Decarbonisation of Electricity Generation: Efforts and Challenges

O. M. Babatunde, J. L. Munda and Y. Hamam

Abstract In satisfying the perpetually increasing energy demand, utility companies have traditionally depended on fossil-based energy sources (natural gas, oil and coal). These fuels are carbon-intensive, and burning them has negative implications on both human health and environment. However, in order to make sure that the global temperature rise is kept below 2 °C based on the Paris Agreement, it is essential that the electricity generation industry is subjected to transformation through the process of decarbonisation. Renewable energy sources have the tendency to mitigate the negative effects of the conventionally powered power plant. The move to renewable sources motivated the start of the process of decarbonisation—reducing the carbon intensity of the electricity generation. Furthermore, the adoption of demand-side management, carbon capture and storage, clean coal technologies, decommissioning of ageing fossil fuel-powered plants (replacing it with renewable energy-based plants), nuclear energy and adoption of stringent low-carbon policies can also aid decarbonisation of the power system sector. This work presents the trends and challenges in the decarbonisation of the power generation. This will help in achieving an all-encompassing strategy for the attainment of green economy. It is predicted that in order to maintain 2 °C temperature rise by 2050, the following technologies will contribute to emission reduction: carbon capture and storage 19%, fuel switching and efficiency 1%, hydro 3%, nuclear 13%, solar photovoltaic 9%, concentrated solar power 7%, wind onshore 9%, wind offshore 3%, biomass 4%, electricity saving 29% and other renewables 3%. It is clear that there is no singular approach that can entirely be used for the decarbonisation of the grid. An integrated approach

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that accommodates various policies and decarbonisation technologies will enhance low-carbon electricity generation.

Keywords Generation expansion planning · Power plant mix · Decarbonisation · Renewable energy · Emission reduction · Demand-side management · Climate change

1 Introduction

The ever-increasing thirst for electricity by human daily activities necessitates the need for periodic investments in new electricity facilities. In order to adequately and conveniently meet the ever-increasing energy demands, the power system industry is therefore categorised into distribution company (DISCO), transmission company (TRANSCO) and the generation company (GENCO). The GENCOs generate electric power which is sent through the transmission facilities owned by the TRANSCOs to the DISCOs. The DISCO is saddled with the responsibility of distributing electricity to consumers. The main objective of specifying the responsibilities of the different players involved in the electricity market is to efficiently and reliably satisfy the power demand based on various contradictory objectives (Sen and Bhattacharyya 2014).

To ascertain the reliability and sustainability of the electricity industry and fore-stall facility breakdown which may result in network collapse, it is essential to plan the generation, transmission as well as the distribution of electricity. Although the satisfaction on customer demands is very important, the sustainability of energy sources, as well as the environment, is also vital. Therefore, energy demands are supposed to be satisfied by reliable, environmentally friendly, and cost-effective power plants. Research efforts to arrive at a compromise between the components (reliability, sustainability and cost-effectiveness) result in a conflict among the subjects of engineering, management and economics.

The conflicting objectives that are derived from an attempt to plan the investments in the electricity industry result in an optimisation problem. In order to ensure that a particular generation expansion planning (GEP) investment is efficiently executed to satisfy the predicted load growth over a certain planning horizon (short, medium or long term), four fundamental questions need to be adequately answered. These include:

- *What*—the varieties of generator that should be included to the existing network.
- *How much*—the size of each new technology to be added.
- *Where*—the *location of the proposed generator*.
- *When*—the approximate time of addition along the planning horizon.

GEP is one of the most enthusiastically researched subjects by both decision-makers and the academics in the energy industry. It has been actively studied for about 70 years when it was first modelled as a linear programming optimisation problem whose only objective is the minimisation of the total cost invested in the generator (Masse and Gibrat 1957). The total cost functions usually include investment, fuel and operation costs over the whole planning horizon. This method for years has been used for centralised planning of the state-owned and regulated power system with strong monopoly on the generation, distribution and transmission networks. However, the deregulation of the electricity market, the introduction of new control strategies, global environmental challenges, inclusion of renewable energy and the attempt to accommodate uncertainties have led to a rapid change in the handling of the GEP. GEP is regarded as one of the most extensively discussed and complex topics in power systems. It has thus been presented by numerous studies in various optimisation dimensions. In a monopolised electricity environment, the objective of the operator is the minimisation of total cost, while the focal point in a deregulated electricity market is maximisation of profit. Thus, these emerging trends have introduced new constraints as well as objective functions which in turn have introduced more complexities in the representation and solution of GEP problems. These emerging trends make many of the new GEP models nonlinear, non-differentiable with high dimension and a combination of discrete and continuous variables.

From the aforementioned, in order to express the GEP close to what is practically obtainable, a large number of objectives and constraints will be needed, and as such, linear programming models may not be sufficient in representing such. To mitigate this challenge, many optimisation techniques/methods have been engaged for the formulation and solution of GEP optimisation problems. These include dynamic programming, mixed integer programming (You et al. 2016; Khodaei and Shahidehpour 2013), decomposition approach (Gorenstin et al. 1993; Tafreshi et al. 2012; Botterud and Korpås 2007; Fini et al. 2014) and nonlinear programming (Ramos 1989; Yakin and McFarland 1987). In a bid to decrease the complex mathematical nature of many of the GEP models and improve computational tractability, the aspects of flexibility are usually neglected (using specific assumptions) or parameters representing such are approximated.

Over the years, concerns about the sustainability of the conventional energy resource (energy security), the perpetual fluctuation in fuel prices, geopolitical changes, negative environmental impact of greenhouse gases (GHGs) emitted by fossil fuels have simulated research efforts into alternative energy resources. Thus, research efforts have been concentrated on the development and adoption of renewable energy sources for electric power generation globally. The technological advances in the two main intermittent RES (sun and wind) have particularly contributed to energy transition. Though capable of mitigating the emission of GHGs and ensuring resource sustainability, the inclusion of RES into the energy mix prompts other emerging issues such as efficiency, reliability and flexible power system network.

As earlier stated, past research efforts involving GEP have been concentrated on minimisation of the costs (Hamam et al. 1979; Sirikum and Techanitisawad 2006; Kothari and Kroese 2009). These include the investment cost, and operation and maintenance cost. More recently, due to environmental concerns, GEP investigations have extended to minimisation of emissions and the environmental impact of conventional generating units (Aghaei et al. 2013). To minimise emissions, various strategies have been proposed. These strategies include the implementation of renewable energy technologies (RETs) for the electricity generation, introduction of emissions penalties and adoption of DSM techniques. Due to the drop in the prices of PV and wind technologies, the use of RES for large-scale electricity generation has been proposed in generation expansion programmes (Aghaei et al. 2012; Rajesh et al. 2015, 2016a, b, 2017). If well planned and executed, RES can constitute a large share of the global energy mix by incorporating them across the entire planning horizon. In this regard, PPM models with renewable energy plants will be a better alternative. On the other hand, such RETs were mostly modelled without considering the fluctuations in their output. Meanwhile, the intermittent nature of RETs has received little attention in PPM models (Oree et al. 2017). The determination of such will help to determine the actual output of the renewable energy generating plants. Real-time determination of the output of renewable energy plants is therefore important. Other approaches in PPM have also adopted the integration of DSM techniques for the reduction of GHG emissions (Martins et al. 1996). According to Martins et al. (1996), when considered from a broader perspective, DSM is termed integrated resource planning (IRP). IRP involves the consideration of energy saving and load management as alternatives to perpetual generation expansion. Therefore, it is important to incorporate renewable energy plants, energy efficiency and storage units into the decarbonisation of GEP.

This work presents the trends and challenges in the decarbonisation of the power generation. This will help in achieving an all-encompassing strategy for the attainment of green economy.

2 Global Electricity Trends

The role of electricity in the development of the global economy is very crucial as its benefits are enormous and diverse. Electricity has great potentials in bringing about improvements in the living standards of people through increased productivity, improved levels of health care, improvement in education services and improvement in communication networks. Access to energy is an important need for human development, economic development and alleviation of poverty (Akinbulire et al. 2014). The quest for global access to electricity is an ongoing challenge affecting global development. The methods of electricity generation also have important impacts on the environment. The fossil-fired power plants (gas, coal and oil) have historically dominated the global energy mix. These methods of electricity generation have brought about increases in the emission of CO_2 and other GHGs which are fundamentally responsible for the recent global climate change (Babatunde et al. 2018a). A concerted transition in electricity sources is needed for global climate targets so as to avoid the negative impacts of climate change (Babatunde et al. 2018b).

There was approximately 3.1% (780 TWh) growth in electricity demand globally in 2017, while the global energy demand only increased by 2.1% in the same period. There was a strong correlation between the economic output of two emerging economies (China and India) and their electricity demand growth. With an economic growth of approximately 7%, China accounted for 48% of the electricity growth globally, while India with an economic growth of a little over 7% accounted for 180 TWh (approximately 23%) (International Energy Agency 2018a).

In total, China and India accounted for nearly 70% electricity demand globally in 2017, while 10% growth is attributed to other developing countries in Asia. Significant steps have been taken to improve access to electricity in many communities in India. The government has been able to extend access to electricity to about five hundred million individuals since the year 2000, thereby almost doubling the rate of access from 43% in the year 2000 to 82% of the present population (International Energy Agency 2018a). The developed countries were responsible for approximately 10% of the global electricity demand growth. The USA reduced its average electricity demand by 80 TWh in 2017. Furthermore, the European Union grew its electricity demand by 75 TWh in the same year. This is equivalent to the predicted economic growth of 2.3% in the same year. The demand for electricity in Japan also increased by about 15 TWh (International Energy Agency 2018a).

The global power plant mix (in terms of ratio) has remained relatively unchanged over the last century. The four key traditional electricity sources that have dominated electricity generation over the last 40 years include natural gas, large hydro, coal and nuclear. In 2017, renewable energy sources were responsible for approximately 50% of the cumulative global additional generation required to satisfy the rising electricity demand. With this addition, the renewable energy fraction in the global electricity mix rose to 25%—a record high. Figure 1 shows the global electricity mix for 2017. Coal accounted for 37%, renewables 25%, gas 23%, nuclear 10% and oil 4% (International Energy Agency 2018a).

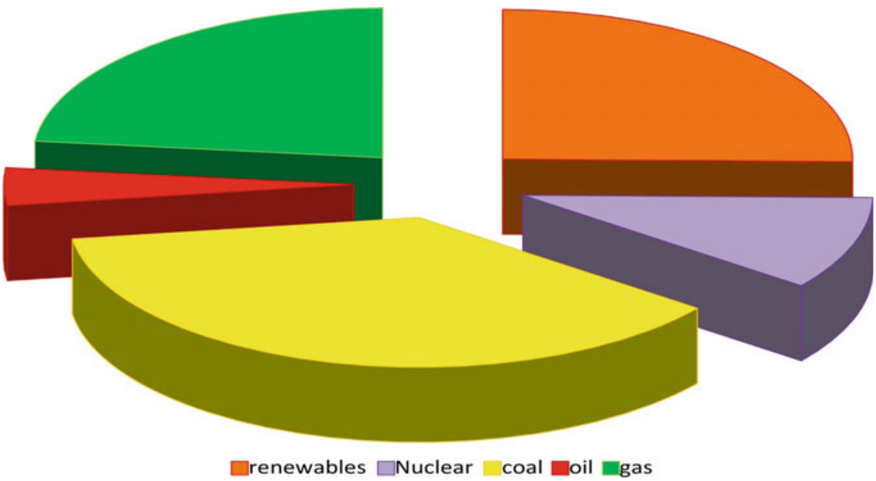

Fig. 1 2017 global electricity mix % (International Energy Agency 2018a)

3 Electricity and Greenhouse Gases

Electricity generation accounts for approximately 43% of worldwide CO_2 emission. Out of this value, coal-fired power plants contribute 70% by releasing 1.024 kg of CO_2 for every kWh of energy generated as compared to gas-fired power plants which emit 0.49 kg of CO_2 for every kWh. On the other hand, the only emissions attributed to RES such as wind, hydro, solar PV and concentrated solar power (CSP) are the ones emitted during their production. With regard to solar energy (PV and CSP), on average, between 7 and 45 g of CO_2 is emitted when one kWh of electricity is generated (Fig. 2). A wind turbine and a hydropower plant release about 16 and 6 g for every kWh, respectively (Société Française d'Energie Nucléaire 2017). For nuclear power plants, even after the future requirement to decommission old plants is included, the CO_2 emission stands at 15 g for every kWh of electricity generated. This is in sharp contrast when compared to the quantity attached to the coal-fired plants (1.024 kg). From the foregoing, it is evident that the CO_2 attributed to renewable energy sources is lower, and as such, the negative environmental impact will be lower when compared to that attributed to fossil-powered plants. Apart from this, fossil sources are exhaustible, while the renewable energy sources can be continuously harnessed. As such, renewable energy for GEP is now receiving research attention and huge investments. It is reported that in 2015, renewable energy received more than double the investment received by fossil-powered plants (coal and gas). Although nuclear electricity generation releases a small amount of CO_2 to the environment, its

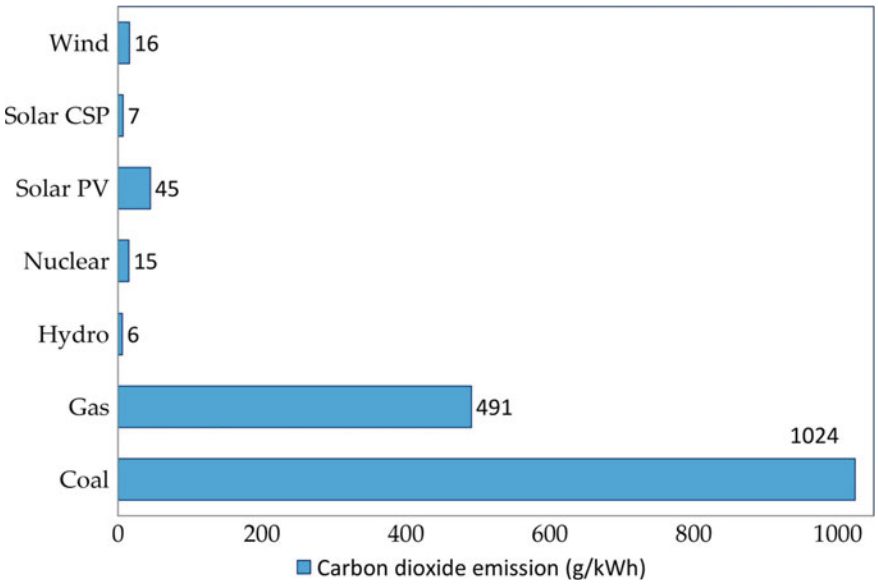

Fig. 2 CO_2 emission attributed to different generation technologies

adoption is receiving stiff opposition because of the danger of proliferation and the concerns of nuclear waste disposal and accidents. One of such accidents was the one that happened in Fukushima. Countries such as China, UK and France are investing in new-generation nuclear plants in a bid to cut emissions (Planete-Energies 2016).

4 Decarbonisation of the Power Industry

4.1 GEP, Environmental Issues and Climate Change

Some of the drivers of the decarbonisation of the generation expansion plans include the negative effects of greenhouse gases on the environment and human health, and the most prominent is the issues surrounding global warming and climate change. As such, various eco-friendly regulations, affecting generation expansion planning programmes, are legislated and adopted as sustainable development policies at both national and international stages. For example, in the 1990s, the federal government of the USA presented a Clean Air Act Amendments which was expected to force utility companies and energy planners to embrace strategies that would reduce the amount of emissions from fossil fuel-fired power plants (Abdollahi et al. 2012). Furthermore, the Kyoto Protocol was globally ratified by many countries for the mitigation of GHG emissions from every sector including the power industry (Protocol 1997). Subsequently, various strategies and constraints that limit GHG emissions from the electricity industry have been put in place. Some of these strategies include DSM and renewable energy technologies.

4.2 Environmental Considerations in GEP Studies

In order to handle the environmental impacts of emissions from GEP, many early studies imposed constraints on the maximum limit of permissible emissions from the generators. Some other methods incorporated the external costs related to the negative environmental effects of power generation by the different generators in the network.

For instance, a GEP model that dealt with the minimisation of investment cost, operation and maintenance cost, generation costs and CO_2 emission-related costs has been presented (Chen et al. 2010). In the face of increasing green environment awareness programme, Mejia-Giraldo et al. proposed a GEP model which embedded the following environmental policies: introduction of CO_2 emissions tax, reduction of annual emission rate and the gradual removal of inefficient generators from the system (Giraldo et al. 2010). Owing to the inclusion of various environmental constraints in the model, the proposed GEP optimisation model selected fewer capacities of the fossil-fuelled power generators due to the emission of pollutants.

The integrated GEP model accommodates the influence of different low-carbon features in its constraints. These constraints are associated with low-carbon technologies, emission trading mechanisms and CO_2 emission reduction targets. The decision variables include CO_2 allowance trading, low-carbon technologies implementation and carbon capture and storage retrofit on conventional generators. The model's objective functions include maximisation of income from CO_2 trading mechanism, CO_2 reduction costs and emission penalty. Furthermore, a GEP model that incorporated two environmental impact-related constraints (air pollutant emission and concentration) was proposed by Sirikum and Techanitisawad (Sirikum and Techanitisawad 2006). In order to make the model robust, the authors also included demand-side management investment cost and environmental cost expected from the damage cost of emissions of thermal plants into the objective function. A GA-based solution technique which breaks the GEP model into two portions was adopted. The GA provides a solution for the combinatorial part (generation mix), and based on these solutions, continuous variables that minimise the total cost subject to the listed constraints are determined using LP. For validation purposes, the Thailand power system was used as a case study. In order to present an energy plan for Apulia region in southern Italy, Cormio et al. presented a linear GEP optimisation model whose technique is based on energy flow analysis (EFA) (Cormio et al. 2003). The model is aimed at reducing both cost and the environmental impact. The EFA presented a detailed analysis of the basic energy sources utilisation which comprised process by-products, biomass, emissions, power and heat generation, solid wastes and end-use sectors. The objective function of the proposed GEP model minimises the total system cost. Some of the constraints considered in the study include construction time, limits on electrical energy generation, plant/facility operation limits, electricity generation and consumption balancing, peak demand satisfaction and limits on renewable energy potentials. The model is verified based on two case studies. The results from the simulation show that combined cycle power plants can contribute more in terms of renewable energy penetration as compared to any industrial cogeneration, biomass, waste to energy and wind power.

4.3 Emission Reduction Handling in GEP

In order to handle the issue of emission reduction in GEP, many studies have defined it either in the objective function (minimisation of its quantity or associated cost) or in the form of constraints by placing limits on the amount of emission expected from the fossil-fuelled power plants. Diverse mathematical techniques have been proposed for estimating the quantities of pollutants generated by various fossil-powered power generators. These include the quadratic model, the quadratic polynomial model, a hybrid polynomial and exponential emission function, linear model and emission coefficients method (Table 1) (Sadeghi et al. 2017). A review of GEP literature shows that the issue of emission reduction has received outstanding attention (Meza et al. 2007, 2009; Unsihuay-Vila et al. 2011; Tekiner et al. 2010; Jadid and Alizadeh 2011;

Table 1 Emission consideration in GEP (Sadeghi et al. 2017)

Type of emission model	Mode of consideration		
	Constraints	Objective	
		Emission quantity	Emission cost
Combined	Kannan et al. (2007), Hariyanto et al. (2009), Jadidoleslam and Ebrahimi (2015) and Hemmati et al. (2016)	–	–
Linear	–	–	Khodaei and Shahidehpour (2013)
Emission coefficient	Park et al. (1998), Tekiner et al. (2010), Jadid (2011), Min and Chung (2013), Surendra and Thukaram (2013), Zhang et al. (2013b), Ghaderi et al. (2014) and Sadeghi et al. (2015)	Martins et al. (1996), Shahidehpour and Kamalinia (2010), Hasani-Marzooni and Hosseini (2011), Unsihuay-Vila et al. (2011), Tekiner-Mogulkoc et al. (2012), Zhang et al. (2012) and Mavalizadeh and Ahmadi (2014)	Sherali and Staschus (1985) and Kaymaz et al. (2007)

Khodaei et al. 2012; Tekiner-mogulkoc et al. 2012; Rouhani et al. 2014; Javadi et al. 2013; Khodaei and Shahidehpour 2013; Aghaei et al. 2014; Palmintier and Webster 2011).

4.3.1 Power Plant Decommissioning

Electricity is a commodity that must be used as soon as it is produced because large-scale storage is not economical in many cases. Furthermore, the society is perpetually thirsty for electricity for the running of daily activities which are vital to human existence. Due to these facts, generating plants on the grid usually run uninterruptedly for many hours annually. Many of the generators are already old and sometimes inefficient due to ageing, while new ones with additional appropriate technological features are being incorporated into the grid. Conversely, environmental policies, regulations and targets fixed by various organisations, governments and establishments have enhanced the motive behind the decommissioning of fossil-fuelled generating facilities (especially coal and heavy oil) (Hillman and Zhang 2012). In the long-term power plant expansion planning, the timing for the removal of old and inefficient generating units usually has a major effect on the schedule of newly commissioned facilities.

In order to obtain a robust model that accounts for plant retirement (most especially conventional units), it is important to include power plant decommissioning decision variable into a GEP model. Apart from the reduction of emission rate, the decision to retire a particular unit is based on factors such as low reliability, high maintenance and operation costs caused by inefficiency of the units, and salvage value. Although the decommissioning of fossil fuel units (and replacing it with renewable energy plants) can encourage a transition from a grossly carbon-reliant energy generation to a low-carbon energy generation, it presents a major challenge for both government and utility companies across the globe. The variability of these low-carbon sources, as well as the cost of retrofitting, is a major barrier. This is evident in the review of previous studies which shows that the inclusion of power plant unit decommissioning in GEP optimisation problems has received limited attention (Tohidi et al. 2013; Min and Subramaniam 2002).

4.3.2 Demand-Side Management (DSM) Practices

Having learnt from the energy crisis that happened in the 1970s, electricity utility companies in the USA initiated the implementation of demand-side management (DSM) practices. DSM practices were effected in response to the persistent and continuous natural gas and petroleum price upsurge as well as the anticipated shortages (Loughran and Kulick 2004). The DSM programmes were implemented with the aim of modifying customer's electricity demand through several techniques comprising of attitudinal changes through enlightenment and financial motivations. Rather than investing in the installation of more generating units to satisfy the ever-increasing appetite of energy-thirsty customers, DSM practices through various incentives encourage consumers to reduce or delay electricity consumption (Babatunde et al. 2018a). Conventionally, DSM is perceived as a tool for the reduction of peak load so that electricity companies (GENCO, TRANSCO and DISCO) can defer the addition of new capacities (Babatunde et al. 2018a). This consequently defers the potential high investments involved in enhancing the power system network to accommodate increased power demand. The reduction of overall electricity demand from the electricity grid through DSM increases the reliability of the system by reducing the frequency of blackouts, brown-outs and other electrical emergencies. Since additional capacities (e.g. power plants) are delayed, electricity prices are reduced, the reliance on expensive imports of fuel is reduced, and reduction in GHG emissions to the environment is ensured. Therefore, the application of DSM in the power system sector offers substantial economic savings, technical benefits (increased reliability) and environmental advantages (reduction of emissions).

Drivers of Demand-Side Management

Various reasons have been attributed for the promotion of the adoption of DSM by utilities. Some of the drivers put forward include cost reduction in operation and maintenance of facilities, improved reliability, improved market as well as enhanced environmental and social improvement (Babatunde et al. 2018c). Ordinarily, promoting increased energy consumption so as to increase sales on the part of the utility will seem like a profitable idea; however, this will only work when there is excess capacity and the only factor that determines profitability is revenues. Conversely, direct proportional relationship between increased revenue and higher profitability does not always exist. According to a report “in some situations, a least-cost planning approach could prove that the implementation of DSM measures is more profitable than investing in new generating capacity” (UNIDO 2010). As a result, electricity companies would rather advise and promote DSM and energy efficiency techniques among their consumers. From the social and environmental standpoint, a reduction in electricity demand due to the adoption of energy-efficient practices reduces the environmental effect of electricity generation (from fossil-fuelled power plants) and consumption. This would project the image of the utility companies involved. DSM can be broadly categorised as demand response or energy efficiency. In terms of the period of application and impact, DSM can be categorised as energy efficiency, time of use (TOU), spinning reserve, market demand response and physical demand response (Koltsaklis and Dagoumas 2018) (Fig. 3). The TOU instantaneously ties the energy tariff to the energy cost. TOU penalises some period of energy use with a higher tariff in order to compel consumers to minimise energy consumption. In TOU scheme, lower tariff usually applies during off-peaks and partial peaks period, while at peak periods, the tariff is higher. This usually modifies the consumption pattern of the consumers by moving energy use away from peak periods which is usually more expensive. With this method, the customers save costs of purchasing electricity, while in the part of the utility, the fatigue on the grid is avoided.

4.3.3 Inclusion of Energy Efficiency Techniques in GEP

Energy efficiency techniques comprise of strategies and efforts that cause permanent changes/reduction in the size of the energy demand from the consumers’ side of the electricity market. The changes are usually caused by the modification on the features of the connected equipment to enhance (reduce) its energy consumption pattern. The EETs when adopted to reduce energy consumption must not distort the comfort level enjoyed by the end-use consumers (Goldman et al. 2010). EETs modify energy consumption through the use of energy-efficient equipment and gargets. The use of such gargets ensures that less energy is consumed to perform their normal tasks and attain the same level of satisfaction.

EETs are also regarded as energy source (just like natural gas, coal, RES and nuclear) and therefore considered as virtual generators whose negawatt power can be used to satisfy energy demands (Hu et al. 2010). The effects of EETs are instantaneous and stable with long-term energy and emission savings (Koltsaklis and Dagoumas 2018). They are therefore regarded as the most effective DSM method (Palensky and Dietrich 2011). As a decarbonisation mechanism, EETs through the reduction in energy consumption will reduce the energy consumption as well as the emission

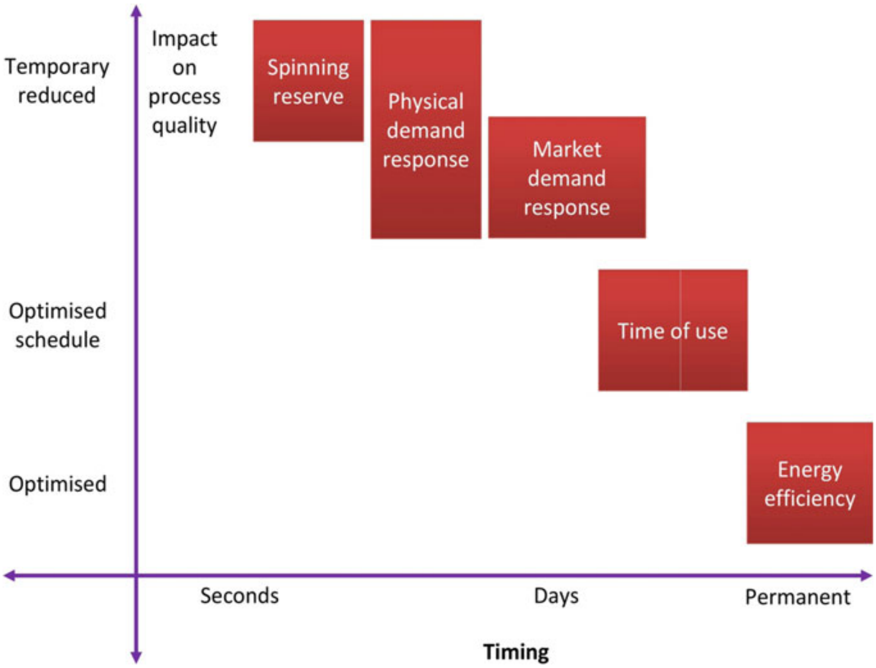

Fig. 3 Categories of DSM (Palensky and Dietrich 2011)

level from fossil-powered generators. When applied on both domestic and industrial loads, the cumulative energy saving can mitigate GHG emissions to a large extent. In 2016, it was reported that through the use of EETs, a cumulative energy savings of about 12%, was achieved since its adoption in the year 2000 (IEA 2017). In an attempt to capture the influence of energy efficiency on generation expansion planning, Ghaderi et al. presented a GEP model in which energy efficiency resources were modelled as efficiency power plant (Ghaderi et al. 2014). To ensure that investors at every stage of the planning obtain maximum profit, the GEP problem was modelled as a two-level optimisation problem. The lower-level problem was modelled to maximise the social welfare, while the upper-level problem ensures profit maximisation. Limmeechokchai and Chungpaibulpatana also presented and integrated GEP model which evaluated the emission reduction and the economic effectiveness of adopting cool storage air-conditioning (CSA) in a commercial sector (Limmeechokchai and Chungpaibulpatana 2001). Simulation results showed that the installation of CSA has the potential to defer the installation of approximately 1000 MW of fossil-powered plant between 2010 and 2011. In another study by Montie et al. (Motie et al. 2016), grid-connected electric cars and wind resource were considered as a technique for achieving energy efficiency goals in GEP. Other studies that included EETs from emission reduction in GEP include Unsihuay-Vila et al. (2011) and Fan et al. (2015). From the reviewed literature, the implementation of EETs results in energy and cost savings, deferment of capacity expansion, minimisation of negative environmental impact. Furthermore, the time of implementation and cost of implementing EETs are generally lower as compared to investing in new capacities to satisfy energy demands.

4.3.4 Demand Response Programmes and GEP

Demand responses are the adjustments in energy consumption made by the demand side of the electricity network. Consumers make modification to their "business-as-usual" consumption pattern in response to variation in energy prices over a period of time or to incentives. These incentives are proposed to ensure reduction in energy consumption at times of high system's market prices or when the reliability of grid is threatened. DR can be categorised along two major dimensions, namely: initiation criteria and motivation dimension (Rocky Mountain Institute 2016) (Fig. 4). The initiation dimension indicates how and when the utilities contact the programme participants to curtail demand, while the motivation dimension indicates how the utilities encourage the programme participants to adopt DR. From Fig. 4, it could be seen that DR could be activated either based on the emergency/reliability related issues or for economic reasons. While the aim of the DRPs is to modify the shape

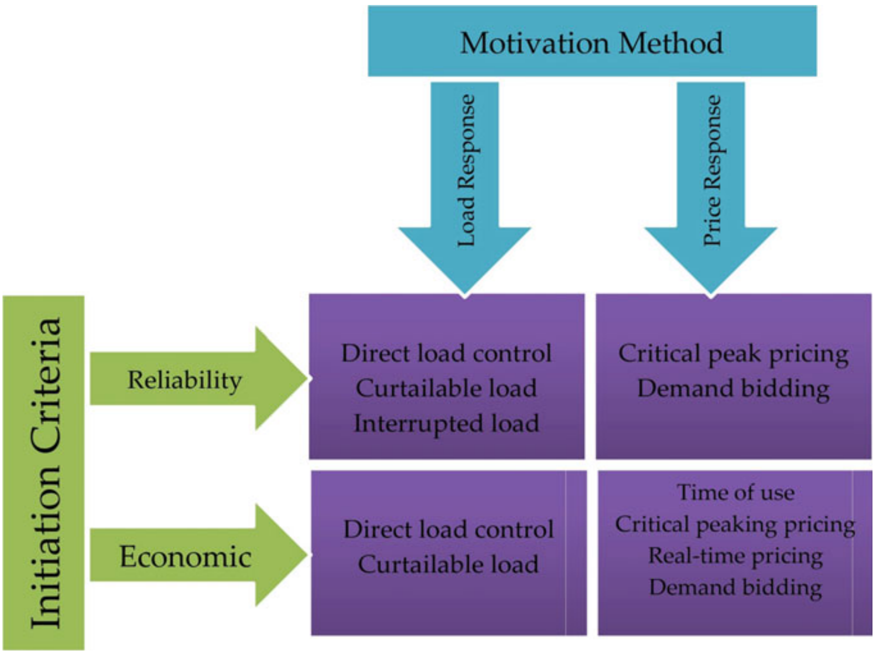

Fig. 4 Classification of demand response programmes based on initiation criteria and motivation method (Rocky Mountain Institute 2016)

of the demand, the EETs adjust the load level. A study which investigates the state-of-the-art systematic frameworks for adopting DRs in energy planning has been presented (Satchwell and Hledik 2014). Using dynamic programming, Sheikhi et al. modelled the stochastic nature of both DGs and DRs and the impact of DRPs on energy resource expansion planning in a deregulated environment (Fini et al. 2013). The outcome of the study indicates that adopting DRP in GEP has the tendency to increase the penetration of renewable resource in the energy mix via efficient demand control mechanism for smoothing the variability of RES-based units during normal grid conditions and by avoiding price spikes during critical grid conditions.

4.3.5 GEP and Carbon Capture Storage

Another possible alternative for the abatement GHG is CCS. Substantial research efforts have been directed at CCS because it can offer a cost-effective and smooth migration to a less carbon-intensive power generation mix in the next few decades. In order to make this a reality, appropriate guiding frameworks and policies for geologically sequestrating the CO_2 have been proposed. Based on these frameworks, many studies and large-scale projects have been launched to develop and improve CCS technologies worldwide (IPCC 2007). Basically, the alternative of capturing and storing CO_2 affords the prospect of allowing huge reserves of fossil fuels to be exploited and consequently being able to control GHG emissions during expansion planning. In this regard, studies that consider the impact of CCS on GEP strategies are beginning to spring up (Nguyen 2008; Chen et al. 2010; Bakirtzis et al. 2012; van den Broek et al. 2008; Chunark et al. 2014; Zhang et al. 2013a; Unsihuay-Vila et al. 2011; Saboori and Hemmati 2016). The outcome of various studies conducted on the impact of CCS on GEP has indicated that the conversion of the conventional coal-fired plants to low-carbon-intensive alternatives combined with CCS can have a positive effect on the total investment cost, operation and maintenance costs and the emission costs. The global growth of CCS is slow due to the high cost of investments and the lack of financial and political will by various governments (World Nuclear Association 2018). In 2016, it is reported that there were only 17 large-scale CCS projects functional worldwide (World Nuclear Association 2018).

4.3.6 GEP and Clean Coal Technologies

Worldwide, coal currently has the largest share of the global electricity mix. It is responsible for nearly 37% of the global electricity production in 2017, and this dominance is expected to continue in many countries for years to come (International Energy Agency 2018b). Other fossil fuel resources account for a combined percentage of 27% (gas—4%, oil—23%). Out of the three fossil fuel sources, coal emits more air pollutants (Sadeghi et al. 2017). The use of inefficient coal generation units increases these contaminants because of inefficient combustion. As these conventional coal-fired units approach their retirement period, they are expected to be replaced with units with no or lower carbon emission capabilities. One of such technologies is the clean coal technology. According to World Nuclear Association, "clean coal is a term gradually being used to refer to supercritical coal-fired plants without CCS, on the basis that CO_2 emissions are less for older plants, but are still much greater for nuclear or renewables" (World Nuclear Association 2018). These technologies often operate at around 42–48% thermal efficiency (World Nuclear Association 2018). Some of these technologies include supercritical and ultra-supercritical pulverised coal combustion, circulating fluidised bed combustion and integrated gasification combined cycles (Chen and Xu 2010). Out of the CCTs mentioned, it is reported that ultra-supercritical pulverised coal combustion and integrated gasification combined cycles have better potentials of future utilisation (Franco and Diaz 2009). At present, CCTs are mainly used as retrofit for medium and small size coal-fired units in countries like Spain and China (National Development and Reform Commission (NDRC) 2007; Delgado et al. 2011). Delgado et al. evaluated the impact of CCTs on GEP-related emissions. The studies recommend that concurrent integration of nuclear and CCTs units is incompatible (Delgado et al. 2009, 2011). Based on the two studies, Sadeghi et al. concluded that "high investment costs from one hand, and low emission and fossil fuels costs of nuclear units from the other hand can result in discarding them" (Sadeghi et al. 2017). In another study, Tanoto and Wijaya investigated the environmental and economic perspective of adopting CCTs in a long-term GEP problem (Tanoto and Wijaya 2011). The study concluded that in order to attain low-carbon generation mix in the future, incentives and policies that support the technologies are inevitable.

4.3.7 Nuclear Power in GEP Studies

The nuclear-fuelled power generator is CO_2 free and has the potentials to mitigate the rise in GHG if it can replace the base-load fossil-powered sources. Nuclear powered plants are one of the major generation alternatives with various advantages which include cheap fuel, compact waste, and ability to serve base loads. However, there are some drawbacks of nuclear power generation option as presented in Table 2. Being one of the leading conventional power generation alternatives, nuclear generators have been included and considered in GEP models with only few of them including its emission-free features (Nakawiro et al. 2008; Careri et al. 2011b; Habib and Chungpaibulpatana 2014; Meza et al. 2007, 2009; Vithayasrichareon and MacGill 2012; Unsihuay-Vila et al. 2011; Delgado et al. 2009; Unsihuay-Vila et al. 2010; Delgado et al. 2011; van den Broek et al. 2008; Tekiner-Mogulkoc et al. 2012; Chunark et al. 2014; Pereira and Saraiva 2013; Zhang et al. 2013a; Gitizadeh et al. 2013; Palmintier and Webster 2011). In many GEP studies, the threats related to the use and daily operation of nuclear power plants are given little research attention. In order to ensure the safe operation of these units, it is essential for the planning process (and model) to include factors that account for radioactive waste conveyance, waste removal, proliferation and level of reactor safety. It is therefore important that GEP with nuclear units considers and guarantees nuclear and radiological safety to the public and environment. Including these factors will ensure that the effects of nuclear power plant accidents that were experienced in Ukraine (Chernobyl) 1986, Argentina (Buenos Aires) 1983 and Japan (Fukushima) 2011 are either avoided or minimised (Sadeghi et al. 2017). Based on the experience of the Fukushima nuclear accident, Zhang et al. (2012) conducted a GEP study to analyse the economic and environmental implication of various nuclear case studies. The study shows that the total removal of nuclear power plants from Japan's 2030 power plant mix may result in a major increase in the cost of power production and GHGs. This will also increase the dependency on exportation of natural gas and coal which will in turn increase uncertainty in the generation expansion plan. The study also reported that only a fraction of the present load served by the nuclear units can be replaced by the renewable energy and natural gas-powered units. In a similar study, the effect of Korea's nuclear expansion policy on GEP was evaluated (Min and Chung 2013). Just like the Japan case, it costs more to replace some of the nuclear units with other energy alternatives. The paper, however, emphasised the need for the Korean energy mix to reduce its reliance on nuclear energy because of undermined social receptivity from the Fukushima disaster. The impact of eco-friendly constraints from hazards and risks related to nuclear power plants on GEP has also been explored (Zhang et al. 2013b; Santos et al. 2013; Kim and Ahu 1993). A summary of studies on emission reduction mechanisms is given in Table 3.

4.4 GEP and Intermittent Renewable Energy

One of the major drivers of green economy in the last decade is the renewable energy resources. This is due to favourable factors such as reduction in costs of RE technologies, technological innovations and developments of sustainable policies. Apart from its tendency to reduce GHG emission from electricity generation, RE sources can also guarantee future energy security, thereby ensuring sustainability. Based on these benefits and strict emission curtailment policies, many countries are now embracing the adoption of renewable energy for electricity generation. This is expected to increase the renewable energy share in the worldwide power plant mix. It is expected that by 2050, the renewable energy share will rise to 57% of the total demand served (International Energy Agency 2012). To achieve this, intermittent renewable energy sources (majorly solar and wind) are presently being explored and expected to take a major share of the renewable energy contributions. Some of the policies that have been proposed and adopted to ensure the increased penetration of renewable energy power generation include feed-in-tariff mechanism, quota obligations system combined with tradable green certificate, auction and tendering scheme, emission trading system (ETS) and carbon tax

For the main part of the last century, the major source of electricity generation is fossil fuel-powered plants. These technologies are flexible and can be easily varied to match the demand side by adjusting the fuel inputs. Conversely, including renewable energies into the power plant mix may lead to instability of the grid system because

Table 2 Comparison of energy sources considered in GEP studies (The Virtual Nuclear Tourist 2019)

Source	Benefits	Drawbacks
Hydroelectric	• Operation is inexpensive • Used for base-load and peak filling	• Construction is very expensive • Water resource depends on meteorological factors which increase uncertainty • Depends on the availability of water resource (variable source) • Collapse of dam may lead to loss of property and lives • Negative effects on aquatic life • Flooding can occur at downstream
Wind	• Wind is freely accessible when available • Can be deployed for water pumping for rural communities and on farms • Technology is fast developing and cheap	• Requires 3 times the quantity of installed capacity to satisfy demand • Geographical limitation of wind resource • May require expensive energy storage • Resource is intermittent in nature • Wind turbine tower can endanger birds and their natural habitat • May cause whale beaching
Biomass	• Industry is emerging • Job creation • Can aid rural electrification • Can be useful for home heating	• If small plants are used, it can be inefficient • It can be a major cause and contributor to GHGs if the plant is not well designed
Solar	• Solar radiation is free	• Intermittent in nature and geographically specific • Requires vast space of land for large-scale generation • Expensive • Sunlight depends on the time of the day (for any location)
Nuclear	• Fuel is not expensive • Concentrated source of energy generation • Compact waste • Well-developed technology • Easy to transport as new fuel • No GHG during energy generation • Used as firm capacity	• Investment cost can be high in order to accommodate adulteration management, waste control, storages systems and disaster management • Nuclear proliferation • Accidents and sabotage can lead to major releases of radioactive elements that can lead to health hazards (a case of Fukushima and Chernobyl)

(continued)

Table 2 (continued)

Source	Benefits	Drawbacks
Oil/gas	• Easy to obtain • Better as space heating energy source	• Not available in every location • Reliance on it causes energy dependency • Political crisis can cause shortages and high purchase prices • By-products of combustion cause releases of GHGs
Coal	• Cheap • Used as firm capacity	• Expensive pollution control mechanisms • Major cause of GHGs and acid rain • Movement of coals to power station is expensive • By-products (fly ash) contain heavy metals that are harmful to the environment • Deaths have been reported during the mining of coal

Table 3 Studies on emission reduction mechanisms

Emission reduction mechanism	References
Power plant decommissioning	Hoffman and Jeynes (1962), Tohidi et al. (2013) and Mavalizadeh et al. (2017, 2018)
Energy efficiency techniques	Gjengedal (1996), Martins et al. (1996), Limmeechokchai and Chungpaibulpatana (2001), Goldman et al. (2010) and Unsihuay-Vila et al. (2011)
Demand response	Pan and Rahman (1998), Antunes et al. (2004), Ghaderi et al. (2014), Monyei and Adewumi (2017) and Monyei et al. (2018)
Carbon capture storage	Nguyen (2008), Unsihuay-Vila et al. (2011), Bakirtzis et al. (2012), Fini et al. (2013), Zhang et al. (2013b), Satchwell and Hledik (2014), Guerra et al. (2016) and Saboori and Hemmati (2016)
Clean coal technologies	Franco and Diaz (2009) and Chen and Xu (2010)
Nuclear power generation	David and Rong-da (1989), Meza et al. (2007), Shahidehpour and Kamalinia (2010), Tekiner et al. (2010), Careri et al. (2011a, b), Delgado et al. (2011), Hasani-Marzooni and Hosseini (2011), Palmintier and Webster (2011), Unsihuay-Vila et al. (2011), Zhang et al. (2013b) and Sadeghi et al. (2015)

of the variability that comes with it. Intermittent energy sources are characterised most times by unanticipated fluctuations that cannot be controlled by the GENCOs. According to Oree et al. (2017), these variations can be recurrent if associated with daily and annual cycles (Oree et al. 2017) which cannot be linked to historical data. Though it mitigates emissions, the integration of renewable energy sources into the power system network introduces uncertainties in power system planning. As such, there arise the challenges of adequately matching the supply and demand. Furthermore, ensuring adequacy of installed spin reserves to satisfy the peak demand becomes a complex issue. At lower renewable energy penetration, flexibility is not a challenge because the grid is able to cancel out the fluctuations (Oree et al. 2017). However, when the penetration of renewable energy is very high in the power system network during GEP, the subjects of adequacy and operational flexibility become vital. Flexibility ensures that the grid promptly adjusts itself to match forecast and unforeseen variations in net electricity demand. The use of energy storage has the tendency to handle the issues of flexibilities caused by intermittent energy in the power system network. The most common energy storage used in GEP is the pumped hydrosystem. Water is pumped during the period when electricity is cheap and used for electricity generation when flexibility is needed.

5 Green Policies for Power Generation Decarbonisation

The climate change is a threat to human existence and needs immediate attention. As its contribution to the mitigation of climate change, the international community has enacted and adopted several conventions that have motivated many countries around the world to be totally engaged and prepared to consciously reduce their emission level. As a result, many countries have developed and adopted various energy policy frameworks (country-specific) geared at mitigating climate change and achieving a green economy. In this regard, the use of renewable energy sources is a fundamental and common policy for attaining sustainable development and reduction of climate change. There have been tremendous successes in many developed economies, but renewable energy penetration in developing economies is still hampered by economic and systematic factors. To ensure an increase of renewable energy share in the global power plant mix and make them competitive with the conventional sources of power generation, it is essential that both developed and developing economies adopt country-specific schemes that can enhance renewable energy. Some countries have therefore implemented favourable schemes that will encourage GENCOs to invest in the decarbonisation of the generating units. These schemes are in forms of subsidies which support the sustainability of green energy generation in order to compete with other sources of electricity generation to limit emission, climate change and dependency on fossil fuels. According to Sadeghi et al. (2017) "investments in renewable energy sources are either encouraged indirectly through efforts to mitigate power sector emission or by direct support schemes". Some of the schemes adopted for emission mitigation and RES generation include feed-in-tariff mechanism, quota obligations system combined with tradable green certificate, auction and tendering scheme, emission trading system (ETS) and carbon tax (Sadeghi et al. 2017).

5.1 Carbon Tax

It has been established that the major cause of climate change is the emission of GHGs. Interestingly, electricity generation contributes about 42.5% of the CO_2 emitted annually. These gases are released during the combustion of fossil fuels used in electricity generation and are related to the carbon content of the fuels. In order to mitigate the indiscriminate release of these gases, carbon tax has been proposed. Carbon tax is a form of carbon pricing (in form of levy) imposed on the carbon content of fossil fuels. It is a mechanism proposed and used for the reduction and eventual elimination of carbon-based fuels whose combustion contributes to climate change. This taxation scheme ensures that users of fossil fuel pay for the damages caused on the environment through the release of CO_2 to the atmosphere. If appropriately formulated, it is a robust tool that can ensure the gradual migration from fossil fuel-powered electricity generation to green electricity production. The tax can be imposed at any point in the product life cycle of the fuel (Metz et al. 2001). Carbon tax can offer socioeconomic benefits such as increased revenue and mitigation of GHGs which consequently reduce the negative impacts these gases have on the environment and human health (Congressional Budget Office 2013). A school of thought has expressed concerns that carbon tax may lead to relocation of firms which may finally lead to workers losing their jobs (Rosewicz 1990). However, on the contrary, proper implementation ensures that emissions are efficiently reduced and provision of more jobs (Hoel 1998). Various studies have been conducted on the inclusion of carbon taxes in GEP (Careri et al. 2011a; Fini et al. 2014; Hu et al. 2010; Krukanont and Tezuka 2007; He et al. 2012; Nguyen 2007, 2008; Santisirisomboon et al. 2001; Gitizadeh et al. 2013).

5.2 GEP and FIT System

Feed-in tariff is a monetary incentive proposed to encourage dynamic investment in the use of renewable energy sources for the generation of energy (especially electricity). Usually, FIT uses long-term contracts and pricing related to the cost of electricity production from renewable energy. By proposing long-term agreements and guaranteed pricing, renewable energy producers are protected from the various risks associated with the generation of electricity through RES. FIT also ensures diversity in power plant mix. FITs are applicable to everyone that generates electricity through RES. FITs have three major features: (1) producers are remunerated based on the resources expended on energy generation; (2) producers are guaranteed access to the grid and (3) long-term agreement for electricity purchase (typically between

15 and 25 years) (KENTON 2018). As regards the major features of FIT, guaranteed investments and long-term contracts for RES-based technologies are the benefits from a decision-maker's perspective during capacity planning. Conversely, the possibilities of over-/underfunding related to the challenges in the estimation of future costs of generating electricity from renewable energy are the major concerns of regulators. The impact of FIT on GEP models has been presented by some studies (Alishahi et al. 2011; Li and Ren 2017; Fini et al. 2013, 2014; Ghaderi et al. 2014a; Sadeghi et al. 2015; Caramanis et al. 1982; Gitizadeh et al. 2013). Results of the majority of these studies show that FIT significantly increases the renewable energy share of the future power plant mix.

As regards capacity planning, a study which proposes a two-level optimisation technique for the design of efficient and effective incentive policies to motivate increased investments in renewable energy for GEP has been presented (Zhou et al. 2011). Sadeghi et al. in their study investigated the influence of FIT schemes on the social welfare for a hybrid renewable-conventional GEP framework. In the study, consumers are considered for patronising the financial burden of FIT (Sadeghi et al. 2015). Using a gravitational search algorithm, the authors presented a GEP model which determines the benefit gained by GENCOs and consumers. Numerical results elucidate the benefits (especially social welfare) of implementing FIT schemes in the GEP. Another study has also presented the impact of system planning on the social welfare based on the adoption of FIT in Ontario. Results of the study show that if FIT is not controlled, they have the tendency of precipitating large negative effects on costumers' social welfare. It is further stated that these adverse effects could be minimised by regulating its magnitudes (Pirnia et al. 2011).

5.3 Emission Trading

Also referred to as "cap and trade" and "allowance trading", emission trading is a GHG emission control mechanism which is market-based. This mechanism achieves emission control through the provision of financial incentives (Stavins 2003). Emission trading schemes have two major features, namely (a) setting a maximum limit or cap and (b) allowances that can be traded (equivalent to the maximum that certified allowance holders can emit). The limit ensures environmental sustainability, while the tradable allowance ensures flexibility for emissions sources to establish a convenient compliance framework. As such, emission trading allows defaulting establishments to choose the best way to achieve and meet the green policy targets. In emission trading, relevant government establishment/agency appropriates and vends a limited number of permits for the emission of specific amount of GHGs for a certain period of time. Companies whose activities lead to emission are mandated to possess a permit that is equivalent to their emission level. Companies that wish to increase their emissions are required to purchase from others with emission allowance and are ready to sell to them (Jaffe et al. 2009; Tietenberg 2003; Stavins 2003). Emission trading has been reported to be the backbone behind the climate change policy within the European Union (European Commission 2014). It has ensured reduction of EU's GHG emission by setting a cap on the maximum limit on emissions for the covered sector (European Commission 2014).

5.4 Auctions and Tendering Schemes

Tendering and auction schemes can also be used as a price-based incentive to encourage investments in renewable energy-based power generation (Careri et al. 2011a). They are viable tools used for the allocation of financial sustenance to RES schemes, based on the cost of electricity production. Through these schemes, the appropriate public authorities are saddled with the responsibilities of tender preparations. The lowest bidders are invited for power purchase agreements until all the allocated quotas have been bought. The bidding process for RES-based electricity is typically in form of a reverse multi-unit auction with offers for multiple units of RES capacity in MW or MWh or for specific RES projects submitted by various sellers to a single buyer. The sole buyer is responsible for ranking the bids starting with the ones with the lowest unit price (Energypedia 2014). GENCOs and buyers which are certified during the bidding process are guaranteed and paid a specific unit price of energy for the defined period when the certificate is valid. Additional costs incurred on such tenders are imposed on the demand side through a special levy (Sadeghi et al. 2017). One of the drawbacks of this scheme is lack of or inadequate participation. If this occurs, there is a risk of lack of competition in a tender which can consequently precipitate expensive offers and low level of implementation. As regards studies related to GEP, Pereira and Saraiva (Pereira and Saraiva 2013) have demonstrated the effectiveness of tendering mechanisms on the addition of new RES capacities across a typical planning period.

6 Emission Reduction Capabilities

An analysis of CO_2 emission avoided through the use of nuclear power generation plant since 1980 shows that 60 Gt of CO_2 has been abated. Hence, if coal- or gas-fired power plants are replaced by nuclear power generation plants, a CO_2 emission reduction of up to 2.6 gigatones can be achieved annually (NEA 2015). This represents approximately 13% of the total estimated emission reduction if a 2 °C rise in temperature is to be sustained by 2050. The CO_2 emission reduction capabilities of other technologies include CCS 19%, fuel switching and efficiency 1%, hydro 3%, solar PV 9%, CSP 7%, wind onshore 9%, wind offshore 3%, biomass 4%, electricity saving 29% and other renewables 3% (Fig. 5) (NEA 2015).

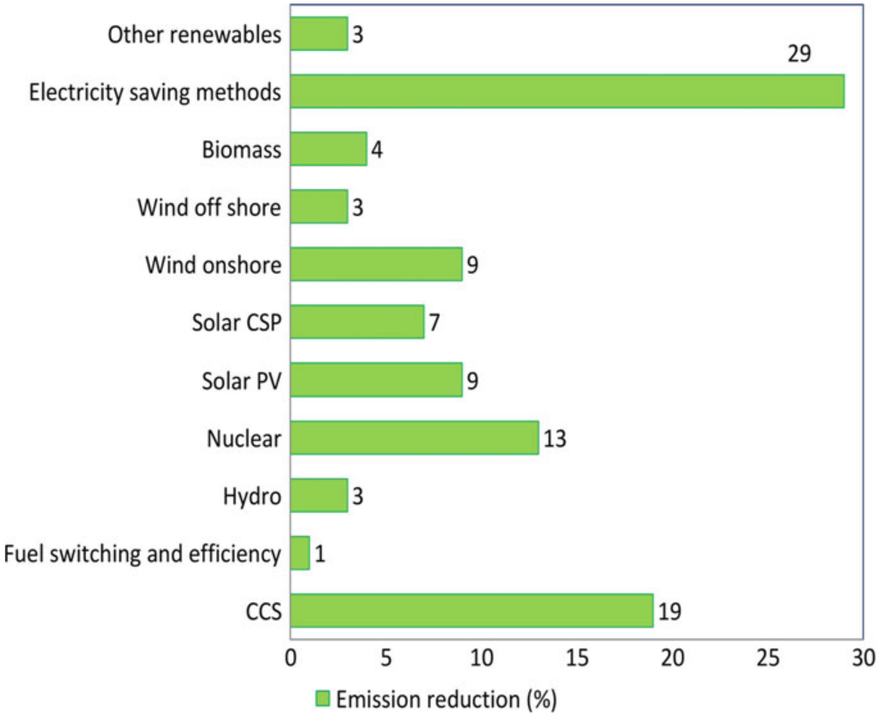

Fig. 5 Emission reduction capabilities if 2 °C rise in temperature is to be sustained by 2050

7 Decarbonisation: Both Sides of the Story

The decarbonisation of GEP comes with multiple benefits as well as drawbacks. It has the tendency to cap emissions, reduce pollution, ensure cleaner atmosphere and water and improve health, reduced energy imports, diversification and the emergence of new industry. In 2015, a total cost of €8.8 billion was saved from the importation of primary fuel due to the adoption of renewable energy (Kreuz and Müsgens 2017). Between 2013 and 2015, a 6% reduction on energy intensity was experienced in Germany and Australia as a result of the continuous adoption of energy efficiency and renewable energy (The World Bank 2018). The inclusion of renewable energy sources in the global energy mix has also encouraged the development of a huge labour market for the industry. For example, the renewable energy industry (wind, bioenergy and geothermal) in Germany was responsible for the employment of 322,000 personnel in 2016 (Ren 2015). Likewise, the renewable energy sector created 350,000 jobs in the solar related industry and another 107,000 in the wind industry in 2017 (Monyei et al. 2019). Apart from job creation, decarbonisation has significantly addressed the challenge of workforce inequity by improving enrolments into the trainee programmes of trade unions involved in the construction of

RE plants in California (Luke et al. 2017). It was also reported that a 33% increase in full-time job in renewable energy was experienced in Australia between 2015 and 2017 (Monyei et al. 2019). As reported by Monyei et al. 2019, these aforementioned benefits have come at the cost of majorly four unintentional effects. These include growing energy dependence, increasing renewable energy curtailment and capacity firming, limited GHG reductions and the increased vulnerability among some "losers".

8 Conclusion

This chapter has presented the efforts and challenges that are involved in the decarbonisation of the electric power system. A wide range of studies that chronologically present the subject of power system decarbonisation have been presented. The following are the summary of the insights drawn from this chapter:

- It is clear that there is no singular approach that can entirely be used for the decarbonisation of the grid. An integrated approach that accommodates various policies and decarbonisation technologies will enhance low-carbon electricity generation.
- The inability to set realistic targets, establish relevant regulatory frameworks and implement such frameworks will increase dependence on fossil fuels with its environmental consequences. Unrealistic targets and non-implementation of the relevant frameworks will slow down the rate of the irreversible momentum of clean energy which was highlighted by Obama in 2017 (Obama 2017).
- With the present and emerging technologies on nuclear power plant, it is the only fossil fuel source that offers the least emission. Although this can be harnessed in a carbon-constrained economy, the issues behind waste disposal, safety and likelihood of nuclear proliferation is still a barrier that must be investigated.
- Increasing the penetration of renewable energy in the global energy mix still remains an effective and vital option of power system decarbonisation. As such, more attention should be given to the development of proper policies that will target the challenges of decarbonisation as discussed by Monyei et al. (2019).
- Carbon capture and storage is crucial in the stabilisation of GHGs in the atmosphere. However, more research and governmental efforts to undertake practical demonstration of large-scale systems capable of exploring various methods for pre- and post-combustion carbon capture are necessary.

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