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Review article

The pathway towards decarbonisation and net-zero emissions by 2050: The role of solar energy technology

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ABSTRACT

Global warming is an environmental issue that threatens life on Earth. A significant rise in global temperature at the end of the century is estimated to be 2.4 °C, which necessitates action. The growth of energy needs urges scholars/researchers to think about developing suitable solutions. The key goal is to achieve zero-net emissions by 2050 in accordance with the goals outlined in the Paris Agreement (Climate Accords). To accomplish this, it is vital to have a strong strategy that initially includes high emissions reduction goals and addresses the challenges of global warming on our planet. Therefore, by 2050, the global energy strategy aims to eliminate emissions from the energy industry to zero. It is worth noting that most energy of the energy consumed comes from transport, power generation, industry, and buildings. The use of renewable technology is a method that is widely recommended to eliminate such challenges. Solar energy has two main technologies: solar photovoltaic (PV) and concentrating solar power (CSP), which have great potential in fulfilling energy needs. This work provides insight into solar energy technology's role in global decarbonisation and towards net-zero emissions by 2050 through wide deployment and energy yield. The perspectives of solar energy technologies can save the environment by reducing emissions and energy supply, lowering energy bills, and creating job opportunities. Hence, investment in solar energy and other clean energy technologies will substantially achieve sustainable development in the coming decades; as forecasted, solar energy will have great installation capacity worldwide.

1. Introduction

Environmental pollution is a consequence of carbon dioxide (CO_2) emissions into the atmosphere; the lack of implementation of environmental legalisation is also an issue some countries have recently encountered [1,2]. Due to the rising rate of urbanisation and industrialisation in many emerging nations, industrial activity has contributed to increased carbon emissions released into the atmosphere [2]. Consequently, the amount of anthropogenic greenhouse gasses, including (CO_2), in the atmosphere has significantly increased, notwithstanding the contribution of climate change and global warming. The shifting seasons, low rainfall, and rising temperatures all contribute to a decrease in worldwide agricultural productivity [2,3]. Therefore, a growing awareness of environmental and climate change concerns accelerates the global energy sector towards commercialising renewable energy.

Based on that, to limit carbon emissions and other pollutants which have a detrimental effect on the environment, numerous state and international policies have been put in place. Unfortunately, however, over the past ten years, the negative impacts of more carbon dioxide in the atmosphere have worsened [4]. This is because elements such as carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO), which are the most momentous contributors to environmental emissions on Earth, are released through the development and utilisation of fossil fuels. Moreover, fossil fuels, comprising petrol, coal, methane and oil, are often utilised in producing electricity or as a source of energy for transportation. Hence, whether used for transportation, generating energy, etc., burning fossil fuels is deemed the biggest emitter. Nonetheless, such sources of energy are characterised as depleting sources of energy because of their excessive consumption [5,6].

The demand for clean/environmentally friendly energy has increased significantly recently, which has resulted in a significant increase in energy prices worldwide [7]. The requirement for this renewable energy motivates us to develop cleaner sources of energy and, in the near future, decarbonise our planet [8,9]. Also, in referring to the global goal of ''the UN's sustainable development goals, in particular, SDG7 (Affordable and clean energy) and SDG 13 (Climate Action)''. Moreover, to decrease carbon emissions and keep energy prices as low as possible, the Global Climate Change Agreement (GCCA), which

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List of Abbreviation

A	Area of emissions active rate	E_{yield}	Energy yield
A_{PV}	Area of solar PV	IEA	International Energy Agency
$A_{collector}$	Area of the collector	IRENA	International Renewable Energy Agency
BIPV	Building-Integrated Photovoltaic	LCOE	Levelised Cost of Electricity
CO	Carbon monoxide	SDG	Sustainable Development Goal
CO_2	Carbon dioxide	SDHW	Solar Domestic Hot Water
CH_4	Methane	S_{irr}	Solar irradiance
CEES	Cost-Effective Energy Storage	RO	Reverse Osmosis
CSP	Concentrating Solar Power	T	Time
CP	Cathodic Protection	T_{amb}	Ambient temperature
CPV	Concentrating Photovoltaic	PV	Photovoltaic
DNI	Direct Normal Irradiance	PV-T	Photovoltaic – Thermal
DHI	Direct Horizontal Irradiance	PCM	Phase Change Materials
E	Emissions	GCCA	Global Climate Change Agreement
EF	Emissions Factor	η_{PV}	Efficiency of solar PV
ER	Emissions reduce efficiency	η_{CSP}	Efficiency of CSP

involves energy efficiency standards in the manufacturing sectors, should be utilised [10–12].

The global energy system will shift towards structural reform and redesign as we move towards a low-carbon energy system. The global electricity sector plays an important role in attaining the Paris net-zero emissions goal [13]. That is a result of adopting a framework (efficient renewable power sources, commonly used to refer to the power generation of wind and solar energy), low-cost renewable energy, and the development of inexpensive carbon capture and energy storage technologies. Therefore, the demand sectors can also make a difference by shifting to electrification in places with fuels with higher emissions [14].

Renewable energy technologies are attractive energy sources that are environmentally friendly, clean, and contribute to meeting global energy demands [15–17]. Renewable energy has many applications, such as solar, wind biomass, and geothermal energy. The most prominent application technology is solar energy, followed by wind energy. Solar energy is classified into concentrated solar power (CSP) and solar PV; the latter is more widely deployed. Hence, due to photovoltaic solar technology having progressed significantly in the past few years, solar PV capacity has been deployed globally to meet global energy needs [18,19]. Therefore, solar energy has great potential to play a substantial role in transitioning to cleaner and sustainable energy. Moreover, solar energy efforts offer a cost-effective and resilient source of electricity.

A solar energy technology that utilises concentrated solar power (CSP) uses mirrors or lenses to direct the Sun's rays onto a small area, where they heat a fluid and create steam [20]. After that, a turbine is turned by the steam to produce power. Based on this technique, CSP systems can be divided into three categories: dish-stirling, parabolic troughs, and power towers [21,22]. Solar PV technology is the key, with the most promising clean and renewable energy source in terms of its ease of installation, dependability, lack of fuel requirements and minimal maintenance costs [23]. Additionally, as they have a low expense and an absence of wear and noise, clean energy production has significant benefits of the photovoltaic modules [24]. This, then, is anticipated to be at the forefront of energy resources in the next decades.

Cumulative solar photovoltaic (PV) installations worldwide have increased dramatically during the last ten years, with over 591 GW generated in 2019, rising to approximately 709 GW in 2022 [18]. In addition, the realisation that levelised electricity costs are now typically lower than those of other sources of energy and are nearing similar costs when storage is taken into account, as well as decreases in production costs, entirely contributed to rapid development [25,26]. The roadmap aims to help industry, funding organisations, and scholars determine the research fields that will greatly influence solar PV technology in the coming years [25]. Based on the climate change of the 2023 synthesis, this gives a current and reliable global climate matric for climate negotiations and decision-making. Subsequently, it seeks to fill the information gap between report cycles and uses the techniques applied in Working Group One (WGI), which is reported in the IPCC Sixth Assessment Report (AR6). According to statistics, the amount of heat caused by humans increased by 1.14 °C between 2013 and 2022 [27]. Ling et al. [28] reported that with the installation of 7.46 TW solar photovoltaic systems on approximately 1.8% of the country's land area and an overall capital investment of 4.55 trillion USD over the coming three decades, China can attain a net-zero electricity system via 2050. Stanbery et al. [29] modelled a sustainable solar photovoltaic industrial system, and gained experience in product design technologies and manufacturing scaling. It ramped up production volume over two decades, followed by relatively modest demand. Saccardo et al. [30] investigated the greenhouse gas emissions and financial requirements for replacing fossil fuels in Brazil's energy matrix with solar PV energy by 2030. The technology of solar PV might substitute with fossil fuels in Brazil's energy mix, potentially reducing greenhouse gas emissions by 36.9% by 2030.

Therefore, clean/renewable energy technology resources are highly needed to protect our planet from environmental disasters. This work is characterised by the pathway towards decarbonisation and net-zero emissions by 2050: the contribution of solar energy technology. Considering its perspectives on energy decarbonisation and the pathways of solar energy transformation. The main objective of this research is to highlight and respond to the following core questions:

- How can we decrease the global environmental temperature by 2050 and use clean energy resources by considering the role of solar energy technology?
- What are the current figures for global emissions, their environmental effects, and global plans?
- How can solar energy development contribute to energy generation by 2050, and what is their perspective on energy decarbonisation?

This work presents an insight into the investigation of solar energy technology and its application either in the application of CSP or solar photovoltaic; hence, it is highly anticipated that this technology will be deployed globally. It also provides a valuable contribution to energy decarbonisation and net-zero pollutions by 2050. The significance of this study is that it highlights and assesses the challenges of current global environmental issues. This work is structured as follows: Section 1 summarises the introduction. Section 2 details the research method; Section 3 specifics the significance and needs for clean energy.

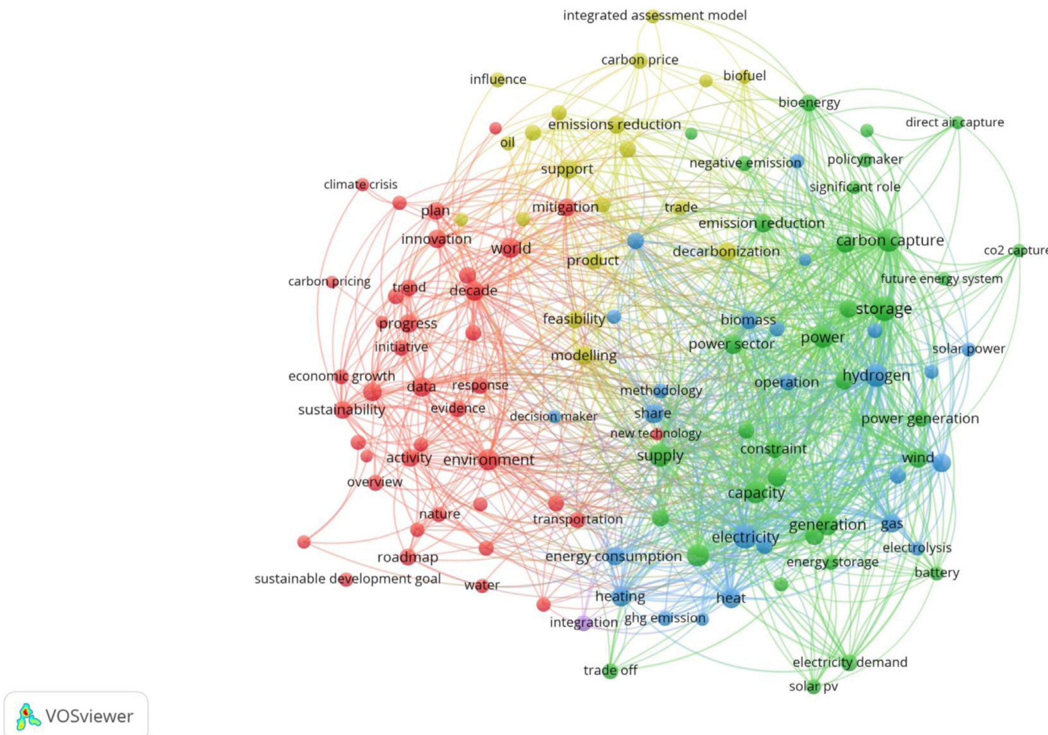

Fig. 1. Visualising and characterising scientific mapping and relations between words and development of field trends.

Section 4 analyses solar energy perspectives on energy decarbonisation. Section 5 presents the pathways of solar energy transformation. Finally, Section 6 summarises the conclusions and suggestions for future work.

2. Methods

This study presents the role of solar energy technology in the pathway of the decarbonisation of net-zero emissions via 2050. In doing so, based on the accumulated knowledge from previous literature related to the transition to decarbonisation and net-zero emissions in the next decades, we have a general overview of how it is important to find a technique to decarbonise our planet and eliminate global warming risk by relying on clean energy resources. In addition, it has been considered a global commitment, planned and strategised by national/international organisations. This critical assessment outlines the contribution of the solar energy outlook towards clean energy resources by 2050.

Through filtering the information, this paper presents summaries from a large number of literatures on science databases. Fig. 1. visualising mapping of the intensity of relations/strength between items by searching for keywords in science databases and filtering to close relevant topics. The VOSviewer was used in the analysis, which guides to the determination of the research links of networks for visualisation and exploration. Therefore, categorical analysis is based on the occurrence and frequency of keywords in relevant publications.

Based on the comprehension/analysis, we built up our perspectives on solar energy and its role in energy decarbonisation. As a result, the development of solar energy technology and its applications has become widespread. Furthermore, this paper summarises solar energy technology development and the expected energy generated from solar technology. The pathways of solar energy transformation are also considered in this study of solar photovoltaics and CSP technology. It is important to mention that solar energy can be used in space missions or in on-earth applications. It is worth noting that adopting emerging energy technology is important for energy decarbonisation and net-zero emissions by 2050.

3. The significance and need for clean energy

There is a significant need for energy, and expected onward that values will gradually increase to meet the energy demand. "Global energy consumption" refers to the overall quantity of energy consumed globally throughout a specific period. The consequence of rapid industrial development, urban growth and technological developments have motivated a tremendous need for energy. Fig. 2. illustrates global energy consumption in different regions and forecasts for 2050. Therefore, European and African countries utilised the least energy throughout the consumption energy cycle, while American and Asian countries represented the top consumers and, thereby, the most populated continents. As forecast, the values of energy consumption will rise gradually, and Aisa will have a high energy demand by 2050.

The need for clean energy has become a necessity in our lives after global greenhouse gas emissions increased caused by industrialisation. However, alternative/sustainable energy resources are available in nature that can provide paramount solutions to the energy sector's requirements. Consequently, this will assist in achieving sustainable goals, improve economic development and help save the environment.

Investors and leading companies are likewise promising to take steps to decrease their carbon emissions. Thus, to re-direct funding towards green energy technology by engaging with technology companies will enhance collaboration and increase investor confidence. This strategy will help in leading to zero emissions by 2050 [32].

Legislation to reduce emissions at international and national levels will have an impact on the global economy. Hence, it might benefit from new economic prospects by preparing for the move to net-zero. "It enables us to plan for ongoing energy affordability, security, and reliability" [33]. The goal of reaching net-zero emissions via 2050 aims to boost low carbon investment and innovation globally, create trust and stability in the private sector, and reduce the expense of the shift towards a net-zero emissions business [32,34].

There are numerous approaches to reducing carbon emissions, including action on energy efficiency, carbon capture, renewable energy technology, and emissions savings from different activities such as

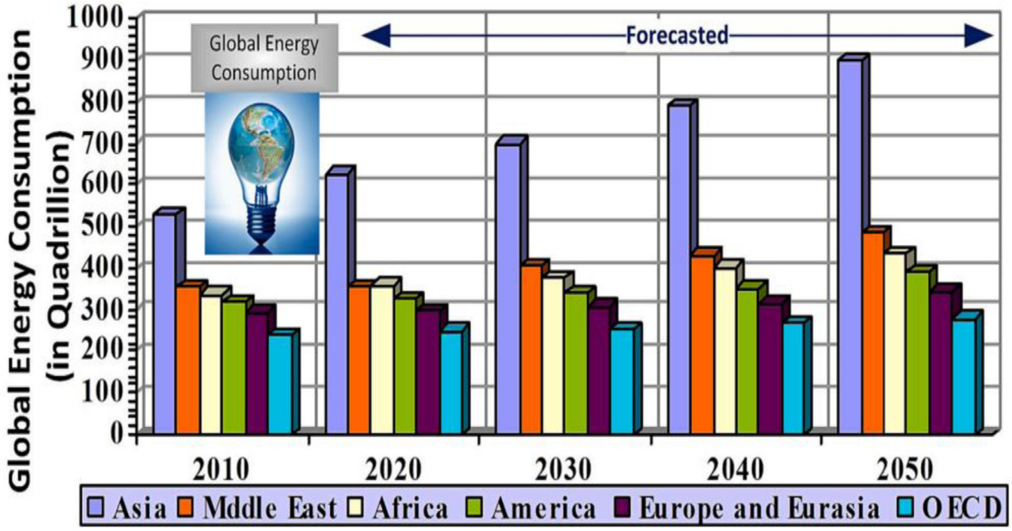

Fig. 2. The world energy consumption in the different regions and forecasting towards 2050 [31].

land and agricultural usage. Understanding that pathways provide the biggest advantages can assist us in achieving net-zero emissions by 2050, despite maintaining an economic boom. In addition to supporting present businesses to increase their production, this will assist in attracting new employment opportunities [32,33].

It is important to mention that an emissions factor represents the quantity used to establish a correlation between an activity and the amount of a pollutant emitted into the environment. Eq. (1) is the general equation that can utilised to estimate the amount of emissions [35].

$$E = EF \times A\left(\frac{1 - ER}{100}\right) \quad (1)$$

where (E) is the approximation of emissions amount, (EF) is the emissions factor, (A) is the emissions active rate and (ER) is the overall emissions reduce efficiency.

When we focus on the implementation of policies, the confidence gap is growing; it is expected that by the end-of-century, global warming will rise by about 2.7 °C, if there is no implementation of a new policy of net-zero emissions [36]. Although this temperature forecast has decreased during the previous assessment, significant new policy developments are not the primary cause. Additionally, the temperature forecast remains well above the 2030 plan, showing that countries as a whole are not on track to meet the goals they have set [37]. Fig. 3. illustrate the global greenhouse gas emission goal in the next decades. According to the global emission, an ambition gap is forecasted to be 19–23 Gt CO_2e by 2030.

The Paris Agreement presented a framework to restrict the rise in global temperatures to lower 2 °C and ultimately to 1.5 °C. As a result, the world energy landscape must undergo a profound transition to meet the agreement's climate goals. The rapid adoption of low-carbon technology in terms of the generation and utilisation of traditional fossil fuels can enable such a transformation [38,39].

• **Carbon emissions reduction**

The gap between actual emissions and the decreases required to achieve the climate change goals set by international agreements is widening. To accomplish the goals of the Paris Agreement, which attempts to limit the increase in the mean global average temperature in the current century to approximately 1.5 °C relative to pre-industrial stages, the world's energy system must undergo a significant transformation. Thus, by 2050, energy-related emissions must be reduced by 70% from their current levels [38,40]. Also, carbon dioxide emissions decreased as a consequence of a decrease in reliance on fossil fuels and increased demand for sustainable development [41]. Environmental effects are the key factors in carbon dioxide emission mitigation. The mitigation of carbon dioxide on energy can be attributed to solar PV and wind turbines in the annual generation of power, which is estimated as follows [42]:

$$CO_2 \text{ mitigation} = \text{Yearly Power}_{(PV,WT)} \times 0.318 \left(\frac{\text{kg } CO_2}{\text{kWh}}\right) \quad (2)$$

• **Improvements in air quality**

A serious public health issue, air pollution is mostly brought on by unregulated, ineffective, and polluting sources of energy, e.g., chemical-related emissions and fossil fuel combustion. Hence, lowering illness, raising productivity, and shifting to cleaner, renewable energy supplies could enhance city air quality and increase prosperity. In addition, lowering net energy subsidies and increasing the utilisation of renewable energy sources could result in lower healthcare expenditures related to air pollution and climate change [38,43]. The increased energy demand is outweighed by the savings from lower externalities related to air pollution and climate change, as well as avoided subsidies. There is a payout of at minimum $3 and maybe up to $7 for every investment in changing the world's energy system between now and 2050, based on how externalities are evaluated [38].

• **Cost reduction of renewable energy technology**

There has been a rapidly falling cost of renewable energy recently; the most commercially viable renewable power production technologies globally weighted mean cost of electricity decreased in 2018. For instance, the levelised cost of electricity (LCOE) from utility-scale solar photovoltaic projects has decreased dramatically since 2010, with a 77% decrease in the globally weighted average LCOE from solar PV between 2010 and 2018. Therefore, in the coming years, it is anticipated that renewable energy sources like wind and solar photovoltaic will generate the most electricity cost-effectively [38,44].

The cornerstone of the energy revolution is lowering CO_2 emissions caused by energy usage produced by carbon fuels. Thus, suppose the globe is to meet the climate targets set forward by Paris. In this case, it is imperative that we rapidly transition away from the fossil fuel consumption which contributes to climate change and move towards cleaner, renewable forms of energy. This transformation is driven by various factors, as illustrated in Fig. 4 [38]. However, by 2050, the estimated energy transformation is about 9.8 Gt, encompassing industry, power, district heat, transport and buildings. Also, 70% of the emissions decrease resulting from energy transformation. The technology of renewable energy and electrification delivers approximately 75% emission reduction.

It is essential to decrease energy-related carbon dioxide emissions by 60% by 2050, and this may be attained owing to the shift to electrified modes of transport and heating and the expansion of renewable

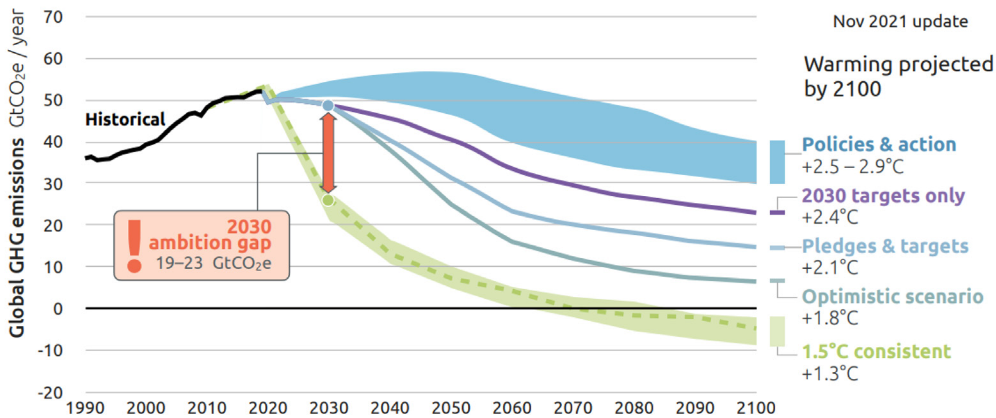

Fig. 3. Global greenhouse gas emission routes for estimations of legislation, plans just for 2030, required long-term targets for 2030, and an ambitious road based on net-zero targets for more than 140 countries compared to a steady 1.5 °C pathway [37].

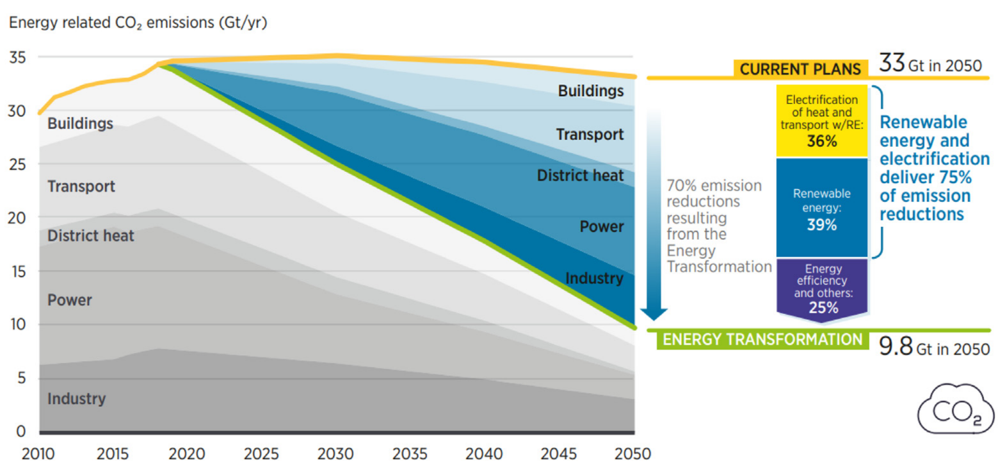

Fig. 4. Renewable energy and efficiency improvements have the potential to reduce CO_2 emissions by more than 90% in 2050 [38,45].

energy generation. However, as subsequent decreases in the usage of direct renewable energy are considered, this share might rise to 75%. Additionally, if energy efficiency rises, this share might attain more than 90%, enabling the globe to meet the goals outlined in the Paris Accord [45,46].

To achieve the aim of net-zero emissions by 2050, it will be necessary to significantly accelerate the deployment of existing technologies and employ them widely [47]. Thus, significant innovation efforts will be required during the next ten years to have these emerging innovations appear in the market over time. Nevertheless, the majority of approaches worldwide used to decrease CO_2 emissions through 2030 come from currently accessible technology. However, by 2050, technologies still in the prototype or demonstration stages will be responsible for over half of the decrease [43,48]. Even more emission cuts are coming from technological innovations currently being developed in long-distance transportation and heavy industry. The main areas for innovation are improved batteries, direct air capture and storage, electrolysers and hydrogen. These three technological areas together significantly reduce CO_2 emissions on our roadmap from 2030 until 2050 [49]. In the coming decade, innovation must be followed by a wide range of technologies for the construction of infrastructures, which will require development research, demonstration and implementation. This contains new pipes for carrying CO_2 emissions that have been captured, as well as systems for moving hydrogen both within and between industrial areas and ports [50].

The shift is not moving at the necessary speed to meet the Paris Agreement. It only stabilises global emissions with a little decrease towards 2050, as in the anticipated energy scenario, and will contribute to existing policies. Furthermore, based on the baseline energy scenario shown in Fig. 5, pollution could potentially increase by 27% over the next three decades if such regulations are not fully implemented. Thus, the projected future growth rate shown in the Planned Energy Scenario is far less than that required to maintain a 1.5 °C pathway. Time is of the essence, and a drastic transition depends on immediately available renewable energy and energy efficiency technology. The 1.5 °C pathway, which the International Renewable Energy Agency (IRENA) refers to as the energy route, is presented in this overview and describes the conditions necessary for such a shift (1.5-S) [51].

The cost of CO_2 reduction and decarbonisation pathways are both heavily impacted by energy service demand response. The expense of alternative solutions and the CO_2 emission of such technology motivate fuel shifting and system efficiency, which in turn causes such demand decreases [52]. Emissions reduction is the process of lowering or eliminating carbon dioxide effects, and other greenhouse gas emissions from a wide range of economic sectors, including industry, transportation, and power sector, in an attempt to reduce or prevent global warming. Several actions and policies are necessary to achieve decarbonisation and net-zero emissions, including:

– Expansion of the usage of clean/renewable energy sources, such as the application of solar and wind power instead of fossil fuels.
– Improving energy efficiency in buildings, industrial processes and vehicles.
– Investment in low-carbon technologies, such as carbon capture, electric transport and energy storage.
– Charging for carbon through methods like carbon taxes or cap-and-trade programmes.

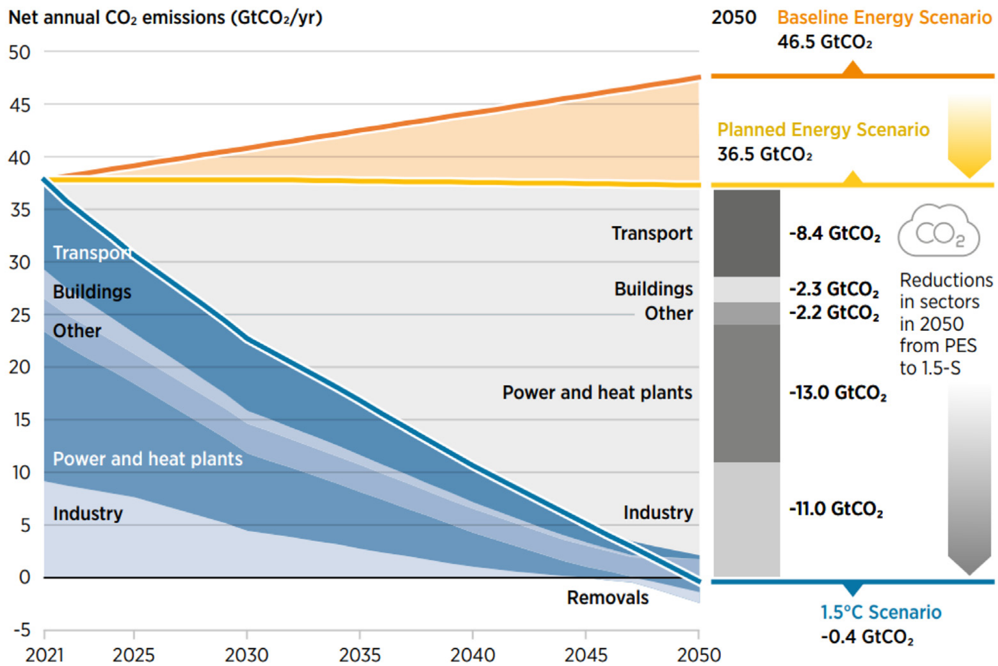

Fig. 5. Global climate target is 1.5 °C, and planning to reduce CO_2 emissions to net-zero by 2050 [51].

– Abolishing subsidies for fossil fuels.

It is essential to remember that emissions reduction is a worldwide effort that necessitates the collaboration of organisations, companies, and citizens. Many countries will have varied pathways depending on their energy mix and economic, social, and cultural environments.

4. Solar energy perspectives on energy decarbonisation

To achieve climate goals, the adoption of clean energy technologies must accelerate. In this regard, solar energy nowadays represents a robust and sustainable investment for potential technological improvements. Energy decarbonisation refers to the procedure to reduce greenhouse gas emissions in the energy sector to battle climate change by reducing carbon footprint. The current work focuses mainly on solar energy technology, its applications, and how it supports the global transition to decarbonisation.

Green hydrogen, which may be utilised as a fuel in transportation, power plants and industry, is also feasible to produce by solar energy [53]. In addition, solar PV and solar thermal systems can be employed to supply heat and electricity in building sectors. Furthermore, one promising role of solar energy is the production of green hydrogen. So, green hydrogen is considered a vital way to achieve global climate goals. It provides a decarbonisation technique that helps decrease greenhouse gas emissions and resist climate change. Hence, green hydrogen is a sustainable/clean energy solution that can potentially be substituted for fossil fuels [54].

The perspective of solar energy by 2050 will help to save the environment by using clean energy sources. Fig. 6 shows the perspective of the plan for solar energy technology gearing towards 2050. Climate condition is a vital parameter to be considered during the process of designing and planning solar energy.

It is important to mention that some countries on the Planet have limited potential for solar energy [55]. The climate conditions parameters of direct normal irradiance (*DNI),* ambient temperature (T_{amb}), wind and direct horizontal irradiance (*DHI*) are important when installing solar energy technology. Environmental parameters differ from one place to another, and these parameters are essential to consider when designing the system framework.

Moreover, climate/environmental factors have significantly affected the design of solar PV systems, and they should be considered to optimise overall system performance and achieve the best effectiveness [56, 57].

The deployment of the latest applications and recent designs has been developed while taking into account the employment of low-cost materials. Also, the newly invented materials in solar cells, such as bifacial and half-cut cells, are important for developing device efficiency.

As a result, this will lead to the expansion of solar energy technology and an increase in the installation of PV and CSP. In this context, installing PV on top of the buildings can help clients financially by lowering the energy bills of small/big clients. Also, it will lower energy demand on the national grid and decrease power plant generation through lower fossil fuel burning.

The investment of subsidies from the government or entrepreneur to the private sector has encouraged the solar photovoltaic sector to attain the economies of scale required to compete with the relative expense of photovoltaic electricity generation.

Solar energy can be attractive for businesses and households looking forward to reducing energy costs. Feed-in tariff policies have been valuable in encouraging the growing use of solar energy [58]. The policy will support solar energy in stimulating investment by building more infrastructure, contributing to the global transition to a sustainable energy goal.

Deploying solar energy can create new employment opportunities in manufacturing, installing, and maintaining solar systems. These jobs can be placed in urban and rural areas to improve economic opportunities for various communities. These rules are employed to support energy independence, the growth of high-technology jobs, and help with the reduction of carbon dioxide emissions contributing to climate change. Solar energy technology can create more employment opportunities worldwide. For instance, as generation capacity expands, solar PV and wind energy jobs are expected to grow by roughly 10% annually between 2021 and 2030 [59].

Distributed generation is also a factor to be considered in the future design of electricity grids. Solar energy can be generated at the point of usage, which means it can be distributed locally throughout a region or community, reducing the requirement for long-distance transmission

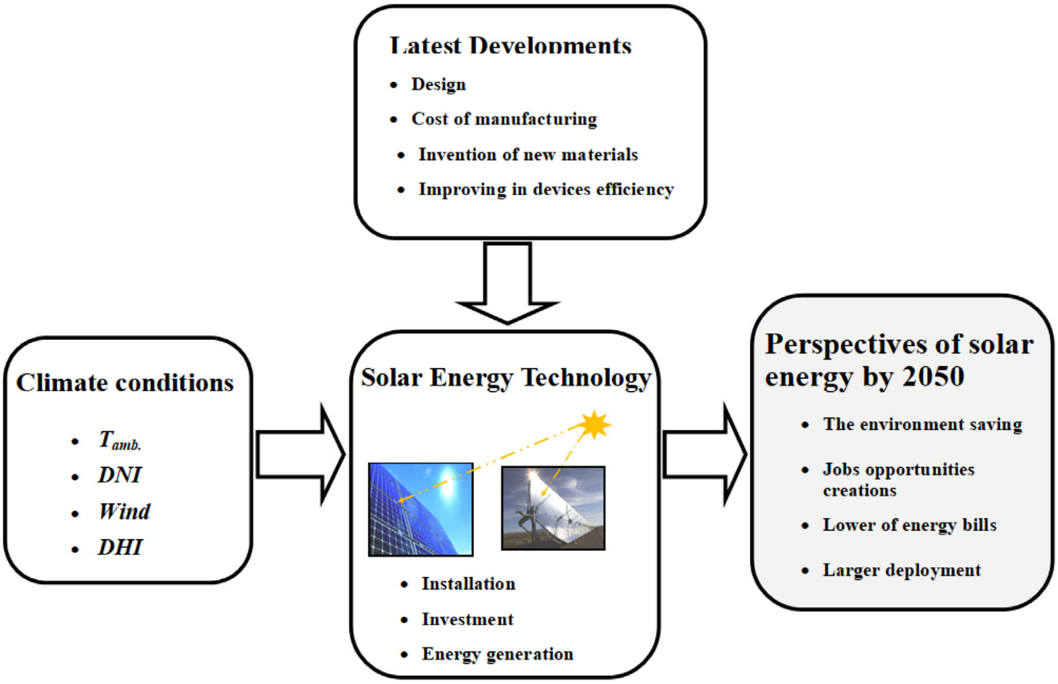

Fig. 6. The perspective of solar energy technology towards 2050.

lines. Therefore, this can increase the energy system's resilience and decrease the risk of other disruptions or blackouts.

Global economic development, especially in most European markets, Brazil and Australia, has not been significantly hindered; however, deploying distributed solar PV applications is still sluggish in key markets like the United States and China [60].

The prospects and future of concentrated solar power were investigated in research by the European Solar Thermal Electricity Association and the Solar PACES group of the International Energy Agency. According to this research, by 2050, concentrated solar power might provide up to 25% of the globe's energy requirements. Furthermore, millions of tonnes of carbon dioxide would not be released due to the development of concentrated solar power, which would also result in the creation of thousands of new jobs. In that period, investment will rise from two billion euros globally to 92,5 billion euros [61,62].

The report stated that CSP technology was evolving and that by 2050, costs will significantly decline. As a consequence, from the present range of 23–15 euros per kilowatt, it was predicted this would decrease to 14–10 euros per kilowatt [61,62].

The promising technological developments in recent years include the electric vehicle and cost-effective storage. Electric vehicles (EVs) are becoming increasingly technologically advanced, and public interest in them is rising. For example, Tesla's leader cares about manufacturing companies designing and manufacturing batteries that can be produced more affordably and have higher power output. Despite the COVID-19 outbreak, the global market for electric vehicles has continued to grow, mostly due to generous government grants. However, it is estimated that it will be 2030 until the cost of electric vehicles catches up to that of gasoline-powered automobiles. Increasing sales and development of battery technologies might significantly accelerate that timeline.

Cost-effective energy storage (CEES) is a promising technological development. To guarantee the availability of electricity despite the weather, utility providers require efficient, affordable methods of storing wind and solar energy. Phase change materials (PCM) are one of the emerging materials used for cooling and energy storage that depend on latent heat. Also, the emerging invention of integrating solar PVT with thermal battery storage has been used recently to save energy bills in buildings.

The markets for solar inverters are now expanding, with several international initiatives to promote the adoption of renewable smart grids, as well as the rising worldwide need for electricity serving as the primary drivers of this progress [59]. As a result, the energy system has the potential to shift rapidly despite continuing to provide customers with value and reliability.

This section aims to highlight the technology powering the solar power sector, their possibility for growth, and how they could greatly influence the energy system. It also discusses the difficulties the market faces as it expands and diversifies. The photovoltaic solar sector is changing quickly, whereas innovations are taking place along the whole value chain. The need for improved efficiency in recent decades has been a key motivator for innovation [63]. The development of passivated emitter and back cell/contact technology, which also provides more effective solar cells and therefore improves the performance of solar photovoltaic modules, reflects this. Furthermore, for competitive module manufacture, rising cell efficiency is essential, since it directly lowers cell overhead expenses by lowering the number of cells needed to produce a given output power [38].

At the system level, efficiency is equally crucial, and several variables cause the demand for higher-efficiency technology. From a technical point of view, increasing efficiency levels decreases the number of modules that must be carried to the installation site, the amount of land that must be utilised, and the length of cables and wires that must be used [38,63].

Considering the solar photovoltaic industry's progress in terms of materials, module manufacturing, applications, maintenance, and operation, as well as methods for retiring modules and addressing their end-of-life period.

5. The pathways of solar energy transformation

Solar energy transformation refers to the process of converting the energy from the Sun into usable forms of energy. Hence, innovating new materials and designs for a solar prototype can improve efficiency and lower costs. The pathways of solar energy transformation include solar photovoltaic and solar thermal energy technologies.

Referencing the 2019 version of "the Global Energy Transformation Report" presented by the "International Renewable Energy Agency",

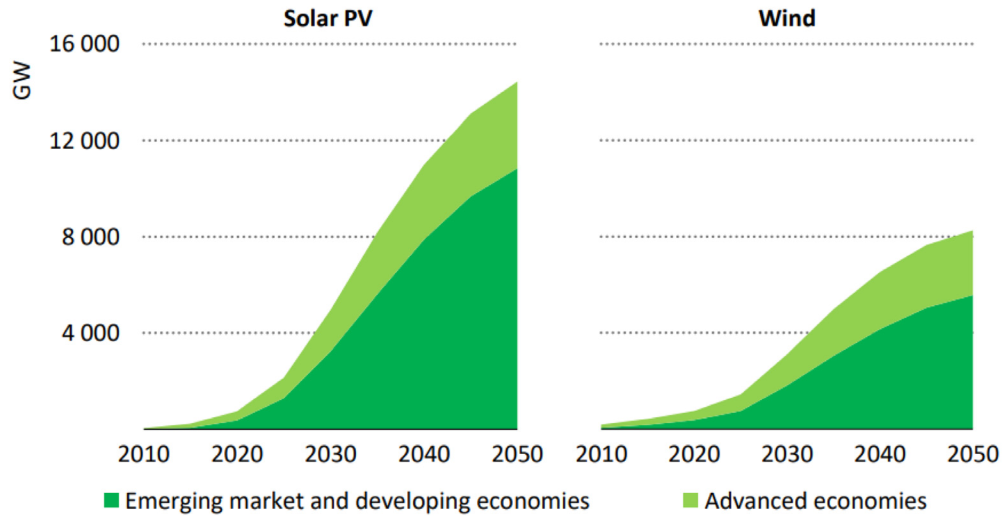

Fig. 7. Solar photovoltaic and wind energy installed capacity in net-zero emissions by 2050 [50].

it also investigated prospects for global energy development from two broad viewpoints through to the year 2050 [64]. The first is an energy pathway determined by existing and planned regulations, and the second is a cleaner, more climate-resilient pathway based in large part on a more ambitious, although realistic, adoption of energy efficiency renewable energy and technologies: "the REmap Case" [38].

The accumulation of solar photovoltaic (PV) installations worldwide has augmented dramatically over the last decade, with over 591 GW produced in 2019, and its value rose to approximately 709 GW in 2022 [18]. The realisation that levelised electricity costs are now typically lower than other sources of energy and are nearing similar costs when storage is taken into account, as well as decreases in production costs, entirely contributed to this rapid development [25]. The roadmap's overall goal is to help the industry with funding from organisations and where scholars can determine the research fields that will have the greatest influence on solar photovoltaic technology in the coming years [25].

The net-zero emissions vision for the energy sector transition calls for significant capacity expansions for all low-emission technologies and fuels. As expected, between 2030 and 2050, the capacity of renewable energy on a worldwide scale will have more than tripled. This requires, as illustrated in Fig. 7., deploying, on mean, more than 600 GW of solar PV capacity and 340 GW of wind energy capacity per year from 2030 until 2050. Although offshore wind's significance rises over time, from about 7% in 2020 to over 20% in 2050, it becomes more and more significant. It is necessary to ramp up the yearly implementation of battery capacity in the electrical sector concurrently, from 3 GW in 2019 to 120 GW in 2030 and to more than 240 GW in 2040. In addition, it is necessary to modify current coal- and gas-fired power stations [50].

To decarbonise electricity, solar energy and wind must grow-up rapidly, with overall solar capacity increasing 20-fold and wind increasing 11-fold by 2050 [50]. Based on research studies, photovoltaic conversions can be performed utilising a wide range of materials, device technologies, and architectural designs with different degrees of technical and financial maturity [65,66]. These take into account the following solar PV application examples: infrastructure-integrated photovoltaic, building-integrated photovoltaic, floating photovoltaic systems, vehicle-integrated photovoltaic and ground-based photovoltaic power plants. A cascade of literature has developed to keep up with the quick-changing subject of photovoltaic devices, drawing increasing interest from scientists, engineers, and business executives [12,67]. As a result, it is anticipated that photovoltaic solar energy will be a substantial component of the upcoming global energy system for sustainable development [12].

The technology of solar photovoltaics has the potential to mitigate energy associated with emissions. This is possible to reduce emissions of 4.9 Gt CO_2 by implementing more than 8500 GW of solar energy, which can produce more than 25% of the world's electricity demands in 2050. This is equivalent to 21% of the entire reducing emissions potential from energy-efficient and renewable sources. Solar photovoltaic technology has the greatest potential to significantly reduce emissions by 2050 of all technology of low-carbon solutions. However, this is mostly because solar power has been widely used to replace traditional power-generating supplies by using abundant available resources and the best technology solutions at effective resource locations throughout different geographies. The benefits from substantial cost decreases and extensive client electrification of heating and transportation systems. A transition in energy requirements to electricity, which the wind can then generate, whether direct or indirect, such as in the case of power-to-hydrogen, as well as growing socio-economic advantages [38].

Solar PV utilisation needs to increase significantly as part of the transition to net-zero energy. Over the years, solar photovoltaics PV has emerged as one of the leading renewable energy technologies. The photovoltaic solar sector has come a long way, with significant developments in recent decades in the installations aspect, including off-grid, decreased costs and technology, and significant associations for solar energy [38,44].

Solar energy will remain a key renewable energy source in the following decades. This explains how solar photovoltaics will significantly affect the worldwide energy environment by 2050. It outlines an expedited deployment pathway for solar photovoltaic systems through 2050 under the REmap case from the International Renewable Energy Agency, world energy transition roadmap, and perspective on price reductions, technological developments, and the need to have future grids ready for increasing shares of photovoltaic systems [38].

The global energy system must be decarbonised, which requires expanding the utilisation of renewable energy sources. Incorporating growing low-cost renewable power technologies and expanding electricity usage for end-use applications, including transport and heating, provides the most significant synergy in the world's energy transition. So, by 2050, the power sector will have to be almost entirely decarbonised in order to achieve the required pace and level of the energy transition. The REmap case establishes a strategy to attain 86% of renewable energy sources with a mixture of electricity generation via 2050, as presented in Fig. 8. In terms of final energy use, the electricity share will rise from 20% recently to over 50% by 2050. Furthermore, the electricity share used by industry and the second similar forthcoming international renewable energy agency (IRENA),

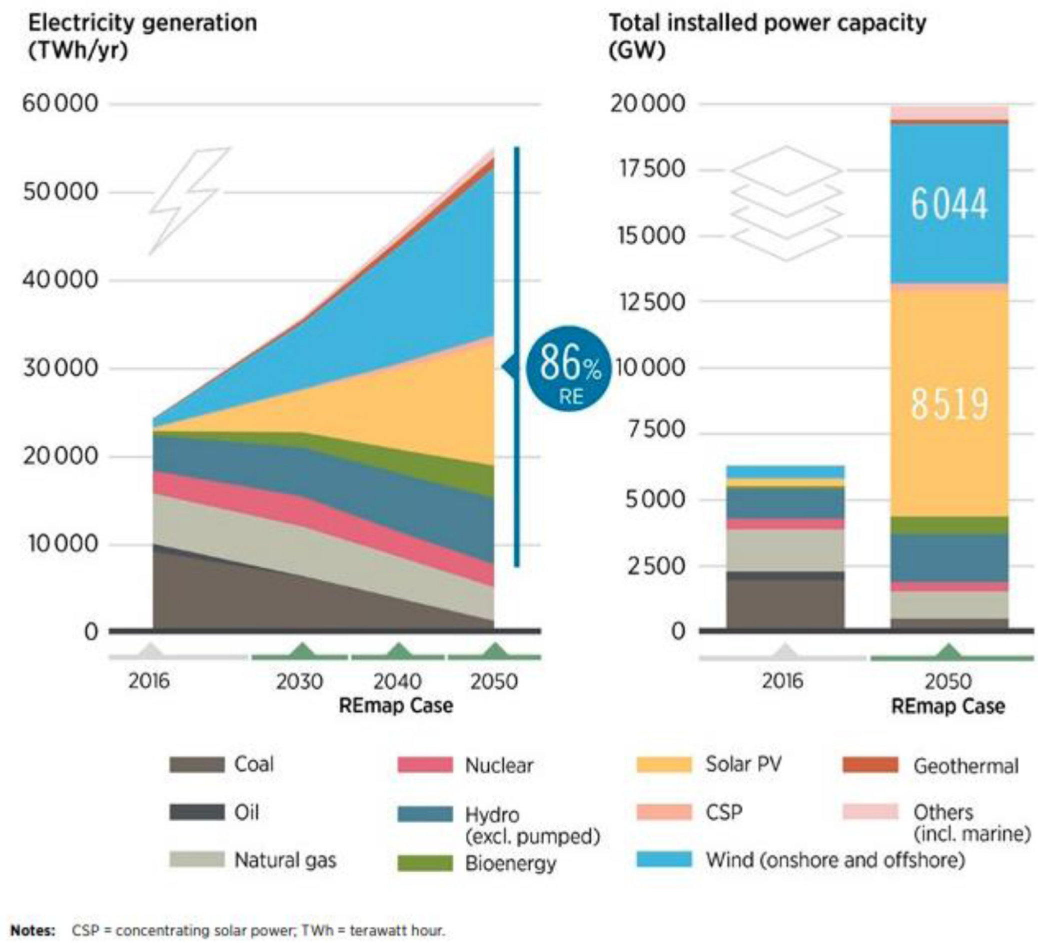

Fig. 8. Anticipation of energy generation and renewable energy technology installation capacity by 2050 [38,64].

wind energy, is in the works, and it examines the role of wind in the worldwide energy transition towards 2050. Although, by 2050, this would rise just from 1% in transportation to almost 40% [64].

Solar and wind energy will pave the way for a transition in producing the world's electricity. More than one-third of the world's electricity consumption would be met through wind power, one of the key sources of electricity generation [7]. Thus, by 2050, the share of solar photovoltaics in the generation mix will have increased more than tenfold in contrast to 2016 levels, supplying 25% of the world's electricity needs. In terms of whole installed capacity by 2050, solar photovoltaic technology of 8.519 GW will require a substantially larger capacity development than wind energy of 6044 GW [38].

The top main source of power production by 2050 will be solar and wind energy. One of the most known and dominant power supplies, solar photovoltaic panels may supply 25% of the globe's entire electricity needs. As a result, transformations will be made, and some rearrangements will be performed in the electricity sector. To boost the global solar photovoltaic PV share of the market, however, it is necessary to regulate the quantity of decommissioned photovoltaic modules and prevent their degradation of the photovoltaic module. It might be accomplished by introducing new systems that can reprocess and recycle the photovoltaic module at the end of its lifetime, along with new approaches to decrease material use, decay, and module degradation [38]. It is important to mention that materials such as copper, silicon, steel, concrete, aluminium, etc., are all widely abundant materials used for solar PV systems [68]. The determination of overall energy yield from solar PV systems relies on the many factors which compress of characteristics of the system, the efficiency, solar irradiance and the specific time as expressed in equation (3) [69,70].

$$E_{yield(PV)} = \eta_{PV} \times S_{irr} \times A_{PV} \times T \tag{3}$$

where (S_{irr}) the solar irradiance characterises the quantity of solar radiation gained per unit area (W/m^2). Also, the (η_{pv}) PV system conversion efficiency represents the solar PV system efficiency in converting incident sunlight into electricity. Area (A_{pv}) is the overall solar PV system area (m^2). Time (T) indicates the period for the solar photovoltaic system is exposed to sunlight.

Previous decades have displayed a tremendous increase in the utilisation of renewable energy sources, which have reached record highs and, in several places, outpaced annual increases in traditional power capacity. Solar photovoltaic deployments have long dominated the renewables sector among all other energy technologies [38].

Solar photovoltaic is anticipated to continue driving overall renewables expansion in various locations in the coming ten years due to cost competitiveness, its abundant available resources and massive market potential. Thus, according to IRENA's REmap assessment, solar photovoltaic power installation might increase roughly six times over the coming years from current levels, reaching a total worldwide capacity of 2.840 GW by 2030 and increasing to 8.519 GW by 2050 [64]. This indicates that the total installed capacity will be nearly eighteen times bigger in 2050 than in 2018, as presented in Fig. 9. Approximately 60% of the world's total solar photovoltaic capacity will be at utility-scale in 2050, with the outstanding 40% distributed in the application of PV rooftops. The REmap evaluation forecasts that distributed photovoltaic solar installations will develop more quickly by 2050, driven by regulations, supportive measures, and consumer engagement in the

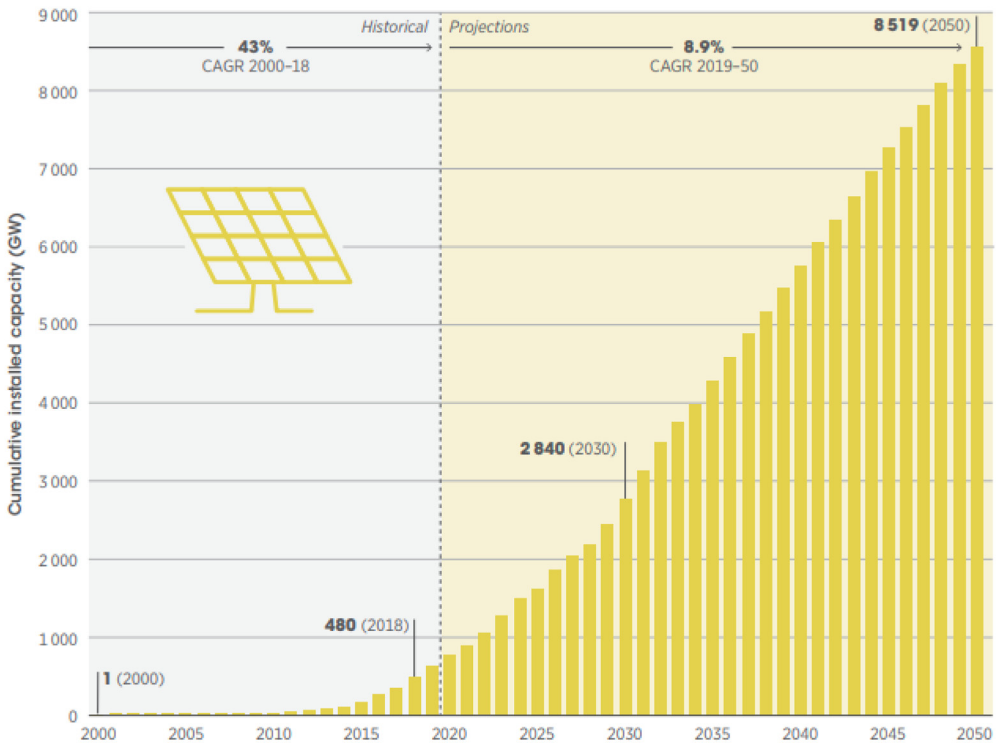

Fig. 9. Solar photovoltaics yearly estimation of installation capacity from 2000-2050 [64].

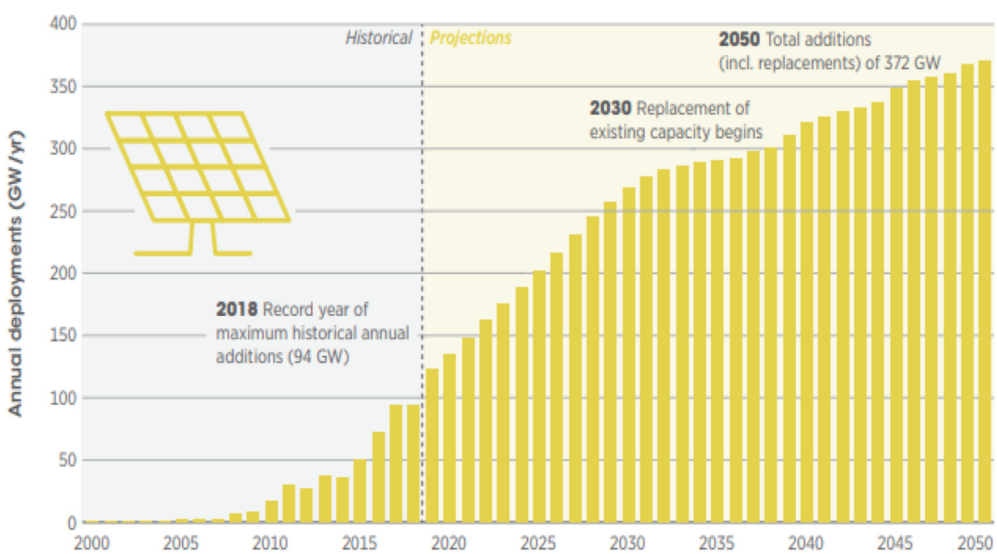

Fig. 10. Yearly world solar photovoltaic estimated deployments from 2000–2050 [64].

clean energy transition, even though utility-scale developments remain predominant [38,71].

Fig. 10 presents a yearly solar photovoltaic capacity that grew gradually in 2011 but declined in 2012. After that, yearly capacity growth rose and fell till the end of 2014. A 94 GW of photovoltaic systems contributed to the world's power capacity mixture in 2018 due to significant cost reductions by technological advancements and legislative and supportive actions [38].

Over the next three decades, the photovoltaic solar market is expected to expand quickly due to ongoing technological advancements and cost reduction. With increasing capacity, replacing solar modules when they reach the end of their lifespans is important and plays a vital role, particularly with the benefit of replacing older modules that make room for cutting-edge technology. In contrast to the current level, annual capacity additions will more than double by 2030 (270 GW); by 2050, they will be four times as large (372 GW versus 94 GW per year in 2018). Fig. 9. illustrates solar photovoltaic estimated deployment [64,72].

Its quick expansion has been made possible by the convergence of various factors. The off-grid solar photovoltaic systems have emerged as a cost-competitive option for increasing energy access due to the fast reduction in photovoltaic module costs. For example, during 2009, these costs decreased by more than 80%, and from 2010 to 2017, the cost of the photovoltaic solar system decreased globally by 73% [73]. To ensure that technology and energy services are affordable and accessible in the long term, innovation in delivery and finance systems has been made possible by reducing technological costs. For instance, this is the East Africa scenario where various distribution models have

Table 1
Lists a solar energy technology classification.

No.	Technology	Applications	Induced energy	Range of efficiency	Refs.
1	PV	Solar PV solar water pumping	Powering devices	20%–40%	[75–77]
2		Solar concentrating PV	Heat/Electricity	33%–47%	[78,79]
3		Solar PV desalination	Powering devices	–	[80,81]
4		Solar PV cathodic protection	Powering devices	–	[82]
5		Solar PV electrification	Electrification	15%–20%	[78]
6		Solar PV vehicle	Powering devices	30%	[83]
7		Solar photovoltaic/thermal	Heat/Electricity	60%–80%	[84]
9	CSP	Solar central receiver	Heat	42%–45%	[85]
10		Solar parabolic dish	Heat	40%	[86]
11		Solar parabolic trough	Heat	52%–55%	[87]
12		Solar linear fresnel reflector	Heat	37%	[88,89]
13		Solar cooker	Heat	4%–7%	[90]
14		Solar dehydration	Heat	20%–60%	[91]

been developed to serve communities without electricity. Although greater systems have been implemented using lease-to-own or fee-for-service methods, smaller systems, like solar lights, are mostly focused on direct cash sales [38,73].

Furthermore, due to the rapid deployment of technology, where the off-grid renewables industry has seen a significant investment increase, the stand-alone industries have grown yearly during the period 2014–2017, reaching about $284 million, and the technology of the mini-grid industry's investment rose from $16 million in 2015 to $81 million in 2018 [73]. As a result, solar photovoltaics will be an important factor in helping to meet the sustainable development goal of having 100% of the world's population access electricity by 2030 [38].

Energy development progress is needed in a variety of fields: biomass, solar and wind, other clean energy sources, and in the economics of power systems, energy storage, infrastructure, and distribution networks. Also, smart home technologies, batteries for electric vehicles, data security, and privacy, to name a few, are some of the many areas that require technological innovation [74]. Furthermore, solar photovoltaic technology is also applied in space; hence, it involves using solar modules to generate electricity from sunlight in the vacuum of space. This technology has been employed in various space missions and satellite systems, so widely using high-efficiency cells.

Solar energy technology can be classified into different categories based on the way solar energy is collected, converted, and utilised. Over a wide range of applications with various efficiencies and kinds of energy induced. Accordingly, Table 1 lists a summary of solar energy classification in terms of energy induced, applications and renege of efficiency.

5.1. Solar PV deployment

Solar photovoltaic devices can be mounted in smaller clusters for mini-grids or private use, or they can be integrated to provide power on a commercial level. In developing countries with extensive solar energy resources, using PV modules to power mini-grids is an excellent way to provide electricity to those not close to power transmission lines. In addition, the cost of solar manufacturing modules has significantly decreased over the past 10 years, allowing them not only to be more accessible but occasionally, the least expensive energy source. Photovoltaic arrays have a 30-year lifespan and come in various shapes depending on the material used in their manufacture.

However, the most common type of solar photovoltaic technology currently used is crystalline silicon, which has an efficiency range of 15%–20% for commercial modules. Fig. 11 represents a schematic of solar photovoltaics technology and applications, including photovoltaic thermal, desalination, photovoltaic water pumping, and electrification, concentrating photovoltaics and photovoltaics cathodic protection.

In addition, the development of energy storage systems, with a high efficacy of lithium-ion batteries, characterise as faster charging, higher energy density, long life cycle, and lower cost [92]. This is widely used by incorporating solar PV technology to provide reliable energy to end-users.

A building with zero net energy emissions and zero emissions of carbon dioxide is referred to as a zero-energy building. As a result, the water desalination process is directly linked to solar PV modules. This methodology employs direct current electricity to extract salt from seawater or other salty liquids. The photovoltaic-thermal (PV–T) technology is comprised of standard photovoltaic (PV) modules with a thermal collector on the Photovoltaic module's backside to pre-heat household hot water. Consequently, this makes it possible to convert a larger proportion of the sunlight that hits the collector into useful electrical and thermal energy.

Despite their tremendous flexibility regarding building integration, solar photovoltaic systems are currently the most common approach to on-site electricity generation [93]. A building with zero net energy emissions and zero carbon dioxide emissions is considered a zero-energy building. Hence, this is because solar energy systems and supplies are incorporated with "building-integrated photovoltaics" (BIPV) technology to fulfil buildings' energy requirements. As a result, innovative technologies like solar cooling are utilised in building-integrated photovoltaics that use thermal energy.

A rural, remote, and arid location typically employs a photovoltaic water pumping system to pump water. This system uses photovoltaic modules to power a pump that delivers water where needed. Numerous variables, including the pumping head and solar irradiation, affect the water pumping rate. A cathodic protection (CP) system powered by solar energy is designed to power a CP framework to control corrosion on the surface of the metal. This technology is used on buried pipelines, concrete structures, tanks, etc., which depends on the high current produced by photovoltaic solar energy systems.

To boost the amount of sunlight that incident on photovoltaic cells, concentrated photovoltaic (CPV) assembly technology employs either refractive or reflective concentrators. Typically, high-efficiency solar cells are utilised, with many sub-cells of semiconductor materials stacked on top of each other. These devices can be used to generate electricity and heat. In addition, another solar PV application is used to power small loads such as home appliances and monitoring devices in remote areas. Further ongoing development is for powering electric vehicles to be a hybrid between solar PV and battery storage.

Furthermore, other emerging solar technologies, e.g., perovskite solar cells and thin-film solar cells, have shown promising results in investigation and development, with efficiencies ranging from 10%–23% and 24%–28%, respectively [78,94]. In addition, the development of bifacial solar modules is designed to capture sunlight from both sides of the modules. Finally, there is a development in high-efficiency cells of III-V multi-junction solar cells where the efficiency of cells is increasing to over 47% [95,96].

The operating challenge of CSP and solar PV module technologies is the soiling accumulation on the PV module's surface, which can be overcome by scheduling cleaning. Therefore, cleaning procedures can be either automatic or manual and can be applied to both small and large modules/systems [97–99].

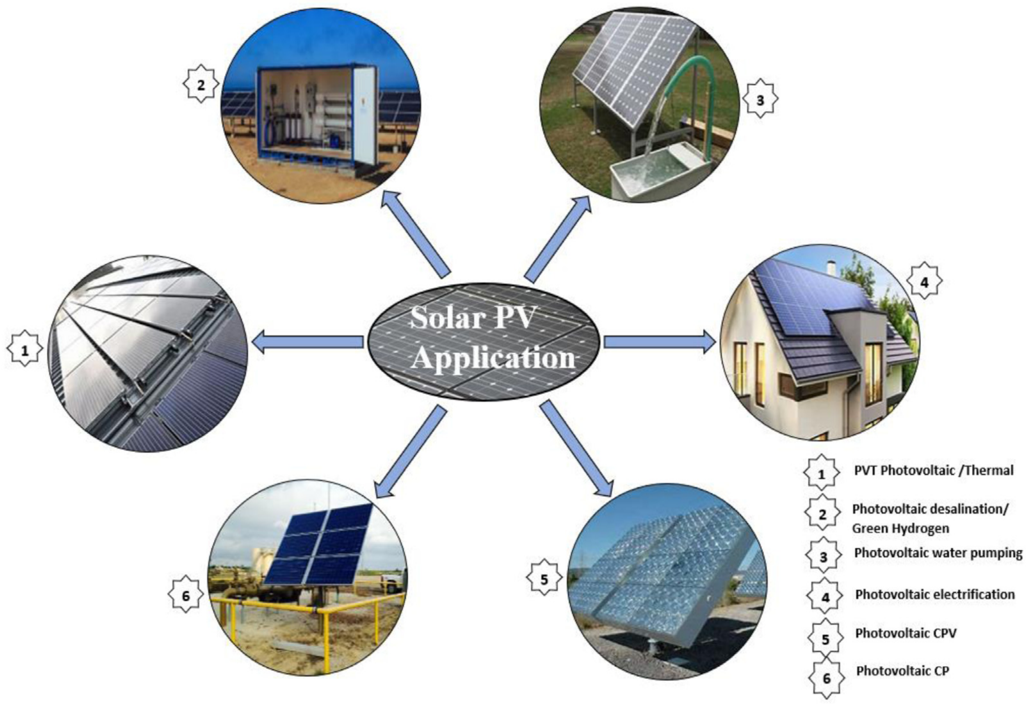

Fig. 11. Scheme of application of solar photovoltaic energy technology.

5.2. Solar CSP deployment

Concentrating solar power (CSP) technology is usually used; solar rays are focused on a specific area using mirrors. Whenever these rays heat a fluid, they generate steam, which is then used to power a turbine and produce electricity. In such a CSP power plant, a field of mirrors usually directs light towards a high-thin tower. Consequently, in power tower systems, often referred to as central receivers, many enormous, fat heliostats (mirrors) have been employed to monitor sunlight and focus its radiation on the receiver or to use it directly once to create steam. The CSP power plant's capability to be constructed with molten salts to store heat and produce electricity at night has many benefits.

In dish engine systems, mirrored dishes are used to direct and concentrate solar radiation onto the receiver. To harness as much solar energy as possible, the dish structure tracks the Sun's motion. Thin tubes operate outside the piston cylinders and open into the helium or hydrogen cylinder, which is an engine component. Ultimately, the pistons turn the crankshaft that drives the electric generator.

Reverse osmosis (RO) is another water treatment method that relies on solar-thermal energy and solar-concentrated power CSP by parabolic trough technology. The desalination utilises the CSP technique, which enables continuous operation and a cost-effective approach. In addition, the CSP technique enables hybrid integration and thermal energy storage. Solar thermal technology can be applied to household appliances like dryers. The so-called food dehydration method has historically been employed in some cultures or communities to preserve certain food products like fruits, meats and vegetables. It preserves food and other products using solar energy to remove moisture. The solar cooker relies on concentrated sunlight to generate sufficient heat to cook foods; this technology is still under development.

Solar thermal technology is applied to a solar domestic hot water (SDHW) system; this renewable energy technology uses sunlight to heat water for various domestic purposes [100]. The design and efficiency of solar domestic hot water systems vary based on factors such as climate, system size, and local regulations that should be considered when selecting and installing a system.

In the forecasting scenario, concentrated solar power CSP will generate 2200 TWh annually by 2050 from 630 GW of local capacity, and by 2050, global energy-related CO2 emissions will decrease to half their 2005 level. In this scenario, CSP is anticipated to provide 5% of the annual world power output by 2050 [85]. The "IEA SolarPACES programme, the European Solar Thermal Electricity Association, and Greenpeace" anticipated that the global CSP capacity by 2050 will be 1500 GW under the developed model of the CSP Globally Outlook 2009. Based on the SolarPACES prediction, large solar and storage fields will provide capacity factors of 59% (i.e., 5200 h annually), producing about 7.800 TWh annually. Based on the German Aerospace Centre, forecasts, by 2050, power stations with a cumulative capacity of 390 GW might provide approximately half of the region's power generation in its analysis of the potential for renewable energy in the North Africa/Middle East region. Based on a recent study, if their respective grids are adequately integrated, North Africa and Europe might generate their electricity from renewable sources by 2050. North Africa might consume 25% of the total, but it would also generate 40%, primarily through solar energy and onshore wind. The cornerstone of North Africa's exporting large capacities to Europe will be CSP plants [101].

This pathway projects a rapid growth of concentrated solar power (CSP) capacity in countries or areas with high direct normal irradiance (DNI) and estimates their energy generation with steadily rising percentages of total demand projected in these areas under the International Energy Agency (IEA) climate-friendly situations. A smaller contribution of CSP power, typically combining local production and electricity from the surrounding sunnier regions, is anticipated in neighbouring, although less sunny, areas. Whereas an initial set of HVDC connections is constructed to link some of the CSP facilities in sunny areas to significant demand locations, plants constructed prior to 2020 mainly respond to medium and peak loads. The determination of the overall energy yield from concentrating solar power (CSP) systems is given by follows Eq. (4) [21]:

$$E_{yield(CSP)} = \eta_{CSP} \times S_{irr} \times A_{collector} \times T \tag{4}$$

where (η_{CSP}) is the overall conversion efficiency of the concentrating solar power system. (S_{irr}) is the solar irradiance, ($A_{\mathrm{collector}}$) is the area of the collector, and (T) represents the period for the CSP system to operate and collect enough solar energy.

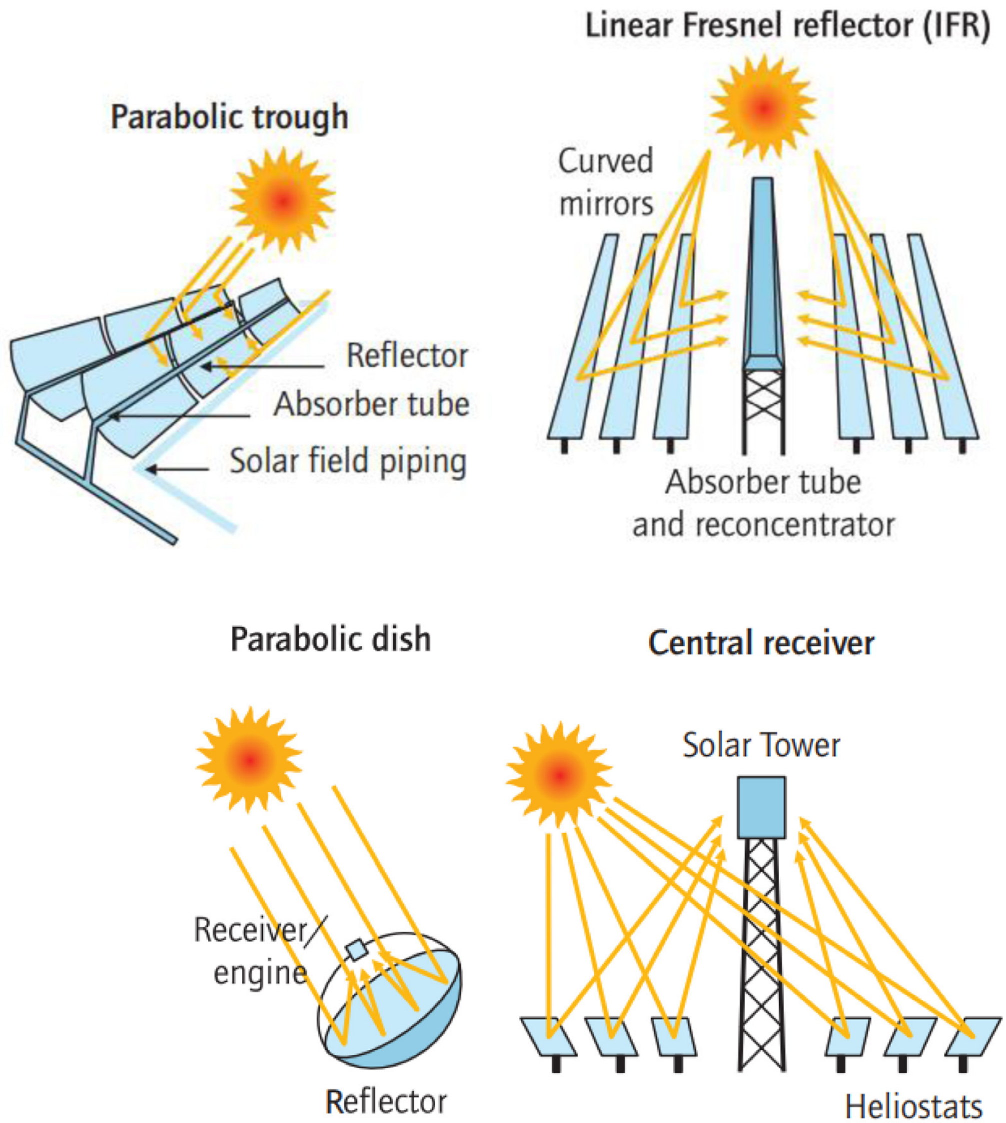

Fig. 12. Application of solar concentrated solar power CSP technology [101].

Implementing CSP with base-load facilities will proceed from 2020 to 2030 as expenditures are decreased and performance is improved, maximising CO_2 reduction emissions. Solar energy will be incorporated into the world's energy mixture beyond 2030 as CSP continues to progress. The CSP is estimated to produce around 11% of the world's electricity by 2050. Fig. 12. compares the expected growth of CSP power generation overall with other scenarios [101]. This technology includes parabolic troughs, linear Fresnel reflectors, parabolic dishes, and a central receiver. This technology has the advantage of storing thermal energy for later usage, allowing electricity generation even when there is no sunlight.

Currently implemented government strategies call for an investment of approximately $98 trillion in energy systems over the following three decades. Sectors with a significant and long-lasting impact on carbon emissions will re-direct $4.6 trillion from the economic incentive packages declared. Therefore, specifically in waste, transportation, energy, manufacturing, and agriculture, less than $1.8 trillion in green energy will be spent annually [51,102].

Important investments must be made in an energy system that emphasises renewables, electricity generation, efficiency, and related energy infrastructure to guarantee a sustainable environment and a more resilient future. However, these investments also must avoid having lock-in effects that conflict with the 1.5 °C pathway. Therefore, in addition to the planned $33 trillion over the anticipated investments, for a total investment of $131 trillion over the period to 2050, the International Renewable Energy Agency (IRENA) 1.5 °C vision might be achieved. Investing in energy transition technologies, such as energy efficiency, renewables, power grids, end-use electrification, advanced innovation in hydrogen, and carbon capture techniques etc., will help achieve this [51].

The 1.5 °C scenario indicates that, from now until 2050, investments worth more than $24 trillion must be shifted from fossil fuels to decarbonisation technologies. Compared to the $1.8 trillion invested in the energy sector in 2019, $4,4 trillion, which is roughly 5% of the projected world gross domestic product, will need to be funded annually until 2050 [51,103]. Moreover, in the next years, the energy sector would require an additional $1.1 trillion in investments compared to the planned energy scenario [51].

Overall energy system investment, up until 2030, counting those for infrastructure and efficiency, would reach about $57 trillion. Investing in people requires inclusive training, labour market programmes and staff reskilling, economic progress, social protection measures, research funds, also further development in technology and infrastructure [51].

However, with the development of renewable energy technology, the employment market has expanded. Using renewable energy technologies has created over 12,6 million new jobs globally. The solar photovoltaic application was the first, leading to the creation of about 4,2 million jobs. Similarly, solar thermal applications (heating and cooling) created over 819,000 employees, while the CSP created over 79,000 jobs during the same period [18].

Globally, net-zero energy research has many challenges in terms of funding and accessibility to tools and other supplies. Efficient methods must be developed to accelerate the transition to clean energy because countries are projected to be significantly impacted by climate change [104]. The world community's support is essential to the success of the clean energy transition since they have the power to negate the advantages of attaining net-zero via their justifiable efforts at social and economic progress [105].

Solar energy transition strategies include solar PV and CSP systems, the latter relies on solar thermal. The selection of plans is influenced by elements such as the potential for direct sunlight, sufficient area, and the cost of installation. Lastly, distributed generation is made possible by small-scale solar energy production, which also helps eliminate the need for enormous centralised power plants. This can decrease transmission and distribution losses, thus increasing the energy system's overall efficiency. In addition, rural communities and other places without grid access can receive electricity through solar energy. These can raise the standard of living and promote economic growth.

It is important to mention that the limitation of this review is that it does not largely cover an analysis of techno-economics in investment. Thus, when comparing environmental matters and expenses, the cost sometimes does not consider the top priorities of engineers and decision makers alike.

6. Conclusions

This work presents an investigation of global generation and gives plans for providing the energy needs from clean energy resources. The barriers, challenges, and comparisons of each flexibility choice were thoroughly examined; this study offers a comprehensive review of numerous perspectives and opportunities. This study also investigated background figures on sustainable development goals (SDGs), including green building and energy efficiency. Solar energy systems, which are used in buildings and include solar thermal and photovoltaic (PV) technology, significantly positively influence the environment and contribute to the long-term progress of human endeavours. The efficiency of implementing technology for building integrated photovoltaics (BIPV) is one of the ways to decarbonise the energy in a building. Therefore, solar energy technology will significantly deploy by expanding installation capacity. Solar energy has numerous applications across various sectors, including the energy sector, electricity generation, heating, water purification and green hydrogen. Hence, this can help address environmental, energy, social, and economic challenges.

Several countries have examined and moved towards environmentally friendly alternative energy to meet increasing energy needs while minimising the negative environmental effects and other issues associated with burning fossil fuels. The decrease in pollution, especially greenhouse gas emissions, is the key advantage of employing renewable energy sources. This can be achieved by shifting out traditional fuels and fossil-based power sources to ones with lower atmospheric emissions. In the upcoming years, solar photovoltaic generation systems are anticipated to play a big role as their effectiveness and cost decrease. Consequently, it is anticipated that solar photovoltaic PV energy will play a crucial role in the future global energy systems for sustainable development.

Both supply and demand will be intelligently integrated into future energy systems. In the upcoming decade and beyond, more low-carbon power will be able to meet a larger quantity of our energy requirements due to innovative and resilient technology. Therefore, to operate the system effectively, save costs, and maintain supply security, it needs to adopt a new emphasis on flexibility and demand-side services. In this context, this will be achieved carefully through interoperable infrastructure and productive markets that add value to the new skills.

With reference to the recent development of electric vehicles that included solar PV modules and other energy storage technologies, such as battery storage, this development of energy device storage also helps in the wide deployment of solar energy. This will boost its efficacy and decrease prices in the future. Further recommended works include other clean energy technology, development, and its role in achieving net-zero emissions by 2050. Hence, green hydrogen energy technology is a significantly promising emerging technology. In addition, more studies will be necessary to identify which technological and scientific investments and legislation are most effective, and that is learning from successful examples worldwide.

CRediT authorship contribution statement

Ali O.M. Maka: Writing – original draft, Visualization, Resources, Methodology, Investigation, Conceptualization. **Tarik Ghalut:** Writing – review & editing, Visualization. **Elsaye Elsaye:** Writing – review & editing.

Declaration of competing interest

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

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