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Renewable energy systems: Comparisons, challenges and barriers, sustainability indicators, and the contribution to UN sustainable development goals

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ABSTRACT

Because of the harsh environmental impacts of fossil fuels, price fluctuation, and resource limitation, renewable energy resources (RERs) are considered the ultimate solution to overcome these challenges. RERs are also abundant and environmentally friendly. It has been reported that the growth rates in renewable energy installations have increased by 8–9% annually since 2010, reaching a cumulative capacity of 2.9 TW by 2020 and exceeding the growth rate for fossil resources. In this work, the different RERs have been critically discussed in terms of their operation principles, advantages, disadvantages, and associated environmental impacts, focusing on wind and solar energies as the most deployed RERs. Barriers to the full deployment of RERs to replace fossil resources are discussed. Based on the discussion presented on RERs, the contribution of deploying RERs towards the achievement of the United Nations (UN) Sustainable Development Goals (SDGs) is also critically discussed. A total of 80 indicators have been identified for RERs' contribution toward the achievement of SDGs.

1. Introduction

During the 20th century, fossil fuels have been over-exploited, and have become the main driver for almost all human activities. However, two main challenges have been seen with such fossil resources, first is their fluctuations in terms of prices, going up more than 5–7 folds over a short time and going down to negative values some other times [1,2]. The second is the severe environmental impacts leading to climate change and global warming [3,4]. Accordingly, it has become necessary to search for alternative energy resources to replace fossil resources. Renewable energy resources (RERs) are considred to be the ultimate solution to the energy supply challenge. RERs are mainly characterized by high global availability and low environmental impact [5,6]. For example, solar and wind energies are available almost everywhere on Earth at varying intensities, as such, there is no need for energy importation [7,8].

The United Nations (UN) launched in 2015, 17 Sustainable Development Goals SDGs to ensure the prosperity of human beings and the planet Earth, including all of its elements, i.e., biosphere, atmosphere, geosphere, and hydrosphere [9]. In the heart of these SDGs lies SDG-7 of "Affordable and Clean Energy", along with SDG-13 of "Climate Action", in which the wide deployment of RERs should contribute most [10–12]. The increased adoption of RERs is strongly believed to contribute toward the realization of all SDGs but to a different extent, with SDG-7 and SDG-13 as the most beneficial goals.

Although there has been notable advancement in the utilization of RERs in recent years, there persists a continuing discourse regarding their capacity to completely substitute fossil fuels and the optimal rate of transitioning to such alternatives [13–18]. One of the primary areas of debate concerns the efficacy and scalability of various RERs in

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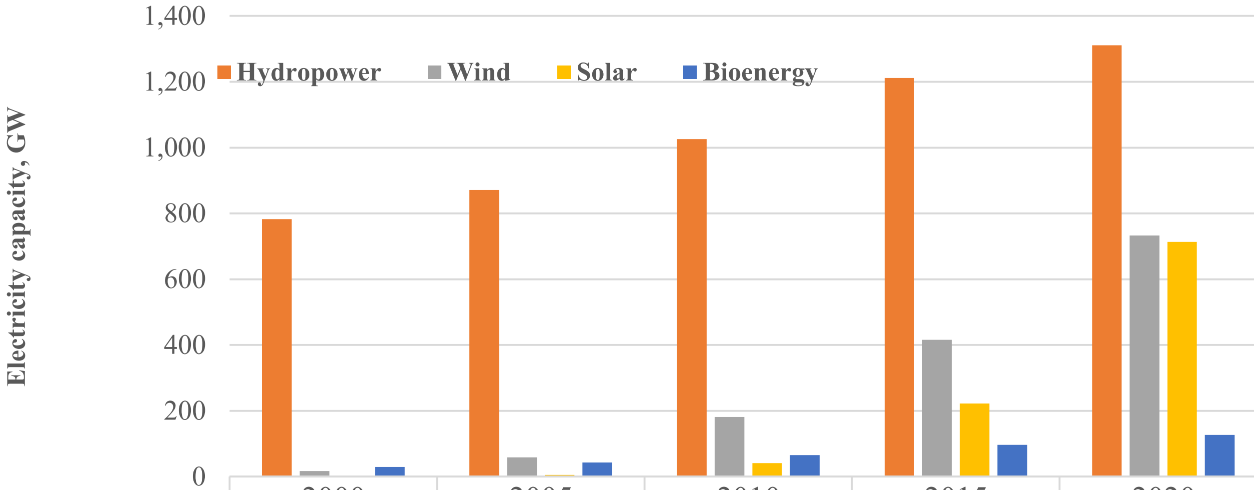


	2000	2005	2010	2015	2020
Hydropower	782.88	870.65	1,025.56	1,211.62	1,311.30
Wind	16.93	58.41	180.85	416.25	733.34
Solar	1.23	4.94	41.55	222.21	713.97
Bioenergy	29.29	42.82	65.57	96.67	126.65

Fig. 1. Electricity capacity from renewable energy resources [35], open access.

addressing worldwide energy requirements, particularly in light of the rapid increase in energy consumption.

Solar and wind energy have emerged as prominent contenders in the renewable energy sector, attracting considerable attention and receiving accolades for their significant potential [19,20]. Nevertheless, it is important to acknowledge the criticisms raised by experts, which highlight the constraints associated with these energy sources. These limitations encompass the inherent unpredictability of such sources and the extensive infrastructure necessary for their extensive implementation. Furthermore, although RERs are commonly regarded as environmentally sustainable, there is a growing academic discussion surrounding their inadvertent ecological consequences, including the utilization of land for expansive solar farms and the ecological ramifications associated with the installation of wind turbines.

The challenges to the wide implementation of RERs are complex and varied. In addition to technical and environmental considerations, the socioeconomic and political aspects also hold significant importance. For example, the adoption of RERs may result in employment reductions within conventional energy sectors and could encounter opposition from industries that have a vested interest in preserving the existing state of affairs. But at the same time it might lead to providing new jobs [21–23]. The rapid adoption of RERs may face additional obstacles due to regulatory and administrative challenges, particularly in developing countries with less robust institutional frameworks.

The correlation between the emergence of RERs and the wider international agenda is evident in the United Nations' SDGs, which serve as a comprehensive framework for achieving a more sustainable future. Nevertheless, despite the crucial significance of RERs in attaining these objectives, there exists a scarcity of agreement regarding the approaches and routes to accomplish them [24–27]. This work highlights the interdependence of these objectives, placing particular emphasis on the direct contributions of RERs to SDG-7 and SDG-13, while also acknowledging the broader impact of RERs on all SDGs.

This work aims to discuss the different RERs with a brief comparison of each type, discussing the solar and wind as the RERs with the highest installed capacity and growth rate among different RERs. The work expands the discussion to the environmental impacts of RERs as indicated by water consumption, resources used, and waste generated. The work then discusses the different barriers to the full deployment of RERs, such as economic, financial, technical, social, environmental, regulatory, administrative, and organizational. The review also evaluates and analyzes the contribution of employing RERs in the achievement of the United Nations SDGs as a global call for human and Earth prosperity.

This study differentiates itself, from previous studies such as [25, 28-30], through its comprehensive examination of the SDGs, specifically investigating the influence of renewable energy on a wider range of objectives compared to other research endeavors. It encompasses the less frequently explored SDGs of 'Life Below Water' and 'Peace and Justice Strong Institutions'. The research delves further into the topic through a comprehensive analysis of keywords, providing insights into the fundamental issues that link each SDG with initiatives related to RERs. The study utilizes global data, specifically from reputable sources, to provide a comprehensive analysis of the role of electricity in promoting sustainable development. The focus extends beyond the broader environmental advantages, as there is a notable emphasis on education and training within the renewable sector, underscoring the pivotal role of capacity-building. The study also undertakes a resource flow analysis, which examines the entire lifecycle of renewable energy, from the extraction of raw materials to the final disposal stage. This analysis highlights the environmental impact associated with each stage and emphasizes the significance of recycling and reusing materials.

In order to bolster the study's credibility, particular attention is directed towards the two most prominent forms of renewable energy: solar and wind. This focus allows for a comprehensive examination of the practical obstacles and potential benefits associated with these sources. The adoption of renewable energy is hindered by various barriers, which encompass economic obstacles as well as administrative challenges. These barriers are subject to critical examination. The work demonstrates a distinctive contribution by effectively integrating the advantages of RERs with the objectives of the SDGs, illustrating how renewable energy can facilitate the attainment of these goals. In addition to engaging in theoretical discourse, this study offers practical methods of assessment by introducing precise indicators that can be used to measure the extent to which renewable energy contributes to the SDGs. The systematic methodology, beginning with an introductory overview of renewable energy and concluding with its convergence with

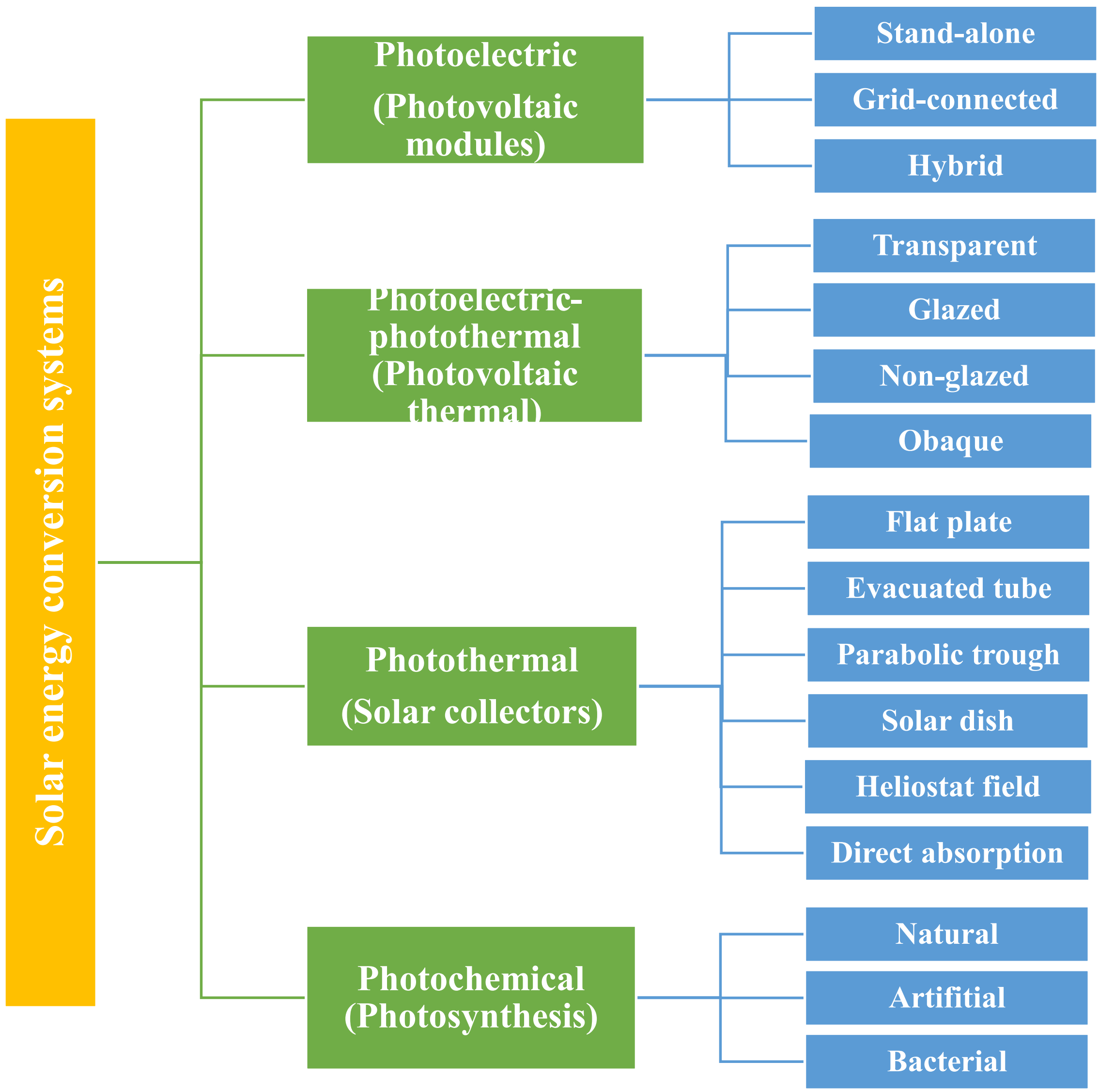


Fig. 2. Solar energy conversion systems.

the SDGs, provides readers with a logical sequence, establishing fundamental understanding before delving into the complex interplay between renewable energy and worldwide sustainability objectives.

Moreover, the primary trigger for undertaking this research stems from the urgent global imperative to align renewable energy initiatives with the broader objectives of SDGs. This motivation was drawn from a myriad of observations and noticeable gaps in the existing literature. For instance, data from institutions such as the World Bank have illuminated disparities in electricity access across different populations, emphasizing that energy is a central challenge in sustainable development. Such insights accentuated the necessity for a detailed study that bridges the divide between RERs and SDGs.

Additionally, while numerous studies have delved into either renewable energy or SDGs independently, there was a notable absence in research that comprehensively explores how specific renewable energy initiatives both correlate with and influence multiple SDGs. Our research ambitioned to address this lacuna. Furthermore, our study highlighted significant gaps in education and training within the renewable energy domain. Addressing these educational voids becomes imperative for both capacity-building and ensuring the sustained growth of the renewable energy sector.

Environmental concerns also formed a significant foundation for our research. The degrading condition of marine habitats, combined with the role of power generation in magnifying these issues, made it crucial to investigate how RERs could alleviate such environmental strains. Coupled with these factors was the emphasis on the importance of renewable energy projects in fostering peace, justice, and community engagement, as encapsulated in SDG-16. In sum, our research was driven by the observed global challenges, existing gaps in scholarly work, and the compelling need to comprehensively analyze the relationship between renewable energy initiatives and their potential in promoting the Sustainable Development Goals.

This work is structured to initially introduce renewable energy, emphasizing solar and wind sources. It then delineates the key barriers to adopting renewable energy, including economic, financial, social, environmental, regulatory, policy, institutional, and administrative challenges. Building on this foundation, the paper provides a comprehensive examination of how renewable energy intersects with the SDGs and suggests specific indicators to amplify renewable energy's contribution to these goals.

2. Renewable energy resources

Renewable energy resources (RERs) have recently attracted much

Table 1
Merits and demerits of photovoltaic cells [13,48-52].

Solar cell	Merits	Demerits
1st Generation solar cells		
sc-Si "Single crystalline silicon"	• Efficiency of 25–27% at lab scale. • Efficiency of 16- 22% at commercial scale.	v Complex manufacturing v High cost.
mc-Si "Multi–crystalline silicon"	• 15–18% Efficiency at lab scale. • More cost-effective.	Lower efficiency.
2nd Generation solar cells		
a-Si "Amorphous silicon"	• 12% Efficiency at lab scale. • 8% Efficiency at commercial scale. • Cheaper	Lower solar absorption.
GaAs "Gallium arsenide"	• 29% Efficiency at lab scale. • Higher efficiency and less thickness compared to the Si cells	More costly
CdTe "Cadmium telluride"	• 10–15% Efficiency. • 21% Record efficiency. • utilize a broader wavelength spectrum. • Cheaper.	Cadmium is toxic.
Copper-indium -gallium selenide	• 20% Efficiency. • Less energy consumption compared to c-Si cells. • Good heat resistance.	v Use toxic chemicals. v More costly.
Copper-indium selenide	• 10–13% Efficiency. • Less energy consumption compared to c-Si cells. • Good heat resistance.	v Use toxic chemicals. v Low efficiency. v More costly
Hybrid (a-Si and c-Si)	• 21% Efficiency. • High carrier mobility. • A reasonable compromise of cost and efficiency.	v Use toxic chemicals. v More costly
3rd Generation solar cells		
Perovskite solar cells (PSC)	• 19–22% Efficiency. • Cheaper to manufacture.	Degradable upon exposure to moisture, snow, heat, etc.
DSSC "dye-sensitized solar cell"	• 10% Efficiency. • Flexible, recyclable, and more environmentally friendly. • Cheaper manufacturing process. • Functional at low light intensities. • Higher efficiencies at higher temperatures.	v Electrolyte freezing leading to intermittent energy generation. v Sealing is crucial due to the potential leak of organic solvent used as electrolyte.
QD "Quantum dot" cells	Easy synthesis.	Low efficiency of 1.9%.

attention as environmentally friendly and sustainable energy resources. This attraction is derived from the non-sustainability nature of currently utilized fossil energy resources, along with the severe environmental impacts and price volatility [31]. It has been reported that renewable power generation sources are more likely to be a solution to salvage the high current dependence on fossil products [32,33]. Fig. 1 below shows the evolution in electricity capacity from RERs over the last two decades, showing an increase in total capacity from 830 to 2,885 GW. By 2020, renewable hydropower, wind, solar, bioenergy, geothermal, and marine RERs accounted for about 43.3, 26.2, 25.5, 4.4, 0.5, and 0.1% of the 2, 885 GW installed electricity capacity, accounting for about 26% of the total electricity generation capacity [34,35]. This section critically reviews the dominant RERs, next to hydropower, given their very special nature and specific characteristics, namely solar and wind RERs with their respective characteristics.

2.1. Solar energy

Solar energy is the utmost plentiful energy source, with a capacity of about 1.2×10^5 TW [36]. Due to the prospect of solar energy availability, most countries around the world are today resorting to it as the primary RER [37] with low or no environmental impacts [38]. Today, most countries have formulated several policies to ensure solar energy development, but there is still the need for further review of some of these policies [39,40]. Today, major investigations being carried out revolve around the approaches and technologies to harness solar energy [41]. The transformation of solar energy can occur via photochemical, photoelectric, photothermal, and photoelectric conversion approaches, as shown in Fig. 2. Photochemical approaches through the photosynthesis process as demonstrated by plants [42]. Photoelectric conversion is commonly through silicon-based photovoltaic (PV) modules [43]. Photothermal conversion takes place via solar collectors [44]. While photoelectric-photothermal conversion via photovoltaic thermal system [45,46]. Solar photovoltaic and solar thermal are the most used approaches to harness solar energy.

2.1.1. Solar PV technologies

Solar photovoltaic (PV) has received huge attention among all solar technology conversion systems, mainly due to its ability to directly convert solar energy into electrical energy, with the latter as the most common, widely used, and highest quality form of energy. Improvements in solar PV are aiming to improve its efficiency and reduce its cost. Solar cells are either made of single/multiple layer(s) that are capable of absorbing solar radiation, i.e., light radiations. PV is classified as 1st, 2nd, and 3rd generation cells [47]. The 1st generation is made of c-Si "crystalline silicon" either as single- or multi-crystalline silicon. The 2nd generation is made of thin-films of a-Si "amorphous silicon", CdS "cadmium sulfide", CdTe "cadmium telluride", GaAs "gallium-arsenide", CIS "copper-indium selenide", CIGS "copper-indium-gallium selenide", and tandem/multi-junction modules based on Si. The 3rd generation includes perovskite, DSSCs "dye-sensitized solar cells", and QD "quantum dot" solar cells, as can be seen in Table 1.

2.1.2. Solar thermal systems

Solar thermal or commonly called CSP "concentrated solar power" systems of a parabolic trough, parabolic dish, solar tower, and Fresnel lens [53,54]. CSP is mature, space-efficient, and simpler than solar PV [55], but has relatively higher capital expenditure and lifecycle costs [56–58]. CSP can significantly help to reduce energy load for domestic heating applications [59,60]. Table 2 provides the main features of the common CSP collectors, including designs and operation specifications [61].

Table 2
Comparison of the main features of the common CSP collectors [61,62].

Motion	Collector type	Absorber	Concentration factor	Temperature (°C)	
Stationary	FPC "Flat plate"	Flat	1	30–80	Low Temp.
	ETC "Evacuated tube"			50–200	
	CPC "Compound parabolic"	Tubular	1–5	60–240	
Single–Axis Tracking	LFR "Linear Fresnel reflector"		10–40	60–250	Medium Temp.
	PTC "Parabolic trough"		15–45	60–300	
	CTC "Cylindrical trough"		10–50		
Two-Axis Tracking	PDR "Parabolic dish reflector"	Point	100–1000	100–500	High Temp.
	HFC "Heliostat field"		100–1500	150–2000	

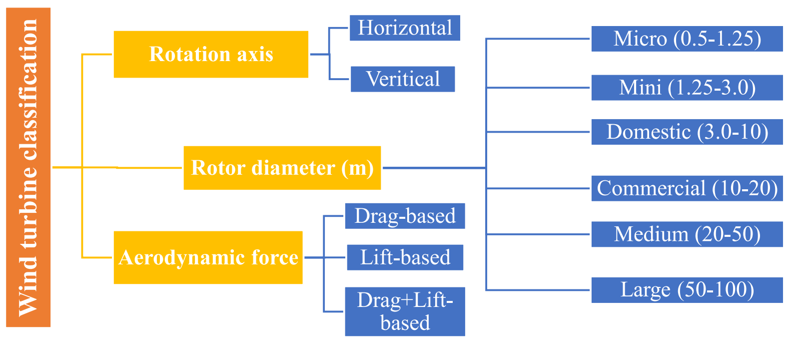


Fig. 3. Various classifications for wind turbines.

2.2. Wind energy

Wind is simply an air current flow across the surface of the earth from high-pressure to low-pressure areas. Evaluation of wind resource potential using wind turbines is essential and considers both geographical location and wind characteristics (velocity and direction pattern) [63]. The turbine blades are affected by turbulence-induced vibration, as such it is recommended to site the wind farm 150 m, away from obstructions [64]. The unpredictable nature of wind makes velocity and hence power generated forecasting very difficult [65–67]. Wind energy can be utilized via two approaches, either mechanical or electrical energy. The wind energy (kinetic) is converted, via a turbine rotor to mechanical energy. The mechanical energy is then turned into electrical energy by means of an electrical generator [68,69]. Fig. 3 shows the different classifications of wind turbines either according to axis orientations, aerodynamic forces, or rotor diameter.

The horizontal-axis wind turbines are commonly used in urban locations, due to their high efficiency at wide-scale range [70–72]. A propeller-type rotor is fixed on the horizontal axis which is continuously directed upwind with the aid of a yaw motor, as efficiency is very sensitive to wind direction [73–76]. Turbine maintenance is always a challenge due to height, in addition to the large space required for high capacity wind turbines, as such it is usually built in rural and coastal areas [77].

In vertical-axis wind turbines, the blades rotate in a vertical path and, as such, can utilize wind from any direction, hence a yaw mechanism is not needed, makes it suitable for urban areas [78–80]. This type of turbine is usually lower in height, enabling easy installation, hence lower installation, and maintenance costs. Vertical-axis turbines are suitable for energy generation at a small scale, varying wind velocity, and turbulent conditions. The energy produced using the vertical axis turbine is usually low and normally used on-site [81,82]. Current

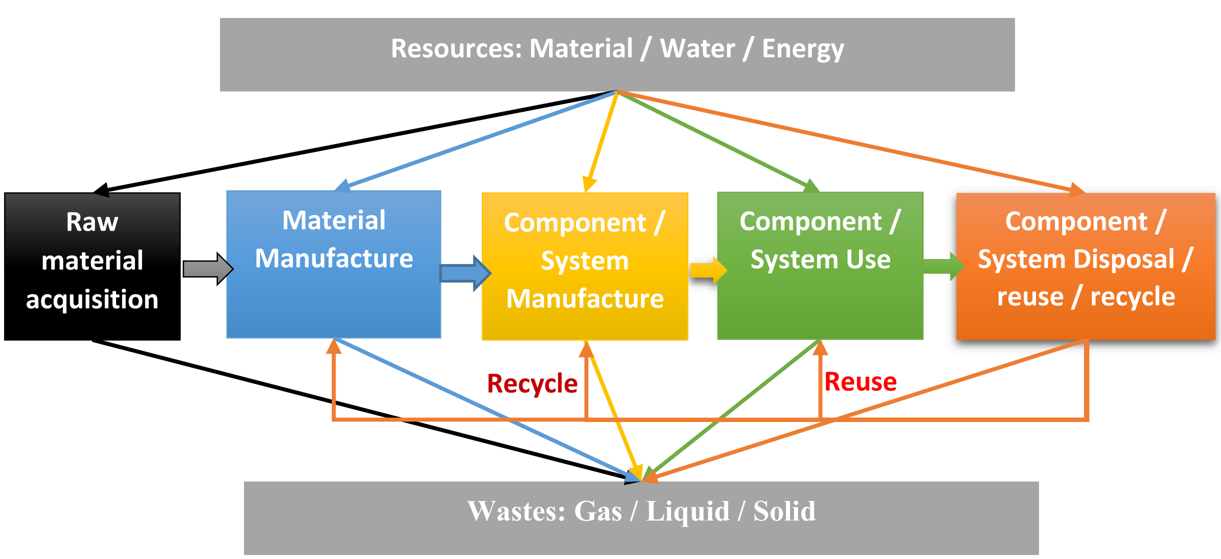


Fig. 4. Illustration of cradle-to-grave life cycle assessment.

Table 3
Collective water consumption for power generation for different energy resources [99].

Energy Resources	Water Consumption, l/kWh	
	Operation	Total life cycle
Coal	0–4.5	1–5.5
Coal- carbon capture	1.9–4.5	2.2–5.8
Nuclear	0.5–3.2	1.1–2.7
Conventional natural gas	0.3–2.6	1.5–3.7
Natural gas – combined cycle	0.1–1.9	0.9–2.7
Hydroelectric – dam	17.4	
CSP "Concentrated solar power"	3–3.5	3.4–4.2
Solar PV "photovoltaic"	0.0	0.3–0.7
Wind – onshore	0.0	0.04
Geothermal – enhanced geothermal system EGS	1.1–2.8	
Geothermal – binary cycle	0.3–1	
Geothermal - flash	0.04	
Biomass	1.2–2.3	

research is primarily focused on decreasing the weight of the complete system in order to reduce structural loads [83–85]. Hence, lower the bending and torsion deformations caused by centrifugal load, which impeded the turbine efficiency [86–88].

3. Environmental impacts of renewable energy resources

RERs have been generally viewed as clean and environmental-friendly energy sources. This is relatively true for most environmental comparison criteria relative to fossil-based energy resources such as coal, oil, and gas, that are well-known for their adverse environmental impacts [89]. RERs are mainly characterized by much lower environmental impacts during the operational phase of energy extraction. However, similar to any technolgies or processes, renewable energy extraction and conversion have many environmental impacts, more specifically during the manufacturing phase [90,91]. Solar energy is the most utilized RERs with an approximate installed capacity of 714 GW in 2020 [92]. However, the material and technology required for the extraction and conversion of solar energy are known to be both material and energy-intensive. This is a clear example that the impacts of RERs should not be limited to operational phases only and have to be expanded to the manufacturing and material acquisition phases.

In general, although water and energy supply projects aim at securing the two most vital commodities to human beings, their environmental impacts have to be carefully considered [93–95]. Herein, the environmental impacts of different RESs will be discussed. The discussion considers the LCA "life cycle assessment" to assess the overall environmental impacts in terms of carbon footprint and other greenhouse gasses (GHGs) emissions, energy consumption, and other resources utilization, as outlined in Fig. 4.

3.1. Water consumption for energy production

One of the essential and common natural resources for energy extraction and conversion is water. Water and energy are strongly connected with one commodity being essential to extract the other in what is so-called the Water-Energy nexus, which can be further extended to food and the environment [96–98]. The amount of water utilized for the production of electrical energy as high-quality sources varies greatly among energy resources. Table 3 below shows the average and range for water utilized per unit of electricity generated from different energy resources. The table shows clearly that RERs have a substantial water consumption relative to fossil resources, except for the case of CSP which has a similar level of water consumption, being used as the heat transfer fluid. The water utilized for RERs is mostly during material acquisition and extraction as well as complex and advanced manufacturing processes, which are in many cases energy and water exhaustive.

3.2. Solar energy

Solar energy is the most explored RER as the sun is considered the origin of all energy forms on Earth. The installed capacity for solar photovoltaic (Solar-PV) is about 714 GW in 2020 up from 481 GW in 2018, at an increasing rate of about 29% over the last two decades, with a maximum growth of 44% in 2011 [100]. Thermal solar power (Solar-T) is less commonly used, representing about 1% as compared to solar PV, with about 5.74 GW installed capacity in 2018, relative to 0.42 GW in 2000 [92]. Environmentally, Solar-PV has more benefits and impacts as it is distinct with the direct conversion of solar energy into electrical energy, which is the most common form of energy with higher demand. On the other hand, the manufacturing of PV panels is much more demanding in terms of resources such as material, water, and energy. Hence the discussion in this section will focus on Solar-PV in relation to the environmental impacts.

Crystalline silicon-based PV, or C-Si, is the most commonly used PV panel for harvesting solar energy, dominating about 90% of the global Solar-PV energy market [101,102]. Monocrystalline silicon or Mono-Si, and poly/multi-crystalline silicon or P-Si/multi-Si, have cell efficiencies of 15.3 and 14.4% and module efficiencies of 14, and 13.2%, respectively [103,104]. Both utilize energy and resources extensively with about 1 and 0.7 MWh/kg for Mono-Si and P-Si, respectively [101,103]. Due to the high energy consumption and resources utilization for the extraction and manufacturing of the high-purity material of PV panels, two main indicators are used, namely energy payback time (EPBT) and GHGs emissions, along with other environmental indicators from LCA [104]. Energy payback time EPBT, is simply the number of operational years required for the PV system to produce energy equivalent to that consumed throughout its lifetime, usually 20–30 years. While, GHGs emissions can be obtained by performing the appropriate LCA on the system. Table 4 below shows a comparison between different silicon-based and some emerging Solar-PV technologies in terms of cumulative energy demand (CED), EPBT, and GHGs, showing the improvements achieved with emerging Solar-PV relative to energy- and resources-extensive silicon-based Solar-PV systems.

Table 4
Comparison of environmental indicators for different PV types.

Type	CED, GJ/m^2		EPBT, years		GHGs, g CO_2-eq/kWh	
Mono-Si	1.12–8.05	2.86–5.25	1.4–7.3	2.1—12.1	29.0–671	35–61
Multi-Si	1.03–5.15	2.7–5.15	0.8–4.2	1.7–3.3	12.1–569	12–72.4
a-Si	0.86–1.73	0.71–1.99	1.1–3.2	2.7–3.2	8.1–57	34.3–50
CdTe	0.81–1.80	0.79–1.80	0.8–2.7	0.7–2.5	8.9–66	14–48
CIS	1.11–1.68	1.07–1.68	1.3–2.8	1.6–2.9	33–95	10.5–95
DSSC	0.28–0.36	–	0.6–1.8	–	9.8–25	–
Perovskite	0.38–0.82	–	0.2–5.4	–	56.6–497	–
Quantum dots	0.37–1.03	–	0.9–1.5	–	2.9–5	–
Ref.	[105]	[106]	[105]	[106]	[105]	[106]

CED "cumulative energy demand", EPBT "energy payback time", GHGs "greenhouse gasses", Mono-Si "monocrystalline silicon", Multi-Si "multi-crystalline silicon", a-Si "amorphous silicon", CIS "copper indium selenium", and DSSC "dye-sensitized solar cell".

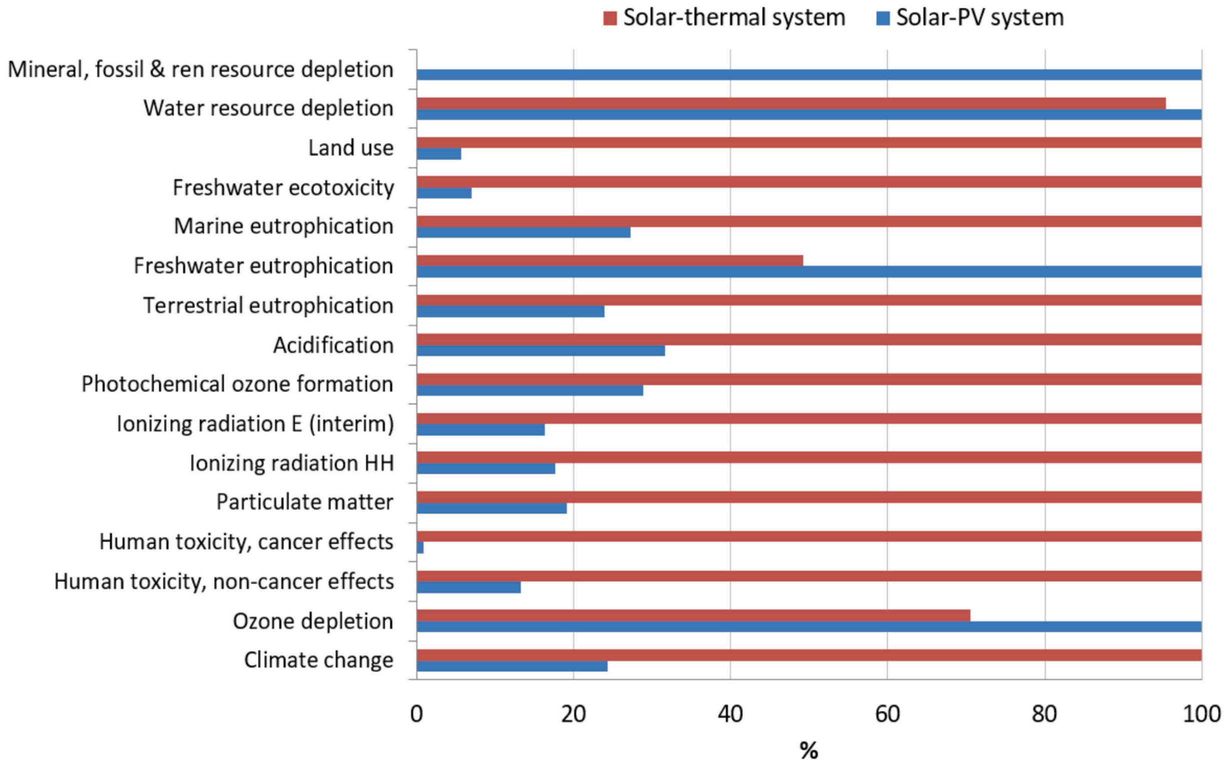


Fig. 5. Comparative environmental impacts of solar-PV and solar-T systems [108].

The other main environmental impact of the solar energy system is the large land area, this is mainly required due to the low incident solar radiation intensity with an annual average of 1–1.3 kW/m^2 [101]. Some additional environmental impacts of solar energy can be summarized as follows: [89-91,107]:

- Ø The use of a large land area, with no other utilization during the construction phase.
- Ø A large amount of waste material at plant decommissioning.
- Ø Impact on eyesight due to light reflection, and visual impact.
- Ø Soil compaction and erosion, with a potential decrease in water evaporation rate from the soil.
- Ø Diversion of wind and airflow pattern.

Kumar et al. have summarized the EPBT and GHGs emissions for some Solar-PV systems showing an EPBT range of 1.7–7 years, compared to a lifetime of 20–30 years, and global warming potential GWP of 10–800 g CO_2-eq/kWh, depending largely on the location [107]. When considering LCA for the Solar-PV, it is paramount to consider the entire PV system, which includes the PV panel, DC/DC controller, battery, and DC/AC converter.

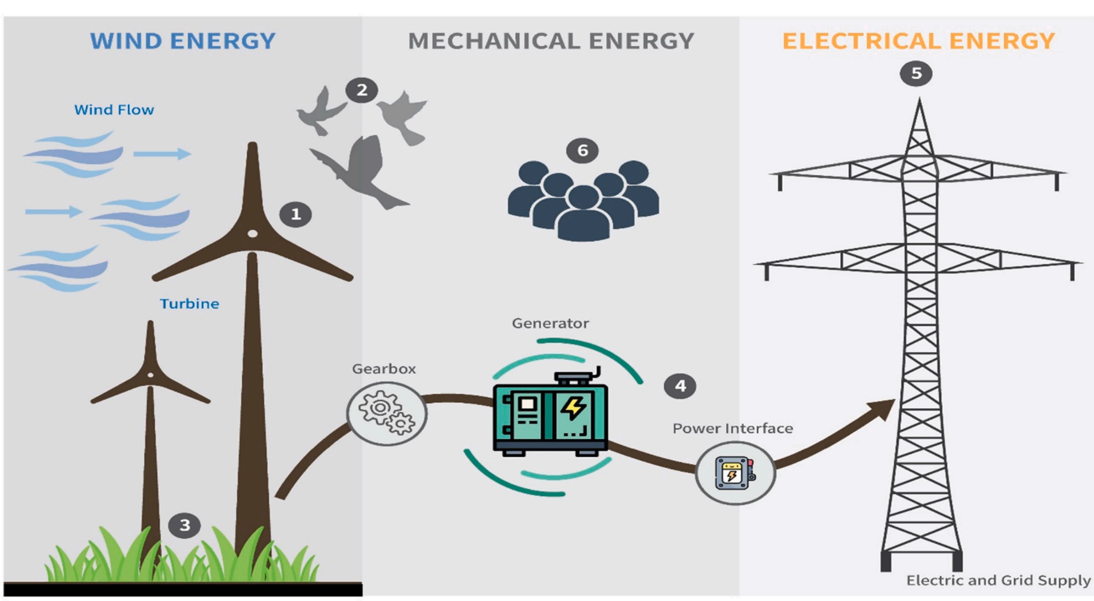


Fig. 6. Summary of the environmental impacts of wind energy: 1) visual and noise, 2) death of birds, 3) deforestation and soil erosion, 4) lightning from towers, 5) radiation (electromagnetic), and 6) surrounding neighborhood, adapted from [111], with permission No. 5317080675033.

Parvez Mahmud et al. recently performed a detailed LCA for different solar energy systems, showing that Solar-T systems require almost five times the resources from nature, while having four times the waste releases of air and soil, with three times the solid waste compared to Solar-PV [108]. Fig. 5 below shows an LCA comparison of different environmental impacts of solar energy systems, showing the relative advantages of Solar-PV relative to Solar-T systems. Jenniches and Worrell conducted an economic and environmental impact assessment for 3.7 MW from 280 Solar-PV plants in Germany, indicating an added value of about €1, 019/kW-installed and €57/MWh-generated, and 2,365 t CO_2-eq (i.e. 640 g CO_2/kWh-generated), 0.97 t of SO_2, 1.48 t of nitrogen oxides NO_x, and 0.07 t of non-methane volatile organic carbons (NMVOCs) avoided annually [109].

3.3. Wind energy

Wind energy represents the second major RERs with a 733 GW installed capacity in 2020, up from 591.1 GW in 2018, at an average growth rate of 11% over 2015–2020. Similar to hydropower, China followed by the USA has the largest installed capacities at 237 and 105 GW, respectively, as of 2019, followed by Germany at 61.4 GW. Wind energy, similar to other RERs has the main advantage of a much lower carbon footprint and GHGs emissions. The American Wind Energy Association (AWEA) reported that power obtained from wind has avoided about 189 Mt-CO_2 in 2017 in the USA alone, which is equivalent to 42 million cars worth of CO_2, along with 103 billion gallons of reduced water consumption [110]. Despite such great reductions in two of the most noticeable environmental issues with energy generation, i.e., water consumption and carbon footprint, wind energy still has some adverse environmental impacts, which are summarized in Fig. 6. The environmental impacts associated with wind energy range from noise and visual impacts, bird fatalities due to collision with wind turbine blades, deforestation and soil erosion, lightning from metal structure of turbine towers, and electromagnetic radiations due to mechanical/electrical equipment.

Noise pollution by wind turbines is considered the most critical environmental impact. It is worth mentioning that the noise generated from the wind turbines was found to be independent of wind speed, and was in the range of 25–30 dBA at distances of more than 300 m, which is the wind turbines construction guidelines [112]. The visual pollution due to wind turbines, usually called “viewshed”, is purely subjective, hence it is difficult to quantify [113]. Birds’ fatalities are another critical environmental impact of wind energy, which has been of major concern and has undergone extensive study. It has been reported that annual birds fatalities due to wind turbines are about 0.15 million, compared to 67, 10–40, 60–80, and 100 due to pesticides, communication towers, vehicles, and hunters and buildings, respectively [114]. The LCA studies of different wind energy plants have shown a GWP with median values of about 9.99 and 9.7 kg CO_2-eq/MWh for offshore and onshore wind turbines, respectively [115].

4. Barriers to renewable energy resources

As common with new technologies, there are always some barriers to their full deployment and many challenges that have to be overcome as well as limitations for their application. RERs are not an exception, but rather face some unique barriers and challenges which are to be critically discussed in this section. RERs have huge potential to be the ultimate provider of sustainable and environmentally friendly energy. This goal has been more realized in recent years with growth rates of RERs capacity exceeding that of fossil fuel resources. However, it is important to note that RERs have to overcome numerous hurdles and barriers, with some of these barriers remaining in place in many nations, preventing RERs from being fully deployed [1,116,117]. Many research projects and efforts have focused on identifying, developing, and strengthening enablers to overcome the various barriers to the widespread adoption of RERs as a reliable power supply [118–122]. The primary roadblocks to RER deployment have been classified, as indicated in Fig. 7, to financial and economic, technical, social and environmental, regulatory and policy, and finally institutional and administrative [123–126].

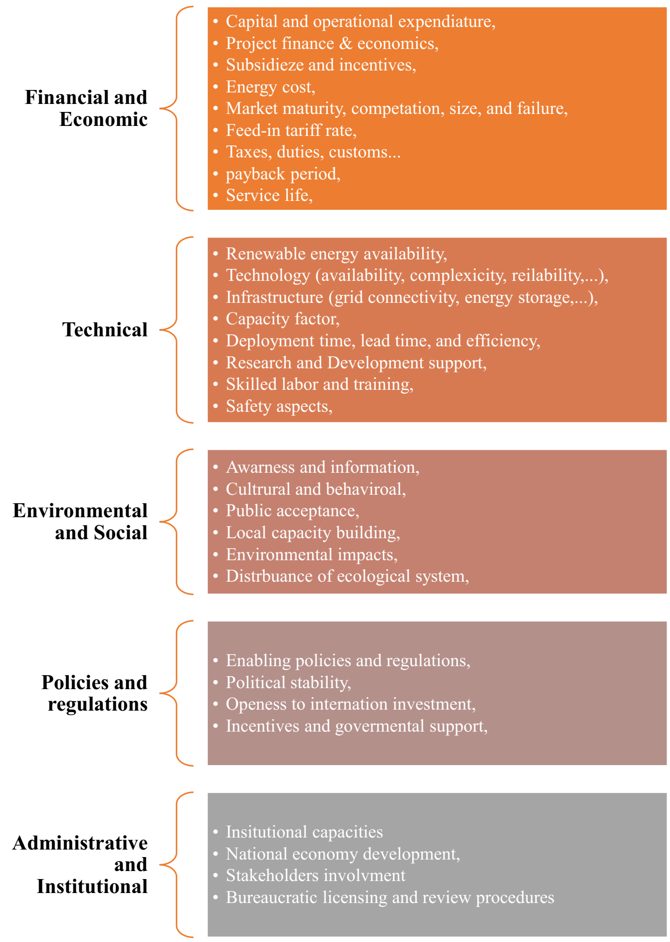


Fig. 7. Barriers facing the deployment of the different RER, adapted from [6] with permission No. 5657200372484.

4.1. Economic and financial barriers

The economics of any process has a huge impact on the deployment of such process, and the technologies of RERs is a good example for this rule, as its implementation has been hindered for a long time due to the unfavorable economics associated with high capital and operating expenditure (CAPEX and OPEX), hence higher energy cost. Accordingly, RERs projects have been challenged to acquire the required financing for a long time. In general, the market for RERs has been challenged by two factors: first, was the high capital investment requirements, second: the hard competition with traditional fossil fuel resources, with the latter being well-establishment and mature technologies. This has made RERs projects economically non-viable for a long time, with a high payback period and limited market size. Hence the LCOE “levelized cost of energy” was for a long time unfavorable for RERs projects, making their financing another challenge.

The energy sector has been highly controlled by fossil energy resources since the start of the industrialization era. This was until the 1970s, with the huge increase in fossil fuels’ prices, along with the increased environmental awareness when strong attention was given to RERs as a secure, available, and more environmentally friendly energy source. It was not until very recently, when the LCOE of RERs, more specifically for PV and wind, to compete with fossil resources. However, RERs projects still require huge capital investment, which is currently favored by regulations and incentives. Governments have been generally supporting the economics of RERs projects through environmental or green incentives, exemptions (for taxes, duties, and customs), lower interest rates, energy credits, and many other forms of support.

4.2. Technical barriers

The primary technical obstacles lie in the method of extracting usable and sustainable RERs, along with other technological attributes. This encompasses the availability, feasibility, and viability of RER, along with considerations regarding infrastructure, grid connectivity, and capacity. Additionally, the human element of trained labor and technical experience is considered. In the realm of technological advancements, Solar-PV technology serves as a notable illustration of progress, as the latest iteration of 3rd generation Solar-PV cells has successfully addressed numerous challenges pertaining to efficiency and cost. Advancements in Solar-PV technology have yielded several notable benefits, including reduced costs, less energy-intensive manufacturing processes, and the utilization of abundant material resources, thereby circumventing the need for precious and scarce metals.

One of the most difficult aspects of RERs projects is connecting to the electricity grid, which is made more difficult by its intermittent nature. Variable renewable energy (VREs) is a term that describes a type of renewable energy, such as solar and wind and their highly intermittent nature when compared to other RERs [116,127]. Eenergy storage systems ESSs have been largely recognized as the ultimate solution to smoothing out the RERs power generation scheme. One additional technical challenge that hinders the implementation of RERs projects is the limited availability of skilled labor. The installation, commissioning, operation, and maintenance of RERs typically necessitate the involvement of highly skilled labor with specialized expertise. The limited availability of training facilities and accumulated experience in the field of RERs has hindered their widespread deployment. Moreover, the prevailing standards, norms, certification procedures, and requirements have been formulated taking into consideration the utilization of fossil fuel resources. Consequently, a comprehensive technical analysis of these codes and standards is required to modify and incorporate the RERs initiatives.

4.3. Social and environmental barriers

Social barriers are mainly related to the weak awareness of the public. Despite the widely communicated merits of RERs and the general support of the public, there are still has some social barriers. RERs projects are site-specific in nature, so acceptance of the local community has a significant impact in their implementation, that is clear in the case of wind energy projects which is highly accepted by framers as it does not hinder land use. Hinder and alteration of land use is one of the main obstacles for accepting RERs among local communities, as experienced with hydropower, solar, and bioenergy RERs projects.

RERs have been widely viewed as a very environmentally friendly energy source, which is true but only to a certain extent. RERs are much more environmentally friendly and greener than current traditional fossil resources in terms of GHGs emissions and many other environmental impacts. However, RERs still pose some environmental impacts as any man-made or synthetic process, which has been the subject of many research efforts [101,128]. Wind energy has been reported to cause both noise and visual pollution effects at installation sites and effects on the local biodiversity of birds. While for solar PV, the use of precious metal resources and energy-intensive processes to produce PV cells have shown a huge environmental impact. Similar impacts are shared with other RERs, which must be well considered, and accepted by the local community and environmental entities. Awareness and public acceptance are strongly related to cultural and behavioral aspects of the local community at the RER project site and at the consumption site as well in relation to the end-user.

4.4. Regulatory and policy barriers

Because RERs projects face multiple economic and financial, technical, social, and environmental hurdles, regulatory and policy support has been viewed as critical to their adoption. The first step in enabling is to remove regulatory and policy barriers, so as to transform them into enablers. Currently, regulations and policies are mostly geared towards an energy market dominated by fossil fuels, giving the latter an advantage over newcomer RERs projects. As a result, given the environmental and social benefits of RERs, legislation and policies should be modified and changed to allow this. Some of the enabling policies to facilitate the implementation of RERs projects include FIT “fixed feed-in tariffs”, quotas, energy bids, and auctions. Energy incentives are a different sort of regulatory and policy enabler for RERs projects that receive financial support. Other legislative and policy products that directly help overcome the economic and financial constraints, therefore enabling RERs projects, include tax exemption, importation duties and customs, low-interest rates, and energy credit.

Fig. 8. The United Nations’ SDGs [133] [https://sdgs.un.org/goals].

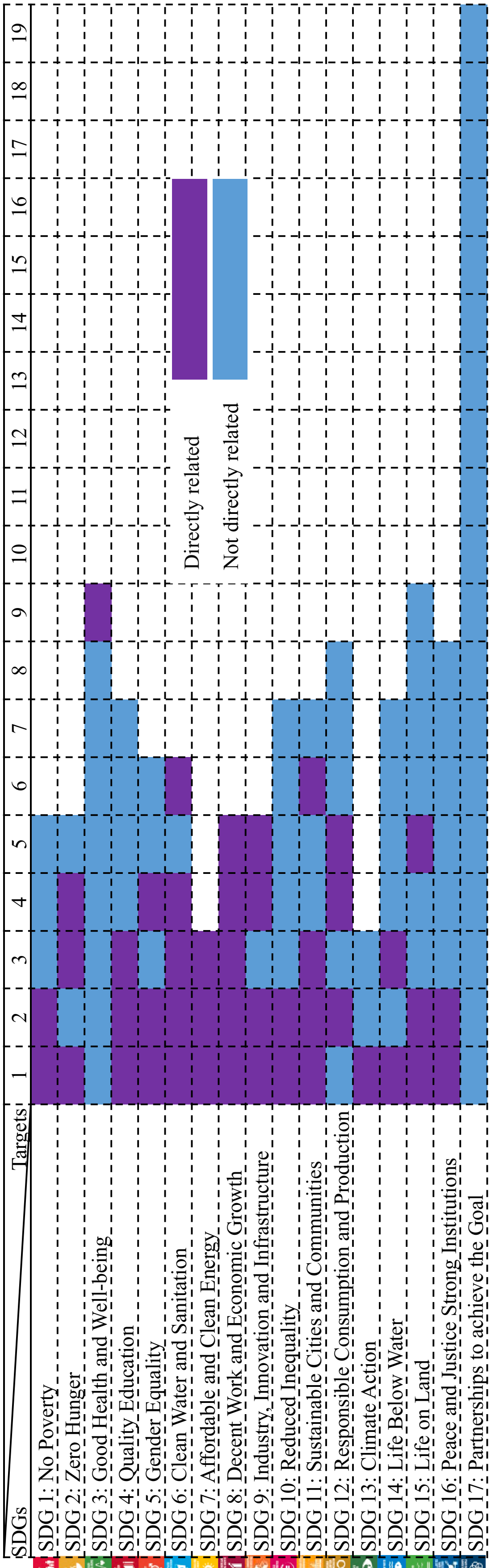


Fig. 9. The relation between renewable energy and the SDG Goals and SDGs Targets.

4.5. Institutional and administrative barriers

Institutional and administrative impediments have gotten a lot of attention because of the wide range of institutions and individuals who contribute to RERs' success. The main goal of forming an enabling institution is to coordinate and collaborate among different entities to help plan, disseminate, execute, and publicize RERs. Institutions should assist in the development of a unified framework for the deployment of RERs projects by bringing together stakeholders such as policy- and decision-makers (governmental entities for regulatory and policy enabling), investors, industrialists, academics, the public, and any other necessary entities. The early involvement of these different entities should help remove and overcome different challenges and barriers faced and support different enablers to realize RERs projects at minimum shortcomings and obstacles. This should also help to overcome any bureaucratic or procedural obstacles related to licensing or legalizations. The institutional framework should help develop an efficient mechanism by which RERs projects are effectively enabled and successfully planned, executed, and operated and ensure the delivery of expected benefits of such RERs projects.

5. Renewable energy resources systems interlinkage to the SDGs

The United SDGs, which were established in 2015, serve as a comprehensive and inclusive appeal for collective efforts to tackle pressing global issues. These challenges encompass a wide spectrum, including the elimination of poverty and hunger, as well as the mitigation of climate change. The set of 17 objectives presented herein provides a comprehensive framework that underscores the interdependence and interrelatedness of our global context. The objectives acknowledge the interconnectedness of problems and the necessity of comprehensive and collaborative approaches in order to effectively resolve them. The prioritization of these objectives is deemed essential from both ethical and economic standpoints. Notably, sustainable sectors such as renewable energy offer substantial prospects for job generation and innovation. Conversely, the absence of action in this regard can result in severe economic and environmental repercussions [129,130].

The SDGs prioritize equitable growth by placing emphasis on inclusivity through the principle of "Leave no one behind." Societies that place a high emphasis on these objectives cultivate a state of resilience, thereby enabling communities to more effectively respond and adjust to various adversities, such as economic recessions or natural calamities. Furthermore, an emphasis on the promotion of peace, justice, and the establishment of robust institutions contributes to the overall stability of society. By aligning with these objectives, businesses can not only enhance their reputation but also gain tangible advantages in terms of risk management and profitability. The SDGs transcend being mere guidelines and instead serve as a crucial pathway toward achieving a future that is both globally prosperous and equitable [131,132].

Since the adoption of the 17 SDGs, shown in Fig. 8, and their 169 targets by the United Nations (UN) and almost all the countries worldwide, decision- and policy-makers are challenged to decide the best policy that balances among the different SDGs. SDGs cover the three pillars of sustainable development i.e., economic, environmental, and social. Additionally, the relation among SDGs could be positive (synergy) or negative (trade-off); hence to determine the best option, there is a need for a comprehensive analysis. One area that requires such comprehensive analysis is the energy sector, more specifically the RERs sector. SDG 7, is calling to "Ensure access to affordable, reliable, sustainable, and modern energy for all", and more specifically target 7.2, which is calling "By 2030, to increase the share of renewable energy in the global energy mix substantially", were developed specifically to encourage the policymakers to work toward increasing the RERs availability [129]. Additionally, many other SDGs can be directly connected to RERs, as shown in Fig. 9. To assist decision-makers, the RERs selection criteria in relation to SDGs and their respective goals have to be identified and critically analyzed.

Another set of multiple indictors was developed to ensure that most other SDGs are covered, as shown in Table 5. A total of 80 indicators distributed under different SDGs were identified. Some were extracted from previous works [134–136], while some other indicators were newly developed from the perspective of the SDGs. It should be noted that there are some overlaps among indicators over different goals, as indicated in Table 5. However, these indicators have been left under each goal to maintain the integrity of the set of indicators for each goal.

In the following sections, the roles of the RERs in the SDGs are elaborated and the most common related research keywords are provided. The most common keywords extracted using Scopus database (www.scopus.com). The predefined keywords were used, (provided by Scopus), in the query together with "renewable energy "as a keyword. The extracted results were analyzed using a text mining tool, namely Bibliometrix [143–145].

5.1. SDG-1: "No poverty"

2 ZERO HUNGER

2-1) Total land occupied by renewable plants.
2-2) Land occupied type.
2-3) Water quality and soil fertility.

Several reports and international guidelines were reviewed and used for developing this set [136–139]. These indicators aim to assist the decision-maker at all levels in determining the role and measuring the contribution of RERs and ESSs into realizing SDGs. Moreover, the developed indicators have the following benefits:

- Enhance sustainability performance.
- Improve stakeholder communications and engagement.
- Improve risk management and mitigation.
- Develop internal data management and reporting practices.
- Benchmark sustainability performance.
- Improve resource allocation.
- Cost-saving.
- Reduce the climate change impact and environmental impact.
- Lower social inclusion.

Energy is both directly and indirectly connected to most SDGs targets, however, this connection could be positive (synergy) or negative (trade-off), which is dependent on many factors [140,141]. According to Nerini et al. a total of 113 of the Targets required actions to change the energy system; 143 Targets had a synergetic relationship with energy, and 65 had a trade-off relationship [142], as demonstrated in Fig. 10 . To understand the relationships among the proposed indicators, a relation matrix was built to show the mutual effects among the different indicators. Fig. 11 was extracted by converting the matrix to a network, whereby each node represents one of the proposed indicators, using the order in Table 5. The complexity of the interrelationship among the indicators and how each one of them impacts other indicators can also be seen. Based on the optioned results, SDG-8 "Decent Work and Economic Growth" and SDG-15 "Life on Land" have the highest relation number in comparison to the other SDGs. While SDG-16 "Peace and Justice Strong Institutions" and SDG-17 "Partnerships to achieve the Goal" have the least number of connections. Similarly, in terms of the proposed indicators, it was found that indicators 3-7, 7-1, 9-2,12-3, 12-4, 13-3, 14-1, and 15-5 had the highest number of interrelationships with other indicators. While indicators 1-2, 1-4, 1-6, 3-6, 4-2, 4-3, 5-1, 8-3, 9-2, 13-2, 16-2, and 16-4 had a lower number of interrelationships among the indicators.

While the onus of ending poverty lies in the hands of a country's government and the bureaucrats, the RER project can also prove to be a real game-changer. The RER project can assist and boost local economic development via increasing the procurement of goods locally, employing the population from nearby locations, and paying relevant subsidies and other fees to governments and communities. Fig. 12 shows the total jobs created by different RERs by 2019. It can also empower towns and cities by increasing access to electricity [146]. This expansion of power and electricity across towns will amplify productive activities in the area, consequently increasing incomes in addition to improving the overall provision of basic amenities. Opting to choose RERs and grid connections for power generation to replace off-grid diesel generators might also significantly contribute to major cost savings. This decrease in the charges to reduce the use of non-renewable resources would imply a lowered marginal cost of power.

Furthermore, a direct consequence of sustainable RER projects is the alleviation of poverty through taxes paid to the governments. This fair taxation can notably help in the funding of public expenditures. A more direct impact of the same can be noted by way of rent, tariffs, and miscellaneous fees to communities and individuals that will eventually be used for land or the use of technology [147]. By promoting excellent employment practices, providing good wages, and sourcing produce and raw materials locally, the RER project will be able to contribute to local economic development. Subsequently, RER projects must abide by the local laws and adhere to following the land tenure rights, in addition to consulting with communities about the various aspects of the project to make certain that RER projects do not undermine livelihoods [147].

The bibliometric analysis of the renewable energy and the twenty selected words directly related to SDG-1 is presented in Fig. 13. As depicted from the figure, RER is highly connected with poverty, poverty alleviation, economics, investment, biomass, biofuel, etc. which is in accordance with the above discussion.

5.2. SDG-2: "Zero hunger"

1 NO POVERTY

1-1) Total paid taxes.
1-2) Total rent paid to landowners.
1-3) Total number of workforces per income.
1-4) Average wages of employees.
1-5) Total products and services provided by the local.
1-6) Employee training.

Table 5
The mapping of sustainable development goal indicators to renewable energy.

SDG Goals	Indicators
SDG-1 "No poverty"	1-1) Total paid taxes. 1-2) Total rent paid to landowners. 1-3) Total number of workforces per income. 1-4) Average wages of employees. 1-5) Total products and services provided by the local. 1-6) Employee training.
SDG-2 "Zero hunger"	2-1) Total land occupied by renewable plants. 2-2) Land occupied type. 2-3) Water quality and soil fertility.
SDG-3 "Good health and wellbeing"	3-1) Availability of reports on occupational health and safety. 3-2) Accessibility of safety policies. 3-3) Total number of accidents happen during projects development and operation. 3-4) Healthcare benefits are provided to employees. 3-5) The proportion of employees covered by health insurance. 3-6) Records of hazard materials used. 3-7) Use life cycle assessment to calculate photochemical ozone potential, particulate matter, and human toxicity.
SDG-4 "Quality education"	4-1) Provide programs to measure employees' expertise levels. 4-2) Zero child labor policy. 4-3) Employee training *(same as 1-6)*.
SDG-5 "Gender equality"	5-1) The percentage of women hired. 5-2) Ensure equality in the salary. 5-3) Ensure equality in leadership positions with the company. 5-4) Ensure equality participation and involvement in all project decisions. 5-5) Availability of gender-based violence policies. 5-6) Availability of gender- equality social investments.
SDG-6 "Clean water and sanitation"	6-1) Level of compliance with the governmental policies. 6-2) Total water consumed during the project lifecycle. 6-3) Nonportable and potable water consumed. 6-4) energy consumption for water desalination, groundwater pumping, and sanitation systems. 6-5) The proportion of partnerships with other stakeholders for water management. 6-6) Availability of wastewater management policies. 6-7) Water footprint. 6-8) Measuring the eutrophication potential and freshwater aquatic ecotoxicity potential using the life cycle assessment methodology.
SDG-7 "Affordable and clean energy"	7-1) Sum of energy produced from renewable energy plants. 7-2) Energy distribution level. 7-3) Sum of the energy generated from the facility. 7-4) Total energy cost before and after project implementation.

(continued on next page)

Table 5 (*continued*)

SDG-8 "Decent work and economic growth"	8-1) Availability of anti-discrimination strategies. 8-2) Zero child labor policy *(same as 4-3)*. 8-3) Taxes paid *(same as 1-1)*. 8-4) Total products and services provided by the local *(same as* 1-5*)*. 8-5) The percentage of housing provided to temporary workforce. 8-6) Incentives given to employees.
SDG-9 "Industry, innovation, and infrastructure"	9-1) Conduct an environmental, social, and economic impact assessment. 9-2) Implementing circular business models. 9-3) Frequent measure to all types of pollution. 9-4) Ensure a compliance to all the government policies *(same as 6-1)*.
SDG-10 "Reduced inequalities"	10-1) Investment and work to ensure meeting human rights and mitigate any human right risks. 10-2) Ensue an equal paid wage between different working groups. 10-3) Diversity and inclusion level.
SDG-11 "Sustainable cities and communities"	11-1) The proportion of energy system models. 11-2) Collaboration with local authorities. 11-3) Availability of resources sustainability policies. 11-4) Total generated waste.
	11-5) Frequent measure to all types of pollution *(same as 9-3)*.
SDG-12 "Responsible consumption and production"	12-1) Total generated waste *(same as 11-4)*. 12-2) Amount of resources procured from the socially responsible organization. 12-3) Frequent measure to all types of pollution *(same as 9-3)*. 12-4) Sum of resources and materials required. 12-5) Measure energy efficiency.
SDG-13 "Climate action"	13-1) Rate of supply chain emissions. 13-2) Ensure an involvement in climate dialogues. 13-3) Frequent measure to all types of pollution *(same as 9-3)*. 13-4) Energies engaged percentage. 13-5) Total of fund provide to climate change research.
SDG-14 "Life below water"	14-1) Measure all type of water-related pollution frequently. 14-2) Use life cycle assessment to measure marine ecotoxicity.
SDG-15 "Life on land"	15-1) Conducted an environmental impact assessment (EIA). 15-2) Report the impact of the project into ecosystem and biodiversity. 15-3) Sum of resources and materials required *(same as 12-4)*. 15-4) Total land occupied by RERs plant *(same as 2-1)*. 15-5) Frequent measure to all types of pollution *(same as 9-3)*.
SDG-16 "Peace, justice, and strong institution"	16-1) Investment and work given to ensure meeting human rights *(same as 10-1)*. 16-2) Availability of human rights policies. 16-3) Level of local community engagement in projects planning. 16-4) Level of transparency.
SDG-17 "Partnerships for the goals"	17-1) Collaboration with industry groups at a high level. 17-2) The percentage of financial resources that have been used. 17-3) The extent to which SDGs are incorporated into company policies. 17-4) The extent to which the government and civil society work together.

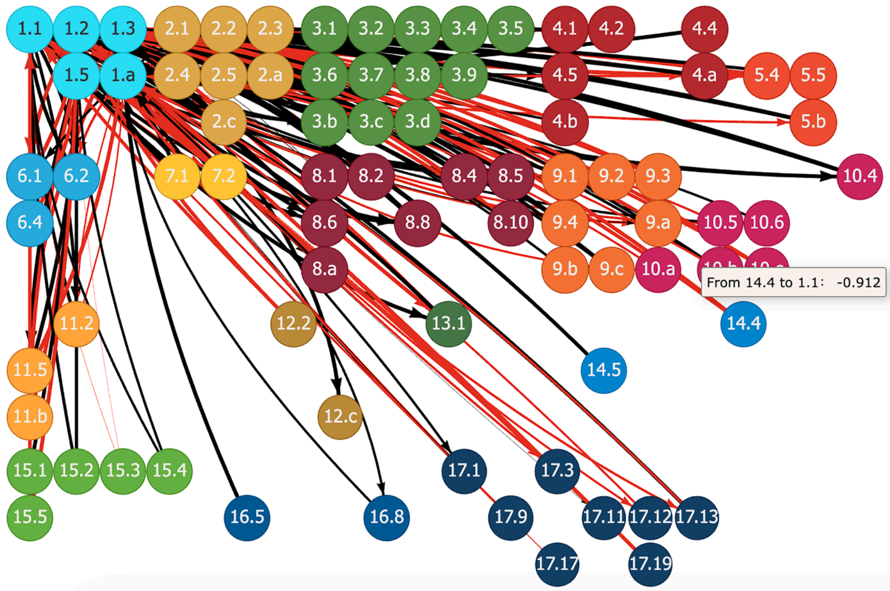


Fig. 10. The interrelationship between SDG 7 and other SDG targets in Malaysia is illustrated as follows: black arrows indicate a positive relationship, while red arrows signify a negative relationship, extracted from sdginterlinkages.iges.jp.

Food scarcity, hunger, and poverty are unevenly spread worldwide, with Asia and Africa suffering most from food deficiencies and health problems. Agriculture is the world's highest employer with about 40 % of the world's population working in agriculture and related fields. In the coming decades, the battle for food security seems likely to continue as a major development challenge. The Food and Agriculture Organization (FAO) indicated the need to raise global agricultural production by 50% by 2050, relative to 2021, to carry on with the demand for food, feed, and bioenergy due to population growth [149]. The contributions of the RER project to SDG-2 would also be largely related to the effect of food systems on local agriculture schemes. A ray of light for people in remote areas will most likely be electricity. That, if provided, will increase agricultural production, and enable the preservation of food by refrigeration/cooling, hence allowing new markets, while reducing food waste at production sites. Local farmers could gain additional income through land leases and co-siting of RERs and plantations harvest. Nevertheless, the fact that many RER solutions are suited for agricultural land use often poses threats, including competing for arable land and the potential for land-intensive RERs, such as solar or bioenergy to compete with food production [150–152]. Another aspect for the energy to realize SDG-2 is through what is known as the water-energy-food nexus in which energy plays a pivotal role. In this regard, energy is used to drive different agriculture activities, and more importantly irrigation water supply [98]. The bibliometric analysis of the role of the RER and the most common twenty words related to the SDG-2 is presented in Fig. 14. From the figure, it is clear that there is a strong relation between the RER and the different types of bioenergy and related keywords such as biogas, biomass, and biofuels.

5.3. *SDG-3: "Good health and well-being"*

3 GOOD HEALTH AND WELL-BEING	3-1) Availability of reports on occupational health and safety. 3-2) Accessibility of safety policies. 3-3) Total number of accidents happen during projects development and operation. 3-4) Healthcare benefits are provided to employees. 3-5) The proportion of employees covered by health insurance. 3-6) Records of hazard materials used. 3-7) Use life cycle assessment to calculate photochemical ozone potential, particulate matter, and human toxicity.

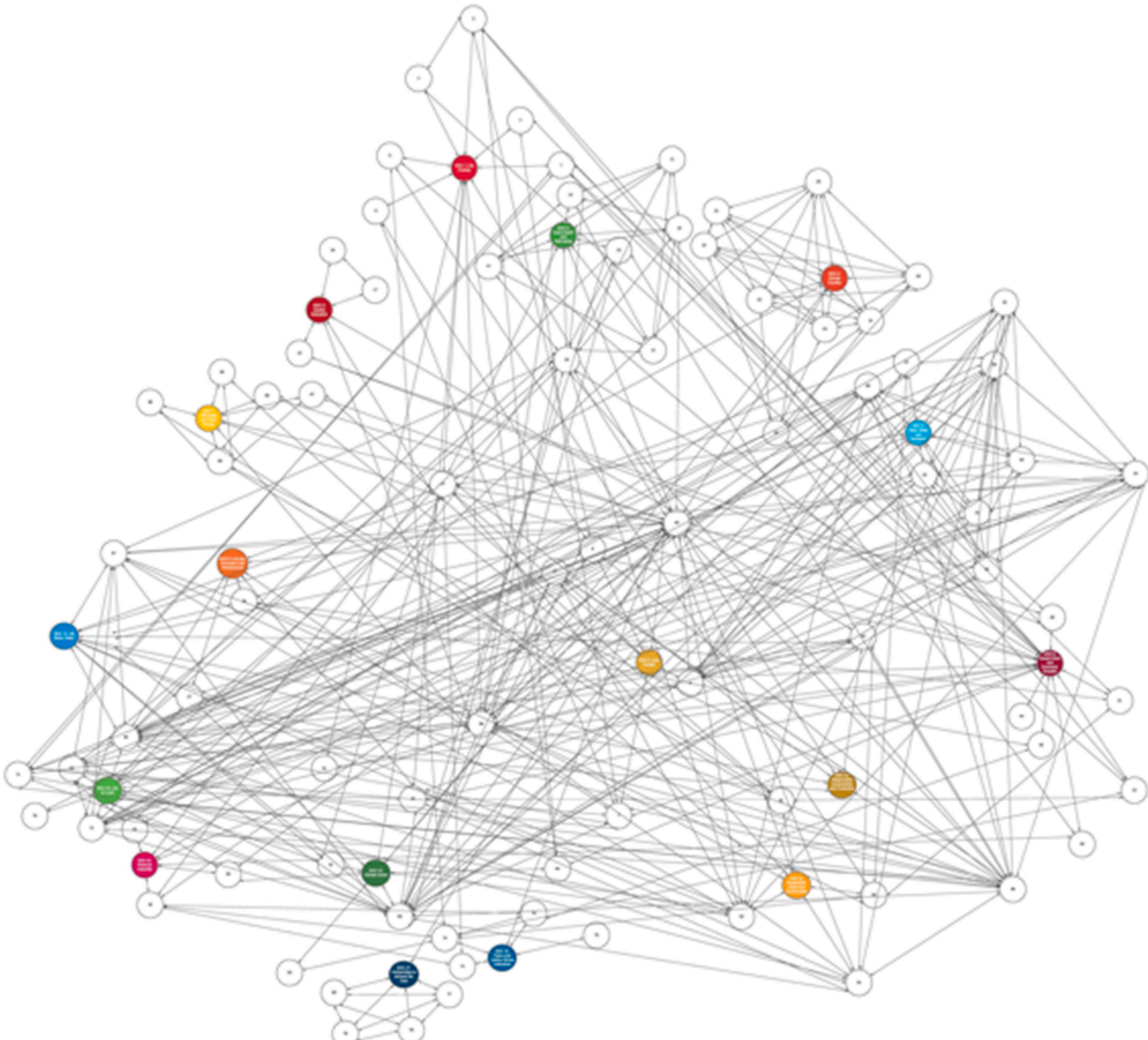


Fig. 11. The interrelationships among the proposed indicators and SDGs.

Basic human rights include -but are not limited to- access to food, well-being, health, employment, schooling, sanitation, information, etc. Despite significant improvements in access to basic health services over the past few decades, progress remains inefficiently distributed. For instance, we have witnessed a decrease in global under-five mortality rates from 44% to 4.08% live births over the years 2000–2015. This rate however doubles up when calculated for the Sub-Saharan African region [153]. The UN reports claim that children born in poverty are more suspectable to early death compared to others in decent-income households.

Contributions that RER can make for the realization of SDG-3 could be in many ways. The on- and off-grid RER developments can ensure empowering distant healthcare providers, increase the availability of electricity, and make hospitals and healthcare affordable for all. Deploying these resources can aid in responding to epidemics and disasters if the electrical grid service gets affected [154]. It can also have positive health outcomes since it doesn't use harmful fossil fuels that cause various forms of pollution. Decision-makers will have to foresee and control any plausible RER project-related threats and make health and safety policies in addition to specifying safety and health requirements in procurement contracts and providing healthcare benefits to employees. It is the responsibility of decision-makers to formulate due diligence assessments, especially in instances where flooding could happen from hydroelectric projects. It must also be ensured that the safety of surrounding communities is not compromised. The bibliometric analysis of renewable energy and the twenty selected words directly related to SDG-3 is shown in Fig. 15. As depicted from the figure, air pollution, particulate matter, greenhouse gasses, and public health are the most frequent keywords of SDG-3 and the RER.

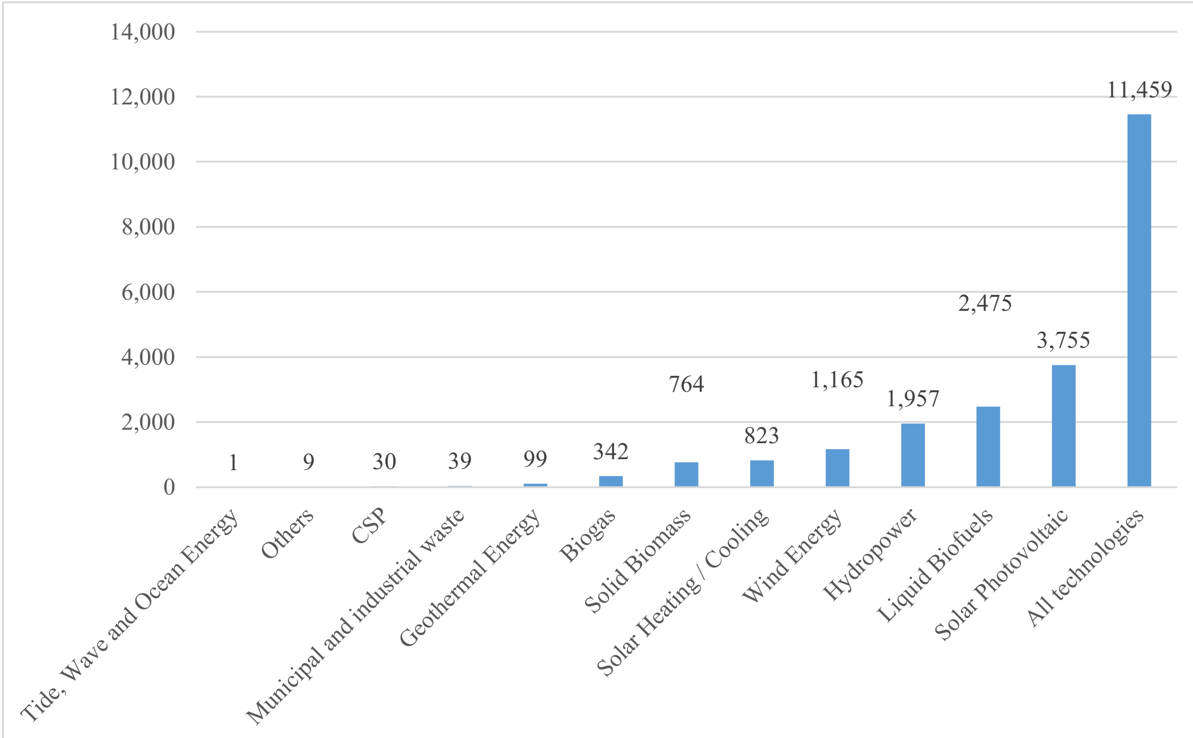


Fig. 12. Number of jobs created by different renewable energy resources (data used from [148]).

5.4. *SDG-4: "Quality education"*

4 QUALITY EDUCATION

4-1) Provide programs to measure employees' expertise levels.
4-2) Zero child labor policy.
4-3) Employee training (same as 1-6).

The importance of quality education on sustainable development cannot be undermined. Education is imperative for the overall development, economy, health, and security of any country. The right for education advocates that states must provide education for all. Causal factors for low attendance among students are poverty, poor educational quality, unsafe learning environments, etc. Successful implementation of SDG-4 equals sustainable development. Providing electricity to practical/vocational education for school students is likely to be seen as a direct contribution of RER to SDG-4 [155,156]. RERs with their decentralized and wide availability nature can help to supply power to the rural and remote communities, which are not served or connected to the power grid, hence aiding the education environment. Curating relevant curriculum in collaboration with schools and universities to aid preparations for RER jobs could prove to be beneficial. Additionally, partnering with local governments and civic societies to cater to the power requirements of houses and schools, thereby improving the learning infrastructure could be the greatest contribution of RER to SDG-4.

5.5. *SDG-5: "Gender equality"*

5 GENDER EQUALITY

5-1) The percentage of women hired.
5-2) Ensure equality in the salary.
5-3) Ensure equality in leadership positions with the company.
5-4) Ensure equality participation and involvement in all project decisions.
5-5) Availability of gender-based violence policies.
5-6) Availability of gender- equality social investments.

Fig. 13. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 1″No Poverty".

Fig. 14. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 2: Zero Hunger.

Fig. 15. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 3 "Good Health and Well-being".

Fig. 16. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 6 "Clean Water and Sanitation".

Fig. 17. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 7 "Affordable and Clean Energy".

Achieving SDG-5 aims to surpass gender-based inequality, which means that it aims to empower women and girls and, allow them to have an equal standing in financial and political decision-making while also eradicating gender-based violence. In areas where energy shortage poses an uneven burden on women, the availability of RER may itself lead to the achievement of SDG-5 [155]. By creating gender-inclusive work conditions and by recognizing and addressing gender-specific project impacts, the RER projects will also lead to gender equality [157]. Contributions include ensuring that women engage actively and efficiently in commercial, economic, and project-related decisions, including in group consultations and benefit-sharing arrangements, and taking steps to promote gender equity in job and management roles. RER projects can, to a possible extent, strive to ensure that women earn and can exert control of their equal share of the profits. Enabling all group members to engage effectively in decision-making is important for community-company agreements [158].

Fig. 18. Word cloud of the top 20 most common author keywords in renewable energy publications with relation to SDG 8 "Decent Work and Economic Growth".

Fig. 19. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 9 "Industry, Innovation and Infrastructure".

Fig. 20. Word cloud of the top 20 most common keywords in renewable energy publications with relation SDG 11 "Sustainable Cities and Communities".

Fig. 21. Word cloud of the top 20 most common author keywords in renewable energy publications with relation to SDG 12 "Responsible Consumption and Production".

Fig. 22. Word cloud of the top 20 most common author keywords in renewable energy publications with relation to SDG 13 "Climate Action".

Fig. 23. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 14 "Life Below Water".

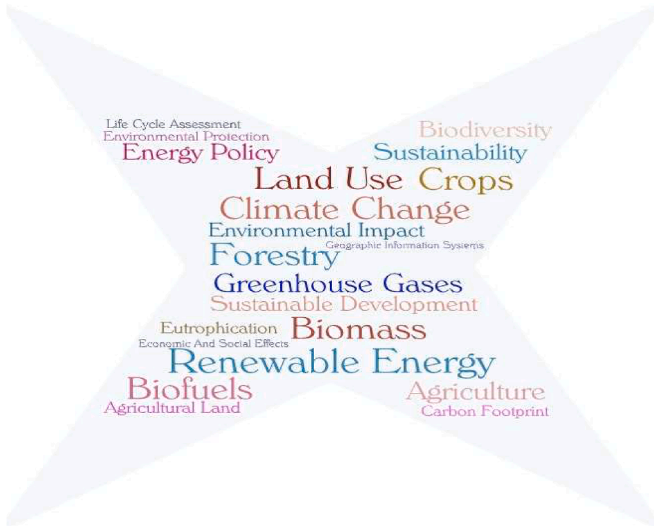


Fig. 24. Word cloud of the top 20 most common keywords in renewable energy publications with relation to SDG 15 "Life on Land".

Fig. 25. Contribution of the RER in achieving the different SDGs.

5.6. SDG-6: "Clean water and sanitation"

6-1) Level of compliance with the governmental policies.
6-2) Total water consumed during the project lifecycle.
6-3) Nonpotable and potable water consumed.
6-4) energy consumption for water desalination, groundwater pumping, and sanitation systems.
6-5) The proportion of partnerships with other stakeholders for water management.
6-6) Availability of wastewater management policies.
6-7) Water footprint.
6-8) Measuring the eutrophication potential and freshwater aquatic ecotoxicity potential using the life cycle assessment methodology.

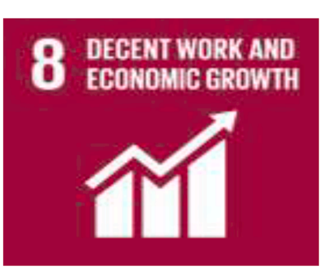
Another human right linked to core human living necessity and public health, which is also supremely important, is the right to access clean water and sanitation services. Sadly, basic amenities such as safe drinking water and sanitization remain an area for development globally [159]. Access to water and sanitation is still intertwined with other disparities, including gender inequality, in addition to health issues. Ensuring water and sanitation access and environmental management for all will help mitigate water-related illnesses, create healthy working conditions, and develop sustainable livelihoods [160]. Water is strongly linked to energy through the water-energy nexus, which interlinks these two essential commodities to drive different life activities [96,161]. The two are strongly interlinked given that one is essential to extract/produce the other. In this regard, the employment of RERs is seen to help to provide water supply to many underserved communities, more specifically remote and rural communities, hence ensuring secure water and energy supply [162–164]. The bibliometric analysis of renewable energy and the twenty selected keywords that are directly related to SDG-6 is presented in Fig. 16. As shown in the figure, the most common keywords between the RER and SDG-6 are water supply, water resources, desalination, and energy resources.

5.7. SDG-7: "Affordable and clean energy"

7-1) Sum of energy produced from renewable energy plants.
7-2) Energy distribution level.
7-3) Sum of the energy generated from the facility.
7-4) Total energy cost before and after project implementation.

SDG-7 is generally seen as the direct and obvious contribution of RERs to the SDGs. However, all SDGs somehow have a direct or indirect connection with access to energy. Since many RER technologies can be installed modularly, including solar, wind, and micro-hydro, RER is best equipped to increase off-grid access to power in rural areas where it is costly to link people to central power grid (it is estimated that around 97 and 77% of urban and rural populations have access to power, respectively [165]). Moreover, SDG-7 not only calls for universal access to electricity but to clean and affordable energy resources, with RERs on the top of the list. RERs help maximize the supply of clean electricity and substitute fossil fuels in the energy mix. The bibliometric analysis of renewable energy and the twenty selected words directly related to SDG-7 is shown in Fig. 17. As depicted from the figure, air pollution, particulate matters, greenhouse gasses, and public health are the most frequent keywords of SDG-7 with connection to the RER.

5.8. SDG-8: "Decent work and economic growth"



8-1) Availability of anti-discrimination strategies.
8-2) Zero child labor policy (same as 4-3).
8-3) Taxes paid (same as 1-1).
8-4) Total products and services provided by the local.
8-5) The percentage of housing provided to temporary workforce.
8-6) Incentives given to employees.

Important milestones towards the mission of sustainable development are inclusive growth and the right to work. Low wages, extreme working conditions, absence of recognized work arrangements, and lack of labor protections are the harsh realities of the current global work environment. The achievement of SDG-1 eliminating poverty and SDG-10 on reducing inequality is also important for good jobs and economic development. RER projects, through their key corporate activities, stand to contribute more directly to SDG-8. This involves introducing solid and equitable labor policies and procedures, paying subsidies and fees to governments and municipalities, and driving economic growth, which takes place through electrification, municipal procurement, and other related economic activities [18,166]. A study and review of 59 RER projects including solar, geothermal, and bioenergy showed that only half the projects had anti-discrimination rules, 42% specifically banned the use of child labor, and one-third had free association and collective bargaining rights laws for employees [167]. RER projects should also encourage the achievement of SDG-8 by promoting a just transition to a low-carbon economy, as the RER market becomes stronger and potentially displaces fossil fuel jobs [92]. This may include training, education, and recruiting of laid-off employees, participating in civic dialog and negotiating with workers and labor unions, as well as promoting and endorsing governmental efforts to revitalize energy-transition-impacted local and regional economies to ensure social and economic security for affected members of the community [168]. Fig.18 shows the most repeated keywords of the SDG-8 and RER. It was clear that the words related to economics, economic growth, energy efficiency, and policies were strongly connected with the RER that supports the above discussion.

5.9. SDG-9: "Industry, innovation, and infrastructure"

9-1) Conduct a environmental, social, and economic impact assessment.
9-2) Implementing circular business models.
9-3) Frequent measure to all types of pollution.
9-4) Ensure a compliance to all the government policies *(same as 6-1).*

Industrialization, innovation, and infrastructure growth processes are intertwined inextricably. To kick start industrialization, sound and sustainable infrastructure is required, while innovation ensures the continual upgrade of the technologies and skills needed to support industrialization. SDG-9 acknowledges that countries continue to underinvest in public infrastructure projects and fail to incorporate the priorities of infrastructure, industrialization, and innovation into their strategies by recognizing the continuing necessity to make robust infrastructure, encourage industrialization, and boost innovation. For instance, in many countries, more work is needed to develop the required infrastructure for power supply to rural communities [169]. As the affordability of RERs improves, frontier and emerging economies, especially in rural communities, have gradually curved to RERs [170]. While renewables can provide cheaper solutions than conventional centralized electricity grids to fill infrastructure gaps, widespread implementation still requires new and significant capital investments [170]. Developments in RERs have been realized by innovative solutions to overcome the historical challenges that have been facing and constraining RERs from being utilized. Such innovations have helped greatly to reduce the high cost previously associated with RER to a very competing level with traditional fossil fuels. Still, more innovations are expected that are critically associated with RERs, which will further foster their development and improve the innovative culture as it improves infrastructure, specifically energy-related infrastructure. This in turn is expected to improve the performance of different industrial processes as well. Fig. 19 demonstrates the strong connection to the RER with the innovation, energy policies, investment, and infrastructure.

5.10. SDG-10: "Reduced inequality"

10-1) Investment and work to ensure meeting human rights and mitigate any human right risks.
10-2) Ensue an equal paid wage between different working groups.
10-3) Diversity and inclusion level.

The achievement of sustainable development for all is critically impeded by systemic inequality and discrimination based on gender, religion, race, ethnicity, nationality, age, or socioeconomic status. The energy scarcity puts a substantial load on women and children to secure fuel in rural and primitive areas, with inhalation of polluted air due to the burning of wood sticks and other similar fuels. As RERs can improve the well-being of those with the least, they can help bridge these disparities.

RERs will support those living in poverty and other vulnerable communities through increased access to energy and rentals resulting from project co-ownership. Economic development benefits can also be generated by sustainable projects in the form of jobs or by possible savings for households, companies, and governments to free up public and private capital for other developmental purposes. In addition, by helping to prevent the inequality-exacerbating impacts of fossil fuel combustion, RER will contribute to achieving SDG-10. According to the UN and World Health Organization WHO, air pollution and climate change are now increasing the health and productivity divide between low-, middle-, and high-income countries [171]. However, these potential benefits are not intrinsic to renewable growth but rather rely on government and corporate policies that promote mutual opportunities for growth from the energy transition. RER projects should perform comprehensive public talks and due diligence on championing inclusivity, human rights and work with governments and communities to ensure that RER benefits are fairly distributed.

5.11. SDG-11: "Sustainable cities and communities"

11-1) The proportion of energy system models.
11-2) Collaboration with local authorities.
11-3) Availability of resources sustainability policies.
11-4) Total generated waste.
11-5) Frequent measure to all types of pollution *(same as 9-3)*.

Urbanization is the most noticeable trend of the past two centuries and is expected to continue in the next century. However, established infrastructure has been challenged by rapid urban growth; additional investments are required to foster sustainable and resilient, healthy, and prosperous communities. Investment and planning to ensure access to housing, transportation, effective waste management, and disaster resilience would be needed to achieve SDG-11. Currently, more than 100 cities are now meeting more than 70% of RER needs, and 70 more cities are committed to moving to 100% RER [172]. RER would be an important part of sustainable cities of the future. Such a change would improve air quality in cities, especially by replacing conventional engine vehicles with electric vehicles. Improved grid stability and efficiency can also be provided by RER incorporated into microgrids. Public buildings can be provided with onsite Solar-PV that feeds power to the grid. Careful land-use planning and partner with governments and utilities to deploy RERs in towns and businesses contribute to SDG-11 [173–175]. In accordance, Fig. 20 shows that the RER is strongly connected to greenhouse gasses, smart cities, municipal solid waste, and energy efficiency.

5.12. SDG-12: "Responsible consumption and production"

12-1) Total generated waste (same as 11-4).
12-2) Amount of resources procured from the socially responsible organization.
12-3) Frequent measure to all types of pollution (same as 9-3).
12-4) Sum of resources and materials required.
12-5) Measure energy efficiency.

The current human consumption and development trajectories are fundamentally unsustainable. Widespread resource waste and inefficiency render wasteful consumption and manufacturing practices worse [176]. RER increases production and usage sustainability by replacing fossil energy resources with RERs [177]. In addition, the modularity of RER would allow it to be produced closer to consumers, thereby increasing efficiency, and reducing transmission losses. Yet, the manufacturing phase of RER technologies utilizes many non-renewable raw materials. RER developers should promote responsible procurement of supply chain materials and create recycling programs for technology. The decision-maker should also analyze the viability of company activities and search for opportunities for productivity enhancement. RERs can play a major role toward the realization of SDG-12 by providing a clean and sustainable energy source to drive different production activities, and as such be consumed in a more responsible approach. Recently, more attention has been given towards green and blue products such as hydrogen, and ammonia, among many, as they are more sustainably produced products, with green products driven by RER [24, 178]. As clear from Fig. 21, the RER is highly connected to global warming, carbon dioxide, and life cycle assessments.

5.13. SDG-13: "Climate action"

13 CLIMATE ACTION

13-1) Rate of supply chain emissions.
13-2) Ensure an involvement in climate dialogues.
13-3) Frequent measure to all types of pollution (same as 9-3).
13-4) Energies engaged percentage.
13-5) Total of fund provide to climate change research.

After the Industrial Revolution, global CO_2 levels have increased by nearly 50%, with current values of about 420 ppm. Although crucial international cooperation on climate change mitigation is already encouraged by the 2015 Paris Climate Agreement, existing commitments are inadequate to keep warming levels at 2 °C compared to pre-industrial, leaving the 1.5 °C goal to be foreseen. On the other hand, in the fall of 2018, the Intergovermental Panel on Climate Change IPCC announced that maintaining global warming at 1.5 °C would necessitate far-reaching and rapid transformations in electricity, infrastructure (including transportation and buildings), and industrial systems unparalleled. Therefore, immediate action is required to avoid disastrous distortions of the climate; rapid deployment of RER would be essential to such effort [179].

The key contribution of RER sector to SDG-13, and even to the Sustainable Development Agenda more broadly, would be the substitution of fossil fuels. The IPCC projects that RER would need to expand to provide between 70–85% of electricity production by 2050 to maintain the 1.5 °C level [180]. This will include the installation of at least an additional 14 TW of RER capacity, on top of the 2.2 TW installed until 2017 [181]. A cumulative 470 Gt-CO_2 emissions through 2050 can be avoided by such a transition to RERs, along with substantial increases in energy efficiency [181,182]. Fossil fuel consumption is not itself displaced by the installation of renewable generation capacity; the deep decarbonization of the energy sector depends on the planning and convergence of states, utilities, and grid operators. Therefore, RER projects should work with these external stakeholders to optimize the effect of RER ventures on fossil fuel displacement, advanced research, and development to make RER technologies cheaper, more efficient, more effective and, overall, accelerate the transition to a low-carbon economy and society. Notably, RER decision-makers should also collaborate with manufacturers in their supply chains to handle climate change-exacerbating activities and to adjust investments to climate-resilient projects. Fig. 22 shows that the RER is strongly connected to global warming, gas emissions, carbon dioxide, and greenhouse gasses. It is also connected to energy policy that can speed up the application of the RER, thus controlling climate change.

5.14. SDG-14: "Life below water"

14 LIFE BELOW WATER

1.14-1) Measure all type of water-related pollution frequently.
14-2) Use life cycle assessment to measure marine ecotoxicity.

Conservation and sustainable use of coasts, seas, and natural resources for sustainable development is essential for the realization of SDG-14. Therefore, sustainable conservation of marine habitats is vital to these livelihoods being preserved and secured. Major threats to aquatic health are pollution, habitat degradation, and over-fishing. The marine environment has been affected severely by pollution and other human activities, with power generation at the core of such activities. The employment of RER should help alleviate the huge burdens caused by pollution, by being more environmentally conscious with less consumed natural resources such as shallow- and deep-water gas and oil exploration, and the use of seawater for cooling purposes in conventional fossil power plants. Improved regulations and procedures are needed to address these impacts and prevent further damage [183]. The decision-maker must ensure that RER projects do not compromise marine conservation by recognizing impacts and mitigation measures and by promoting the fisheries sector to prevent displacement driven by energy production [184]. RER projects exploiting marine energies such as wave, tidal, and ocean energy should carefully consider the local marine environment during design, construction, and operation phases to maintain the integrity of the local marine environment. The interconnection of the RER with the common keywords of the SDG 14 is shown in Fig. 23. From the figure, it is clear that RER is strongly connected to the keywords that are related with the aquatic life directly or indirectly such as ocean currents, tidal power, and marine renewable energy.

5.15. SDG-15: *"Life on land"*

15-1) Conducted an environmental impact assessment (EIA).
15-2) Report the impact of the project into ecosystem and biodiversity.
15-3) Sum of resources and materials required (same as 12-4).
15-4) Total land occupied by RERs plant (same as 2-1).
15-5) Frequent measure to all types of pollution (same as 9-3).

Most human essential commodities such as food, water, shelter…etc. are simply sourced from land areas. The ecosystem depletion pattern has been delayed but not reversed by UN policies and agreements on deforestation, desertification, and biodiversity loss. Accordingly, biodiversity sustainability, climate mitigation, human prosperity, and terrestrial ecosystems' health are crucial [185]. The primary duty of the RER projects in conjunction with SDG-15 is to ensure that RER project during their construction and operations phases do not harm local ecosystems and minimize the destruction of natural resources. Project siting decisions include following environmentally sustainable practices and considering environmental impacts [186]. RER project should also work appropriately and sensibly to protect ecosystems with other stakeholders by managing land responsibly. Fig. 24 demonstrates the strong correlation between the RER and some representatives' keywords from the SDG-15 such as land use, greenhouse gasses, climate change, and forestry.

5.16. SDG-16: *"Peace and justice strong institutions"*

16-1) Investment and work given to ensure meeting human rights (same as 10-1).
16-2) Availability of human rights policies.
16-3) Level of local community engagement in projects planning.
16-4) Level of transparency.

Peaceful and just communities are essential for sustainable growth and responsible institutions. SDG-16 seeks to foster peace and justice for all by enhancing institutions and values of good governance to protect human rights, uphold the rule of law, reduce abuse and lawlessness, and access to justice. By pre-empting and resolving project-related complaints and disputes and by cultivating a culture of transparency both within the business and in the larger communities in which they work, RER projects may contribute to SDG-16 [187]. This involves carrying out inclusive and participatory community meetings, upholding the rights of communities to the security of tenure and free, informed consent, and developing processes for structured and available grievance mechanisms [187]. RER projects are also expected to contribute to SDG-16 to ensure that workers respect human rights, enforce best practices on responsible business behavior, and foster transparency for project-related impacts [188,189]. RER projects should publicly report project records, including project-related payments and contracts, to contribute to inclusive and open decision-making and to prevent corruption [190].

5.17. SDG-17: "Partnerships to achieve the goal"

17 PARTNERSHIPS FOR THE GOALS

17-1) Level of working with industry groups.
17-2) The proportion of financial resources utilized.
17-3) Level of SDGs' incorporation in company policies.
17-4) Level of collaboration with government and civil society.

RER contributes to the SDGs by core market practices, more than other industries. The efficient and successful realization of the SDGs depends on strong partnerships for the different SDGs. Developments in the RER field, whether on-grid or off-grid, enable businesses to establish good partnerships with communities to maintain human rights. Collaboration with governments and utility operators is required to displace fossil fuels with RERs. The ability to optimize the effect of economic growth depends on the involvement of good and efficient education and training practices, preparation, and agreements with local enterprises. Potential growth prospects for the RER industry will rely on government policies, private and foreign development funding, and the ability to drive RER costs down through technological advances [191]. The contribution of the renewable energy sector to the SDGs would be lower than its potential without multi-stakeholder engagement [192]. The contribution of the different RER into the different SDGs is summarized in Fig. 25.

6. Conclusions and future work

The wide deployment of renewable energy resources RERs is becoming an essential move toward more sustainable environmental and climate change mitigation. The work presented here critically discussed RERs, with detailed discussion on their operation principles, environmental impacts, challenges and barriers including: financial and economic, technical, social and environmental, regulatory and policy, and finally institutional and administrative. This work then critically discussed the contribution of RERs towards the achievement of the Sustainable Development Goals SDGs. Sixty-eight indicators over 17 SDGs have been identified in the current work to measure RERs contribution toward SDGs directly. The preliminary assessment of RER contributions found that it significantly enabled the achievement of all SDGs. SDG-7 of "Affordable and clean energy" was logically the most impacted of all SDGs, hence SDG-13 of "Climate action", followed by SDG-15 of "Life on land", and SDG-8 of "Decent work and economic growth". Wind and solar-PV RERs were found to be the most RER enablers of SDGs, which is affirmed by the more extensive deployment of both RER, representing about 26.2 and 25.5% of the global renewable energy installed capacity, just next to the 43.3% of hydro energy.

Understanding the intricate relationships between renewable energy initiatives and SDGs a plethora of opportunities for future research works. One valuable direction is exploring these connections, specifically investigating how suggested indicators directly impact the achievement of particular SDGs.

Another pivotal area for future research works is the transition of the carbon economy. Given the challenges posed by climate change, there's an urgent need to delve into how affordable electricity and carbon dioxide utilization can synergize to reduce emissions. Such studies can yield insights into sustainable methodologies for energy consumption and production. Additionally, the arena of long-term investment planning, especially focusing on integrating renewable energy into diversified energy infrastructures, stands out as a rich topic for research.

Future research works can also extensively focus on regional nuances. For instance, an in-depth analysis of the regional integration prospects in Africa, like the African Clean Energy Corridor, could provide insights into the challenges and triumphs of pushing sustainable economic growth through renewable energy.

A promising avenue for future research works is to understand the repercussions of global warming on worldwide economic inequality. Grasping this interrelation can be pivotal for drafting policies that address both environmental and socioeconomic challenges. On a more localized front, cities, leading the charge in adopting renewable energy, offer a snapshot of the inherent challenges and solutions. Investigating their adopted strategies can be instrumental for other cities on the path to sustainability.

Additionally, future research works should emphasize the enhancement of distributed photovoltaic systems, especially within apartment complexes. Probing into strategies to boost self-consumption and energy efficiency in urban locales could dramatically shift conventional energy consumption paradigms. As we approach what many term the "next industrial revolution," understanding its underpinnings, particularly in the context of sustainability and renewable energy, becomes imperative.

The expansive domains of renewable energy and sustainable development are brimming with opportunities for future research works, holding the potential to significantly reshape our global energy narrative.

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.

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