Integration of Renewable Distributed Generators into the Distribution System: A Review

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Abstract: Recent advances in renewable energy technologies and changes in the electric utility infrastructures have increased the interest of the power utilities in utilization of distributed generation (DG) resources to generate electricity. The recent trends in the development and utilization of DG resources for power generation application are subject to the deregulation of the electric power sector and technical constraints to extend distribution and transmission networks to some areas. The electric power system planners, regulators and the policy makers have derived many benefits from integration of DG units into the distribution networks. These benefits depend on the characteristics of DG units such as photovoltaic (PV), wind system and reciprocating engines, characteristics of the loads, local renewable resources and network configuration. This article comprehensively reviews various research works on the technical, environmental and economic benefits of renewable DG integration such as line loss reduction, reliability improvement, economic benefits and environmental pollution optimization. These benefits can be optimized if all the renewable DG units such as photovoltaic (PV) and wind system and local renewable resources are optimally sized, located and configured. This paper also reviews the current status of renewable DG technologies based on different characteristics and the operational issues of integration of renewable DG into the electric power systems.

Keywords: Distributed generation, distributed system, PV system, renewable energy, wind power.

1. Introduction

With recent initiatives on renewable energy coupled with the profound public assessment of the environmental impacts of using fossil fuels to generate electricity, penetration of renewable DG into a power system plays a vital role in the emerging electric power systems. Abrupt changes in power demand and the inadequacy of distribution facilities due to technical and financial constraints have set the trends towards the utilization of renewable energy resources to generate electricity. These trends have made power utilities to decentralize their power systems so that smaller units of renewable DG are directly tied to the distribution network at or near the load points. The integration of renewable DG into a power system has technical, environmental and economic benefits on the distribution system as well as to the consumers. The significant impacts of renewable DG units' integration into the distribution system have been reported to be increasing in different parts of the World due to the deregulation of the electricity market, environmental impacts of conventional methods of power generation, reliable power demand by the consumers and the development of modern renewable DG technologies [1]. These benefits depend on the optimal sizing and location of renewable DG units, distribution system configuration, type of renewable DG units and the technology used to convert the energy [2-3]. To achieve the maximum benefits of renewable DG's penetration into a power system, strategic studies must be carried out for the optimal location and sizing of renewable DG units. If renewable DG units are not optimally located, this could result in an increase in power system losses, voltage drop, harmonics and low voltage stability [4]. This implies an extra cost of installing additional auxiliaries that will take care of the abnormalities that might have caused contradictory effects on the purpose of using renewable DG units. For these reasons, the power system planners and engineers must apply several optimization techniques for optimal location and sizing of renewable DG units.

DGs are small scale power technologies within the range of 3 kW to 10 MW that are located very close to where electricity is being used to provide an alternative or enhancement to the conventional electric power system [5]. DG units can be tied directly to the distribution system or on the customer side of the meter as a way of reducing transmission and distribution losses [6]. The high rate at which fossil fuel is depleting has compelled exploitation of renewable energy resources for generation of electricity [7]. Furthermore, the environmental impacts of using fossil fuels in the conventional power plants have increased the opportunities of utilizing renewable DG resources for power generation. Renewable DG systems can be connected to the grid to serve as a peak shaving during the peak load period or as a stand-alone system to serve a particular load or an area. The integration of renewable DGs into the power system has many benefits, but it has to be properly coordinated and integrated into the power system otherwise the penetration will cause many adverse effects on the existing distribution systems. The improper sizing and location of renewable DG units can cause the following negative effects in the distribution system: voltage rise, reverse power flow, increments in power system line losses, creation of harmonics and degradation of voltage quality [8]. To maintain the optimal quality of the power supply by the renewable DG units and to avoid power interruption, the power system components must operate within the designed and operational limits. Optimal sizing and location of renewable DG units in the distribution power system have many technical and economic benefits; these benefits can further be enhanced with proper sizing of the distribution system and the load [9-10]. As a result of the current status and future perspectives of the global application of renewable DGs, their penetration can be considered as one of the significant contributions to the world energy and environmental crisis. This paper presents a review of the technical, economic and environmental benefits of integrating renewable DGs into the distribution networks.

2. Definition of DG

DG is a small scale power generation technology that is tied to the consumers' loads through a power utility's distribution system to provide electric power at a site that is closer to the customers than a central station generation [11]. However, there is not yet an accepted standard definition of DG but a number of international organizations have offered several definitions on the basis of DG' location, ratings, purpose, technology, mode of operation and power deliverable area. Among which some selected definitions are presented in Table 1 [12-15]:

Table 1: Definitions of DG [12-15]

Definition of DG	Organization/Ref.
"DG is defined as small generation units from a few kW up to 50 MW and/or energy storage devices typically sited near customer loads or distribution and sub-transmission substations as distributed energy resources''.	Electric Power Research Institute (EPRI) [12]
"DG is defined as all generating units with a maximum capacity of 50 MW to 100 MW, that are usually connected to the distribution network and that are neither centrally planned nor dispatched''.	International Council on Large Electric Systems (CIGRE) [13]
"DG is defined as the generation of electricity from facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system''.	Institute of Electrical and Electronics Engineers (IEEE) [14]
"DG is a type of generating plant that is tied to the grid at the distribution level voltages to serve a customer on site and at the same time to provide support to a distributed network. The technologies include reciprocating engines, turbines, fuel cells, and PV systems''.	International Energy Agency (IEA) [15]

2.2. Benefits of DG

The penetration level of DG units in the distribution system is increasing rapidly due to high rate of global electricity consumption. With the recent trend of technological advancement, DG has contributed with a substantial part of global electricity generation at reduced cost and high efficiency. The application of DG in a modern power system helps consumers to meet their load requirements at a reasonable quality and continuity since DG technologies are more efficient and reliable [16-17]. The technical advancement in the design and manufacturing of DG's components, coupled with changes in the consumers' power consumption pattern and uncertainty of the global petroleum market has opened more opportunities for the power utilities to utilize all the available renewable energy resources to generate enough electricity that will meet consumers' load demand. With the latest power deregulation, it is universally accepted that in the meantime, centralized power systems will be replaced by decentralized power systems. This will seriously shift the attention of the utilities to the usage of DG units to meet their customers load demand [18-19]. To achieve these objectives, more entities must be involved in planning, coordination and the penetration of DG units in the power systems. The technical, economic and environmental benefits of DG penetration are presented in Table 2.

Table 2: Benefits of Distributed Generation [20-27]

Technical Benefits					Economic benefits	Environmental benefits
Reliability improvement	Voltage profile/quality improvement	Line loss/energy reduction	Security enhancement	Operational advantages		
1. Improved power system reliability 2. Reduced capacity release 3. Improved generation diversity 4. Peak power reduction	1. Voltage quality improvement 2. Voltage profile improvement 3. Reduced voltage flicker 4. Voltage support and better regulation	1. Reduced line losses 2. Better control of reactive power	1. Enhanced security of the critical loads 2. Reduced security risks to the grid 3. Improved power utilities security 4. Reduced impacts of cyber-attacks 5. Reduced vulnerability of terrorist attacks	1. Provision of ancillary services 2. Increased productivity 3. Easy and quick to install 4. Easy operation and maintenance (O & M) 5. Reduced reserved requirements 6. Infrastructure resilience improvement 7. Enhanced total efficiency	1. Reduced O&M costs 2. Deferments of investment in infrastructures 3. Reduction in losses associated costs 4. No fuel cost with renewable DG 5. Reduction in the right of way acquisition costs 6. Reduction in the cost of installation 7. Maintaining of constant running cost for longer time period 8. Reduction in auxiliaries' costs	1. Reduction in land use effects 2. Reduction in health costs with renewable DG 3. Environment friendly with renewable DG 4. Reduction in greenhouse gas (GHG) emission pollutants with renewable DG

2.3. Technologies of distributed generation

DG technologies are modular generating units that are used to provide an alternative to conventional power system as a measure to reduce power interruption. They have different limitations, characteristics and benefits. DG technologies are classified into renewable and non-renewable classes based on the type of fuels they use for their operations. Fig. 1 shows the classes of DG technologies and Table 3 shows the general description of renewable and non-renewable DG technologies with their characteristics.

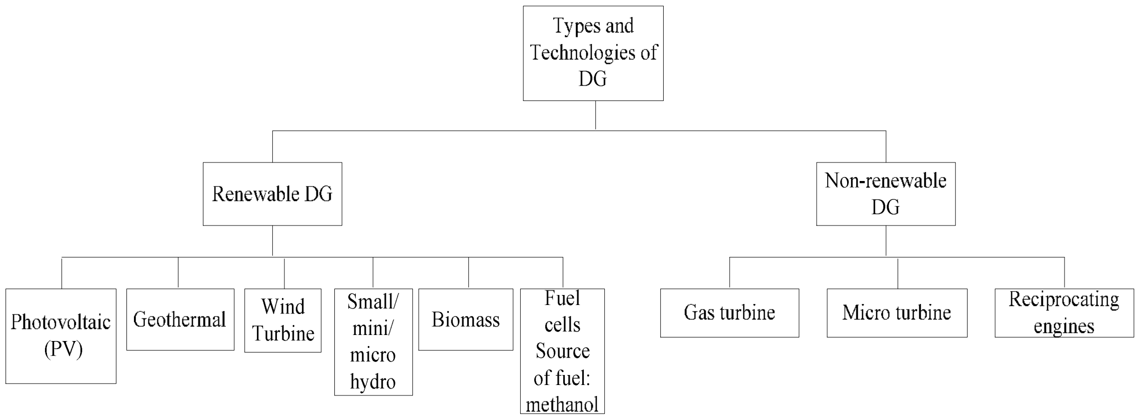

Fig. 1: Types and technologies of DG.

Table 3: A comparison among different DG technologies [3, 28-31]

	Non – renewable DG technologies			Renewable DG technologies			
DG technologies	Reciprocating engines	Gas turbines	Micro turbines	Fuel cells	PV	Wind	Small/mini/ micro hydro
Capacity range	Diesel: 20 kW - 10MW Gas: 50 kW-5 MW	1 MW-20MW	30 kW-250 kW	50 kW-1 MW	1 kW-20 kW	0.2 MW-3 MW	Small:100 kW-100MW Micro:25 kW-1 MW
Efficiency, %	Diesel: 36-43 Gas: 28-42	21-40	25-30	35-60	8-35	35-45	60-90
Fuel	Diesel, heavy oil, natural gas, bio-diesel, biogas and landfill gas	Kerosene and natural gas	Natural gas, landfill and biogas	Hydrogen and Methanol	Sun	Wind	Water
CO_2 emission, (g/kWh)	Diesel: 650 Gas: 500-620	580-680	720	430-490	No direct emission	No direct emission	Small:10-12 Micro:16-20
CO emission, (g/kWh)	Diesel: 2.8 Gas: 1.8	0.42	0.47	0	No direct emission	No direct emission	Negligible
SO_2 emission, (g/kWh)	Diesel: 0.032 Gas: 1.25	0.032	0.037	0.024	No direct emission	No direct emission	Small:0.024-0.029 Micro:0.038-0.046
NO_x emission, (g/kWh)	Diesel:10 Gas: 0.2-1	0.3-0.5	0.1	0.005-0.001	No direct emission	No direct emission	Small:0.046-0.056 Micro:0.071-0.086
Installation cost/kW, (US$/kW)	Diesel:125-300 Gas:250-600	300-600	500-750	1500-3000	1550-3830	900-1400	30-250
O&M cost (US$/MWh)	Diesel: 5-10 Gas: 7-15	3-8	5-10	5-10	1-4	10	0.045-0.09
Applications	Standby and combined heat power (CHP) services	Peak load, base load, standby units and CHP	Transportation sector, domestic and industrial applications, backup power generation and CHP	Transportation sector, domestic and army applications, power generation, recreational vehicles and CHP	Household, industrial and commercial applications, communications, navigation and transportation systems and off grid applications	Industrial, domestic and commercial applications	Productive application and power generation
Advantages	Low capital cost, high efficiency, high reliability, fast start up and modular sizes	Low O&M costs, low emissions and high operating speed	High speed, less noise and lower emissions	Compact, low O&M cost, co-generation capability, high efficiency, reliability and low emissions	Low O&M cost, sustainable, modular and no emission.	No emission, modular, sustainable and low O&M cost	Low O&M cost, no environmental impact, reliable and flexible operation
Drawbacks	Noise, high cost of maintenance and high NO_x emissions	Lower efficiency and high capital cost	High cost and recently commercialized	High cost, not environmentally friendly and recently commercialized	Electro-magnetic field effects, fragmentation of landscape, loss of habitat, impacts on vegetation and biodiversity loss.	Wildlife habitat loss, noise and aesthetic pollution and interference with the television reception	Variation of water level reduces the average power output and difficulty of energy expansion
Technology Status	Commercial	Commercial	Commercially available in modular sizes	Commercial scale demos	Commercial	Commercial	Commercial
Co-generation	Yes	Yes	Yes	Yes	No	No	No

2.4. Non-renewable DG technologies

Non-renewable technologies use fossil based fuels like natural gas, coal and petroleum to produce energy for different operations. However, the burning of fossil fuels has contributed the largest percentage to global warming, greenhouse gases, acid rain and petrochemical pollution that are experienced currently on a global note. Non-renewable resources are not sustainable and cannot be replaced by a natural means. Due to these reasons, they will eventually run out of use because of high rate of energy demand from the non-renewable energy resources is much faster than the rate of restoring them within the earth. Non-renewable DG technologies can be used for power generation as well as for production of thermal energy for domestic and industrial applications through a co-generation arrangement. Examples of non-renewable technologies are: reciprocating engines, gas turbines, micro turbines and steam turbines.

2.5. Renewable DG technologies

Renewable DG technologies are the electric power generation resources that are directly connected to the consumers' load on the distribution systems at the medium voltage (MV) or low voltage (LV). The DG technologies that fall under this category include geothermal power, biomass, solar power, PV, small/mini/micro hydro power and wind turbines. The output power of the renewable DG technologies can be dispatched to the grid based on the request of the utility grid operators or to operate as a stand-alone system to serve a particular load or an area. Recent studies by the World Energy Council have predicted that the global power output from renewable energy resources will increase from 23% as it was in 2010 to about 34% in 2030 [32]. In this paper, renewable DG technologies such as wind, PV and hybrid systems are captured.

2.5.1. Wind System

The wind system converts the available power in the wind to the electrical power with the following main parts: electric generator, mechanical shaft, blades, rotor, gearbox, and an electronic circuit interface [33-34]. The output power of the wind system depends on the capacity of the wind speed and the height of the wind system above the ground [35-38]. The wind speed is proportional to the amount of kinetic energy that is available for the wind system to operate [39-40]. A wind system could produce electricity at the optimal cost if it is installed on a site that has good wind resources. This means the power system planners must carry out feasibility studies and environmental impact assessment to better locate the wind system. This can be achieved with a proper wind resource assessment [41]. The wind systems have the following advantages over conventional power plants: no greenhouse gas emission, low effective cost, low cost of installation, long life span of the system's components, no fuel cost, low O&M costs and possible export of reactive power to the grid. These benefits have prompted the integration of wind power into the grid [42].

The following factors should be considered before installing a wind system for generation of electricity: availability of land, understanding of the wind resource, availability of transmission or distribution lines for a grid connected system, access to capital, identifying a reliable power customer and understanding of wind energy's economics [43]. The rapid acceptance of a wind system as a way to mitigate the problem of power outage and the greenhouse gas effect is a demonstration of the best characteristic of the wind system. This attribute has doubled the world wind energy capacity for the past five years. The installed capacity of wind system at the end of 2014 was about 370 GW [44]. While the global installed capacity of wind power capacity is projected to reach around 2000 GW by 2030 [44], which means the wind system is expected to supply between 16.7% - 18.8% of global electric power. Also, the carbon emissions per year are projected to be reduced by over 3 billion tons by 2030 [44].

2.5.2. Photovoltaic systems

The PV system is an array of PV cells coupled with the controller, electronics interface and other associated auxiliaries that convert solar energy directly into electrical energy [45-47]. The output power of PV cell depends on the solar insolation, PV modules position and cell temperature. Solar energy is a potential alternative to the conventional power system because of the environmentally friendly nature of solar resources. With appropriate configuration and conversion devices, PV systems can be designed to produce alternating current (AC) or direct current (DC) based on the load requirements. PV systems can operate in parallel with the utility grid to act as a peak shaving unit or operate as an independent unit to serve a specific load. PV systems can be configured and connected to the grid system either through feed-in and net-metering [48]. PV systems are classified into different classes based on the following prerequisites: functional and operational requirements, configurations of PV system with other power sources and electrical loads [49].

The merits of incorporating PV systems into a power system are stated as follows: PV systems are modular, easy to install, energy independence and environmental compatibility, no fuel cost, pollution free, long service lifetimes and minimum O&M costs [50]. Solar energy is widely accepted as one of the sources of renewable energy that can reduce over dependence on the fossil fuel based conventional power generation. The PV system improves security of power supply since it is not momentously affected by the variation in fuel price or deregulation of the oil and gas sector. With all these characteristics, the PV system will stabilize the costs of power generation in the long run. Based on the International Energy Agency (IEA) report of Global PV installations, the installed capacity of PV system at the end of 2014 was about 140 GW [51] and it is expected to reach 872 GW by 2030 [52].

2.6. Electric storage system

Electrical storage system (ESS) is a process by which electricity imports from a power grid or renewable energy resources is converted into a form that could be stored at an off-peak demand when energy cost and consumption are usually low [53]. The stored energy is converted back to electricity at the peak period when electricity is needed even at high energy cost [54]. EES technologies can be categorized into various classes based on the functions, response times, form of energy stored in the system and suitable storage durations [55-58]. The benefits of ESS are summarized as follows [59-63]: improved power system reliability, deferred investment in transmission and distribution facilities, improved power system quality, supplied ancillary services, reduced generation capacity, reduced congestion on the power system and line loss, reduced electricity cost at the peak period and low O& M costs. The form of energy stored in the system is one of the methods that is universally used to categorize ESS into different classes [59]. Table 4 shows different classes of ESS.

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Table 4: Classification of electric storage system [55, 59, 64-67]

Classes	Technology	Available power rating	Power capital cost ($/kW)	Energy capital cost ($/kWh)	Lifetime (years)	Overall Efficiency %	Applications
Mechanical	Pumped hydroelectric storage (PHS)	10-5000 MW	600-2000	5-100	40-60	70-82	Energy management, black start, standing reserve, frequency regulation, voltage regulation, peak shaving, load levelling and uninterrupted power supply (UPS)
	Compressed air energy storage (CAES) underground	Up to 400 MW	400-800	2-50	20-40	70-89	
	Flywheel energy storage (FES)	Up to 250 kW	250-350	350	15	93-95	
Electrical	Capacitors	Up to 50 kW	200-400	500-1000	5	60-65	Frequency and voltage regulation, power quality, UPS and peak shaving
	Super capacitors	Up to 300 kW	100-300	300-2000	10-30	90-97	
	Superconducting magnetic energy storage (SMES)	100-10 MW	200-300	1000-10,000	20+	95-98	
Thermochemical	Solar fuels	Up to 10 MW	3-24	-	20-25	20-30	Grid stabilization, frequency regulation, voltage regulation and load levelling
Chemical	Hydrogen storage with fuel cells	0.3-50 MW	1500-3000	3-23	5-15	33-42	Backup power, co-generation and electric vehicles
Thermal energy storage (TES)	Aquiferous low temperature TES (AL-TES)	Up to 5 MW	100-400	20-50	10-20	30-62	Frequency regulation, standing reserve, voltage regulation, load levelling and standing reserve
	Cryogenic energy storage (CES)	100-300 kW	200-300	3-30	25+	85-95	
Electrochemical: Conventional rechargeable Batteries	Lead-acid	Up to 20 MW	300-600	200-302	5-15	70-90	Load levelling, island grids, UPS, frequency and voltage regulation, power quality, spinning reserve, peak shaving, residential storage system and hybrid electric vehicles
	NiCd	Up to 40 MW	500-1500	800-1500	10-20	60-73	
	NaS	5 kW-8 MW	1000-3000	300-500	10-15	75-90	
	ZEBRA	Up to 300 kW	150-300	100-200	10-20	86-88	
	Li-ion	1-100 kW	1200-4000	600-2500	5-15	85-95	
Electrochemical: Flow batteries, energy storage (FBES)	VRB	30 kW-3 MW	600-1500	150-1000	5-10	65-85	Frequency and voltage regulation, island grid, power quality, peak shaving and time shifting.
	ZnBr	50 kW-2 MW	700-2500	150-1000	5-10	60-70	
	PSB	1-15 MW	700-2500	150-1000	10-15	65-85	

2.7 Diesel generator /PV/wind hybrid system

A hybrid system allows integration of multiple power sources as a way of improving reliability of the distribution power system [68-69]. It may consist of PV, wind and diesel generator systems [70]. Hybrid power system can be used as off grid or grid connected system. In off grid system, a diesel generator is connected in parallel with PV/wind systems to act as a backup due to the stochastic characteristic of wind and PV resources and to meet the load requirements whenever the PV and wind systems are not sufficient enough to meet the consumer load demand. The integration of diesel generator into the PV and wind hybrid systems will enhance the performance of a power system [71]. Hybrid technologies have received the attention of the power system planners as an alternative to conventional system due to the rapid development of hybrid components, the depleting of fossil based energy resources and environmental impacts of using fossil fuel to generate electricity [72-73]. One of the key drawbacks of the hybrid system is the stochastic characteristic of the renewable resources. The risks that are associated with uncertainty of the renewable output can be minimized with the incorporation of the ESS and diesel generator into the system as shown in Fig. 2 [74]. The hybrid system may supply electrical power to the rural communities that are not connected to the grid due to some technical and financial constraints [75]. Hence, to achieve a continuous and reliable power supply at minimum cost, all the available renewable energy resources must be utilized at optimal sizes and locations. The merits of PV-wind /storage battery and diesel generator hybrid system are as follows [68-70]: minimized operational costs, low maintenance costs, improved system reliability, increased operational life of the power system components, improved energy services, no greenhouse gas emission and low noise pollution.

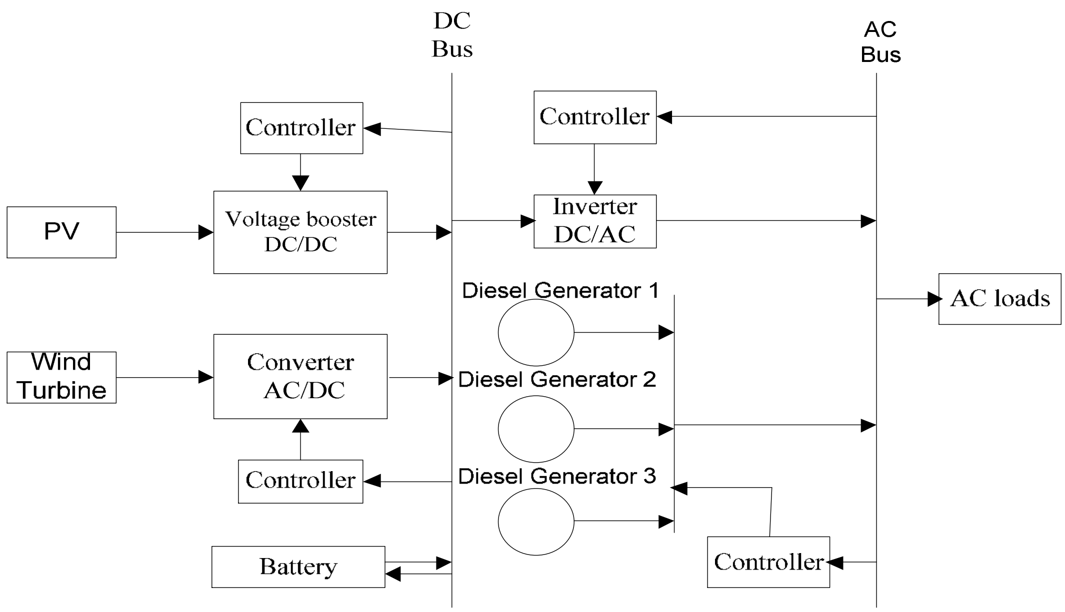

Fig. 2: PV/wind /diesel hybrid system.

3. Technical, environmental and economic benefits of renewable DG units in the distribution system

This section reviews the technical, environmental and economic benefits of integrating renewable DG units into the distribution side of the power network because of their modular sizes and rating. The integration of renewable DG could influence the reliability, power quality, stability and line loss of the power system.

3.1. Benefits of integrating renewable DG units on the reliability of the distribution system.

The evaluation of the renewable DG units' effects on the reliability of the distribution system is analysed based on failure and repair rates of the load and feeder components. This objective is achieved if all the technical problems that are associated with integration of renewable DG in a power system are overcome [76]. Reliability is one of the key performance indicators that power utilities use to analyse the power system adequacy and security. Incorporation of renewable DG units into the electrical distribution system has many positive impacts on the power system adequacy and security [77-78]. These impacts depend on the capability of the renewable DG units to maintain a continuous power supply at the load points in the event of a power outage from the utility. This requires the renewable DG units to serve the loads and all the necessary distributed system control capabilities [79].

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3.1.1. Key Reliability Indices

The reliability indices of the distribution system depend on the restoration times; component failures and repair times. The basic reliability indices of distribution system at a load point i are the annual outage duration (*U);* average failure rate (λ) and average outage duration (*r*). The three basic reliability indices in conjunction with some parameters can be used to estimate the customer oriented indices and energy reliability indices as presented in Table 5. There should be a substantial improvement in the reliability of the distribution system with penetration of renewable DG units [80]. The benefits of renewable DG penetration in the distribution system can be estimated with the reliability indices presented in Table 5 and Fig. 3.

Table 5: Reliability indices of the distribution system [81-85]

Reliability indices	Formula	Description
1. Average failure Rate (λ_s) (failure/year)	$\lambda_s = \sum_{i=0}^{n} \lambda_1 N_e$	λ_i = Average failure rate at load point i N_e = The number of component whose fault will interrupt the load point i n = Number of outage at load point i
2. Average outage time (U_s) (hour /year)	$U_s = \sum_{i=0}^{n} \lambda_i r_i$	r_i = Failure duration at load point i
3. Average outage duration (r_s) (hour)	$r_s = \frac{U_s}{\lambda_s}$	
4. System average interruption frequency index (SAIFI) (failure /customer/year)	SAIFI = $\frac{\sum \lambda_i N_i}{\sum N_i}$	N_i = Number of customers at load point I
5.System average interruption duration index (SAIDI) (hour/customer/year)	SAIDI = $\frac{\sum U_i N_i}{\sum N_i}$	U_i = Annual outage duration at load point i
6. Customer average interruption duration index (CAIDI) (hour/customer interruption)	CAIDI = $\frac{\sum U_i N_i}{\sum \lambda_i N_i}$	
7. Customers average interruption frequency index (CAIFI)	CAIFI = $\frac{\sum N_{ci}}{\sum N_{ca}}$	N_{ci} = Total number of customer interruption N_{ca} = Total number of customers affected by power interruption
8. Average service available index (ASAI)	ASAI = $\frac{\sum N_i * 8760 - \sum U_i N_i}{\sum N_i * 8760}$	
9. Average service unavailable index (ASUI)	$ASUI = 1 - ASAI$	
10. Expected energy not supplied index $(EENS_i)$ at load point i (MWhr/yr)	$EENS_i = P_i U_i$	P_i = the average load at load point i
11. Average energy not supplied index $(AENS_i)$ at load point i (MWhr/Customer/yr)	$AENS_i = \frac{\sum EENS_i}{\sum N_i}$	
12. Expected interruption cost index ($ECOST_i$) at load point i (k$/yr)	$ECOST_i = P_i \sum N_e f_{r,j} \lambda_i$	$f_{r,j}$ = Cost of interruption /composite customer damaged function (CCDF)
13. Interruption assessment rate index ($IEAR_i$) at load point i ($/kWhr)	$IEAR_i = \frac{ECOST_i}{EENS_i}$	

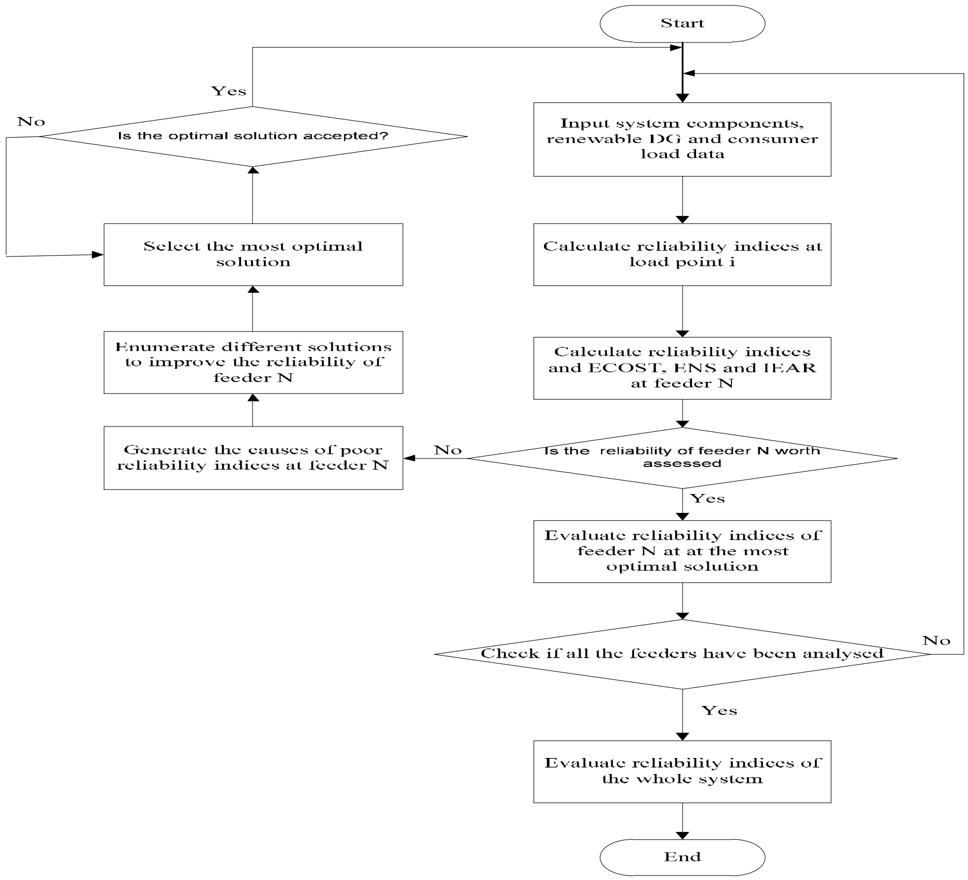

Fig. 3: Estimation and improvement of reliability indices of the distribution system.

3.1.2. Methods of improving reliability of the distribution system

Power interruption is caused by the state of electrical components when it is not available to perform its intended function due to the events that are directly associated with that component such as lightning strikes, component malfunction and maintenance [86]. Power interruption is a consequence of a physical disconnection of the customers from the power supply system due to scheduled and unscheduled events [87]. The power system operator and maintenance team must strategize different mitigation techniques to improve the system reliability, among which are system configuration, integration of DG units, installation of protection and switching devices, installation of lightning arresters, animal protection guards, tree trimming and preventive maintenance practices [88-92].

3.2. Power loss reduction benefits with integration of renewable DG

One of the major reasons of integrating renewable DG units in a power system is to reduce the amount of electrical power losses in the system. In some cases the cost of electrical losses is charged to the consumers in terms of very high electric energy costs [93]. The electrical power loss occurs in the distribution system when current flows through it. This line loss depends on the distance of the distribution network and the amount of current that flows in the network. The line loss can cause a significant impact on the optimal economic dispatch based on the network configuration [94-95]. The distribution line loss can be reduced by decreasing the line in the current distribution system. If renewable DG units are strategically integrated into the distribution system, the amount of current that will be flowing in the feeders or parts of the network will be reduced to a certain percentage. This will contribute to a power loss reduction and contribute to deferment of network upgrading [96-97]. The impact of renewable DG on power losses depends on the size of the DG, location, size of the load and network configuration [2, 98-100]. However, improper sizing, location and poor planning of renewable DG units can cause excessive power losses and feeders overload [101-102]. Integration of renewable DG units into the distribution network has triggered many technical challenges that have not yet been fully solved. These challenges have attracted the attention of many researchers to minimize distribution system power losses with the application of renewable DG units [101]. Many researchers have developed different approaches to determine the optimal size and position of each renewable DG unit in the distribution network at the minimum power losses, among which are Elgerd's loss formula or exact loss formula, branch current loss formula and branch power loss formulae as given in Table 6.

Table 6: Approaches to determine the optimal size and position of DG units in the distribution network at minimum power losses [103-106]

Approach	Formula	Description
Elgerd's loss or exact loss	$P_{Loss} = \sum_{i=1}^{n} \sum_{j=1}^{n} \left[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j + P_iQ_j) \right]$	$\alpha_{ij} = \frac{\gamma_{ij}}{V_iV_j}\cos(\delta_i - \delta_j)$ $\beta_{ij} = \frac{\gamma_{ij}}{V_iV_j}\sin(\delta_i - \delta_j)$ $z_{ij} = \gamma_{ij} + jx_{ij}$ z_{ij} = The ijth $ijth$ element of impedance matrix γ_{ij} and x_{ij} = The ijth element of resistance and reactance matrix P_{Loss} = Power losses P_i and P_j = Active power injected at ith and jth buses Q_i and Q_j = Reactive power injected at ith and jth buses n = Number of buses V_i and V_j = Magnitude of voltage at ith and jth buses δ_i and δ_j = Phase angle of voltage at ith and jth buses $\delta_i - \delta_j$ = Voltage phase angle difference between ith and jth buses
Branch power loss	$P_{Loss} = \sum_{i=1}^{n} \frac{P_{bi}^2 + Q_{bi}^2}{\lvert V_i \rvert^2} R_i$	P_{bi} = Active power at branch i Q_{bi} =Reactive power at branch i V_i = Magnitude of voltage at bus i
Branch current loss	$P_{Loss} = \sum_{i=1}^{n} I_{aci}^2 R_i + \sum_{i=1}^{n} I_{reci}^2 R_i$	I_{aci} = Active current at branch i I_{reci} = Reactive current at branch i R_i = Resistance at branch i

3.2.1. Optimal sizing of renewable DG

In the past, different approaches such as analytical approach, loss sensitivity technique, ant colony search (ACS) algorithm, particle swarm optimization (PSO) algorithm, dynamic based programming approach, genetic algorithm (GA), GA and Fuzzy method, GA and PSO technique and the dynamic based programming approaches have been proposed to establish the optimal location and the size of renewable DG units in a power system [107-117]. The main objective of these approaches is to reduce line losses to an accepted level. Elgerd's loss technique, branch power loss technique and branch current loss technique are the notable approaches to establish the optimal size of renewable DG units at bus i with minimum power loss as shown in Table 7.

Table 7: Optimal sizing of DG [103-106]

Approach	Formula	Description
Elgerd's loss (P_{DGi})	$P_{DGi}=\dfrac{\alpha_{ii}(P_{DGi}+a_nQ_{DGi})-X_i-a_nY_i}{\alpha_{ii}(a_n^2+1)}$ $Q_{DGi}=a_nP_{DGi}$ By setting $PF_{DGi}=1$ and $a_n=0$ $P_{DGi}=P_{Di}-\dfrac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\j\neq i}}^{n}(\alpha_{ij}P_j-\beta_{ij}Q_j)\right]$ $Q_{DGi}=Q_{Di}-\dfrac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\j\neq i}}^{n}(\alpha_{ij}P_j-\beta_{ij}Q_j)\right]$	$X_i=\sum_{\substack{j=1\\j\neq i}}^{n}(\alpha_{ii}P_j-\beta_{ii}Q_j)$ $Y_i=\sum_{\substack{j=1\\j\neq i}}^{n}(\alpha_{ii}Q_j-\beta_{ii}P_j)$ $a_n=\pm k\tan\{\cos^{-1}(PF_{DG})\}$ k = -1 for DG injecting reactive power k = +1 for DG injecting active power Q_{DGi} = Reactive power P_{DGi} =Active power P_{Di} =Active load demand at node i Q_{Di} =Reactive power at load i
Branch power loss (P_{DGi})	$P_{DGi}=\dfrac{\sum_{i=1}^{n}\frac{R_iP_{bi}}{\lvert V_i\rvert^2}+a_n\sum_{i=1}^{n}\frac{R_iQ_{bi}}{\lvert v_i\rvert^2}}{(1+a_n^2)\sum_{i=1}^{n}\frac{R_i}{\lvert V_i\rvert^2}}$ $Q_{DGi}=a_nP_{DGi}$	P_{bi} = Active power at branch i Q_{bi} = Reactive power at branch i $a_n=\pm k\tan\{\cos^{-1}(PF_{DG})\}$
Branch current loss (P_{DGi})	$P_{DGi}=\dfrac{\sum_{i=1}^{n}I_{aci}R_i+a_n\sum_{i=1}^{n}I_{reci}R_i}{(1+a_n^2)\sum_{i=1}^{n}R_i}$ $Q_{DGi}=a_nP_{DGi}$	I_{aci} = Active current at branch i I_{reci} = Reactive current at branch i R_i = Resistance of the line section bus i

3.3. Voltage Profile improvement benefits with integration of renewable DG units

Renewable DG is integrated into the distribution system to enhance the voltage profile and ensure that voltage received at the consumers' load points is within the designed and acceptable limits. The voltage profile of the system will improve because renewable DG will supply a percentage of active and reactive power at the load points. This will reduce the current along the section of the distribution network and boost the voltage supply at the load points. Integration of renewable DG units in a power system has a substantial effect on the system voltage profile and voltage stability [21, 118-125]. In addition to these, penetration of renewable DG units into the distribution power system will reduce system overloading, provide the greatest released capacity and improve voltage regulation. These can be achieved by determining the maximum size of renewable DG units and the optimum renewable DG operating conditions. Injection of renewable DG into the radial distribution system can change the direction of power flow and improve the voltage profile of the system [126]. Penetration of renewable DG units into the distribution system provides a voltage support to increase the low voltage at the end of the distribution feeder to a certain extent. The benefit of the renewable DG's penetration is more effective at the end of the distribution feeder where consumers normally experience high voltage drop [127]. The benefits of renewable DG penetration on the voltage profile improvement can be estimated as follows [93]:

$$V_{11} = \frac{V_{11/wDG}}{V_{11/woDG}} \tag{1}$$

$$V_{11/wDG} = \sum_{i=1}^{n} V_i LP_i W_i \tag{2}$$

$$V_{11/woDG} = \sum_{i=1}^{n} V_{io} LP_i W_i \tag{3}$$

$$\sum_{i=1}^{n} W_i = 1 \tag{4}$$

If all the loads at bus i are equally weighted, W_i is expressed as

$$W_1 = W_2 = W_3 = W_n = \frac{1}{n} \tag{5}$$

Where

V_{11} = Voltage profile improvement benefits

$V_{11/wDG}$ = General expression for voltage profile at bus i with the application of renewable DG units

$V_{11/woDG}$ = General expression for voltage profile at bus i without the application of renewable DG units

V_i = Voltage at bus i per unit with renewable DG

V_{io} = Voltage at bus i per unit without renewable DG

LP_i = Load at bus i (per unit)

n = Number of buses in the power system

W_i = weighting factor for bus i

Table 8 shows several techniques that can be used to evaluate the impacts of DG penetration in the distribution system.

Table 8: Summary of different approaches on DG penetration

Method	Objectives	Ref.
Analytical method	Reliability improvement, power loss reduction and optimization of the restoration time	[104, 110, 121]
General approach with a set of indices	Improvement of voltage profile, line-loss minimization and environmental impact minimization.	[96, 93]
New multi-objective index analytical functions	Reduction of energy loss and improvement of voltage stability	[99]
Loss sensitivity approach	Optimal location of DG and loss minimization	[111]
ACS	Optimal placement of DG, active loss reduction and reliability improvement	[112, 129, 132]
PSO	Optimal placement of DG and minimization of energy costs for consumers	[113-115]
Dynamic based programming approach	Optimal placement of DG and profit maximization	[115]
GA	Voltage profile and reliability improvement, line loss reduction and power flow reduction in the critical lines.	[116-118]
GA-Fuzzy method	DG placement with loss minimization, voltage profile improvement, reduction of the risk of distribution feeder overloading and profit maximization	[119]
GA and PSO based approach	DG placement with voltage stability, losses and improved voltage regulations.	[120]
Heuristic method	Emission reduction	[128, 131]
Ordinal optimization (OO) method	Active loss reduction	[130]

3.4. Economic benefits with integration of renewable DG units

The economic benefits of renewable DG penetration can be achieved by deferring any investment made on the distribution and transmission system since renewable DG is located at or near the load points. Renewable DG integration reduces power system losses that should have been transferred to the consumers in terms of high energy cost. For a power plant to be economically and optimally viable, the cost of generating electricity should be less than the price of selling it [29,132]. It has been reported in difference literatures that utilities would gain a lot of financial benefits when renewable DG units are integrated into the distribution power systems. The income of the utilities that allow incorporation of renewable DG units into their networks will come from the energy generated and the saving due to the distribution line power loss reduction. The economic benefits of using renewable DG in the distribution system can be estimated by using benefit to cost ratio. The integration of renewable DG units in a power system is only acceptable if the net benefit exceeds the investment costs of installation. This section presents an overview of the key performance indicators that can guide the power utilities to estimate the components of renewable DG economics. The parameters are levelised cost of energy (LCOE), internal rate of return (IRR), return on investment (ROI), payback period (PB) and benefit to cost ratio. Optimization is the only means to select the optimum renewable DG system configuration that can maximize the financial benefits of the utilities [29]. This can be achieved by carrying out economic analysis on various resources and prioritize them based on the economic indicators. Table 9 gives a description of economic indicators of renewable power plants.

Table 9: Key economic indicators of renewable power plants [29, 51, and 133]

Approach	Formula	Description
LCOE is the price at which electricity from various sources of renewable energy must be sold in order to break even over the economic life of the project.	LCOE = $\dfrac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$ (\$/kWh)	I_t = investment expenditures in the year t M_t = O&M expenditures in the year t F_t = fuel expenditures in the year t E_t = electricity generation in the year t r = discount rate n = economic life of the system.
IRR is a benchmark that allows any investment that has been expended in renewable energy project to be measured and compared with the profit that might be gained from any other competing investment.	IRR= $\dfrac{\sum B_n - \sum C_n}{(1+i)^n} = 0$	B_n = Benefits at year n C_n = Costs at year n n = years i = Discount rate
ROI is a performance indicator to measure energy efficiency and any investment expended on the distributed generation.	ROI = $\dfrac{Total\ return}{Total\ cost\ of\ investment}$ ROI for wind turbine/ PV system = $\dfrac{365 * 24 * L_t * P_m * P_r}{(T_c + F_c) + (A_r * L_t)}$	P_m = Mean power produced by the wind turbine at wind speed V_m / PV at the insolation I_m L_t = Wind turbine/PV system life time (year) P_r = Price of electricity produced by the wind turbine/PV system T_c = Wind turbine/PV system cost F_c = Other fixed cost A_r =Annual recurrent cost
SPB is the number of years it will take to recoup back any investment expended on the renewable energy resources to generate electricity or the number of years it will require to reach the breakeven point.	Simple payback period (SPB) = $\sum \dfrac{I_c}{Y_b - Y_c}$	I_c = Investment costs Y_b = Yearly benefits Y_c = Yearly costs
Benefit to cost ratio (BC) is a standard that measures the financial benefits of the renewable energy project against the investment costs expended on the project.	BC = $\dfrac{\sum_{t=1}^{n} B}{\sum_{t=1}^{n} C} \geq 1$ C = $(C_x + C_y + C_z)$ B = $B_{loss} + B_{env} + B_{\inf} + B_o + B_{rev} + B_{cf}$	BC = Benefit to cost ratio B = Benefit C = Cost C_x = Capital cost C_y = O&M cost C_z = Other cost B_o = Cost of other benefits B_{loss} = Reduction in T&D power losses costs B_{env} = Reduction in environmental costs $B_{\inf}$ = Reduction in T&D infrastructure costs B_{cf} = Reduction in fuel cost B_{rev} = Revenue from power generation

3.5. Emissions reduction benefits with integration of renewable DG units

It is widely accepted that integration of renewable DG technologies into the distribution system can significantly reduce the intensity of carbon emissions from the power sectors that are predominantly dominated by the fossil fuels conventional power plants. Penetration of renewable DG into a power system has led to the generation of electricity at minimum greenhouse gas emissions and reduction in other pollutants such as NO_2, SO_2 *and* CO_2. These benefits can be quantified by comparing the environmental impact of using renewable DG and conventional technologies in a power system. Greenhouse gas emissions effect is a result of increasing NO_2, SO_2, CO_2 and other pollutants from conventional power generating plants, industrial and transportation and agricultural sectors. Introduction of renewable DG will reduce the capacity and number of the conventional power plants and the percentage of the greenhouse gas emissions that are emanating from them. Many organizations are more concerned about how the greenhouse gas emissions and other pollutants have caused the global warming and how to minimize them. Many techniques have been proposed in the literature [93] to compare the emissions from a conventional power plant with and without penetration of renewable DG units. The quantity of greenhouse gas emissions reduction with penetration of renewable DG depends on the locations, size and operating power factor of renewable DG units. The benefits of emissions reduction by incorporating renewable DG units into the distribution system can be estimated as follows [93]:

$$EIR_i = \frac{PE_{i/wDG}}{PE_{i/woDG}} \tag{6}$$

For different i_{th} pollutant such as NO_2, SO_2 *and* CO_2

Quantity of emissions from a conventional power plant with the integration of renewable DG units.

$$PE_{i/wDG} = \sum_{i=1}^{m} x_i y_{ii} + \sum_{j=1}^{n} x_j y_{ij} \tag{7}$$

Amount of emissions from a conventional power plant without the integration of renewable DG

$$PE_{i/woDG} = \sum_{k=1}^{m} x_k y_{ik} \tag{8}$$

Where

$PE_{i/wDG}$ = Quantity of emissions with the application of renewable DG

$PE_{i/woDG}$ = Quantity of emissions without the application of renewable DG

x_i = Quantity of electricity produced by the i_{th} conventional power unit with the application of renewable DG (MWh)

y_{ii} = Quantity of emission of the i_{th} pollutant for the i_{th} conventional power unit per MWh of electricity produced

x_j = Quantity of electricity produced by the j_{th} DG unit (MWh)

y_{ij} = Quantity of emission of the i_{th} pollutant for the j_{th} DG unit per MWh of electricity produced

x_k = Quantity of electricity produced by k_{th} conventional power unit without the application of renewable DG (MWh)

y_{ik} = Quantity of emission of the i_{th} pollutant for the k_{th} conventional unit per MWh of energy produced

m = number of conventional units in the power system

n = number of renewable DG units in the power system

EIR_i = Environmental impact reduction index for the i_{th} pollutant

4.0. The impact of market mechanism on the popularization of renewable DG

The numbers of consumers who have installed renewable energy resources for power generation application have increased tremendously in recent times due to technical, environmental and economic benefits that are attributed to application of DG resources [134]. The significance of the renewable energy is also felt by different stakeholders in the power sector, such as: electric power system planners and operators, energy policy makers and regulators. The amount of renewable DG installed has risen sharply in different part of the world over the past few years due to the policy put in place by government for carbon emission reduction [135]. A renewable energy investment mechanism has been introduced in some countries to provide financial incentives for companies that want to invest in renewable energy technologies or energy efficiency improvements include inter alia taxes, subsidies, feed-in tariffs, tax incentives, preferential financing, credit guarantees, carbon tax, differentiated pricing, cap-and-trade program, baseline and credit program, certificate systems, portfolio requirements and trading systems [136]. The impact of market mechanism on the popularization of renewable DG in the presence of energy policies that promote the installation and operation of renewable energy DG is presented in Table 10.

One of the major drivers for the renewable DG increased capacity is the market mechanism put in place by the government agencies, coupled with the declining cost of renewable energy DG technologies. This development has prompted an important reduction in renewable DG installation costs. The rapid increase in renewable technologies is also driven by the high price of fossil fuel and carbon pricing. Many customers have benefitted from developmental schemes put in place by several renewable DG manufacturers to produce renewable DG technologies of various sizes. This development coupled with the technological advancement has further reduced the costs of renewable DG. Production of modular sizes of renewable energy DG with improved electric storage systems could allow customers to become totally grid independent. Some countries such as Germany, Denmark and Spain are leading in the implementation of innovative policies which have driven most of the growth recorded in popularization of renewable energy over the past decade. Presently, Denmark's electricity consumption is covered by nothing less than 30% of renewable energy. The Danish government aims to get 50% of its electricity from renewable energy resources by 2020 and 100% from renewable energy resources by 2050 [137-138]. While China, United States, Italy, and Brazil have committed to an energy portfolio that is dominated by renewable energy, energy efficiency and sustainable development [139-140].

Table 10: Instruments for market mechanism [141-142]

Type of Instrument	Support scheme
Feed-in tariffs	Feed-in tariff is a mechanism to promote investment in electricity generation through the renewable energy sources.
Tax incentives	Tax exemptions for the consumers that use low-emitting activities or renewable energy technologies for industrial or domestic applications. Tax incentives encourage power generation from renewable energy resources and increased energy efficiencies, smart-grid and electrical storage technologies, etc.
Preferential financing	Financing for power generation from renewable energy resources. This is in the form of credit facilities from different financial institutions to stimulate capital investment in renewable power generation.
Credit guarantees	Credit guarantee funds to finance any innovative renewable energy and energy efficiency projects that will reduce greenhouse gas emissions.
Carbon tax	Tax on carbon emissions from vehicles and electricity from non-renewable energy resources. This will reduce greenhouse gas emissions and switch to renewable energy resources.
Differentiated pricing	Higher industrial electricity prices for more energy intensive enterprises
Cap and trade program	The emissions trading legislation is an emission trading system that creates an environmentally and economically platform to control greenhouse gas emission which is the primary source of global warming.
Baseline and credit program	A voluntary emission reduction program that provides incentives for activities that reduce carbon emissions. These initiatives will result in a quantifiable reduction of industrial and domestic carbon emissions.

4.1. The field of the renewable DG application for practical purposes

In recent times, renewable energy has received a focus attention for power generation, industrial applications and domestic applications. Renewable energy plays a proactive role in economic and sustainable development. This report focuses on the potential of renewable energy sources for practical purposes such as solar water heating systems that use solar power to produce hot water for domestic and industrial applications, wind and solar PV pumping water for agricultural applications and domestic consumption, power supply to the remote settlements though micro grid systems, wind turbines that provide mechanical power to drive many agricultural tools, etc.

5. Conclusions

This paper has reviewed the benefits of penetrating renewable DG units such as solar, wind and hybrid systems into the distribution system. Renewable DG units can play many significant roles in the economic, technical and environmental operation of a power system. The benefits of renewable DG technologies have changed the operation of the distribution system and encouraged direct connection of smaller DG units to the distribution systems at or near the load points. This has reduced energy and power losses, improved system reliability, improved voltage profile and reduced greenhouse gas emissions. These objectives are subject to the optimal size of DG, location, network configuration, operation and characteristics of the load. Hence, the power system operators and planners must develop a model that will aid the consumers to meet their load demand at minimum cost with integration of renewable DG units.

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