perform a comparative study between fossil fuels and renewable energy sources in economic, environmental, and social aspects. This can assist policy makers in making informed decisions about the selection and prioritization of energy projects.
- o Conduct an application study using renewable energy sources and compare it with a conventional system.
- o Categorize the renewable energy sources per location, and optimum climate for each type.
- o Study renewable energy sources with heat recovery systems, so investigate how much energy is being saved and how it affects the system as a whole.
- o Evaluate the public perception and acceptance of renewable energy projects. Understanding community attitudes can inform communication strategies and contribute to the success of projects.
- o Carry out a quantitative social LCA that expresses the impact of each source in a more accurate way.
- o This study was conducted on a global scale, and the results may vary when examined at a local level. For instance, in some regions, photovoltaic panels are produced at a lower cost but have a higher environmental impact compared to other areas where production is more expensive but environmentally friendlier. Conducting a downscaling analysis could offer valuable insights into these regional variations and better reflect the local context.
- o It is recommended to study the electricity mix in various countries over different years, with a focus on the technological advancements

of each energy source. This research will provide valuable insights into the evolution of energy sources and the impact of technological enhancements on their efficiency and viability. Understanding these dynamics will shed light on the progress of renewable energy integration and help identify strategies for optimizing the electricity mix.

Author contributions

Conceptualization, RA; Methodology, RA, MA, MLP, TL; validation, RA; formal analysis, RA, MA, MLP, TL; investigation, RA, MA, MLP, TL; data curation, RA; writing original draft; RA; writing, review and editing; RA, MA, MLP, TL.

Declarations

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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

No data was used for the research described in the article.

References

- [1] Aridi R, Faraj J, Ali S, Lemenand T, Khaled M. A comprehensive review on hybrid heat recovery systems: classifications, applications, pros and cons, and new systems. *Renew Sustain Energy Rev* Oct. 2022;167:112669. <https://doi.org/10.1016/j.rser.2022.112669>.
- [2] Hu C, Du D, Huang J. The driving effect of energy demand evolution: from the perspective of heterogeneity in technology. *Energy Jul.* 2023;275:127361. <https://doi.org/10.1016/j.energy.2023.127361>.
- [3] Aridi R, Faraj J, Ali S, Gad El-Rab M, Lemenand T, Khaled M. Energy recovery in air conditioning systems: comprehensive review, classifications, critical analysis, and potential recommendations. *Energies Sep.* 2021;14(18):5869. <https://doi.org/10.3390/en14185869>.
- [4] Ritchie Hannah, Ritchie Max RoserHannah, Roser Max. "Electricity mix, our world in data,". 2022.
- [5] Kiselev A, Magaril E, Karaeva A. Environmental and economic efficiency assessment of biogas energy projects in terms of greenhouse gas emissions. *Energy Ecol. Environ.* Feb. 2024;9(1):68–83. <https://doi.org/10.1007/s40974-023-00305-5>.
- [6] Aridi R, Faraj J, Ali S, Lemenand T, Khaled M. Thermoelectric power generators: state-of-the-art, heat recovery method, and challenges. *Electricity Sep.* 2021;2(3):359–86. <https://doi.org/10.3390/electricity2030022>.
- [7] Baz K, et al. Asymmetric impact of fossil fuel and renewable energy consumption on economic growth: a nonlinear technique. *Energy Jul.* 2021;226:120357. <https://doi.org/10.1016/j.energy.2021.120357>.
- [8] Aridi R, Ali S, Lemenand T, Faraj J, Khaled M. Innovative concept of vortex generator-equipped multi-drain heat recovery systems–Numerical study and energetic analysis. *Int. J. Thermofluids Nov.* 2023;20:100455. <https://doi.org/10.1016/j.ijft.2023.100455>.
- [9] Aridi R, Ali S, Lemenand T, Faraj J, Khaled M. Pioneering hybrid heat recovery systems: thermoelectric generators as insulators and channels boosted by vortex generators. *Int. J. Thermofluids Jul.* 2024;100769. <https://doi.org/10.1016/j.ijft.2024.100769>.
- [10] Alabbasi A, Sadhukhan J, Leach M, Sanduk M. Accelerating the Transition to sustainable energy: an intelligent decision support system for generation expansion planning with renewables. *Energy Sep.* 2024;304:131999. <https://doi.org/10.1016/j.energy.2024.131999>.
- [11] Hanif MA, Nadeem F, Tariq R, Rashid U. Energy resources and utilization. In: *Renewable and alternative energy resources*. Elsevier; 2022. p. 1–30. <https://doi.org/10.1016/B978-0-12-818150-8.00011-3>.
- [12] Inganäs O, Sundström V. Solar energy for electricity and fuels. *Ambio Jan.* 2016;45(S1):15–23. <https://doi.org/10.1007/s13280-015-0729-6>.
- [13] Bojek P. "Renewables increased their share of power generation in 2021 despite record growth in electricity demand and droughts affecting hydropower generation," Paris. 2022.
- [14] Chu W, et al. Capacity determination of renewable energy systems, electricity storage, and heat storage in grid-interactive buildings. *Energy Dec.* 2023;285:129438. <https://doi.org/10.1016/j.energy.2023.129438>.

- [15] Oosthuizen AM, Inglesi-Lotz R, Thopil GA. The relationship between renewable energy and retail electricity prices: panel evidence from OECD countries. *Energy Jan. 2022*;238:121790. <https://doi.org/10.1016/j.energy.2021.121790>.
- [16] Kocak E, Ulug EE, Oralhan B. The impact of electricity from renewable and non-renewable sources on energy poverty and greenhouse gas emissions (GHGs): empirical evidence and policy implications. *Energy Jun. 2023*;272:127125. <https://doi.org/10.1016/j.energy.2023.127125>.
- [17] Khan A, Min J, Hassan Shah WU, Li Q, Sun C. Efficacy of CO2 emission reduction strategies by countries pursuing energy efficiency, nuclear power, and renewable electricity. *Energy Aug. 2024*;300:131418. <https://doi.org/10.1016/j.energy.2024.131418>.
- [18] Department SR. Renewables share of electricity generation in Switzerland 2010-2021. Share of renewable sources in electricity generation in Switzerland from 2010 to 2021. Mar. 2023.
- [19] Romano E, Patel MK, Hollmuller P. Applying trade mechanisms to quantify dynamic GHG emissions of electricity consumption in an open economy - the case of Switzerland. *Energy Dec. 2024*;311:133398. <https://doi.org/10.1016/j.energy.2024.133398>.
- [20] Aguayo-Pérez LM, De Lira-Flores JA, Fuentes-Cortés LF. Environmental and economic valuation of user behavior in the optimal design of renewable energy systems. *Energy Ecol. Environ. Jun. 2024*. <https://doi.org/10.1007/s40974-024-00330-y>.
- [21] Dodo UA, Ashigwuike EC. Techno-economic and environmental analysis of utility-scale hybrid renewable energy system integrating waste-to-energy plant to complement an unreliable grid operation. *Energy Ecol. Environ. Oct. 2023*;8(5): 439-56. <https://doi.org/10.1007/s40974-023-00276-7>.
- [22] International renewable energy agency with minor processing by our world in data. Levelized cost of energy by technology. World; 2023.
- [23] Roser Max. Why did renewables become so cheap so fast? Our World in Data 2020. Available: <https://ourworldindata.org/cheap-renewables-growth>.
- [24] Francesco La Camera. Renewable power generation costs in 2023. IRENA – International Renewable Energy Agency; 2024 [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf.
- [25] Det Norske Veritas (DNV). Energy transition outlook: the rise of renewables [Online]. Available: <https://www.dnv.com/energy-transition-outlook/rise-of-renewables/>; 2024.
- [26] Aridi R. “Advanced heat recovery systems: use of Vortex Generators and hybridization with thermoelectric generators, considering renewable energy sources and life cycle assessment,”. 2023. <https://doi.org/10.13140/RG.2.2.12482.56008>.
- [27] Aridi R, Ali S, Lemennand T, Faraj J, Khaled M. Thermo-economic and environmental impacts of vortex generator-equipped multi-drain heat recovery systems under various renewable sources. *Energy Convers Manag X Oct. 2023*;20: 100431. <https://doi.org/10.1016/j.ecmx.2023.100431>.
- [28] Aridi Mona, Marie-Lise Pannier Rima, Aridi Rima, Lemennand Thierry. Evaluating environmental impacts of Domestic heat pumps: a review through life cycle assessment. La rochelle - Oléron, France: Conference. IBPSA France; 2024, May 2024.
- [29] Aridi R, Yehya A. Review on the sustainability of phase-change materials used in buildings. *Energy Convers Manag X Aug. 2022*;15:100237. <https://doi.org/10.1016/j.ecmx.2022.100237>.
- [30] Aridi R, Yehya A. Refining the integration of encapsulated phase change materials in building envelopes. *Jan 2024*;23. <https://doi.org/10.46855/energy-proceedings-11091>.
- [31] Aridi R, Yehya A. Anaerobic biodigesters heating sources: analysis and recommendations. *Renew Sustain Energy Rev Sep. 2024*;202:114700. <https://doi.org/10.1016/j.rser.2024.114700>.
- [32] IRENA. “Renewable energy and jobs: annual review 2023,”. 2023.
- [33] Internationale Agentur für Erneuerbare Energien and Methanol Institute. Renewable energy and jobs: annual review 2021. in *Labour and policy perspectives - special edition*. Abu Dhabi: International Renewable Energy Agency; 2021.
- [34] Kumar M. Social, economic, and environmental impacts of renewable energy resources. In: Eloghene Okedu K, Tahour A, Ghani Aissaou A, editors. Wind solar hybrid renewable energy system. IntechOpen; 2020. <https://doi.org/10.5772/intechopen.89494>.
- [35] psilca. Understanding social impacts [Online]. Available: <https://psilca.net/>.
- [36] Ritchie Hannah, Roser Max, Rosado Pablo. “Renewable energy,” our world in data. 2020.
- [37] World Population Review. “Energy consumption by country 2024,”. Nov. 2024.
- [38] Enerdata. “World energy and climate statistics - yearbook 2024,”. 2024.
- [39] Ritchie Hannah, Rosado Pablo, Roser Max. “Energy production and consumption,”. 2020.