Conversion Technologies for Decentralized Generation and Their Payback Ratio

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Abstract

The integration of energy sources especially the decentralized and distributed energy resources (DERs) most of which are renewable and sustainable encounters various integration and utilization challenges. The DERs constitute technologies like diesel engines, micro turbines, fuel cells, photovoltaic, small wind turbines, among others using local energy resources, most of which are both sustainable and renewable. Investments in energy integration measures may be costly and hance the need for cost effective options. The payback ratios can be used to make investment decisions in terms of energy conversion technology and financing. Energy payback ratio is the ratio of energy produced during the power plants normal life span, divided by the energy required to pay for the construction, maintenance and fuel for the power generation facility A payback ratio is used to measure the time taken or the percentage of costs that are recouped to recover an initial cost of investment based on either simple payback period (time) and the payback ratio (percentage). The main challenge with variable renewable energy sources is that they are associated with intermittence and are stochastic in nature, which requires optimal energy management strategies to attain a high level of system reliability and operational efficiency. The grid integration is a significant challenge associated with the global expansion of distributed energy systems that should be addressed. This study examines and synthesizes the various energy resources, conversion technologies, integration techniques, and scalability factors associated DER integration in smart grid and microgrids as well as the traditional grid. The integration of distributed and decentralized energy resources (DERs) in the grids is very important for the energy transition because it reduces greenhouse gas emissions and helps in mitigating global climate change while at the same time it advances critical components and deliverables of the sustainable development goals with additional socio-economic benefits derived from the renewable energy systems. The growing global concerns about greenhouse gas emissions and climate change as well as the resource depletion have led to increased interest in renewable energy alternatives and decentralization of generation to exploit the massive renewable sources which are sustainable, and environmentally sound, and offering a cost-efficient solution for electricity access.

Key words:Decentralised generation; energy conversion; performance ration;

Highlights

1. Introduction

The integration of distributed energy resources (DERs) into micro grids presents immense opportunities and challenges for the improvement of power system efficiency, reliability, and sustainability. The intermittence and variability, of variable renewable sources, is the main challenge to grid stability, while enhancing grid resilience, increased uptake of renewables and reduction of transmission and distribution losses, as well as creation of new business models are the opportunities presented by decentralized generation. These innovations are key if the world has to achieve a sustainable, low-carbon energy through pathways and technologies like green hydrogen and Power-to-X technologies while global energy interconnections will enhance energy security and grid stability on a global scale.

1.1 Problem Definition

The DERs constitute technologies like diesel engines, micro turbines, fuel cells, photovoltaic, small wind turbines, among others using local energy resources, most of which are both sustainable and renewable[1, 2]. The main challenge with variable renewable energy sources is that they are associated with intermittence and are stochastic in nature, which requires optimal energy management strategies to attain a high level of system reliability and operational efficiency. The grid integration is a significant challenge associated with the global expansion

of distributed energy systems that should be addressed. The integration is associated with multiple technical challenges in terms of grid stability, quality of power, and the need for robust control and communication system[3-5].

Deployment of Decentralized Energy Systems (DES) signals a new frontier in power system design, and planning of local energy systems. As decentralization of power systems grows, cities and urban centers are transforming into venues, of both energy consumption and distribution, which calls for systemic and paradigmatic change in existing energy infrastructure[6]. For variable renewables, integration costs increase as the share increases in the mix. As an example, integration of large amounts of wind energy is technically and economically viable or feasible up to 30% of total generation, at integration costs generally being less than 10% of the cost per MWh of wind and often significantly less [7-9].As investments in electricity increase globally, there is need for grids to be robust and technologically sophisticated to cope with the growth. It is projected that Smart grids and digital infrastructure will get significant investment by 2030, based on the net-zero emissions by 2050 scenario. Growth of global electricity demand growth together with high need to identify sustainable energy sources, leading to a paradigm change in how power networks are planned and run. Decentralized and distributed energy resources (DERs) pose a significant threat to traditional centralized power generating and distribution models[10-12]. Global electricity demand increased by 3% year-on-year in 2025 after realizing 4.4% in 2024, on account of intense heat waves and strong industrial activity. The annual demand, annual demand growth over the next five years is projected to be 50% higher on average compared with the average across the previous decade[13, 14]. To meet this demand growth calls for strategies to exploits local energy resources most of which are renewable like wind, solar, and other environmental sources through energy harvesting technologies[15-17].

1.2. Rationale

The integration of distributed and decentralized energy resources (DERs) in the grids is very important for the energy transition because it reduces greenhouse gas emissions and helps in mitigating global climate change while at the same time it advances critical components and deliverables of the sustainable development goals with additional socio-economic benefits derived from the renewable energy systems. The integration of energy sources especially the decentralized and distributed energy resources (DERs) most of which are renewable and sustainable encounters various integration and utilization challenges. To overcome the technical challenges and realize the full potential of decentralized generation requires careful planning, advanced control strategies, and robust communication system.

2. Conversion Technologies for Decentralized Distribution

The share of decentralized intermittent renewable energy is growing which reinforces the need to balance local production and consumption. Decentralized energy systems, based on renewable energy technologies and incorporating storage and various conversion technologies, are promising options[15, 18]. The main reasons for increased deployment of renewable energy technologies and hence decentralized power systems climate change mitigation efforts, growing electricity demand, and phase-out of nuclear power in some countries. As a result, the global power-generation capacity by renewable energy technologies has almost doubled in a decade to reach 2,011 Gigawatt (GW) by the end of 2016, with solar photovoltaics (PV) and wind being the most popular renewable energy technologies predominantly employed in decentralized settings[3, 12].

The need to balance generation with load, has created need for other measures for flexibility and balance with improvements being provided by decentralized systems employing multiple energy carriers with conversion and storage technologies, in a combination that allows storage of surplus renewable energy and conversion between different carriers to balance load with demand and offer additional flexibility in energy management[19-21].

There are different technology options for distributed generation n which includes wind turbines, geothermal, solar systems, , combustion engines, and some smaller hydrothermal plants [22].There are many technology options for decentralized generation with the internal combustion engines more frequently used by end-point users. The grids can easily absorb with easy without structural changes the penetration of distributed generation of 10–15% of maximum load, although many networks have less than the practical limit expected. Decentralized technologies vary in terms of efficiency, fuel used, size of units applied, installation cost,

maintenance cost, operation and maintenance cost, reliability, peak shaving capability, power quality and green power [22, 23].

There are many energy technologies used in decentralized power systems with the choice depending on the requirements, based on the type of energy resource i.e., renewable like solar thermal, solar photovoltaic, wind turbines and non-renewable like gas turbines, energy systems. Commonly used renewable technologies in decentralized generation include solar energy, wind power, hydropower, bioenergy, geothermal energy, and wave and tidal power as well as conventional combustion technologies using renewable fuels like solid biomass, biofuel and green hydrogen . Some of these categories can further be classified into other subcategories e.g. Solar technologies, can be can be classified into solar PV, solar thermal power, solar water heating, solar distillation, solar crop drying, etc. Biomass can take the form of solid fuels, liquid fuels e.g. Biodiesel and bioethanol, and gaseous fuels. Wind sources can wind onshore, wind offshore, wind mechanical applications like water pumping ad milling among others. Hydro can be classified in sizes like micro, mini and small hydro for decentralized generation. The technologies can also be classified into variable sources which cannot be controlled or dispatchable sources which can be controlled directly in terms of operation output, sequence and demand [24, 25].

Electrochemical conversion technologies, including the fuel cells and electrolyzers are important elements in the decentralized conversion technologies. Fuel cells (FC) allow for co-generation of electricity and heat at high electrical efficiency regardless of the technology size[26]. Because of their modularity and ability to employ different types of electrolytes allowing them to be deployed both at micro and large-scale generation schemes. The electrolyzers, produce hydrogen and oxygen by absorbing electric power by splitting of deionized water making it an established technology for seasonal storage of energy with limited (virtually zero) losses of energy over time[27]. Fuel cells and electrolyzers are described with constant performance or as black box models depending on the manufacturer or literature data. Their performance is not clearly connected to first principle thermodynamic models which is an important consideration whenever an integrated system perspective is adopted in the development of new devices or to compare different fuel cells[26, 28, 29]

Non-renewable-based DES technologies include the internal combustion (IC) engine, combined heat and power (CHP), combined cooling, heating and power (CCHP),Stirling engines gas turbines, micro-turbines, and fuel cells. Some technologies like internal combustion engines can use either renewable or nonrenewable energy. Stirling engines can apply a fossil fuel and renewables like solar thermal energy. CHP and CCHP systems have the prime mover, heat recovery unit, and thermally operated unit like an absorption chiller. CHP/CCHP can also have a steam turbine (ST), heat exchangers, and energy storage systems and devices [15, 24, 30].

2.1. Size of Decentralized Systems

In terms of size, the Electric Power Research Institute defines distributed generation as one that ranges from ‘a few kilowatts up to 50 MW’, while the Gas Research Institute, defines distributed generation as ‘typically ranging between 25 and 25 MW while Preston and Rastler suggest size ‘ranging from a few kilowatts to over 100 MW’. On his part, Cardell defines distributed generation as generation ‘between 500 kW and 1 MW’. Since renewable energy is generally produced within decentralized networks, the progress and advances in distribution grid is strongly influenced by progress in smart grid technology [31] . Generally, decentralized generation systems apply small-scale power technologies generally between 3 kW– 10 MW installed close to consumers as either alternative or enhancement to centralized power systems [32]. The units are connected directly to consumers, to the distribution system, or to the consumer side of the meter, thereby reducing the transmission and distribution losses. The units can also be connected to the grid for peak shaving or for use in stand-alone mode powering specific load centers [33, 34].

Based on their size, or capacity, distributed generators can be classified as micro, small, medium, and large as summarized in table 4 below.

Table 4: categories of distributed systems based on capacity[31].

	Category	Capacity
1	Micro	1 watt - <5 kW
2	Small	5kW – <5 MW

3	Medium	5 MW -< 50 MW
4	Large	50 MW- <300 MW

From table 4 it is noted that distributed generators vary in size from as low as 1 watt to 300 MW. Microsystems vary between 1watt and 5 kW, small size generators between 5 kW and 5 MW, medium between 5 MW and 50 MW and large between 50 MW and 300 MW.

2.2. Size of decentralized Generators

A decentralized power system can be powered by a single generator technology or a combination. Different technologies are generally available in different sizes for optimum techno economic operation. Most decentralized conversion systems modular generators in construction designed to deliver alternative and conventional power and are summarized in table 5.

Table 5: Technologies and power plants for distributed generation

	Technology	Typical Capacity Per Module
1	Combined cycle gas turbines	35 MW - 400 MW
2	Internal combustion engines	5 kW -17 MW
3	Combustion turbine	1 MW -250 MW
4	Micro gas turbine	35 kW - 1 MW
5	Stirling engines	2 kW – 10 kW
6	Small hydro	1 MW -100 MW
7	Micro-hydro	25 kW- 1 MW
8	Wind turbines	200 watts -5 MW
9	Photovoltaics arrays	20 watts -100 kW
10	Solar thermal -Central receiver	1 MW -10 MW
11	Solar thermal -Lutz system	10 -80 MW
12	Biomass gasification	100 kW -20 MW
13	Fuel cells- phosacid	200 kW- 2 MW
14	Fuel cells- molten carbonate	250 kW- 2 MW
15	Fuel cells-Proton exchange	1 kW -250 kW
16	Fuel cells-Solid oxide	250 kW- 5 MW
17	Geothermal	3 MW -100 MW
18	Ocean thermal	100 kW- 1 MW
19	Battery storage	500 kW -5 MW
20	Small modular reactors (SMRs)	50 MW-300 MW

From table 5, it is noted that different technologies come in different sizes with geothermal, small modular rectors and combined cycle gas turbines being the largest in terms of unit sizes.

To meet the electricity needs of the 1.3 billion people lacking electricity requires innovative approaches while simultaneously transitioning to a decarbonized energy system. Focus in particular should be on the energy needs of the underserved. A historical analysis demonstrates that the present day is a unique moment in the history of electrification in which decentralized energy networks are growing and spreading rapidly on more efficient end-use appliances and low-cost photovoltaics. Disruptive technology systems can rapidly increase access to basic electricity services and directly influence the emerging Sustainable Development Goals for quality of life, while at the same time drive action towards low-carbon, Earth-sustaining, and all-inclusive energy systems[35].

9.1.1. Energy Payback Ratio

Energy payback ratio is the ratio of energy produced during the power plants normal life span, divided by the energy required to pay for the construction, maintenance and fuel for the power generation facility[36]. A high energy ratio is an indicator of a good environment and performance, while low payback ratio of 1 and 1.5, shows that the consumes nearly as much energy as it generates and should be avoided. A system with a low payback ratio, requires much more energy to maintain it and which generates more environmental impacts. The environmental impacts for fossil fuels are realized during extraction, transportation, and processing of fuels while for renewable sources, the main impact is from building or facility construction [36, 37]. The main benefit of using energy payback ratios as a metric is that is less affected by upstream choices of energy supply, which minimizes the fluctuation in evaluation of greenhouse gas emissions energy payback ratio one of the most reliable indicators of environmental performance. Energy payback ratio as an

indicator minimizes fluctuations in results of studies without eliminating them. Renewable energies can have very large variations in energy payback ratios. due to wide variation of site-specific conditions i.e. topography for the case hydro, quality of the wind for wind energy, and solar intensity of solar radiation for solar energy[36, 38]. Table Hata**! Belgede belirtilen stilde metne rastlanmadı.**-1 shows the payback ratios for different generation technologies.

Table **Hata! Belgede belirtilen stilde metne rastlanmadı.**-1: Energy payback ratio of different generation technologies. [39-44]

	Technology/power plant	**Range**	**Average**	**Rank**
1	Natural gas fired Gas turbines -Open	2-4	3	22
2	Gas turbine -Combines cycle (Gas fired)	4-6	5	14
3	Geothermal wellhead	20-35	27.5	8
4	Geothermal conventional	30-40	35	7
5	Hydro pumped storage	0.5-1	0.75	27
6	Hydro river run off	170-267	218	2
7	Hydro with storage/reservoir	205-270	238	1
8	Wind -offshore	60-80	70	3
9	Wind -onshore	60-80	70	3
10	Bagasse power Plants	6-12	9	12
11	Coal power plants	3-8	5.5	13
12	Nuclear – Conventional	14- 16	15	10
13	Nuclear – Small Modular Reactors	10-20	15	10
14	Wave power plants	50-70	60	5
15	Tidal power plants	50-70	60	5
16	Diesel power plants	3-7	5	14
17	Fuel cells	1.5-3	2.25	23
18	Grid Scale Battery Storage	0.5-3	1.75	24
19	V2G	0.5-2	1.25	26
20	Solar PV	3-6	4.5	16
21	Solar CSP	3-8	4	18
22	Biomass (Energy crops)	2-5	3.5	19
23	Forestry biomass	3-6	4.5	16
24	Wate biomass	-	27	9
25	Biogas	2-4.2	3.1	21
26	Biomethane	1.5-2	1.75	24

27	Biodiesel	1.8-4.6	3.7	20

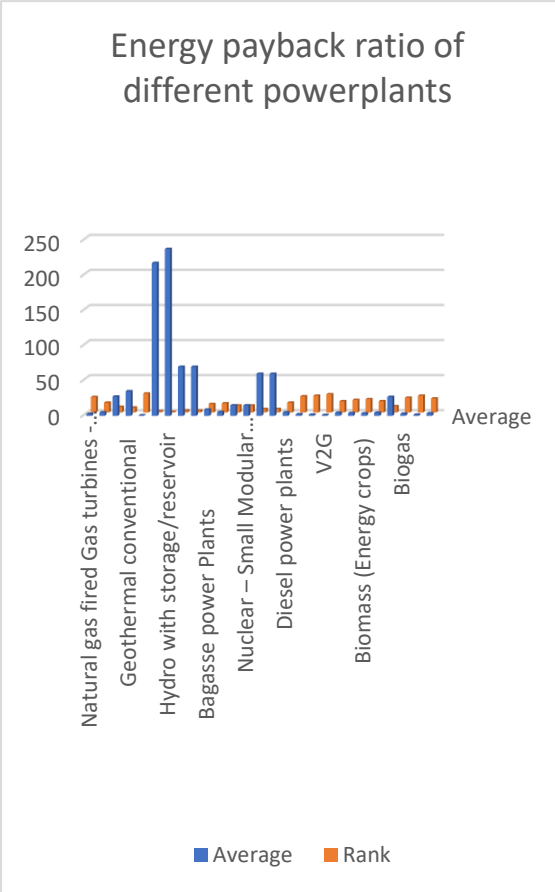

Figure1: Energy payback ratios of different powerplants

From Table Hata**! Belgede belirtilen stilde metne rastlanmadı.**-1 and Figure, it is observed that hydro with reservoir has the highest payback ration, followed by wind. Coal, natural gas and cultivated biomass have the lowest payback ratios. Among the emerging energy sources, hydrogen and biomethane have some of lowest payback ratios hence the need to invest in process efficiency improvements. Fossil fuels sources of energy have low energy payback ratios compared to noncombustible renewables. Their payback ratios continue to reduce over time due to reasons like depletion of reserves which tend to be replaced by wells that have higher energy requirement deep into the sea. Exploitation of fossil fuel resources like coal located far away from load centers and power stations increases transport costs by road and rail[45].

Various analyses show hydropower clearly has the highest performance, with energy payback ratios of 205 and 267 while fossil fuels have of 5 to 7. The value for hydro with reservoir 205 and 267 for run-of-river. Best wind sites have payback ration of about 80 without back up. Biomass has about 7 for power from forestry waste and 5 for. planted trees due to higher energy inputs. The higher the distance of the power plants from biomass sources, the lower the payback ratio. Natural gas has a payback ratio of about 5 with some energy being spent on transportation over long distances. The ratio for natural gas power plants located close to the source of natural gas is higher. With high investment on transportation, the payback ratio for coal is also low at about 5 as well as investment on scrubbing of SO_2, which requires lime and other resources that need transportation and other investment in production and delivery on site and disposal[36].

Further investment in emission reduction technology like scrubbing of SO_2 can reduce the overall efficiency of coal generation and hence reduce payback ration while capture and sequestration of CO_2 will require huge investment in capital and energy for operation of scrubbing and disposal equipment while noting that sulfur is about 1% of coal and carbon is more than 50% of the coal. Therefore, mandatory investment in emission reduction technologies will reduce the overall efficiency and feasibility of coal and other fossil fuel power plants[36, 46].

3. Summary, Results and Discussion

Grid integration of DERs requires a coordinated operation and control and use of controllable loads and storage devices, like batteries, flywheels, and capacitors being central to the concept of micro grid among other strategic, design and operational measures. The flexibility of local energy generation and energy use has increasingly become relevant for planning energy systems having high share of renewables, vehicle electrification, and decentralization.

4. Conclusions

Grid integration of DERs requires a coordinated operation and control and use of controllable loads and storage devices, like batteries, flywheels, and capacitors being central to the concept of micro grid among other strategic, design and operational measures. The flexibility of local energy generation and energy use has increasingly become relevant for planning energy systems having high share of renewables, vehicle electrification, and decentralization. Investments in energy integration measures

may be costly and hance the need for cost effective options. The payback ratios can be used to make investment decisions in terms of energy conversion technology and financing. Energy payback ratio is the ratio of energy produced during the power plants normal life span, divided by the energy required to pay for the construction, maintenance and fuel for the power generation facility A payback ratio is used to measure the time taken or the percentage of costs that are recouped to recover an initial cost of investment based on either simple payback period (time) and the payback ratio (percentage). This study showed that hydro with storage and river runoff, wind offshore and onshore, wave and tidal power plants have the highest payback ratios. A high energy ratio is an indicator of a good environment and performance, while low payback ratio of 1 and 1.5, shows that the plant consumes nearly as much energy as it generates and should be avoided. A system with a low payback ratio, requires much more energy to maintain it and which generates more environmental impacts

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The first author (MJBK) developed the manuscript draft under with the e second author (OAO) providing administrative and technical support and guidance and review. The authors jointly agreed on content and submission of manuscript for peer review and publication.

5.4. Declaration of competing interest

The authors declare that there are no known competing interests or personal relationships that could have appeared to influence the contents of this manuscript.

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