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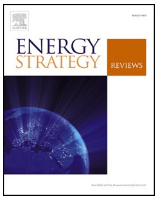

Review

Distributed energy systems: A review of classification, technologies, applications, and policies

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ABSTRACT

The sustainable energy transition taking place in the 21st century requires a major revamping of the energy sector. Improvements are required not only in terms of the resources and technologies used for power generation but also in the transmission and distribution system. Distributed generation offers efficiency, flexibility, and economy, and is thus regarded as an integral part of a sustainable energy future. It is estimated that since 2010, over 180 million off-grid solar systems have been installed including 30 million solar home systems. The article concludes that support policies play a critical role in the promotion of DES. Since 2010, the number of countries with distributed generation policies has increased by almost 100%. This article presents a thorough analysis of distributed energy systems (DES) with regard to the fundamental characteristics of these systems, as well as their categorization, application, and regulation. It outlines and highlights the key characteristics of the energy technologies that are currently in use for distributed generation. Furthermore, significant aspects of a variety of DES projects from across the globe are discussed and analyzed to formulate a globalized visualization of DES technologies their challenges, potential solution, and policies.

1. Introduction

Energy is one of the main driving forces behind modern infrastructure and advancements. All aspects of life including household, industry, transportation, agriculture, health, education, and entertainment are becoming increasingly dependent on energy. In the wake of factors like growth in population, urbanization, and socio-economic development, global energy demand is experiencing rapid growth. Almost 80% of the global energy supplies are met through fossil fuels. The fossil fuels dominant energy scenario faces many challenges. Contrary to growing energy demand, conventional fossil fuel reserves are experiencing a depleting trend. Energy prices frequently fluctuate posing challenges for the masses, especially in developing countries. There are also energy security risks associated with supplies from geopolitically unstable countries and regions. Climate change is another major challenge associated with the energy landscape since the use of fossil fuels is regarded to be the prime source of greenhouse gas emissions [1–4].

Energy supply infrastructure has traditionally relied on a centralized approach. Power plants, for example, are typically designed to provide electricity to large population bases, sometimes even thousands of kilometers away, employing a complex transmission and distribution system. Large-scale centralized energy systems are not only expensive to develop and maintain, but they also face multiple constraints and issues. Subsequently, access to refined energy remains to be a major issue across the world, especially in developing regions like Sub-Saharan Africa, South Asia, and Latin America. Despite the significant and focused electrification efforts over the last couple of decades, nearly one billion people lack access to electricity. Despite the grid penetration, the quality of power/energy supply is also a major issue in developing countries. It is also estimated that over 2.8 billion people have to rely on raw biomass to meet cooking and heating requirements [5,6].

The global sustainability drive, as is evident from the United Nations Sustainable Development Goals (SDGs) regards energy as one of the key areas that need improvement. The SDG 7 calls for access to affordable, sustainable, and modern energy for all wherein the concept of distributed energy integration is directly influential while having an indirect impact on achievement of the goal set in SDG 11. According to the

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Acronyms

AEDB	Alternative Energy Development Board	KVC	Kalina/vapor-compression
BPS	Biofuel Production Source	WHRB	Waste Heat Recovery Boiler
BC	Brayton Cycle	LCOE	Levelized Cost of Electricity
CCHP	Combine Cooling, Heating, and Power	WHU	Water Heating Unit
CCL	Climate Change Levy	Li	Lithium
CNY	Chinese Yuan	LiBr	Lithium Bromide
CO_2	Carbon Dioxide	MENR	Ministry of Energy and Natural Resources
FIT	Feed-in Tariffs	MESSs	Mechanical Energy Storage Systems
RES	Renewable Electricity Standards	MFC	Microbial Fuel cell
GHG	Greenhouse Gas	MGT	Micro Gas Turbine
RPS	Renewable Portfolio Standards	CHP	Combine Heating and Power
GT	Grid-Tied	MHP	Micro Hydro Plant
SDG	Sustainable Development Goal	MILP	Mixed Integer Linear Programming
H_2O	Water	NDRC	National Development & Reform Commission
SOFC	Solid Oxide Fuel Cell	COP	Coefficient of Performance
HPDHS	Heat Pump District Heating System	OG	Off-Grid
SIGT	Steam Injection Gas Turbine	CST	Concentrating Solar Thermal
IC	Internal Combustion	ORC	Organic Rankine Cycle
ST	Steam Turbine	DES	Distributed Energy Systems
IFBHS	Individual Fuel Boiler Heating System	PEMFC	Proton Exchange Membrane Fuel Cell
UNDP	United Nations Development Program	DG	Distributed Generation
IPCC	International Panel on Climate Change	PV	Photovoltaic
USD	United States Dollar	EU	European Union
		REMP	Renewable Energy Master Plan
		WWTP	Wastewater Treatment Plant

International Panel on Climate Change (IPCC), in the fight against climate change, radical changes are required to be in the global energy systems. Replacement of fossil fuels with renewable energy is regarded as critical to these efforts as IPCC suggests that the world needs to annually invest $2.4 trillion in sustainable energy systems up to 2035 [7].

Distributed generation (DG) is typically referred to as electricity produced closer to the point of use. It is also known as decentralized generation, on-site generation, or distributed energy – can be used for power generation but also co-generation and production of heat alone. DG is regarded to be a promising solution for addressing the global energy challenges. DG systems or distributed energy systems (DES) offer several advantages over centralized energy systems. DESs are highly supported by the global renewable energy drive as most DESs especially in off-grid applications are renewables-based. DES can employ a wide range of energy resources and technologies and can be grid-connected or off-grid. Accordingly, distributed generation systems are making rapid advancements on the fronts of technology and policy landscapes besides experiencing significant growth in installed capacity. Renewable technologies, contributing to most of the global distribution generation, are becoming efficient, flexible in terms of deployment, and economically competitive with conventional energy systems. Globally, installed renewable capacity surged from 1430 MW in 2019 to 1668 MW in 2020, with distributed generation accounting for a large share of this growth [8].

Distributed generation is becoming an active area of research. Researchers have examined distributed generation from various perspectives. Mehigan et al. [9] for example have explored the role of distributed generation systems in potential future electricity scenarios. They also discussed the existing tools which can influence the role of DES in future electricity. The review concludes that no one tool can impact the DG. Lee et al. [10] studied DES in Malaysia in terms of current deployment, power quality issues, and implementation constraints. They also discussed the energy prospects of both fossil fuels and renewable energy systems. They recommended that fossil fuel-based energy systems would not be a long-term solution to electrical power production in years to come. Singh and Sharma [11] presented the status of DES planning in a decentralized power system network. They also discussed the optimization techniques for DES planning and concluded that artificial intelligence techniques are more suitable for optimal DES planning as compared to conventional optimization techniques. Huda and Živanović [12] reviewed the models and tools for the integration of distributed generation and distribution networks. They discussed that several additional components need to be modeled to overcome the power quality issues during the integration of DES into the grid. They also summarized the key features that the ideal computational tools should study for the integration of DES. Silva et al. [13] reviewed the policy frameworks of photovoltaic (PV) based DES. Han et al. [14] studied the status of DES in China covering system optimization, applications, and policies. They reported that hybrid energy systems such as gas-fired combined, cooling, heating and power (CCHP) with renewable energy systems (solar and wind) will become the mainstream for future energy supply technologies in the world. They also concluded that a fully developed financial incentive system should be set up to prompt the R&D and application of DES. Wen et al. [15] reviewed DES in terms of application and support strategies. They summarized the criteria for DES performance evaluation. The methods and criteria are discussed in terms of energy, environmental and economic aspects. Ramli et al. [16] analyzed the potential of DES for Saudi Arabia for solar energy and wind power with the aim to maximize the utilization of available resources. They also reported that the Kingdom of Saudi Arabia has intensified its effort to implement the policies that will help it achieve the solar and wind power targets. Garlet et al. [17] studied the challenges associated with the diffusion of Photovoltaic (PV) based DESs in southern Brazil. They reported that despite having immense solar energy potential in southern Brazil, installed capacity is much lower due to the existence of technical, social, economic, and political barriers. Khetrapal [18] reviewed the DES technologies in terms of grid integration challenges and also suggested some solutions to those challenges which will be of most interest to stakeholders in the electrical energy supply industry. Thopil et al. [19] examined the performance of a grid-tied PV system in South Africa. They reviewed the optimization techniques to reduce the undesirable concerns that occur during grid integration. The objectives such as minimizing power losses, voltage deviation and net cost can be obtained by determining the optimal location, size and design of DES. Katyara et al. [20] discussed the applications and limitations of DES. They not only discussed majority of the numerical and analytical methods for efficient placement and sizing of DES but also studied artificial intelligence, adaptive and non-adaptive, multi-agent developed protection coordination techniques for utility networks in the presence of DGs. Faria et al. [21] focused on the application, policies, and challenges of photovoltaic (PV) systems in Brazil. They discussed the incentive policies that are implemented and the suggestions that could further develop solar electricity generation. They also discussed the main obstacles to the extensive generation of solar electricity. Hirsch et al. [22] studied DES in terms of micro-grid applications, key drivers, and the associated challenges. They categorized the drivers into three categories: energy security, economic benefits, and clean energy integration.

The aforementioned studies facilitate a state-of-the-art insight into DESs outlining numerous challenges and prospective solutions in terms of technical limitations, national policies, and deployment initiatives. Henceforth, a need for a globalized platform for decision and policy makers as well as researchers is pertinent in the formulation and upgradation of present regulatory measures and policies with expedient standardization of DESs installation locally as well as globally. In this regard, this review study aims to contribute to this effort. Furthermore, it is evident from the literature that there is a lack of studies covering broader dimensions of DESs. From the above discussed studies, it can be said that the existing studies have covered DES with a relatively specific scope, especially in terms of technologies and application but they have not provided the policy aspects and the challenges associated with the DES. The present study aims to provide a comprehensive review of DESs essentially taking into account technological, application and policy aspects along with the challenges and their possible solution. It presents a detailed account of DES in terms of the following.

- Technologies used in DES and their key features
- Application of DES in small residential/commercial, district and urban level
- Policies to promote DES
- Challenges facing DES and their potential solutions

In terms of structure, section 2 provides an overview of DES before presenting their detailed classification. Section 3 describes the key features of different technologies used in distributed energy systems. Section 4 provides a detailed review of the applications of DES around the world at the three key levels: small building, district, and urban scales. Section 5 discusses the DES trends in terms of policies, targets, and accomplishments. In this respect, sample countries have been selected from three sets of nations: developed economies, emerging economies, and developing economies. Section 6 reviews the major challenges facing DES besides highlighting the corresponding solutions. Finally, section 7 presents a discussion and conclusions.

2. Overview of distributed energy systems

Distributed energy systems are fundamentally characterized by locating energy production systems closer to the point of use. DES can be used in both grid-connected and off-grid setups. In the former case, as shown in Fig. 1 (a), DES can be used as a supplementary measure to the existing centralized energy system through a bidirectional power flow arrangement. In the latter case, DES can serve a particular site without feeding potential excess generation into the grid, as depicted in Fig. 1 (b) [23]. DESs can help energy demand be met locally by pooling input from multiple and diverse resources.

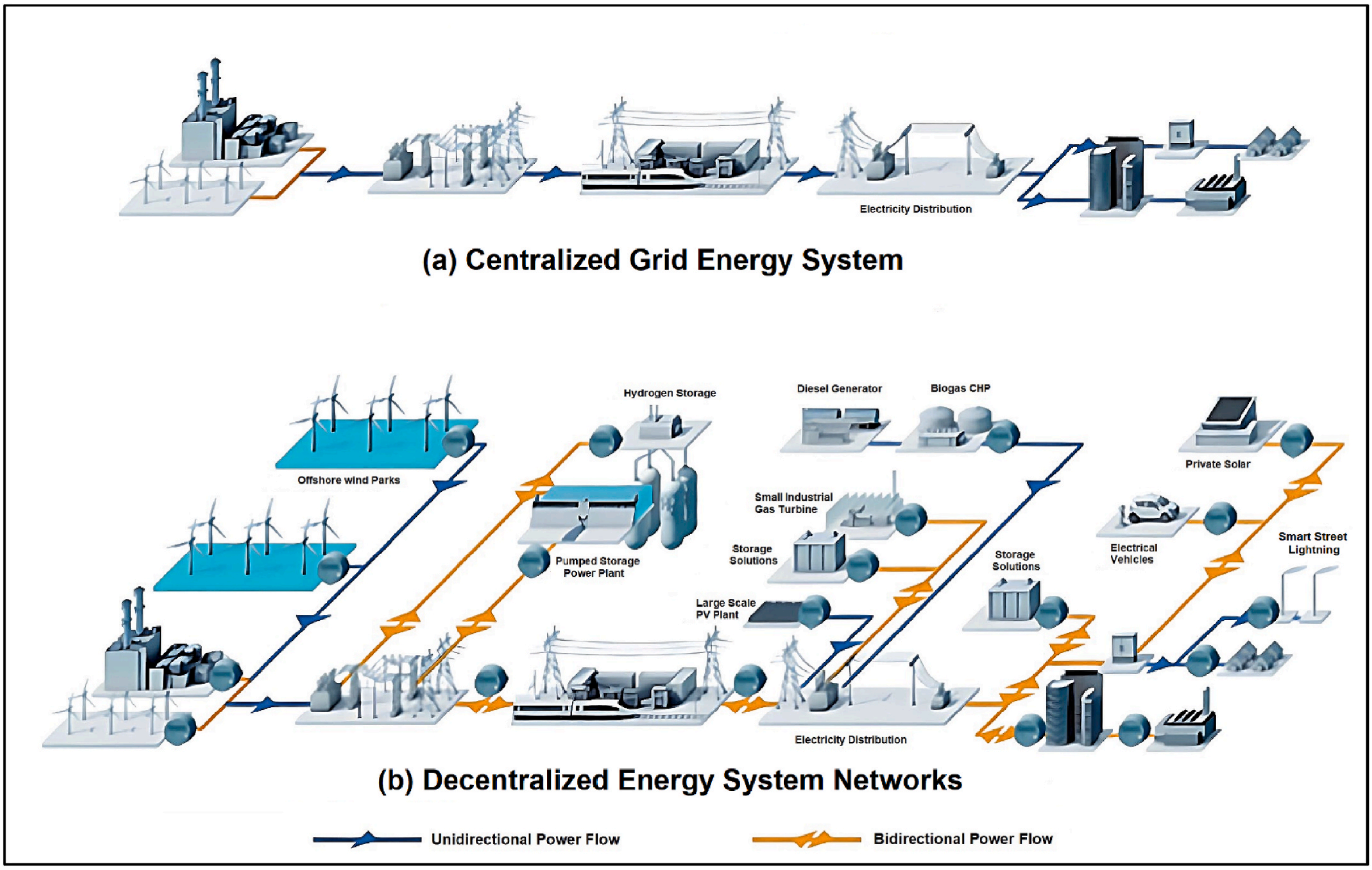

Fig. 1. Typical schematics of (a) Centralized Grid and (b) Decentralized Energy networks.

2.1. Advantages and disadvantages

DESs can present a wide range of advantages over centralized energy systems as highlighted below.

- Deliver cost-effective energy solutions due to local production and avoid/reduce transmission and distribution costs
- Offer more efficient energy systems
- Provide clean energy access to rural and remote facilities
- Provide environment-friendly energy through renewable technologies
- Help shave off peak load demand by supplementing the grid supplies
- Improve energy security
- Require shorter lead/development time to materialize new projects
- Help avoid expensive up-gradation/replacement of transmission and distribution systems
- Exhibit better resilience against natural disasters including floods and storms

DES also has disadvantages as compared to centralized energy systems as highlighted below.

- Pose power quality issues in terms of grid connectivity, especially in the case of renewable-based systems
- Affect the grid stability
- It may require a backup energy storage system

2.2. Classification of decentralized energy systems

Distributed energy systems can be classified into different types according to three main parameters: grid connection, application, and supply load, as shown in Fig. 2.

2.2.1. Based on grid connection

In terms of grid connectivity, DESs can be classified into two types: grid-tied (GT) systems and off-grid (OG) systems. Grid-tied (GT) systems can be further sub-categorized into two arrangements. GT systems are sometimes further classified into utility-scale projects and those serving the local grid. In off-grid (OG) systems, DES is not connected to the central grid. These systems are more appropriate for areas with no or weak grid penetration such as remote and rural communities. OG systems, mainly solar PV-based, have played a key role in the global electrification efforts. OG systems can further be classified as: with battery back-up, without battery, and hybrid systems. Figs. 3 and 4 represent the typical schematic of grid-tied (GT) and off-grid (OG) DES.

2.2.2. Based on application-level

In terms of application level, DES can be divided into three types: small buildings level, district level, and urban level [15]. Small buildings DES can be further sub-classified depending upon the type of building and its use. Hospitals and educational institutions, etc. are considered public buildings while offices, hotels, and shopping complexes are considered commercial buildings [24]. Similarly, district-level DES can be subdivided into two types: neighborhood scale and community scale. The neighborhood scale may include residential and mixed-use neighborhoods [25], while the community level may include housing societies, university campuses, and mixed-use communities [26]. The distinction between the neighborhood scale and community scale is debatable but it is still considered that in comparison to neighborhood-level, community level fulfills the demands of more end-users. For example, the neighborhood as analyzed by Ref. [27] has 4–5 residential units, while the community level investigated by Ref. [28] has around 2500 households.

2.2.3. Based on load type

According to the power availability, DES can be categorized into two different types: base/firm and intermittent-load [29]. The firm-load DES

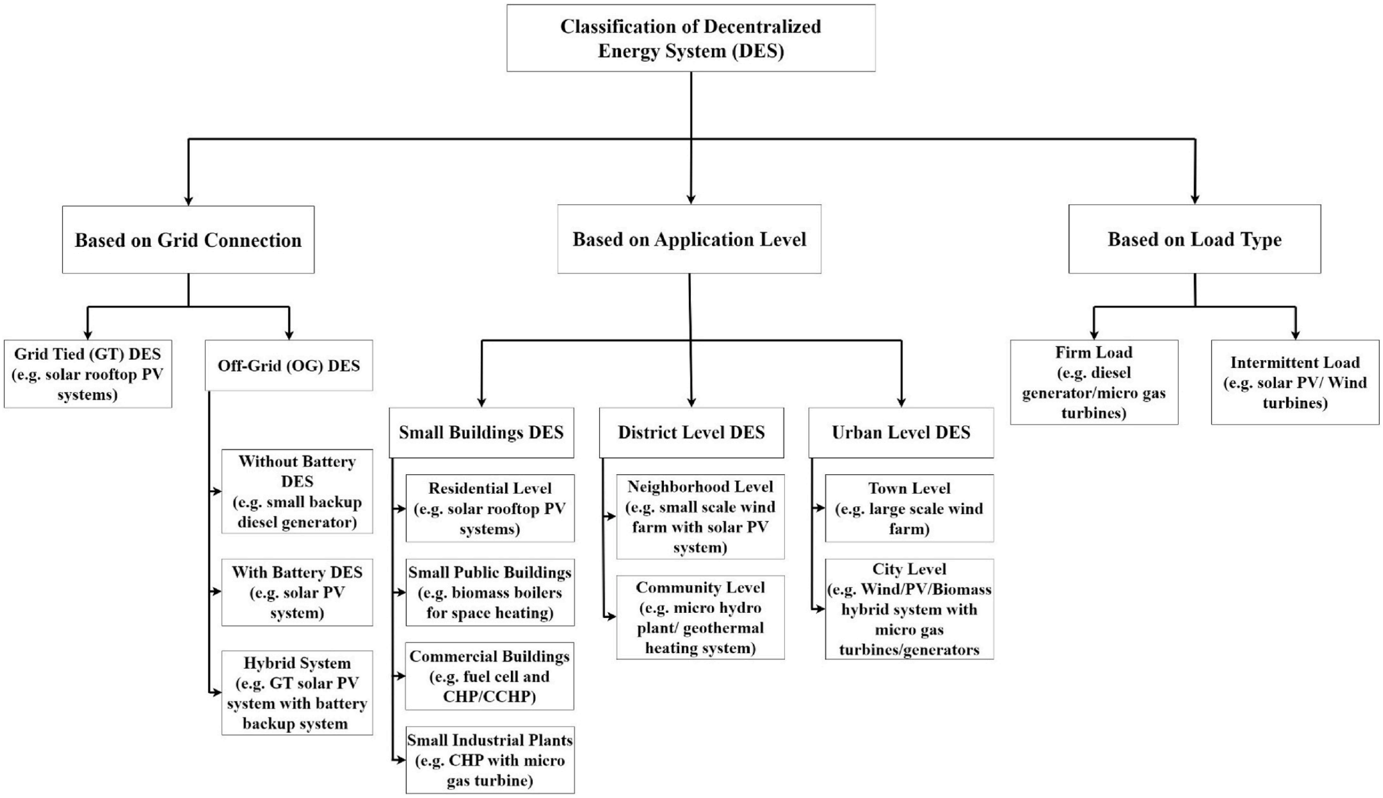

Fig. 2. Classifications of distributed energy systems.

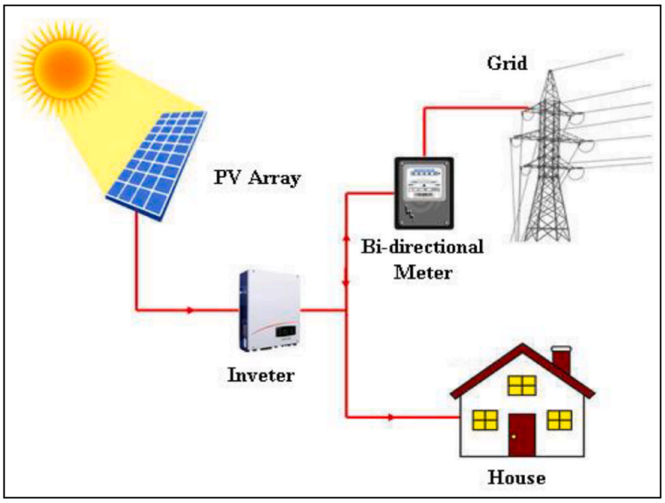

Fig. 3. Grid-tied (GT) PV system [32].

can be relied on to fully meet the energy/load demand. It can be utilized as a backup power source when there is an unavailability of grid electricity and during peak consumption hours. Intermittent-load DES cannot be relied on to satisfy the energy requirements at will. Typically, these include solar and wind power systems which have resource intermittency issues and need storage systems as a backup for offering a reliable solution.

3. Distributed generation technologies

Many energy technologies can be used in DES depending on the project requirements. Based on the type of energy resource, DES technologies can be classified into renewable-based systems and non-renewable-based systems.

Renewable technologies include solar energy, wind power, hydropower, bioenergy, geothermal energy, and wave & tidal power. Some of these technologies can be further classified into different types. Solar technologies, for example, can be categorized into solar PV, solar thermal power, solar water heating, solar distillation, solar crop drying, etc. Similarly, biomass can be used to deliver solid fuels, liquid fuels such as biodiesel and bioethanol, and gaseous fuels. Generally, major benefits of renewables-based DES include reduced greenhouse gas emissions, and lower operation, and maintenance costs [30]. It is noteworthy that the life cycle cost of these systems may vary from place to place depending on local weather conditions. Feasibility of wind power, for example, critically depends on wind speed, which may significantly vary depending on local climatic conditions, prevailing wind patterns and topography. Also, renewable energy-based systems are inherently intermittent and need a storage system for reliable solutions. There can be only two possible outcomes of renewable energy systems; electrical energy and thermal energy. Electrical energy can be generated through solar PV, wind turbines, biomass energy, hydroelectric power, geothermal, fuel cell, ocean energy and tidal energy. However, thermal energy can be produced using solar thermal heaters, biomass fuels, geothermal energy and fuel cells.

Non-renewable-based DES technologies are also available in a wide range and may include: internal combustion (IC) engine, combined heat and power (CHP), combined cooling, heating and power (CCHP), gas turbines, micro-turbines, Stirling engine, and fuel cells. These technologies can use different types of fossil fuels. Stirling engines can also be used on some renewables such as solar thermal energy. CHP and CCHP systems usually consist of a prime mover, heat recovery unit, and thermally operated unit such as an absorption chiller [31]. CHP/CCHP systems may also have steam turbine (ST), heat exchangers, and energy storage devices. Figs. 5 and 6 show typical schematics of internal combustion (IC) engine/gas turbine and steam turbine-based CHP units respectively.

There have been many studies carried out on the integration of renewable resources with CHP/CCHP. Hidalgo et al. [35] evaluated the technical performance of combined solar PV with a Stirling engine-based micro-CHP and reported over 36 tons of reductions in CO_2 emissions using this hybrid DES. Ji et al. [36] carried out technical and sensitivity analyses of stand-alone PV and biomass-CHP hybrid DES for a remote village. This system consisted of PV, diesel generator, and biomass-CHP with thermal energy storage and battery systems. The Levelized Cost of energy was determined to be 0.355 $/kWh. Chang et al. [37] coupled Proton Exchange Membrane (PEM) fuel cells based micro-CHP system with Lithium (Li)-ion battery reporting efficiency of

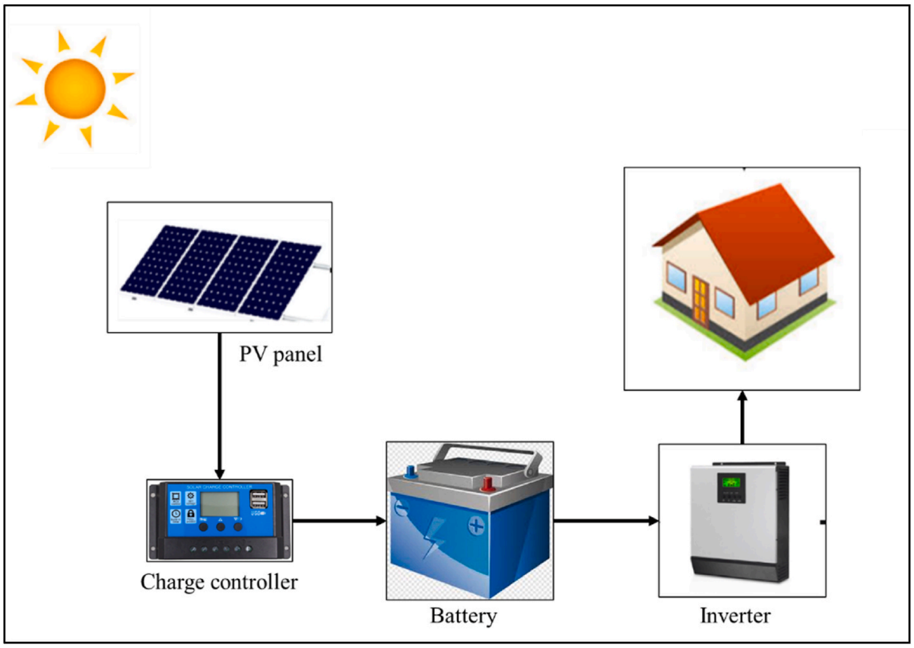

Fig. 4. Off-grid (OG) PV system [33].

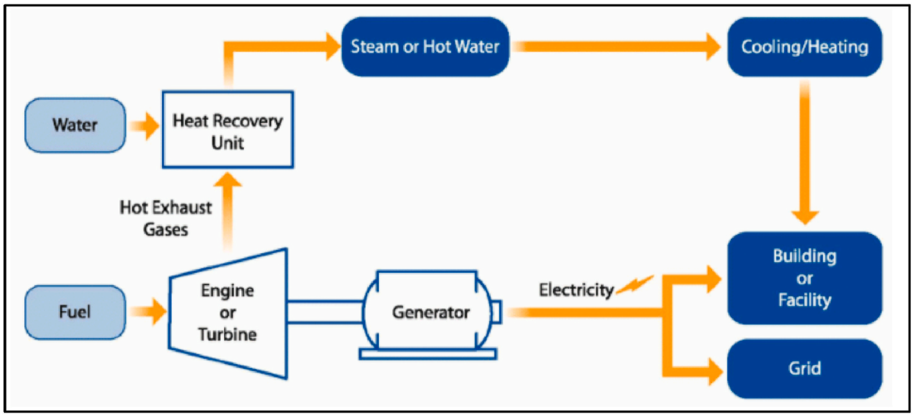

Fig. 5. A typical schematic of CHP which consists of an engine/gas turbine with a heat recovery unit [34].

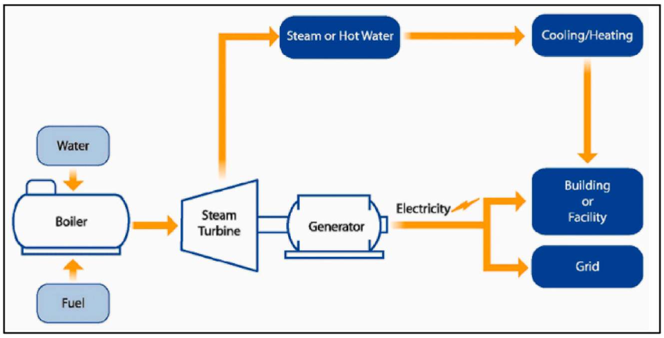

Fig. 6. A typical schematic of CHP which consists of ST with a heat recovery unit [34].

81.2%. Fig. 7 represents the schematic of solar-assisted CCHP.

Table 1 has summarized several DES technologies which are available for commercial applications.

4. Distributed energy networks

4.1. Small building/industrial applications

Small buildings may include individual residential houses, and small public, commercial and industrial buildings. A domestic house generally comprises a single family while a residential/commercial building may contain several families/customers. Some examples of small-scale residential/commercial/industrial DES applications are summarized in Table 2.

4.2. District-level applications

The district-level DES applications are further subdivided into two divisions (i) neighborhood and (ii) community-level. They are more complex compared to individual residential/building-level applications. Some examples of the neighborhood and community-level DES networks based on photovoltaic (PV) cells, biomass, fuel cell, wind energy, CHP, and CCHP are presented in Table 3.

4.3. Urban-level applications

The application of urban-level DES is still not so mature in comparison with small-building and district-level decentralization units. There have been only a few studies on the implementation of DES at the urban scale, which are summarized in Table 4.

5. Artificial intelligence in future distributed energy systems

Considering the randomness that is involved with renewable and distributed energy integration, models based on artificial intelligence (AI) possess the capability to significantly enhance the energy supply as well as trade and consumption patterns. Technology that uses artificial intelligence (AI) serves as the driving force behind the new digitalization

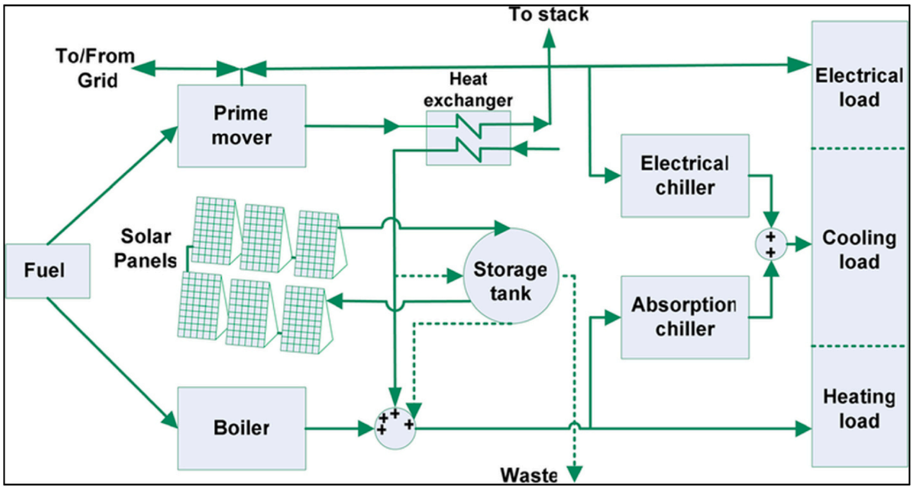

Fig. 7. Schematic of a solar-assisted CCHP system [38].

Table 1
Available technologies for distributed energy systems.

DES Technology	Energy Resource/Fuel	Output	Efficiency	Description	Ref.
Solar Photovoltaics (PV)	Renewable	Electricity	5–35%	• Often rooftop panels are installed to generate electricity at residential, commercial, and industrial levels.	[43,44]
Solar water heating	Renewable	Space Heating	30–45%	• Air/Water is heated using energy from the sun.	[41,45]
Wind Turbines	Renewable	Electricity	30–40%	• Micro-wind turbines (<1 kW) mounted on the rooftop of residential buildings to generate electricity. • Large-scale onshore and offshore wind turbines for power generation.	[46]
Biomass	Renewable	Both Electricity and Space Heating	10–60%	• Wood, energy crops, and waste are combusted to provide water and space heating. Small-scale biomass projects range from 10 kW to 2 MW. • However, landfill gas generation to large electricity-generating projects can range up to 40 MW. Sugar mills often have a very high potential for their power generation from sugar cane residues.	[47]
Hydroelectric	Renewable	Electricity	70–85%	• Hydroelectric systems convert the power of flowing water into electricity. • Micro-hydro ranges from 5 kW to 100 kW and is usually used for the electrification of small rural communities/industries. Mini-hydro ranges from 100 kW to 1 MW and they can be either grid-tied or off-grid. Small hydro ranges from 1 MW to 5 MW feeding into the central grid. Above 5 MW are considered as large hydropower plants [48].	[15]
Geothermal	Renewable	Both Electricity and Space Heating	10–15%	• Heat Pumps are usually employed for space heating. Energy stored in-ground is utilized via water. • Geothermal powerplants are used for electricity generation as well. There are three main types of geothermal power plants named (i) flash steam plants (ii) dry steam plants and (iii) binary cycle plants.	[39]
Fuel Cells	Renewable	Both Electricity and Space Heating	30–70%	• Fuel cells can serve as the best alternative to small scall IC engines application because they are greener to the environment and less noisy. Fuel cells can be employed for the electrification of residential buildings, hospitals, etc.	[41]
Hybrid DES*					[40,42]
(i) PV and Wind	Renewable	Electricity	–	• Both PV and wind can be used in a hybrid system for electricity generation.	
(ii) PV and Biomass	Renewable	Both Electricity and Space Heating	–	• Hybrid systems based on PV and Biomass can be employed either for power generation or both heating and electricity.	
(iii) PV and Fuel Cell	Renewable	Both Electricity and Space Heating	–	• Hybrid systems based on PV and fuel cells can be used for electrification and combined heating and power.	
(iv) CHP/CCHP with Micro gas turbine (MGT)	Non-Renewable (Natural Gas)	Both Electricity and Space Heating	–	• Waste heat recovery boilers (WHRB) can be employed for utilization of waste heat from gas turbines exhaust which can be employed for space heating or cooling.	

*In Hybrid DES, efficiency depends upon the combination of technologies.

paradigm. AI-based intelligent optimized decision-making and operation can enable effective control over the complex stochastic association between the deregulated unpredictable energy market, variable renewable energy generation sources, and uncertain load demand. This would be a significant step toward achieving the goal of reducing environmental impact while simultaneously increasing efficiency. The accomplishment of this objective will be significantly aided using AI.

Development of AI techniques and machine learning (ML) methods is projected to play a pivotal role in the establishment of future sustainable energy systems as they facilitate significantly better performance in case of big data handling, security, energy optimization, computational efficiency, and predictive grid operation. Load forecasting, renewable energy production forecasting with direct or indirect optimization of energy price, detection of power quality problems, and defect detection on power systems and equipment are all common uses of smart energy systems. Forecasting the production of renewable energy sources, such as wind and solar, has attracted a lot of interest lately because of the substantial influence it may have on choices about the operation and management of power networks. To guarantee grid stability and permanence, decrease energy market risk, and lower energy system costs, precise forecast of renewable energy generation is essential. Renewable energy forecasting will be beneficial not just to the power grid and the operator, but also to the participants of the energy markets and policymakers [87].

Energy production from solar and wind energy sources will always be unstable due to the changing nature of weather [88–90]. As a result, predicting their production is challenging and necessitates more sophisticated methodologies. Physical, statistical, AI, and their hybrid models and techniques are the four main types of methodologies employed for the output power predictions problem [91]. Physical methods are mathematical models that simulate the dynamics of the atmosphere in accordance with physical and mechanical principles. They are used for long-term forecasting horizons because of their reliance on computer simulation, which necessitates the usage of substantial computational resources [92]. Alternatively, statistical models are implemented to ascertain the mathematical connection that exists between inputs-outputs under the assumption that these relationships are linear.

While they are popularly and expensively implemented, their effectiveness fell short of expectations since they are ineffective for identifying nonlinear correlations [5]. AI techniques, such as ML and deep learning (DL) models have been identified to have significantly better performance owing to their capacity to formulate nonlinear correlations which can be observed with their application in several other multidisciplinary fields of research such as image identification, classification problems, and language recognition [93]. Due to their capacity for generalization as well as their ability to of unsupervised learning, DL in particular is proving to have great potential towards renewable output power prediction as well as implementation in energy and grid operation [94,95]. Typically, the effectiveness of AI models in any application in distributed energy systems is dependent on the data, data sets, data processing methodologies, selection of the forecasting technique, and evaluation [96].

For an increased accuracy of the models, historical and

Table 2
Applications of Distributed Energy Systems in small residential/commercial/industrial level.

DES Technology	Grid Type	Level	Load Type	Location	Important Remarks	Refs.
PV System	Off-Grid	Residential level	Intermittent	Argentina	• Infeasibility from the investment point of view was noted due to current technological costs, nationwide financial conditions, and electricity tariffs. • Government should implement policies related to low-interest-rate loans for investment in solar PV systems because of high capital investment for an average citizen.	[49]
PV System	Grid-Tied	Residential level	Intermittent	India	• A reasonably good performance ratio of around 75% was observed. • Annual energy requirement from the main central grid was found to be reduced by 41.09%. • GT rooftop PV systems were technically feasible and substantial reductions in CO2 emissions have been noted as well.	[50]
PV System	Grid-Tied	Residential level	Intermittent	Algeria	• The residential house received electricity from the PV system during the daytime, while it used electricity from the central grid during the night or cloudy days. • 67.6% of the total required energy was produced by the solar PV system, while only 32.4% was taken from the national grid.	[51]
PV System	Both Grid-Tied and Off-Grid with Battery Storage system	Residential level	Intermittent/ Firm	Australia	• System consisted of 5 kWh Li-ion battery, 250 W twelve polycrystalline PV panels, and 3 kW inverter. • It was also observed that a decrease in PV panel costs would result in lower capital costs and smaller payback periods.	[52]
Microbial Fuel cell (MFC)	Grid-Tied	Small public building-level	Intermittent	Ghana	• The capital investment of the MFC washroom system was $3900. All materials were bought locally, except granular graphite, which comprises a major portion of the initial cost, and the LED electrical circuit. • Electricity generation from MFC at full-scale was consistent when school was in session.	[53]
Fuel Cell and CHP	Grid-Tied	Residential level	Intermittent	Brazil	• This CHP technology was not only highly efficient but also resulted in fewer pollutant emissions with power outputs ranging from a few kilowatts to 50 MW. Simple Payback Period was determined to be around 3–5 years with capital investments of around 1000–1500 USD/kW in fuel cells. • Energy analysis was carried out for determining the fuel utilization efficiency which was found to be 86% for the particular fuel cell cogeneration system. This efficiency exceeded the fuel utilization efficiency of Gas Turbine Cogeneration (CHP) of 82.6% reported previously by Utgikar et al. [54].	[55]
Fuel Cell (SOFC) and CHP/CCHP	Grid-Tied electricity during peak hours	Commercial building-level	Intermittent	Hong Kong	• This hotel required 1000 kW of electricity along with 630 kW of cooling without any interruption around the clock. • A simple payback period for this project was determined to be around 10 years. • It was also suggested that the overall efficiency of the system could be improved from 84% to 94% by conversion of cogeneration to trigeneration system.	[56]
Hybrid PV and SOFC system	Off-Grid	Commercial building-level	Firm	Cyprus	• The system was designed based on load profiles, with maximum electricity outputs of around 70 kW and 152 kW for PV and SOFC, respectively. • PV and SOFC subsystem contributed to 135.9 and 451.2 MWh, respectively on annual basis to fulfill load profile. • The life cycle cost for this hybrid system was determined to be USD 1,241,369. The Levelized Cost of Electricity (LCOE) was determined to be 0.1057 USD/kWh. • This system reduced the unit cost of electricity and CO2 emissions significantly. Around 36% reduction in CO_2 emissions was observed.	[57]
Hybrid Wind and PV system	Grid-Tied and Battery Storage system	Small residential building	Intermittent	Iran	• The LCOE of the hybrid PV-Wind system in Tehran was determined to be 0.62 USD/kWh, being 78% and 34% cheaper than a wind turbine system and PV system, respectively.	[58]
Hybrid Wind and PV system	Both Grid-Tied and Off-Grid	Commercial Building-level	Intermittent/ Firm	Australia	• This hybrid system was self-sufficient to fully meet its required demand but it was not financially viable due to the higher requirements of capital investments. • Simple Payback Period of 14 years was reported for this hybrid system. A 65% reduction in CO_2 emissions was also observed over its lifespan.	[59]
Hybrid Wind and PV system	Off-Grid Battery Storage system	Residential level	Firm	Denmark	• The hybrid system is comprised of 17 PV panes of 360 W rated power each, thus making it an approximately 6 kW PV system, a wind turbine with the rated power of 10 kW, Li-ion battery storage system.	[60]
Biogas Digesters	Off-grid	Residential level	Firm	China	• Reduction of around 10.18% less energy consumption was observed in families with biogas digesters.	[61]

(continued on next page)

Table 2 (*continued*)

Biogas Digester	Off-grid	Residential level	Firm	China	• Around 2500 biogas digestor systems were installed in eight rural villages of Shandong Province. • The system consisted of a biogas digester including gas scrubbers. • The utilization of sludge in biogas digester has resulted in the consumption of conventional fuel.	[28]
Biomass Boilers	Off-grid	Residential level	Firm	Canada	• Carried out the viability analysis of biomass projects for water heating and space heating in remote, off-grid regions in Canada. • Biomass DES using pellet boilers in homes and commercial buildings was compared with a centralized heat generation system fueled by wood chips. • Such individual projects were found more viable for reducing heat costs. Not only that, but such projects also reduced greenhouse gas (GHG) emissions. Projects have also resulted in increasing the energy independence for faraway regions.	[62]
CHP with PV System	Grid-Tied	Industrial plant level	Intermittent	Germany	• In this system, a CHP unit was combined with a heat storage system. The former system had a capacity of 95 kW_{el} and 145 kW_{th}, whereas the latter had 675 kWh. It also used 215 kW of the PV system. • Electricity demand of 13.7% and 7.1% were delivered by CHP and Solar PV system, respectively. However, still, around 79.2% of the electricity demand was fulfilled by purchasing electricity from the grid. • 93.7% of space heating requirement was fulfilled by CHP unit, only 6.3% was provided by pellet heating system.	[63]

DES Technology	**Grid Type**	**Level**	**Load Type**	**Location**	**Important Remarks**	**Refs.**
PEM Fuel Cell	Grid-Tied	Industrial plant level	Firm	China	• Ten 216 V and 48 kW fuel cell arrays were arranged in parallel.	[64]
CHP with micro gas-turbine (MGT)	Grid-Tied	Industrial plant level	Intermittent	Italy	• Carried out the financial viability of (i) Organic Rankine Cycle (ORC) and waste heat recovery (WHR) from exhaust gases coupled with energy storage and (ii) CHP based on micro gas turbine (MGT). CHP based on MGT was found to be a more viable solution financially. • A 2 × 100 kW AE-T100NG micro gas turbine was used. • Two- and 10-years payback periods of CHP and MGT, respectively.	[65]
CHP based on SOFC-Steam Injection Gas Turbine (SIGT)	Grid-Tied	Industrial building-level	Intermittent	Iran	• Four cases were studied (i) SOFC (ii) SOFC/MGT (iii) SOFC/Gas turbine/ST (iv) SOFC/SIGT. • CHP based on SOFC/SIGT was found to be the most profitable. It was also observed that electrical efficiency could be increased by 5.1% with the injection of 3.3% steam. Optimized LCOE was 11.15 ¢/kWh lower than the baseline LCOE of 17.56 ¢/kWh. • An annual reduction of 62% CO2 emissions was observed by using this hybrid DES in comparison with the conventional system.	[66]
CHP based on biomass boiler	Grid-Tied	Industrial plant level	Firm	Italy	• The boiler was fueled by wooden scraps from the sawmill. • CHP provides heating power of 5 MW_{th} and electricity of 81 kW_e was fed to the main grid. • Heleix GenSet Model HP145-132 kW was used.	[67]

DES Technology	**Grid Type**	**Level**	**Load Type**	**Location**	**Important Remarks**	**Refs.**
CHP based on SOFC integrated with MGT	Grid-Tied	Industrial plant level	Firm	Italy	• Analysis on two cases was carried out (i) SOFC-wastewater treatment plant (WWTP) (SOFC was used as the CHP unit), and (ii) integration of both SOFC & MGT with WWTP. • Results showed that the use of SOFC-MGT systems could increase the self-generated electricity within the WWTP by up to 15%. • The efficiency of the SOFC-MGT-WWTP system was determined to be 7% higher when compared with SOFC-WWTP. • LCOE of 0.118 $/kWh was determined for the SOFC-MGT-WWTP system. Around 12% reduction in LCOE was observed in comparison to the SOFC-WWTP system.	[68]
CCHP based on Rankine/ ORC	Grid-Tied	Industrial plant level	Firm	Turkey	• In this study, a comparison between Rankine-based CCHP and ORC-based CCHP was carried out. • $LiBr–H_2O$ absorption chiller was used in Rankine and ORC. • Energy analysis of ORC-based CCHP resulted in an energy utilization rate of 98.07%. Along with that, the sustainability index was determined to be 2.747%. • Exergy analysis was also carried out for both systems. The exergy efficiency of ORC and Rankine-based CCHP was found to be 63.6% and 53%, respectively. • A payback period of CCHP based on Rankine was calculated to be 4.738 years. On the other hand, the payback period of 5.074 years was observed for CCHP based on ORC.	[69]

DES Technology	**Grid Type**	**Level**	**Load Type**	**Location**	**Important Remarks**	**Refs.**
CHP based on biomass boiler	Grid-Tied	Industrial plant level	Firm	UK	• The boiler was fueled by litter from a bird poultry farm. • CHP provided heating to five chicken sheds and electricity of 115 kW_e was fed to the main grid. • Burning of poultry birds litter offered a low-cost fuel resource for the biomass boiler, effective disposal of the poultry waste, and saved fuel related to 1036 tons of CO_2. The payback period was less than one year.	[67]
CCHP based on biofuel	Grid-Tied	Industrial plant level	Firm	South Korea	• Biofuel production from the textile wastewater was used to operate this CCHP system. This system primarily included a Brayton Cycle (BC) for electricity generation.	[70]

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Table 2 (*continued*)

					- This CCHP unit is also comprised of Rankine Cycle (RC) for power generation. Water Heating Unit (WHU) was incorporated for hot water and modified Kalina/vapor-compression refrigeration system. - This CCHP system provided 88 kW$_{el}$ power. - Yearly saving and LCOE of this system were determined to be 123,476 $/year and 0.5015 $/kWh, respectively. - The overall system Coefficient of Performance (COP) was determined to be 6. - Thermal efficiency (η_{th}) and overall efficiency of CCHP unit (η_{CCHP}) were 47%, and 62%, respectively.	
Biogas fed SOFC based CHP integrated with CST	Grid-Tied	Industrial plant level	Firm	Italy	- Concentrating solar thermal (CST) system was integrated with Biogas fed SOFC for a WWTP. - Up to 8%, 18%, and 30% of the total heat load of the digester were covered with the installation of 300 m^2, 700 m^2, and 1100 m^2 of solar collectors, respectively. - Payback of the CST system was about 9 years.	[71]

meteorological data on the electricity and weather conditions are utilized. However, in the case of a new location and in the early stages of renewable installation studies, the feasibility study for a potential location of wind or solar farms can be performed with an indirect prediction of the energy output. This is achieved by predicting the wind speed or the solar radiation and formulating a preliminary profile of the potential output using the associated formulas. Such an indirect approach provides a better margin of flexibility [97]. For instance, considering the case of wind speed prediction, as the amount of power produced by a wind turbine is dependent on its parameters, the process of forecasting wind speed may be modified to account for these factors. It is simpler to forecast the speed of the wind than the output power generation profile by the wind, which is because the production of wind power is dependent on the particular characteristics of the wind turbine [98]. Moreover, using indirect techniques, additional meteorological data, in addition to wind speed and solar irradiation, may be utilized as inputs to further enhance the forecasting models. This can be done to a greater extent than with direct methods. When the data are irregular, including meteorological variables is extremely beneficial since it helps to offset the irregularity impact on the model's prediction performance. This effect may be caused when the data are not collected regularly [99].

Development and formulation of correlation of data in the data preprocessing stages help in the identification of parameters and features that affect the output power predictions and results in effective training model development [100]. Considering the case of PV output power prediction, data sets of solar irradiances, temperature of the air, and dew points are observed to be positively correlated while the cloud type and humidity data sets are negatively correlated [101]. Accordingly, the data set of blade pitch angle highly impacts the accuracy of the output power associated with wind energy than the associated wind shear and wind speed data while certain data sets such as yaw error, ambient temperature, and nacelle can be removed as they have no impact in the prediction problem [102]. Typically, time series data are used in the forecasting of renewable energy sources, but they also can include sky images [103], or spatial data [104].

Data normalization, handling wrong data, missing values, outliers, managing data resolution, augmentation, correlation, and clustering are a few considerations in the data preprocessing stages. When the inputs to a prediction are numerical data with varying scales, normalization becomes a necessary procedure. Leaving out this procedure might skew performance results, particularly for algorithms that rely on gradient descent to learn and converge to minima [105]. There are numerous methodologies to overcome missing and outliers in a data set. For instance, replacing the negative output power by zeroes [106], filling with mean values from previous time steps [107], compensating the missing values with previous time series values to Ref. [108], hampel filter for removing outliers [109], and data interpolation [110]. When dealing with renewable data sets the higher resolutions are averaged to develop a lower resolution data set while it decreases the computational time impacting the development of the AI model as useful information might be lost that might be necessary, for instance, in terms of developing data correlation [111]. Similarly, correlation, data clustering, and formulas can be utilized in the process of data set expansion in case of scarce data availability [112].

One of the major fields of application of AI in distributed energy systems is forecasting. Broadly AI based renewable models are classified into probabilistic and deterministic methods. The goal of probabilistic forecasting is to either give a probability to a predicted outcome or to locate the prediction ranges within which the actual values lie. It is crucial for helping in the planning and management of the electric systems to quantify the uncertainty associated with the forecasting of the power generated by renewable energy sources. Numerous parametric as well as nonparametric approaches have been developed [113–115]. The study in Ref. [116], utilized the mixed gaussian model to formulate an uncertainty analysis based on their long-short-term-memory (LSTM) model for wind output power forecasting. A comparative analysis with a mixture density neural network and relevance vector machine is provided to present the effectiveness of their forecasting model wherein the probabilistic forecasting is obtained as confidence intervals.

The deterministic model for forecasting and DER applications are broadly classified into categories namely convolution neural network, recurrent neural network, stacked autoencoder, deep belief network, hybrid, and ensemble models [117]. Convolutional layers are used in CNN-based forecasting models to extract features from data, whereas the fully connected layer at the very end of the network is responsible for carrying out the regression operation. CNN is the preferred choice when the inputs contain pictures, such as in Ref. [118], where photos of the sky were utilized to collect important information about the cloud covering, which assists prediction models in achieving a greater level of accuracy. In this study, the authors carried out many tests to investigate the impact that the sensitivity of various CNN architectures, as well as the input picture resolution, had on the PV output prediction. The created models give a high level of accuracy when the weather is bright but a lower level of accuracy when the weather is partially cloudy or gloomy. While it is more common to utilize CNN when the data being analyzed can be represented in two or three dimensions, such as in the case of photos and videos, it is not impossible to use CNN with one-dimensional inputs, as shown in Ref. [119].

Forecasting data often consists of time series data that are captured sequentially at a set time interval, anything from a few seconds to an hour. RNN-based models and their more sophisticated versions, such as LSTM and GRU, are often used in the processing of sequential data [120]. When using stacked LSTM, the output of one LSTM layer serves as the input for the next LSTM layer. The use of this deep architecture makes it possible to represent sequential data in a way that is increasingly sophisticated with time [121]. Autoencoder networks are well-known for their capacity to decrease dimensionality in data while simultaneously generating a representation that is very similar to the data that they were trained on. Denoising autoencoders are more resilient than regular autoencoders because they learn more features from the data by purposely adding noise to the inputs [122]. A deep belief

Table 3
Applications of Distributed Energy Systems in District level.

DES Technology	Grid Type	Level	Load Type	Location	Important Remarks	Refs.
Biomass	Off-Grid	Neighborhood level	Firm	Columbia	• Utilization of 30% available biomass reduced CO$_2$ emissions by 22% and provided an additional income of 99–121 USD/house/yr.	[72]
A multi-source system consisting of PV, fuel cell, and gas turbine	Grid-Tied	Neighborhood level	Firm	Switzerland	• Seasonal energy storage was studied and designed by mixed-integer linear programming (MILP). • MILP model was used to validate this multi-energy generation system • A significant reduction in total cost was attained by seasonal storage in the system. • For a significant decrease in emission, this model could be convenient seasonal storage.	[73]
Wind turbine, Hydrogen gas storage, and PEM fuel cell	An off-Grid system with an IC engine for backup power	Neighborhood level	Intermittent	Norway	• This hybrid DES was designed for the electrification of ten houses on the island. • This system is comprised of a 600-kW wind turbine, water electrolyzer with a hydrogen production capacity of 10 Nm^3/h, a 10 kW PEM fuel cell, hydrogen gas storage with a capacity of 2400 Nm^3 at 200 bar, and a 55 kW hydrogen engine. • The hydrogen storage facility of this unit is self-sufficient for 2–3 days of uninterruptable operation.	[74, 75]
CHP based on biomass boiler	Grid-Tied	Community-level	Firm	Scotland	• This system provided hot water to nearly 200 households in Scotland using thermal energy from a 3.5 MW$_{th}$ biomass boiler. • Boiler was fueled by wooden chips. • 106 kW$_{el}$ of electricity was generated, which was used to power the boiler plant control room.	[67]
DES Technology	**Grid Type**	**Level**	**Load Type**	**Location**	**Important Remarks**	**Refs.**
DES-based on PV System	Off-Grid	Community-level	Intermittent	KSA	• PV output in residential buildings was estimated • PV panel efficiency of 10% was observed in the hot climate of KSA [76].	[77]
CHP based on biomass boiler	Grid-Tied	Community-level	Firm	Austria	• This system was utilized for district heating, using thermal energy from a 6 MW$_{th}$ biomass district heating plant. • Low maintenance and fuel cost of around 30 €/MWh allows low-cost electricity production. • Payback under the given conditions was under 3 years.	[67]
Hybrid PV, Wind and Biogas Digester System	The off-Grid system with biogas DG for backup power	Community-level	Intermittent	Kenya	• The LCOE of this renewable energy resources-based hybrid DES was determined to be $0.25/kWh which was 20% lower than the cost of electricity ($0.31/kWh) with a diesel generator used for backup. • Emissions analysis determined that by using a biogas engine, 17 tons of CO$_2$ could be reduced annually.	[78]
Micro Hydro Plant (MHP)	Off-Grid Microgrid systems	Community-level	Firm	Venezuela	• System provides electricity to 580 people of an office and a tourist center. • MHP has a capacity factor of 32.6% and has produced around 436,668 kWh/year.	[79]
PV System and Wind Turbines	Off-Grid	Community-level	Firm	Fiji	• In the existing system, electricity was available for about 4 h in the evening generated by a Diesel generator. • Island had total demand of 876 MWh/year. • Batteries were used for electricity storage.	[75, 80]
DES Technology	**Grid Type**	**Level**	**Load Type**	**Location**	**Important Remarks**	**Refs.**
Geothermal Heating Systems	Natural Gas Off-Grid	Community-level	Firm	Turkey	• The total heat load of the campus was estimated to be about 11.2 MW, with 15 buildings and a total floor area of 50,370 m2. • Two locations were studied for the new heat center. The first location was close to that building while another was close to the production well. • Piping cost of the first location for the heat center was 34% lower than the other option. • Heat Pump District Heating System (HPDHS) was determined to be more viable, over 20-year period, as compared to the current Individual Fuel Boiler Heating System (IFBHS), with 4.07% profit.	[81]

network is a kind of generative model in which neurons from various levels are linked to one another, but neurons within the same layer do not connect to one another. Restricted Boltzmann Machines are stacked one on top of another to create Restricted Boltzmann Machines [123]. The accuracy of the forecasts has been enhanced by using either many DL models or a single DL model in conjunction with other approaches, such as data deconstruction or feature selection.

In most cases, the components of data representing time series are as follows: level, trend, seasonality, and noise. Using one of the available data decomposition techniques to disentangle each of the four components, or at the very least disentangle the level from the noise, is necessary for successful forecasting. Before training a forecasting model for each subseries, researchers in hybrid models employ one of the decomposition techniques as a data processing step to decompose time-series data into numerous subseries. Each subseries may then be analyzed individually. The ultimate outcome of the prediction is determined by compiling the information provided by each of the many forecasting models [124]. Similarly, in hybrid forecasting techniques,

Table 4
Applications of Decentralized Energy Systems in Urban level.

DES Technology	Grid Type	Level	Load Type	Location	Important Remarks	Refs.
Wind, PV, and Biomass Hybrid System	Grid-Tied	Urban level	Intermittent	Pakistan	• The load was shared between PV, wind, and biomass power plants and additional electricity could be supplied to the grid. • The system cost for a maximum peak load of 74 MW was USD 180 million. LCOE for this system was 0.0574 $/kWh. • Due to the situation of electricity shortfall in the country, it was highly suggested that Government should devise a regulatory framework for effective utilization of renewable energy resources.	[82]
Vertical Axis Wind Turbine	Grid-Tied	Urban level	Intermittent	Netherland	• The case study considered the Netherlands because urban wind energy in the Netherlands was predicted for the case. • More than 18,000 small-scale wind turbines were installed on over 1500 buildings. • On average o12 wind turbines were installed per building across 12 cities.	[83]
CHP based on ORC	Grid-Tied	Urban level	Intermittent	Germany	• ORC used brine at low temperature <100 °C. • Geothermal water heating plant was extended to generate power, 210 kW to the main grid, by utilizing ORC with n-Perfluorpentane (C_5F_{12}) as the working fluid. • The CO_2 emissions were reduced by about 2700 tons and the saving of natural gas was about 1.7 million. • Around 1300 houses, 20 small business owners, and one industrial organization were provided with economically & environmentally friendly heat [84].	[85]
CHP operated by seawater	Grid-Tied	Urban level	Intermittent	Netherlands	• 750 energy-efficient homes constructed in Hague. • Seawater was used as the source of energy to operate this CHP unit. • This heat generation unit was 50% more efficient than the conventional system. • Significant reductions in carbon emissions were observed.	[86]

some researchers choose to employ diverse feature selection approaches, while others take use of the benefits offered by DL models like CNN or LSTM for non-linear feature extraction from data [125]. Accordingly, in some hybrid forecasting models, the inaccuracy that was gained through forecasting is input into the model together with the forecasting results to produce the final forecasting output. This is done in addition to the forecasting results in itself [126].

Finally, the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE), and the Mean Absolute Percentage Error are the three metrics that are often used for deterministic forecasting (MAPE). Moreover, the coefficient of determination, also known as R2, and the standard deviation of error, also known as SDE, are used rather often. On the other hand, the outcomes of probabilistic forecasting are often provided using the Continuous Ranking Probability Score (CRPS), the Average Coverage Error (ACE), and interval sharpness (IS). The other applications of AI in DER include parameter estimation and sizing of the solar cells. Presently, single-diode and double-diode algorithms are used to outline the non-linear characteristics of the solar cell [127]. Increasingly, utilities are turning to AI methods for energy planning and management [128]. AI has the potential to provide benefits over other technologies when it comes to the provision of active/reactive power coordination, especially in radial distribution networks with high renewable integration. An intelligence system installed at grid-scale will be able to manage load demand needs, power balancing, negotiate actions, and enable resilience among a variety of other ancillary, and grid-participant services. By being able to appropriately assist with the analysis of several types and structures of data on energy supply and consumption, the intelligent system will make it possible for power firms to run their operations more effectively.

To provide an example, the AI devices will automatically identify the total load demand and net energy consumption, and the total load demand may be lowered and regulated with the help of AI. Using machinery that is more energy efficient and cutting down on wasted energy are both aspects of demand-side management (DSM) [129]. Using

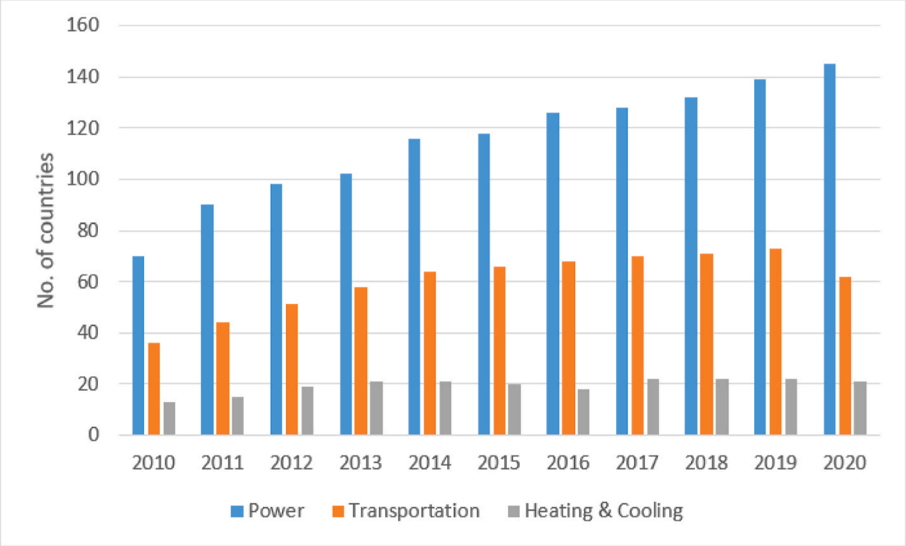

Fig. 8. Countries with active renewable policies.

Table 5
Current Policy, targets, and their achievements in different countries.

Country	Description	Targets	Achievements
United States of America	Renewable Portfolio Standards (RPS) are policies implemented to support renewables for electricity generation. Each state has its RPS.	• The US has targeted to go 80% renewable by 2050 or earlier [145].	• According to US Energy Information Administration, renewable energy resources provide 22.5% of US electricity generation [145,146]. • A total 292 GW of electricity is generated through renewable energy resources in the U.S [147].
United Kingdom	The UK has set the world's most ambitious target to achieve Net-Zero emissions. The UK is legally bound to Climate Change Act 2008 and has taken an international pledge to the Paris Agreement.	• The UK has set the world's most ambitious goal to cut emissions by 78% by 2035 [148]. • UK has aimed of reducing GHG by 100% [149].	• Recently, the UK has achieved a ground-breaking reduction in emissions by 8.9% in 2020 [149]. • Overall reduction in emissions is 49% as compared to 1990 [150]. The UK is on right track to achieve its goal of becoming Net-Zero in terms of emission. • In 2020, 43% of the UK's electricity was generated by renewable energy resources [151].
	Electricity tariff rates of the grid have been increased by the British government through Climate Change Levy (CCL).	• The objective of CCL was to increase the energy efficiency of the industrial sector and promote renewable-based DES.	• DES projects were exempted from Climate Change Levy [152]. • 20% of total energy consumption was saved by this policy. • Installed capacity of CHP in the UK was about 4.2 MW [15].
Germany	The German Climate Law has been implemented nationwide to reduce emissions.	• Germany plans to have net-zero emissions by 2050 [15].	• By 2020, 40.8% of emissions have been cut off as compared to 1990 by promoting the use of renewable-based DES. Germany has reduced emissions by nearly 9% in 2020 compared to 2019 [153,154].

intelligent systems, load demand management may become more intelligent and automated. The use of artificial intelligence in the United Kingdom helps to support the grid in controlling devices (such as relays and circuit breakers) with better performance in terms of flexible operation and real-time control. Accordingly, such models can effectively manage the DSM especially during peak hours with having a negative impact on the consumers [130]. Therefore, AI presents the opportunity for the development of new services, some of which include direct load management, dynamic tariff deployment, and customized charging of electric vehicles. Other subcategories that emerge are auxiliary support, energy efficiency, scheduling, and demand response [131].

Furthermore, considering the global need of establishing smart grid technology, DSM is of the utmost significance. This is because the stability and dependability of electricity grids are dependent on the modification of peak load demand [132]. In addition, grid dependability may be accomplished by integrating variable demand with intermittent renewable energy via demand response and a variety of DSM programs. This combination will result in a more dynamic energy mix. Recent developments in the field of decentralized load demand management systems may be found in Refs. [133,134]. The extension of AI has also been observed in identifying theft of energy [135,136], load demand forecasting [137], predictive maintenance, and energy trade [138]. An in-depth review and discussions on AI models for distributed energy systems are presented in Refs. [139–141].

6. Policies and trends

The progress of decentralized energy systems has been strongly helped by conducive policies besides advancement in technology and economy of scale [142]. Effective policy support has resulted not only in the development of DES technologies but also in the implementation of projects across the globe. Implementation of DES, particularly those based on renewables, is also related to low-carbon and climate change policies. Relevant policies cover areas such as reduction in the share of fossil fuels especially coal, reduction in GHG emissions, incorporation of renewables, and development in carbon pricing and emissions trading programs. Given the fact that there is no database available specifically on DES policies, and that most of the DESs are based on renewable technologies, the present study considers the renewable energy policy landscape as representative of DESs. Over the last decade, renewable policy development has seen tremendous growth. A large number of countries have already committed to using renewable and sustainable technologies and the number is growing every year. The benefits of these policies are increasingly being realized around the world as over 10,000 cities and local government bodies have enacted such frameworks [143,144]. Fig. 8 shows the renewable energy policy trend in terms of countries with active policy frameworks. These policies may be classified into electricity generation, heating/cooling, and transport policies. Electricity generation policies may include net metering, feed-in tariff (FITs), and Renewable Portfolio Standards. Schemes like renewable heat FITs and solar heat obligations fall under the heating/cooling policies. Transport policies may include policies to promote Electric Vehicles, biodiesel mandates, and ethanol mandates. By the end of the year 2020, 165 countries in the world have active policies around the power sector, heating & cooling, and transportation [8].

Energy policy frameworks in different countries depend on various factors including the stability of their energy sector, available resources, environmental scenario, economic conditions, and socio-political dynamics. Policies in different countries therefore can vary significantly. Even though European Union (EU), for example, has adopted low carbon and emission reduction targets for all its member states, individual member states can set even more stringent targets for themselves. To reflect on broader policy dynamics, the present study has selected three countries from each of the three types of economies: developed economies, economies in transition, and emerging economies. United States (US), United Kingdom (UK), and Germany are selected as developed economies; China, Brazil, and Turkey are selected as economies in transition; and India, Pakistan, and Nigeria are selected as developing economies. Table 5 provides an overview of relevant policy aspects in these countries.

Similarly, policies related to FIT are also very important as far as the economics of DES projects are concerned. For example, the British government revised its FIT scheme in 2014, which was first issued in 2010. The revised FIT scheme is more favorable for promoting the development of small-scale DES projects (≤5 MW) particularly based on renewable energy resources [187]. Details of FIT/net metering schemes

Country	Description	Targets	Achievements
Germany (cont.)	The Germany Renewable Energy Act 2021 was enacted on January 1, 2021 which is a coalition and modification of its existent energy law. It outlines the various national policies and plan of integrating renewables such as solar and wind into the national electricity grid.	• Continuation of the existent law that is to ensure both electricity supply and consumption becomes carbon neutral by 2050. • Continuation and expansion of long-term energy and meet the target of 65% energy production through clean sources by 2030 [155]. • Enacting laws and policies that lowers the cost burden on the customers.	• Electricity bill reduced to £0.065 from £0.06756. • Intend household power prices fall intentions • Intend household power prices fall by 1%.
	In 2016, Germany revised laws to promote renewable energy resources utilization.	• Power generation from renewables is around 35% of total electricity generation by 2020. • Application of renewables is likely to increase by 50% by 2030 and by 80% by 2050 [15].	• As per recent data disseminated by the Ministry of Energy and Economics, renewable-based DES accounts for 42.1% of Germany's total energy production. However, initial targets were to achieve 35% [156]. • Primary renewable energy source in Germany is wind. Wind energy is responsible for 21.9% of overall energy generation and 51.9% of renewable electricity generation [156]. • Majority of the investments have been made for small-scale renewable-based DES projects [157].
	In 2012, Germany revised its Combined Heat and Power Act.	• It is expected that 25% (145–150 TWh) of annual total energy production will be from CHP by 2025 [158].	• 18.1% (107.7 TWh) of Germany's total electricity is generated via CHP, while 20% (200 TWh) share of the heating market depends on CHP [159].

Country	Description	Targets	Achievements
China	National Development and Reform Commission (NDRC) disseminated its Renewable Energy Development plan (2007). In this plan, targets were established for several renewable-based DES.	• China aimed for 300 GW installed capacity for hydropower generation by 2020 [160].	• China's current installed hydropower capacity is around 370 GW in 2020 [161].
		• Solar power installed capacity of China will be around 1.8 GW.	• Current solar power installed capacity of China is around 253 GW [162]. • The contribution of PV for decarbonization has reached 875 million tons of CO_2 equivalent [162].
		• Solar thermal applications will reach 300 million m^2 of collector area.	• China has achieved the highest solar thermal application across the world, with 346.5 GWth [163]. • 92% of installed capacity is employing evacuated tube water heaters. • It accounts for 72.3% of the world's total capacity [163,164].
		• Wind power installed capacity of China will be 30 GW.	• Current installed capacity for wind power has reached 288.32 GW [165,166]. • 278 GW is onshore wind turbines, and 10 GW is offshore wind turbines [165].
		• Biomass power installed capacity of China will be 30 GW.	• China has a biomass power installed capacity of 25.2 GW [167].
		• Geothermal power installed capacity of China will be 500 MW.	• Installed capacity of geothermal power is 27.78 MW [168].
		• Tidal power installed capacity of China will be 100 MW.	• Current installed capacity of tidal power in China is 6.3 MW [169].

Country	Description	Targets	Achievements
Brazil	Brazil's renewable energy targets are set in its Ten-year energy expansion plans.	• This plan aims to produce 86.1% of Brazil's total electricity from renewable energy resources by 2023 [170].	• Renewable energy resources account for 46% of national grid electricity [171].
	In 2007, Brazil's National Climate Change Plan set a target to promote CHP, mainly from bagasse.	• It is expected that CHP will generate 11.4% of the total electricity supply in 2030 [170].	• CHP systems account for 8.9% of the total electricity supply. 78% of such CHP operates on sugarcane bagasse, 20% on forest residuals, and 2% on other biomass resources [172].
Turkey	Vision 2023 is Turkey's most prominent policy related to small-scale renewable-based DES [173,174].	• 11th development plan of Turkey has increased the share of renewable energy resources from 32.5% to 38.8% of total electricity production. • Ministry of Energy and Natural Resources (MENR) is focused on increasing the capacity of hydropower to 34 GW, wind power to 20 GW, solar to 5 GW, geothermal and biomass to 1 GW each. The total projected investment of this object is nearly $60 billion [175,176].	• Currently, 51.5% (49,398 MW) of total electricity generation of Turkey is produced by renewable energy resources [177,178]. • Installed capacity of hydropower in Turkey is 30,984 MW, wind power is 8832 MW, solar energy is 6668 MW, 1301 MW by biomass and geothermal is 1613 MW [179].
Pakistan	Alternative Energy Development Board (AEDB) is a government entity for implementing Energy Security Action Plan (2005–2030) in Pakistan.	• Government of Pakistan has set very ambitious targets to increase the renewable energy generation share to 30% by 2030 [180–182].	• The current ratio of renewable energy resources (excluding large hydropower projects) is less than 900 MW (less than 4%) [183]. • The ratio of hydropower electricity is 24% of total electricity generation [184].

Country	Description	Targets	Achievements
India	In 2016, Paris Agreement's Intended Nationally Determined Contributions targets, India committed	• In 2019, India aimed of generating 175 GW of its electricity from DES based on renewable resources by the end of 2022.	• Currently, 30.9% (134,197 MW) of total electricity generation of India is produced by renewable energy resources [179].

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	to generating 40% of its electricity from non-fossil fuels sources by 2030.		• Installed capacity of hydropower in India is 50,680 MW, wind power is 38,559 MW, solar energy is 39,211 MW, and biomass is 5747 MW [179].
Nigeria	In 2006, Nigeria's Federal Ministry of Environment has implemented Nigeria Renewable Energy Master Plan (REMP) with the support from United Nations Development Program (UNDP) to increase the contribution of renewable energy resources in Nigeria.	• REMP aims to increase the share of electricity generated from renewable energy resources to 23% by 2025 and 36% by 2030 [185]. • 2000 MW of installed capacity of small hydro projects is estimated, 500 MW from solar PV, 400 MW from Biomass-based power plants, and 40 MW from wind energy by 2025 [185].	• In 2021, the total installed capacity of renewable energy resources for electrification is 2153 MW [179]. • 2111 MW is produced from hydropower projects, 3 MW from wind energy, 28 MW solar PV, and 11 MW from biomass-based powerplant [179].
Saudi Arabia	Saudi Vision 2030 is an ambitious policy that was established in 2016 and has been updated periodically. The policies aim at reducing the dependency from oil resources thorough systematic diversification and digitalization in health, education, and economics with targeted focus on sustainable energy realization.	• Integration of renewable energy sources that includes solar PV, wind, hydro, and bioenergy. • Generating 9.5 GW electricity through renewables by 2023. • Reaching 58.7 GW electricity generation through renewables by 2030, in which wind energy is 16 GW, solar energy is 40 GW, and other renewables contribute 2.7 GW [186].	• Completion of operational planning stage of the 2023 target and installation of 9.5 GW solar PV and wind has been initialized considering short- long-term planning, network contingencies, security, and economic aspects. • Smart meter and digitalization of the entire grid network including residential, industrial, commercial customers as well as grid substations.

of various countries are provided in Table 6.

7. Challenges

While DESs are making significant progress and are regarded to have a key role in the emerging global energy landscape, they are facing several challenges too. These challenges can be broadly classified into two types: management or socio-political and techno-economical.

7.1. *Socio-political*

Socio-political or management-related barriers are related to the conventional centralized energy models. Traditionally power generation, and transmission and distribution sectors are administered by centralized private or government sector entities. In many countries, utilities have a strong monopoly and control the policy and other dynamics of the energy sector [15,203,204]. DESs pose a challenge to the established business model of these utilities and hence face hindrances. Established market players resist the development of a decentralized energy system since distributed systems encourage a large number of actors to become power producers and hence competitors. Grid integration and interconnection can also face legal and administrative hurdles for DES. Changes are being made to pave way for distributed generation. However, due to political and sometimes economic factors reversal or suspension of the favorable policies for DES is also common which usually has serious implications for them at least on a short-to-medium basis. Improvement and continuity of policies are therefore critical. The socio-political influence impacts the expediency of the DESs integration. Eventually, the realization, upgradation, and efficacy of sustainable renewable-based DESs are steered by the hierarchal governing bodies. Therefore, a transition from a centralized hierarchy is needed to upgrade from utility-customer to utilities-prosumer energy platforms. The socio-political aspect of DES is related, in many research studies to a social acceptance of renewables which is basically the public attitude towards installing localized renewable energy sources and bearing the costs and contributing towards the electricity generation.

7.2. *Techno-economic*

Various techno-economic factors are also challenging DESs. Off-grid renewables-based DESs require energy storage systems. Storage technologies however are still expensive and result in extra investment. A large number of DESs can also adversely affect the stability of the grid. Therefore, it is necessary to address the question related to the quality standards of the equipment and services in DES projects. There are some serious concerns about the reliability and resiliency of DES in moving away from the baseload electric power sources. DES units will also affect the system's frequency since they are not commonly equipped with a load-frequency controller. Transmission grid operators of the regulatory body often maintain the system's frequency. Hence, careful evaluation and planning are required before connecting a large number of DESs altogether with the central grid. Moreover, variation in electric power production is another factor in technological aspects that should be addressed. For example, PV-based DES will not provide electricity during nighttime and/or in cloudy conditions leading to increased capital investments. Similarly, DES-based wind turbines will also suffer from the uncertain variations in the wind speed resulting in the deviations in power produced by the wind turbines. Table 7 highlights various technical challenges faced by DESs along with their potential solutions. The economic viability of DESs, especially in countries with highly subsidized conventional energy supplies, is still a major issue. Another important factor is related to the changes in financial support policies. In the initial stages, many countries tend to offer high subsidies to DES projects particularly based on renewable energy resources to attract investors. For example, Germany has offered substantial subsidies which resulted in the maturity of the DES projects based on renewable energy resources. After the maturity of DES projects, countries tend to reduce the subsidies which results in decreasing the investment attraction and economic feasibility of these projects. Therefore, the revision of policies related to subsidies should be carried out carefully.

7.2.1. *Stability, reliability, and resiliency*

Most renewable technologies being non-dispatchable owing to their unpredictable transiency systematically introduces challenges to the power grid. In addition, most DESs are renewable energy sources that are integrated into bulk or as small DGs which further increases the dimension and complexity of the challenges as well as the solutions. Therefore, challenges inclusively associated also involve the selection between a centralized or de-centralized control solution [205]. The lack of control over the electricity generated by renewable energy sources creates one of the major concerns which is a demand-generation mismatch which requires additional auxiliary support. Primarily, there exist many concerns about the frequency stability with the introduction and quantity of DESs in an interconnected power network. The lack of inertia support from globally favored solar PV and wind energy technologies heavily limits their integrative potential as it will not contribute towards grid resilience in fault and catastrophic events [206,207]. Similarly, the operation of renewable energy sources is operated to harvest maximum active power which creates voltage stability issues, especially in residential and urban power grids. High renewable-based DESs in the case of residential installation will face voltage violation

Table 6
Details of FIT/net metering schemes in different countries.

Country	Initial Year	Latest Revision	Main Features
United Kingdom	2010	2014	• Export rate for electricity is 5.24p per unit [188]. • Half of the electricity units generated through DES can be sold back [188]. • Money can be saved on the electricity bills for the energy which is used through DES.
United States of America	1978	2008	• Grid access is guaranteed for small DES projects [189–191]. • FIT contract typically ranges from 15 to 25 years. • Cost-based purchase prices are guaranteed.
Japan	2012	2020	• FIT policy for renewable-based DES was enacted in 2012 as remuneration to accelerate the implementation of DES across the country [192]. • In 2012, initially FIT for plants larger than 10 kW was 40 yen/kWh [193]. • But over the years, after the maturity of renewable-based DES, FIT has been reduced to 12–13 yen/kWh in 2020 [193]. • In 2020, DES smaller than 10 kW still has a FIT rate of 21 yen/kWh [194].
Germany	2000	2014	• In 2000, FIT Erneuerbare-Energien-Gesetz (EEG) was announced to encourage electricity generation from DES based on renewable resources [195,196]. • After the implementation of EEG share of electricity produced from renewable resources has been increased from 6.2% in 2000 to 35% in 2018 [197]. • At this growth rate, Germany can be powered by 100% electricity generated through renewable-based DES by 2030 [195].
China	2011	2016	• In 2011, the first FIT policy was introduced to promote the implementation of PV-based DES projects [198]. • In 2016, tariff levels for solar PV-based DES projects ranged from 0.80 to 0.98 CNY/kWh [199].
Egypt	2014	2016	• Installations of small-scale PV systems, mounted on rooftops, reached 300 MW between 2014 and 16 reached 300 MW. • Tariffs were revised and FIT policy extended in 2016 [200].
Pakistan	2015	2016	• Remuneration levels for PV-based DES projects were provided in this net metering for 25 years [201]. • In the Northern region, remuneration for <20 MW PV-based DES project from 1 to 10 years was 19.2 PKR/kWh and from 11 to 25 years was 8.6 PKR/kWh [201]. • Similarly, in the Southern region, remuneration for <20 MW PV-based DES project from 1 to 10 years was 18.4 PKR/kWh and from 11 to 25 years was 8.25 PKR/kWh [202].

Table 7
Technological barriers related to DES and their possible solutions.

Technological Issue	Reason(s)	Possible Solution(s)
Loss of Stability	• DES is usually available in either OG or GT application which results in reducing the stability and reliability in power supply. • Several DES are connected to the central grid which leads to load supply fluctuations.	• Designing highly efficient power electronic converters can overcome this problem [221].
Energy Storage Systems	• DES based on renewable resources requires energy storage systems to provide sustainable supplies. • Electrochemical storage systems such as batteries have issues of low life, low energy density, environmental problems, and safety issues due to flammability. • Mechanical energy storage systems (MESSs) usually face issues related to high self-recharging for a short time and low energy density.	• The 100 MW battery project installed in Australia in 2017 has been a turning point in battery storage solutions. There are now several larger battery projects in operation while the USA is working on a GW scale project. • Several researches have been carried out in which it is evident that low energy density is the main issue with electrochemical storage systems. • There are several other technologies under consideration such as metal-air batteries. • Theoretical energy density of Li-Air battery is 11,429 Wh/kg. The energy density of metal-air batteries is about 10–30 times greater than the Li-ion batteries [222]. • Pumped storage hydro is a technically and economically mature MESS option [223,224]. • Hybridization of battery technologies with high-density energy storage (such as supercapacitors) that lower the impact of short-term peak power variations and reduces the size of battery energy storage system [211].
Power Quality	• Operation of DES based on renewable energy resources is a challenging task. These challenges occur due to supply intermittency as compared to conventional supplies from fossil fuels which are stable enough to meet baseload demand [225–228]. • Voltage congestion caused due to lack of reactive power support.	• DES can only be matured when smooth integration with the central grid and stable operation is possible. • Integration of power electronics inverters is improving particularly for harmonics distortion and complications in attaining stable frequency [229–231]. • Utilization of reactive power capability of renewable inverters in accordance with the IEEE standard 1548–2018 and utilization of energy storage system for active power curtailment [232].
Bidirectional Power Flows	• Conventional protection schemes result in undesirable tripping of the system due to failure for identification of forward and backward faults [233,234]. • Utilization of bipolar converters may face short circuit issues [234].	• Sitharthan et al. [221] have suggested the use of a bidirectional power controller. • The inter-circulating current is suppressed by the inner loop control method while DC voltage is managed by the outer control loop method [235].

as the amount of reactive power required to maintain the voltage stability is limited. Considering a case of a residential radial distribution network with high solar PV integration. An over-voltage violation occurs during peak solar PV production and an under-voltage violation will occur during the zero solar PV production time interval [208]. In this case, the power flow dynamics of the power grid are heavily changed and due to high solar PV penetration, the active power flow is high with limited to negligible reactive power production that leads to a predictable voltage variation in accordance with the solar PV's active power production. This impedes the hosting capacity of renewable-based DESs in the power grid and makes it vulnerable to fault conditions.

7.2.2. Energy storage

The concept of energy storage system is simply to establish an energy buffer that acts as a storage medium between the generation and load. The objective of energy storage systems can be towards one or more but not limited to the followings: frequency stability, voltage stability, peak shaving, market regulation, independency from forecasting errors, and reserves. Diversification, identification, and selection based on the targeted challenge of DES considering the complete technical capabilities of energy storage technologies is pertinent. The high cost of energy storage systems is among the key economic driving factor that limits their integrative efficacy [209]. Therefore, many research studies are focused on optimal siting and sizing facilitating numerous optimization frameworks. In this regard, most research studies consider parameters such as energy storage efficiency, life cycle, reliability indices, network dynamics among other parameters to formulate the optimal size and location of an energy storage system. Though these optimization solutions provide a state-of-the-art framework for storage cost reduction and at times power quality enhancement, the complete technical characteristics of energy storage systems are not considered in such studies [210]. For instance, considering high efficiency and energy density, battery energy storage systems are highly favorable in reducing the impact of renewable-based DESs. Batteries facilitate unparallel solutions towards the challenges associated with long-term planning in power system operation. However, due to low power density batteries are not techno-economically viable for facilitating short-term grid discrepancies such as abrupt load or demand surges and primary frequency support resulting in oversizing, premature replacement, and high current stress leading to the decreased life cycle. Alternatively, the implementation of different types of energy storage or hybridization of energy storage systems can further not only obviate these discrepancies but can also reduce the size of the overall energy storage size that collectively reduces the storage costs [211].

7.2.3. Digitalization and security

The shift from conventional-centralized generation to variable-renewable-based DES generation systems and progression towards a decentralized power grid and governance requires a rapid state-of-the-art measurement and communication platform. Most of the solutions available for reducing the impact of renewable-based DESs in terms of power quality, stability, energy market, and forecasting requires numerous rapid detections, measurement, monitoring, communication, and complex optimization with possibly automated decision-making [212]. In comparison to the conventional transactive energy process, modern technologies emerging from the fourth industrial revolution that comprises intelligent optimization, big data analytics, block-chain, internet-of-thing, smart meters, and high-performance computing lays the foundation for grid upgradation to establish the concept of internet-of-energy which is posited to facilitate automated operation of the power grid that has the potential to establish an effective communication infrastructure of smart grid [213,214]. Nevertheless, the progression from paper and computer to cloud-based energy tracking and optimization introduces the risk of security and limitation imposed by interoperability. Cyber security is emerging as a major challenge facing utilities in the wake of increasing penetration of distributed energy systems. Real-time monitoring, swift communication, and enhanced sensing, to enable analysis and effective control increase the likelihood of a cyber-attack on the power generating and distribution system. At the same time, the quantification of such threats and their physical impact on the power grid cannot be predicted. Some of the broader and well-known set of threats include fraudulent data, suppression of error alerts, accessibility to utility-prosumer data, undetectable susceptibility of technologies, and malicious signal transmission [215–217]. To mitigate these risks, DES operators need to invest in cyber security measures such as encryption, firewalls, and intrusion detection systems.

8. Discussion

Distributed energy systems offer better efficiency, flexibility, and economy as compared to centralized generation systems. Given its advantages, the decentralization of the energy sector through distributed energy systems is regarded as one of the key dimensions of the 21st-century energy transition [218]. Distributed generation is the energy generated near the point of use. The ongoing energy transition is manifested by decarbonization above all. Renewable energy is at the heart of global decarbonization efforts. Distributed energy systems are complimenting the renewable drive. Renewables like solar and wind power systems are leading the DES landscape. Distributed generation (DG) is also playing an important role in the global electrification efforts and is presenting viable solutions for meeting modern energy needs and enabling the livelihoods of hundreds of millions who still lack access to electricity or clean cooking solutions [219,220].

DES can be classified according to three categories: grid connectivity, application-level, and load type. In terms of grid connectivity, DES is primarily divided into grid-tied systems and off-grid systems. According to the level of application GES are classified into three types: small building scale, district scale, and urban scale. Residential houses, small public buildings, commercial buildings, and small industrial plants typically qualify for building-level DES. Applications of DES at a small residential house/building-level can employ various prime movers such as solar PV, wind turbines, fuel cells (usually SOFC and PEMFC), and biomass, employed either for electrification or for space heating/cooling. DES applications in small public/commercial buildings and industrial plants are generally a combination of waste heat recovery and renewable energy resources, to reduce not only fossil fuel consumption but also CO_2 emissions. District-level DES deals with neighborhoods and community-level applications. Urban-level DES covers town-level and city-level applications. There are not many studies dealing with the applications of DES at the urban level. District-level and urban-level applications have focused mainly on the pipeline network and the balance between supply and demand. Based on the load type, DES are categorized into firm load-based systems and intermittent load-based systems. Intermittent systems are generally based on renewables. Renewables-based DES employs technologies like solar energy, wind power, hydropower, biomass, and geothermal energy. Some of these technologies can be further classified into different types. Solar technologies, for example, can be categorized into solar PV, solar thermal power, and solar water heating. Similarly, biomass can be used to deliver solid fuels, liquid fuels such as biodiesel and bioethanol, and gaseous fuels. Renewables-based DES offer several benefits such as reduced greenhouse gas emissions, and lower operation and maintenance costs. These systems, however, are typically intermittent and need energy storage to offer reliable solutions. Non-renewable-based DES technologies are also available in a wide range and may include: internal combustion (IC) engine, combined heat & power (CHP), gas turbines, micro-turbines, Stirling engine, and fuel cells. These technologies can use different types of fossil fuels.

Solar PV is one of the most successful DES, especially at small-scale and off-grid levels. The building sector offers tremendous potential for DES PV systems [236–238], as rooftop application accounts for over 40% of the worldwide installed capacity of solar PV [239]. It is estimated that since 2010, over 180 million off-grid solar systems have been installed including 30 million solar-home systems. In 2019, the market for off-grid solar systems grew by 13%, with sales totaling 35 million units. Rooftop PV systems make up 40% of the total PV installations worldwide. Further to stand-alone solar systems, renewables-based mini-grids are playing an important role in improving energy access in developing countries. A recent study surveyed 5544 mini-grids operating in energy access settings, 87% of which were renewables-based DES. Solar PV is the fastest-growing mini-grid technology, being used in 55% of the total mini-grid installations in 2019 compared to only 10% in 2009. Renewable-based DES also supports around half of the 19,000 mini-grids installed worldwide. Efficient biomass systems such as improved cooking stoves and biogas systems are also helping the global efforts towards clean energy access. In 2020, the installed capacity of off-grid DG systems grew by 365 MW to reach 10.6 GW. Solar systems alone added 250 MW to have a total installed capacity of 4.3 GW [240]. Renewable DES comes under the intermittent load type. Recent advancements in battery technology are helping a long way in addressing the intermittency issues even at the urban level as is evident from Tesla's 100 MW battery project developed in Australia in 2017. A hybrid and diverse renewable resource can also help address the intermittency issues with renewables-based DES.

Support policies play a critical role in the promotion of distributed generation systems [241,242]. The impact of policies can be gauged from the fact that the introduction of feed-in-tariff boosted the PV capacity in the UK from less than 20 MW in 2010 to over 10,000 MW in 2016 [243]. In developing countries, numerous policies have been implemented to promote the utilization of renewable-based DES. Amongst the developed nations, Germany is a glaring example of successfully implementing DES. Germany pioneered DES policies with the introduction of "Stromeinspeisungsgesetz", also known as the Electricity Feed-in Law of 1991 [244]. Germany's success with DES is paving way for the country's sustainable energy transition [240]. The policies for DES in China are primarily focused on energy transmission and reduction in environmental pollution through the exploitation of DES. Meanwhile, the DES policies in developing countries such as Pakistan and Nigeria are mainly aimed at rural electrification with emission reduction. Overall, 165 countries have active renewable energy policies for power generation, transportation, heating, and cooling applications. Since 2010, the number of countries with distributed generation policies has increased by almost 100%. Similarly, the number of countries with transportation and space heating policies has increased by 57% and 50% respectively. Renewable energy systems, which are largely DES, are contributing to almost 26% of the global power supplies. At least 32 countries have more than 10 GW of renewable-based DES capacity in operation [8].

Despite thir success, DES still faces several challenges on technological and policy fronts. Especially, renewables-based DES experience a great deal of fluctuation in supplies due to resource intermittency and require robust control systems for smooth grid connectivity. Effective forecasting the production from renewables-based DES, such as solar and wind power systems is critical for ensuring grid stability and permanence, decreasing energy market risk, and lowering energy system costs. Some of the complexities associated with the DES, especially in terms of generation forecasting, grid integration and energy market stability can be significantly helped by Artificial intelligence. DES in off-grid applications require backup energy storage solutions. Distributed generation is regarded as disruptive technology as it entails a paradigm change in the traditional centralized business models in the energy sector and is competing with the established utilities and energy companies on multiple fronts. In many cases, distributed generation is hampered by state-controlled electricity markets. In terms of interconnection, distributed generation systems also face legal and administrative challenges. DG can potentially also face resistance at the policy and regulatory forums. Solutions to this challenge include reforming regulations to enable DES to access the grid and incentivizing utilities to incorporate renewable energy into their portfolio. Renewables based DES also face the challenge of high capital cost. However, the cost of renewable energy technologies has been decreasing, making DES increasingly competitive with traditional fossil fuel-based power systems. To overcome this challenge, governments and private sector organizations can provide financial incentives, such as tax credits and subsidies, to encourage investment in DES. A sustainable outlook for DES requires not only technological advancements especially on the fronts of grid-connectivity and energy storage but also favorable socio-political environment and policy support.

The present work has discussed them in terms of technologies, applications and policies. There are, however, several areas requiring attention for future research. DES, due to their relative complexity and variability, pose challenges in terms of grid integration. Researchers can look into developing advanced optimization algorithms that can accurately predict the energy demand and supply, and optimize the operation of DES. Since DES are regarded as disruptive technologies, there is need for robust policy and regulatory support for their effective development and implementation. Future research could also focus on identifying optimum policies and regulatory frameworks for promoting the deployment of DES. It is also worth investigating the impact of DES on energy markets, consumers, and the environment.

9. Conclusion

This study reviewed DES from the perspective of key technological, application, and policy perspectives. It particularly studied DES in terms of types, technological features, application domains, policy landscape, and the faced challenges and prospective solutions. Distributed energy systems are an integral part of the sustainable energy transition. DES avoid/minimize transmission and distribution setup, thus saving on cost and losses. DES can be typically classified into three categories: grid connectivity, application-level, and load type. In terms of grid connectivity, DES is primarily divided into grid-tied systems and off-grid systems. According to the level of application GES are classified into three types: small building scale, district scale, and urban scale. Based on the load type, DES are categorized into firm load-based systems and intermittent load-based systems. Small-scale applications of DES can employ different prime movers such as solar PV, wind turbines, fuel cells (usually SOFC and PEMFC), and biomass, employed either for electrification or for space heating/cooling. Solar PV is one of the most successful DES, especially at small-scale and off-grid levels. Rooftop application accounts for over 40% of the worldwide installed capacity of solar PV. Estimates indicate that since 2010, over 180 million off-grid solar systems have been installed including 30 million solar-home systems. In 2019, the market for off-grid solar systems grew by 13%, with sales totaling 35 million units. Rooftop PV systems make up 40% of the total PV installations worldwide. Further to stand-alone solar systems, renewables-based mini-grids are playing an important role in improving energy access in developing countries. A recent study surveyed 5544 mini-grids operating in energy access settings, 87% of which were renewables-based DES. Solar PV is the fastest-growing mini-grid technology, being used in 55% of the total mini-grid installations in 2019 compared to only 10% in 2009. Renewable-based DES also supports around half of the 19,000 mini-grids installed worldwide. Efficient biomass systems such as improved cooking stoves and biogas systems are also helping the global efforts towards clean energy access. In 2020, the installed capacity of off-grid DG systems grew by 365 MW to reach 10.6 GW. Effective implementation of DES depends on support policies. The impact of policies can be gauged from the fact that the introduction of feed-in-tariff boosted the PV capacity in the UK from less than 20 MW in 2010 to over 10,000 MW in 2016. Overall, 165 countries have active renewable energy policies for power generation, transportation, heating, and cooling applications. Since 2010, the number of countries with distributed generation policies has increased by almost 100%. Similarly, the number of countries with transportation and space heating policies has increased by 57% and 50% respectively. Renewable energy systems, which are largely DES, are contributing to almost 26% of the global power supplies. At least 32 countries have more than 10 GW of renewable-based DES capacity in operation.

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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