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(EGY_EGY-D-15-01736) Developing an optimal electricity generation mix for the UK 2050 future

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Abstract

The UK electricity sector is undergoing a transition driven by Climate Change policies and environmental policies from Europe. Aging electricity generating infrastructure is set to affect capacity margins after 2015. These developments, coupled with the increased proportion of inflexible and variable generation technologies will impact on the security of electricity supply. Investment in low-carbon technologies is central to UK meeting its energy policy objectives. The complexity of these challenges over the future development of the UK electricity sector has motivated this study which aims to develop a policy-informed electricity generation scenario to assess *the sector's transition to 2050. The study analyses the level of deployment of electricity generating technologies* in line with the 80% by 2050 emission target. This is achieved by using an excel-*based "Energy Optimisa*tion *Calculator" which captures the interaction of various inputs to produce a least cost generation mix. The key* results focus on the least cost electricity generation portfolio, emission intensity, and total investment required to assemble a sustainable electricity generation mix. A carbon neutral electricity sector is feasible if low-carbon technologies are deployed on a large scale. This requires a robust policy framework that supports the development and deployment of mature and emerging technologies.

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1.1 Introduction

A transition to a sustainable electricity generation future is a priority for UK energy policy development. The threat of climate change and the uncertainty over future energy supplies has led the government to set a legally binding target to cut emissions by 80% by 2050 against the 1990 levels [1]. The UK electricity sector is dominated by fossil fuels which account for 27% of the total emissions [2]. However, the legacy of coal generation is under threat from the European Union (EU) Large Combustion Plant Directive (LCPD) and the Industrial Emissions Directive (IED) which seek to enforce the environmental pollution regulations earmarked at controlling the emission of gases and particulates from industrial installations [3]. The impact of LCPD and IED on coal is further aggravated by the fact that most of the existing UK coal fired power plants are old, dating back to the 1960s with the newest having first opened in 1974 [4].The uncertainty over the future of coal generation coincides with the anticipated retirement of all but one of the UK 16 reactors by 2023 [5] as they reach the end of their operational life. These developments, coupled with the need to decarbonise the electricity sector, are having a huge impact on the UK's security of electricity supply.

The EU requires the UK to source 15% of its energy from renewable sources by 2020 [6] as part of its contribution to enable the EU as a whole to achieve 20% of its renewable energy target for 2020. In response, the government set a 40% target to source electricity from low-carbon technologies by 2020 [7]. In order to develop a clean and sustainable electricity sector, the Committee on Climate Change (CCC) is recommending the government to adopt 50 g/kWh grid carbon intensity by 2030 in order to assist the nation to achieve the 80% emission reduction target by 2050 [8]. A system of carbon budgets enacted by the Climate Change Act sets a Fourth Carbon budget emission reduction target of 50% by 2025 [9] to be achieved during the budget period from 2023-2027. The government believes that 40-70 GW of low-carbon capacity is required through the 2020s to decarbonise the power sector [2]. Based on this scale of deployment, the [8] believes that 97% of electricity should be generated by low-carbon sources in 2030, compared to 26% now. This ambitious low-carbon future would require total investment up to 2020 to be around £100 billion while investment through the 2020s needs to be around £90 billion [10].

The UK energy modelling and scenario capabilities have been instrumental in helping to design policies and iteratively evaluate the impact of new energy policies [11]. These tools have assisted UK policy makers to assess the costs, trade-offs and pathways related to achieving long-term emission targets and energy security challenges. Hybrid approaches which integrate economic systems and energy technologies such as the UK MARKAL model [12] have been developed to answer a range of questions pertaining to the evolution of the UK energy system.

Also, the UK energy transition has been examined based on socio-technical approaches focused on the actions of 'actors' and the governing arrangements that influence their choices [13]. This transition framework employs the multi-level perspective which analyses the co-evolution of ecosystems, technologies, institutions and business strategies for a transition to a low carbon economy [14]. In reviewing the literature on low carbon scenarios, [15] concluded that studies focused on either qualitative, social, technological or engineering based approaches are consistent with meeting specified energy demands within specified emission constraints.

This paper is based on the 'Energy Optimisation Calculator', a multifaceted tool which adopts a qualitative, economic and technological embedded approach to develop an optimal and sustainable policy-informed electricity generation pathway for the UK 2050 future. The methodology framework used has the capacity to trace the evolution of the UK electricity sector as it decarbonises from 2030 through to 2050. The model approach adopted endorses the government's vision to foster a least cost approach to meeting the 80% emission reduction target by 2050 [16]. The generation mix is developed through the use of the Committee on Climate Change's 'path to 50 g' decarbonisation framework. In adopting this radical emission reduction framework, the model approach aims to create a least cost generation mix that mitigates climate change while ensuring energy security. The technology penetration from this pathway is mirrored against other current scenarios, such as Gone Green [17] and the High Renewables Ambition [8] that have been developed from different modelling systems. In this respect, the plausibility of this pathway to fulfil energy policy ambitions can be examined. This paper is structured as follows: Section 2 characterises the "Energy Optimisation Calculator" in terms of how it is used to develop a sustainable electricity pathway for the UK 2050 future. Section 3 brings the UK electricity transition to 2050 in greater detail by discussing the technological combinations required to achieve electricity demand and emission target in a cost effective manner. Finally, Section 4 provides a conclusion which summarises the outputs of this paper.

1.2 Methodology

1.2.1 Developing a diversified generation mix for the pathway

The process of developing a sustainable pathway to a low carbon electricity supply system requires radical changes to technologies, institutions and business strategies [18]. The impact of these elements have been considered through the use of the 'Energy Optimisation Calculator' to produce an electricity generation pathway that seeks to create an almost carbon neutral electricity generation sector by 2050. The 'Energy Optimisation Calculator' is an in-house excel based tool used to generate energy scenarios for which input variables are determined based on the current UK energy policy developments. Multiple runs are processed for five year periods and data from each point in time is carried on to the next run. The model calculator uses a baseline scenario with 16 specified generation technologies to achieve emission target (185.8 $MtCO_2e$) and electricity demand (379.2 TWh) targets based on the 2007 energy policies developments. The model is used to develop the Sustainable Policy Pathway (SPP), a new low carbon technology scenario portraying the least cost and polluting generation mix for decarbonising the electricity sector in 2030 and through to 2050. The diverse technological distribution reflected in this transition pathway is shaped by the following assumptions:

1. A decarbonisation target of 50 gCO_2/kWh by 2030 is applied.
2. Emission grid intensity in 2050 is close to zero.
3. Commercial deployment of CCS begins in 2025.
4. No unabated coal generation in 2030.
5. Unabated gas generation reserved for system balancing purposes.
6. Most of the nuclear capacity retired by 2023 with about 9.6 GW new nuclear capacity operational by 2030.

The key input assumptions computed in the 'Energy Optimisation Calculator' to develop the Sustainable Policy Pathway include electricity demand, emission target, fuel costs, and technology costs as highlighted in Tables (1, 2, 3 and 4). Current primary electricity demand, emission trends and fuel costs for the electricity generation sector are projected to 2035, but for the purpose of this study, the trends to 2050 for the electricity demand is extrapolated lineally using equation (A.1) while primary fossil fuels; coal and gas costs and carbon emissions are extrapolated based on equations (A.2), (A.3) and (A.4) respectively, to determine the general outlook of the electricity supply sector in line with the decarbonisation ambitions. Technology emission and load factors are also part of the input variables adopted to determine the carbon footprint and the electricity generation capacity for each technology, commensurate with the emission target and electricity demand set. The model depicts the electricity generation transition in five year intervals from 2010 to 2050. The technology capital investment used in this model is amortised over the "technical life of 30 years" at a 10% discount rate. This article opted for this discount rate for consistency purposes, as it was used in major government reports [19], [20] and other organizations reporting on the technology cost estimate data for the UK electricity sector. The technology cost data input applied in the model is based on the medium cost estimate and the annual inflation rate (2010 - 2013) was used to harmonies the costs to 2013 price money. Other input variables used in the model include a physical installation limit (GW) for each technology, which gives the estimated total deployment capacity in line with industry and government development ambitions. The model approach sets an installation constraint which allows the maximum feasible capacity to be added in the generation mix at any given time, taking into account the technical, economic, environmental and social factors that impact on technology penetration. This sets the maximum capacity limit for each technology that the model can add to the generation mix to meet the set demand and emission targets.

1.2.2 The Optimisation Function of the Calculator

The optimisation process aims to develop a least cost and polluting generation mix that meets energy demand and carbon emissions for this pathway. Optimisation starts with the generation technologies set in the baseline scenario shown in Figure 1 which are modified to develop the Sustainable Policy Pathway based on the set inputs and the various constraints applied. The model optimises the generation mix in two-stage sequential process based on the cost of electricity generation and emission target set. This implies that for the electricity demand set, the model builds the cheapest technology first, that is, a TWh at a time until the installation constraint is reach before moving the next cheaper technology. The process of selecting technologies based on the least-cost hierarchy is repeated for all the technologies in the mix until the electricity demand is achieved. In the event that the generation portfolio developed in each model run fails to meet electricity demand, the model continues its optimisation process by closing down capacities of the most expensive technologies and replacing them by building/adding cheaper sources to the mix until demand is met by the least-cost generation mix possible.

The next stage in the optimisation process assesses the capacity of the assembled generation to meet the emission target. If the emissions are met, then the process ends but if not, optimisation will continue. At this stage the model replaces high carbon intensive technologies with low carbon technologies until the carbon target is just met, as depicted in Figure 1. During this process, the model keeps track of the total investment outlay for both the baseline and the low-carbon scenarios accrued in developing the generation mix that meets the conditions set. The model calculations also account for the extra investment resulting from the capacity added to the mix during the optimisation process. Once the optimisation process is completed, the output module then displays the proportion of generation capacity (GW) required to meet the demand from the assembled technologies and the corresponding generation achieved in TWh/yr, as highlighted in Figure 1.

1.2.3 Levelised Cost of Energy

The levelised cost of electricity (LCOE) has been defined by the International Energy Agency (IEA) as the average price that would have to be paid by the consumers to repay exactly the investor/operator for the capital, operation and maintenance and fuel expenses with a rate of return equal to the discount rate [21]. This cost methodology has widely been used as a ranking tool to assess the cost-effectiveness of different energy generating technologies [22]. This technology accounting approach has been used by policymakers to determine the relative investment options available for different technologies. As outlined in this paper, the LCOE considers the lifetime generated energy and costs to determine the price of electricity per unit energy generated (£/MWh).The assessment of the levelised cost of electricity (LCOE) for any given technologies is framed by a set of assumptions on a wide range of variables, such as capital cost, construction times, the expected plant life, operational and maintenance costs, fuel costs, plant availability, load factor and discount rate [23]. For the LCOE analysis adopted in this study, the stream of future costs and generation outputs are discounted by 10% to the present value taking into account the time value of money. The competitiveness of each of the technologies considered takes into account the likely impact of the sensitivity on the various input parameters adopted in the model. The model formula (A.5) is used to calculate the COE (as highlighted in Appendices), where I, is the capital investment (cost per kW multiplied by the total installed capacity), r is the discount rate at 10%, E is the annual electricity generation (TWh), n is the lifetime of the plant, TOM is the total operation and maintenance costs.

The levelised cost of electricity generated from this model is not discussed in this paper as attention is focused on the capital investment required to build low carbon technologies. However, the COE component of the model is only shown as an output in Figure 1.

1.2.4 Dealing with uncertainty in the energy scenario discourse

The range of assumptions used in the model are designed to development a diversified and least cost electricity generating portfolio for the UK 2050 future. However, the construction of such futures is fraught with uncertainty particularly with regards to the development and deployment of emerging technologies, fuel resource availability and prices as well as the dynamics of energy and climate change related policies. In order to enhance the credibility of the scenario outputs from the 'Energy Optimisation Calculator', a sensitivity study is carried out focused mainly on the technology and fuel cost inputs for nuclear, offshore wind and CCS, the three key technologies considered to be indispensable in decarbonising the electricity generation system. The study also includes unabated gas plants in the analysis to assess the likely changes in the proportion of installed gas capacity in the mix as the key inputs are either increased or decreased. Variation of these input variables has a potential to significantly impact on the level of technology penetration earmarked for system decarbonisation. Therefore, the sensitivity of the model to variations in the technology and fuel cost inputs for the selected technologies is independently assessed by a factor of +/-30%. The outcome of this sensitivity assessment is mirrored against the key conclusions drawn from this study, thus assisting in determining the credibility and the level of confidence that can be ascribed to the 2030 and 2050 electricity futures envisaged.

1.3 Results and Discussion

The installed generation capacity exhibited in Figure 2 captures the results of a low-carbon driven policy framework which seeks to balance the need to mitigate climate change while ensuring security of supply and affordable electricity to consumers. This characterizes a policy undertaking which embraces the "trilemma of energy sustainability" devoted to promote energy security, social security and environmental impact mitigation [24]. The penetration of low carbon and renewable electricity generation technologies over the 2020 to 2030 period shown in Figure 2, is consistent with the 30-40 GW and 30-70 GW estimated scale of new capacity deployment required by 2030. This ambitious target is earmarked to have a dual impact of replacing the ageing UK's electricity infrastructure at the end of this decade as well as laying the foundation for sector decarbonisation through the 2020s.

Renewable technology deployment in 2020 results in 50.2 GW of installed capacity with offshore and onshore wind accounting for almost 65.1% of the technology build-up. The substantial surge in offshore wind (18GW) during this period is consistent with the notion that such a level of deployment will assist the UK in meeting the 2020 target [25]. The introduction of incentive mechanisms in the form of Renewable Obligation (RO), exception from climate change levy (CCL) and feed-in-tariffs (FiT) have combined to boost the level of deployment of offshore wind in the UK [26]. The investment enabling environment has also been promulgated by a favourable consenting system driven by The Crown Estate (TCE) which owns and leases the near-shore and offshore sea bed up to 12 nautical miles in the UK to offshore wind developers [27].

The government has also unlocked barriers to offshore wind development by setting up bodies, such as the infrastructure planning commission (IPC), Collaborative Offshore wind farm Research into the Environment (COWRIE) [27], dedicated towards creating the most attractive investment climate for offshore wind development. This makes the UK the largest market for offshore wind energy in Europe and also across the globe. In view of this enabling environment for offshore development, a 31 GW installed capacity is built by the model in 2030 which is almost close to the government's 'best case' deployment scenario projected at 39 GW in the same period [28]. The sensitivity analysis on the future costs of offshore deployment show no change in the level of penetration from 2025 to 2050 as shown in Table 5. This implies that the build-up of offshore wind in Figure 2 is the optimal capacity that is commensurate with decarbonising the electricity infrastructure by 2030 as well as developing a near carbon neutral sector by 2050 regardless of the variations in the magnitude of the deployment costs. The rollout of onshore wind achieves 14.7 GW and 20.6 GW growth by 2020 and 2030 as highlighted in Figure 2. The level of deployment of onshore wind achieved from 2015 through to 2030 is mainly due to the abundant wind resource in the UK and the maturity and proven nature of the technology. This makes it the most economically attractive alternative to transition towards a sustainable electricity sector by 2050. However, the attainment of this milestone in onshore wind development hinges primarily on policy and the availability of sites [29]. The political willingness and appetite towards the continued onshore wind deployment appears to be ebbing away. It can be argued that the lack of enthusiasm for this technology on the political front could be attributed to the view that the UK's 2020 renewable energy target is almost set to be achieved. In this regard, the seemingly polarised attitude towards onshore wind is encapsulated in the remarks made by the Prime Minister in which he suggested that the public is basically fed up with wind [30].

Indeed, the arguments over the potential exhaustion of development site for onshore wind projects can be drawn from the understanding that the 'best sites' with reduced visual impact are increasingly being used up, thus limiting any future growth in the sector. As a result, this has had the impact of forcing developers to encroach onto more difficult sites, most of which have a proximity implications to radar and residential areas, hence increasing the likelihood for planning application to be rejected [31]. In comparison to offshore wind and other renewable technologies, onshore wind is arguably much cheaper [32] and this, combined with other favourable factors, can be judged to have promoted the scale of development and deployment projected in Figure 2.

The deployment trend for solar PV, shown in Figure 2, depicts a growth at unprecedented levels from 2015 to 2050 to reach 17.8 GW in total capacity. This solar 'revolution', particularly in the period after 2010, was a result of the implementation of favourable policies like the small scale FiT scheme and the RO which in September 2011 alone, saw a total of 15855 installations with a total capacity of about 80.5 MW [33].This growth was also due to the significant reduction in installation costs estimated to have fallen around 50% between 2010 and 2012 [34]. It was at the backdrop of this growth that solar PV was considered as one of the key renewable energy technologies that can assist in creating a balanced UK energy mix, with a projected 20 GW upper limit capacity by 2020 [35]. However, a deployment capacity below 10 GW by 2020 was adopted for this pathway following the National Grid modelling suggesting that an estimated capacity above this margin could make balancing the existing grid infrastructure more challenging in its current form [36]. This technical constraint has been used in this scenario to curtail the level of deployment of solar PV to allow a balanced contribution from other technologies within the generation mix. The recommendations made by National Grid to DECC over the grid support for 10 GW were construed by the sceptic solar power industry as a ploy by the policymakers to water down ambitions for solar in the UK [37].The government's decision to close the RO to new solar projects above 5 MW by the 1 April 2015 [38] confirms the industry's concerns over the indecisive policy towards solar despite its acknowledged significance in decarbonising the electricity sector. The deployment trajectory beyond 2020, as shown in Figure 2, is consistent with the government's belief that the industry has matured enough to compete for funding under the Contracts for Difference (CfD), thus allowing growth to be sustained up to 2050.

A low-carbon oriented policy focused on creating a viable market to invest in low-carbon technologies such as nuclear and CCS has been prioritised by the UK policymakers. Such policy initiatives are set to be driven by the CfD mechanisms, which, if successfully implemented could be a game changer in guaranteeing viability to low-carbon investment especially in the period leading to 2030 as the electricity sector decarbonises. The 2030 installed capacity for nuclear is set at 10.8 GW with 9.6 GW constituting the new build plants while 1.198 GW is the remnant capacity from old fleet which is due for closure in 2035. This is about 60% less of the estimated 16 GW new nuclear capacity estimated in the UK Nuclear Strategy expected to be commissioned by 2030 [39]. The uncertainty over the build-up rates for new nuclear capacity over this period can be attributed to what [40] observed as the consistently rising costs and associated problems of financing nuclear power plants and the shortage of technical expertise. These factors combined with the traditional concerns for accidents and radiation risks and nuclear waste management [41], have a greater potential to stall momentum in both investor interest and the actual deployment of the technology. In the context of these constraints and the on-going delays currently facing UK's first new nuclear plant (Hinkley Point C), a 14 GW new nuclear capacity would contribute towards achieving the decarbonisation aspirations set by the government to 2050. In demonstrating the significant role that the new nuclear is anticipated to play in achieving the deep cuts in emissions from the electricity generation sector, its deployment capacity from 2025 through to 2050 (see Figure 2) is retained by the model despite varying the capital, operational and fuel cost inputs by +/-30% as shown in Table 5.

Carbon Capture and Storage, as a new technology that removes CO_2 from the atmosphere, involves either pre or post combustion separation of CO_2 in either new or retrofitted plants leading to an energy system with negative emission characteristics [42]. Retrofitted CCS on fossil fuel and biomass plants account for 8.9 GW installed capacity in 2030 and about 44.9% and 41.6% of this capacity constitute coal and gas-fired plants, respectively. The application of CCS technology on biomass power plants has a unique potential to create simultaneously CO_2 negative emissions [43] without which could be extremely costly and difficult, if not impossible to reach emission targets below 450 ppm [44]. However, due to its technical and economic uncertainty, CCS development in the UK is still a challenge as it hasn't been deployed at a commercial scale. The technology is still at demonstration stage and the full chain technology has not yet been demonstrated on a working power station or industrial facility in Europe [45]. Thus the challenge to decarbonise the electricity by 2030 is dependent on the successful rollout of commercial scale CCS on power plants and the accelerated deployment of offshore wind and new nuclear other from now and through the 2020s.

In 2020, fossil fuel generation accounts for 44.1 GW, which is about 41.6% of the total installed capacity. Gas-fired generation becomes the dominant unabated fossil resource as coal generation capacity declines as a result of the LCPD and IED requirements effective from January 2016 [46]. By 2030, renewables increase by 66.5% from the 2020 capacity to reach 83.6 GW. There is an increased build-up of nuclear and CCS to reach 18.5 GW by 2030. The increased scale of low carbon and renewable technology deployment demonstrated by these figures culminates in the attainment of the 50 g/kWh carbon intensity for the electricity sector. By 2030, unabated generation is derived from gas as higher-emitting coal plants no longer form part of the generation mix.

Due to high levels of intermittent generation in the mix, 24-26 GW capacity of unabated gas assumes a peaking or back-up role from 2035 onwards. This approximates the 24.8 GW capacity estimated for the 2035/36 period in the Gone Green scenario [47]. Given the (350-400 g/kWh) carbon intensity and the potential effect of 'investment lock-in' on new gas CCGT, large investment in this technology may have profound implications for the long-term decarbonisation objectives [48]. However, CCGT generation during this period is expected to have little impact on emissions as it is expected to be run at extremely low load factors, roughly below the 20% margin [49]. Even if the cost of fuel or capital investment in gas plants were to be varied by a +/-30% margin from 2025 through to 2050, the capacity level of unabated gas plants in the mix will remain unchanged (see Table 5) especially from 2030 to 2050. However, a 2.9 GW capacity increase in gas plant builds occurs in 2025 when the costs are reduced by 30%, mainly due to the slightly higher emission target (26.9 $MtCO_2e$) which allows the model to build more gas plants. The results of the sensitivity analysis on unabated gas generation suggest that the uncertainty over future fossil fuel and capital investment costs has a limited impact in altering the projected installed capacity in an energy system transitioning to a low-carbon future. CCGT's back-up role is demonstrated by a declining generation profile as shown in Figure 3, where plants are operated at load factors below 5%. Unabated gas generation at this load factor allows the generation mix to achieve the 50 gCO_2/kWh in 2030. Based on the model simulations, an increase in the load factor beyond 5% for unabated gas will result in an increase in the cumulative emissions, thereby exceeding the 2030 grid emission intensity unless the deployment capacity of low-carbon technologies is increased. For example, a load factor of 8% and 10% achieves 57 gCO_2/kWh and 60 gCO_2/kWh in 2030, respectively, compared to 50 gCO_2/kWh at a 5% load factor. Based on this level of plant utilisation under this decarbonisation framework, gas generation capacity for back-up purposes would need to be adequately incentivised in order to maintain its economic viability on the system.

However, the policymakers appear to have a different perspective on the role of unabated gas vis-à-vis intermittence beyond 2030. The government's policy position appears to be that which "see gas as continuing to play an important role in the energy mix well into and beyond 2030..[not] restricted to providing back up to renewables" [50]. Such a policy shift has a potential to compromise on the wider commitment to decarbonise the energy system as well as on the objective of promoting rapid emission reduction commensurate with keeping global temperature within 2^{o}C of pre-industrial levels. In view of the technology build-up exhibited in Figure 2, the electricity generation sector is almost carbon neutral in the period leading to 2050 as the renewable installed capacity reaches 68.7GW, while low carbon technologies surges to reach 27.7 6GW. This technology combination would literally squeeze out carbon emissions from the electricity sector thereby allowing the electricity generation infrastructure to achieve a grid carbon intensity of about 5 gCO_2/kWh in 2050 (see Figure 2).

The proportion of renewable electricity generation shown in Figure 3 supplies 187.4 TWh and 183 TWh, which represents about 54.4% and 48.5% of the anticipated demand in 2030 and 2050, respectively. System security against this high level of renewable generation is maintained by a 136.7 TWh and 182.6 TWh of low carbon generation mainly nuclear, fossil fuel with Carbon Capture and Storage (CCS) as well as biomass with CCS over the same period. Unabated dedicated biomass generation is reduced significantly from 2035 through to 2050 compared to biomass with CCS. This variation in the installed capacity for unabated dedicated biomass and biomass with CCS is in keeping with the Committee on Climate Change's analysis suggesting the important case for the long-term role of biomass in large-scale generation where CCS is available [51]. As noted by [52], land used for biomass production often compete with food crops, forest and urbanisation. Therefore, a 4 GW capacity constraint limit for biomass plants that could be supported by government subsidies and sufficient sustainable biomass resource [31] has been adopted for this pathway analysis. The installed capacity and generation portrayed in Figures 2 and 3, succeed in reducing the overall carbon intensity from 455 g/kWh in 2010 to 5 g/kWh in 2050, as shown in Figure 2. In comparison, the Super Carbon Ambition (CSAM) a carbon reduction scenario developed from the MARKAL Model achieves less than 10 gCO_2/kWh by 2050 with almost 38 GW nuclear, 12 GW CCS and 65 GW wind [53].

The role of nuclear and biomass CCS is crucially important in achieving the emission intensity levels from 2030 through to 2050, as shown in Figure 2. In the context of this study, the carbon footprint for biomass CCS is assumed to be negative or neutral. This is based on the understanding that the application of CCS technology on biomass plants captures the CO_2 from the flue gas to create a net negative effect [54]. However, the carbon neutrality of biomass energies has been widely contested in policy forums, especially on the sustainable procurement of biomass resources and utilisation. This study upholds the view of a carbon neutrality biomass in line with [55] argument that it is dependent on definition of carbon neutrality, feedstock type, technology used and the time frame examined. Any alternative interpretation of the carbon-neutrality of biomass power could successfully increase the level of uncertainty as to the emission reduction benefits that can be realised from using biomass in electricity generation instead of fossil fuels [56].

Figure 4 compares the technology penetration of other scenarios in 2020 and 2030 against the Sustainable Policy Pathway (SPP), a least-cost scenario developed by the 'Energy Optimisation Calculator' which forms the basis of this study. The level of technology deployment in SPP is comparable to the Committee on Climate Change's High Renewable Ambition and that of National Grid's Gone Green scenarios. Capacity projections for technologies in Market Rules-FESA (Future Energy Scenario Assessment) show high levels of total CCS deployment capacity, that is 2.3 GW and 21.37 GW in 2020 and 2030, respectively (see Figure 4).This scenario is part of the transition pathways [13] and [57] concede that they are already becoming out of date. This assessment is contrary to the low capacity projection highlighted in the other three scenarios where CCS development is still at demonstration stage in 2020 and remains below 10 GW by 2030, as shown in Figure 2. CCS deployment ambition in 2030 show a similar trend of 8.9 GW and 10 GW in SPP and High Renewable Ambition' respectively, while the level of deployment in Gone Green is just 4.5 GW. It is quite interesting to note that the contribution of solar PV in the generation mix in Market Rules and the High Renewable Ambition scenarios is negligible if not zero both in 2020 and 2030. Its contribution in Market Rules is less than 150 MW by 2030 while in the High Renewable Ambition scenario is not accounted for at all. This technology is conspicuous by its absence from the two scenarios despite it being flagged as one of the eight key renewable energy technologies that can help to create a clean, balanced UK energy mix [34], a view that is shared and demonstrated by the other three scenarios exhibiting significant installed capacities, as shown in Figure 5.

Offshore wind capacity in 2030 reaches 31 GW and 40 GW in SPP and High Renewable Ambition, respectively, while in the Gone Green scenario, 31.9 GW capacity is deployed. The variation in installed capacities for emerging generation technologies (new nuclear and CCS), shown in Figure 4, is to some extent due to the impact of technology readiness which affects the time schedule of deployment [53]. All scenarios project high installed capacities for gas although the capacity level of 46 GW in 2030 for the High Renewable Ambition appears to be extraordinarily high especially if the plants are to be operated at extremely low load factors. There is no coal generation capacity in the Gone Green and SPP in 2030 whereas Market Rules and CCC scenarios still have coal (6 GW and 2 GW) installed capacities in their generation mix in 2030. This is mainly due to the uncertainty over the exact timing of the possible retirement of plants that have opted out of the LCPD [16]. Nonetheless, the residual coal capacity in the mix implies that the plants would have to be operated at uneconomically low load factors if the overall generation mix is to attain the 50 g/kWh carbon grid intensity. Furthermore, the operational economics of these plants would also have to take into account the costs accrued in achieving the IED pollution standard which allows them to play a role in the mix beyond 2023.

The economics of this sustainable policy pathway is assessed over the 2015 to 2030, the period to which the electricity sector is expected to transform due to increased investment in the infrastructure for a sustainable electricity future. The capital investment analysis focuses on the cost of building renewable and low-carbon capacities over this period. The cost analysis centres on solar PV, onshore wind, offshore wind, marine technologies, biomass, nuclear and fossil fuel and biomass with CCS. These technologies are central in building up to the 50 g/kWh carbon grid intensity by 2030. As shown in Figure 5, the level of capital investment for each of the technologies assessed mirrors the installed capacity portrayed in Figure 2. The least cost technology mix assembled for this decarbonisation programme would require an estimated capital investment of about £213.4 billion by 2030. This investment outlay surpasses the respective estimates of about £190 billion and £200 billion projected by the Committee on Climate Change and Ofgem for decarbonising the electricity supply system up to 2020 and through the 2020s [8], [58]. It is important to note that the investment estimate made by the Committee on Climate Change is consistent to electricity generation only while Ofgem's projection is directed towards the whole energy supply system. In the wake of the imminent closure of the UK's ageing electricity infrastructure, DECC envisages that up to £110 billion of capital investment is required from now until 2020 to replace the ageing capacity [59].

Offshore wind is the dominant technology by 2030 in terms of installed capacity and it accounts for 0.36 of the overall capital investment. New nuclear development by 2030 would require 0.2 of the low carbon investment budget while the financial investment for onshore wind and renewable CHP constitute 0.11 and 0.08 of the overall investment portfolio, respectively. Taking into account the technical constraints applied to solar PV, the installed capacity over this period would take about 0.05 of the estimated low carbon budget to establish this technology to the level shown in Figure 2. By 2030 CCS, wave and tidal technologies are fully commercialised but cumulatively, their build-up rates are still low as shown in Figure 2 and this is reflected in the low investment trend demonstrated in Figure 5.

The level of capital investment required to deliver a secure and a low carbon electricity sector is enormous, as shown by the share of expenditure for the technologies shown in Figure 5. The support mechanisms earmarked to attract investors to build the UK's low-carbon infrastructure to 2030 and beyond will be driven extensively by Feed-in Tariff with Contracts for Difference (FiT CfD) and other incentive instruments such as the RO and small scale FiT. The potential game changer in the future of low-carbon investment comes in the form of the 'strike price', a key element of the CfD mechanism which guarantees the payment of "a variable top-up between the market price and a fixed price level" [59]. The CfD contractual framework is designed to bolster investor certainty and a guaranteed return of investment. The 'strike price' for offshore wind and onshore wind projects commissioned in the period 2014 – 2016 is set at £155/MWh and £95/MWh, respectively [59]. Investment for large scale solar PV projects would be spurred by a £120/MWh strike price while developments of over 30 MW arrays of tidal and wave power will be commenced at £305/MWh for the 2014 – 2016 commissioning period respectively [59].

New nuclear strike prices are subject to negotiation between the government and the developers. As for the EDF Energy's Hinkley Point C, the UK's first potential new nuclear project, is set at £92.50/MWh or £89.50/MWh if the planned new nuclear power plant at Sizewell goes ahead and this will be contracted for a duration of 35 years for each of the two 1600 MW reactors [5], [60]. This agreement sets a precedent for future new nuclear development in the UK as it demonstrates the potential future and flexibility of the newly created market framework for low carbon technologies. The CfD mechanism as unveiled by the Electricity Market Reforms (EMR) is guaranteed to unlock investor finance desperately needed to develop the renewable and low carbon technology capacity required to decarbonise the electricity sector while ensuring secure and affordable energy supplies to consumers.

1.4 Conclusion

The electricity sector accounts for about 27% of the UK total greenhouse gas emissions. The UK is legally bound to reduce emissions by 80% against the 1990 baseline by 2050. To achieve this target, the government envisages that 40-70GW of new low-carbon generation capacity is required by 2030. This capacity is also anticipated to bolster the energy security challenges heightened by the imminent closure of coal and nuclear plants by 2023. The Committee on Climate Change insists that the carbon intensity of power generation needs to fall from the current 500 g/kWh today to 50 g/kWh by 2030. This would allow the sector to be almost completely decarbonised by 2050. This study has adopted the Committee on Climate Change's 'path to 50 g' emission projection to develop an optimal electricity generation mix with the scope to decarbonise the power sector while ensuring security of supply to 2050.

The results from the 'Energy Optimisation Calculator' highlight the indispensable role of nuclear, offshore wind and CCS in achieving the decarbonisation target set for 2030. In this respect, a 9.6 GW, 31 GW and 8.9 GW capacity contribution of new nuclear, offshore wind and CCS achieve the emission intensity of 50 gCO_2/kWh by 2030, respectively. The level of low-carbon and renewable energy penetration from 2015 to 2030 totals 18.5 GW and 66.2 GW capacity, respectively. The attainment of the 50 gCO_2/kWh grid intensity in 2030 has significant implications on assisting to achieve a near carbon neutral electricity generation system as well as meeting the legally binding 80% emission target by 2050. A transition pathway to a near carbon neutral electricity generation future demonstrated in this paper offers a limited role for unabated fossil fuel generation in the mix. While unabated gas installed capacity retains an average installed capacity of 26 GW in the period 2025 to 2050, its primary role is to offer system back-up to mitigate intermittent generation created by an increased build-up of variable electricity generation technologies in the mix.

The low-carbon scenario development espoused by this paper acknowledges the difficulty paused by uncertainty particularly over the future fuel prices as well as the technology investment cost on energy scenarios projected over long time horizons. To this end, a sensitivity study was undertaken to analyse the potential impact of this uncertainty on the three key technologies (nuclear, offshore wind and CCS) that are central to this the decarbonisation agenda. By virtue of being decarbonisation scenarios, the results from the sensitivity analysis indicated that any variation of either fuel or capital investment costs would not change the optimal capacity levels required to contribute towards decarbonising the electricity generation sector. While the generation mix is still going to retain significant amounts of unabated gas-fired generation from 2025 through to 2050, the plants will be under-utilized, hence the uncertainty over future gas prices and its likely impact on future energy projections is significantly limited. Unabated fossil fuel generation will be used in baseload generation plants fitted with CCS technology where future fuels prices would not affected the projected deployment capacities required to develop a near carbon neutral electricity generation infrastructure by 2050.

There is still uncertainty as to whether the projected capacities for emerging technologies can be delivered on time to decarbonise the electricity sector. However, the findings from this study suggest that the projected grid emission intensity in 2030 and beyond would be difficult to attain without offshore wind, nuclear and biomass and fossil-fuel with CCS. The variation in capacity projections across scenarios given in Figure 4, clearly highlight the level of uncertainty over the deployment feasibility of emerging technologies. These uncertainties mirror the level of difficulty inherent in determining the technology mix and pathway development that will help decarbonise the power sector while ensuring security and affordable supplies of energy in 2050. Despite these difficulties, the Sustainable Policy Pathway (SPP) provides the optimal possible technology mix that can be used to develop insights into the transition of the UK electricity to 2050. A high penetration of offshore wind is dependent on the cost falling to £100/MW [61] while CCS technical and economic viability still needs to be demonstrated at a commercial scale.

Nonetheless, the large scale deployment of low-carbon technologies (see Figure 2) from 2015 to 2030 will require an estimated total of £213.4 billion compared to the CCC's £190 billion estimate for the period up to 2020 and through the 2020s. As a result of the high penetration of CCS, nuclear and renewable technologies in the electricity generation mix after 2030, the grid carbon intensity reaches 5 g/kWh by 2050. The increased proportion of intermittent generation in the mix has huge implications on security of supply. However, as shown in the scenarios in Figure 5, unabated gas generation capacity is maintained at significant levels to provide back-up for intermittent generation. The installed gas generation capacity over the transition period is presumed to have little impact on emissions as plants would be run at very low load factors. However, this would need to take into account the potential impact of 'investment lock-in' [48] on new CCGT plants which could potentially promote their continual and maximum utilisation. Such a development could compromise on the government's decarbonisation policy ambitions. The results of this study indicate that the UK emission and renewable energy targets are achievable. However, this hinges on the ability of current and future policy to attract capital investment to build the level of low carbon technology required to transform the electricity generation infrastructure. It also depends on policymakers being mindful of the potential negative impacts that might arise from the deployment of large scale gas fired gas generation at a time when the power sector should be decarbonising.

1.5 Acknowledgement

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1.6 Appendices

Eq. (A.1), $y = 1.558x - 2816.7$

Eq. (A.2), $y = 0.000000001350e^{0.01234274x}$

Eq. (A.3), $y = 0.000000000042e^{0.01388205x}$

Eq. (A.4), $y = 5E + 76^{0.085x}$

Formulae. (A.5), $COE = \frac{I}{\left[\frac{(1+r)^n}{r(1+r)^n}\right]*E} + \frac{TOM}{E}$

1.7 References

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Table Captions

1.8 Figure Captions

1 Main components in the process flow of the 'Energy Optimisation Calculator'

2 Installed generation capacity – SPP

3 Electricity generation capacity – SPP

4 Comparison of the projected installed capacity 2020 – 2030, SPP and other scenarios

5 Low carbon-capital investment 2015-2030

1.9 Tables

Table 1. Projected UK electricity demand to 2050 [62]**.**

Year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Projected primary electricity demand (TWh)	345	324	303	301	344	388	362	369	377

Table 2. The UK electricity generation sector decarbonisation trend to a near zero Carbon emissions by 2050 [10]

Year	2020	2015	2020	2025	2030	2035	2040	2045	2050
Projected emission target ($MtCO_2e$)	157	131.4	63.5	26.9	20.7	10.3	5.9	3.4	1.9

Table 3. The projected local cost of fuel (£/GWh) [20], [62], [63]**.**

Year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	62434	51995	60,093	63,178	66,391	69,797	74,953	79,103	83,253
Gas	3,914	5,652	5,488	6,526	6,953	6,953	7,717	8,191	8,666
Wood Pallets	23,292	23,292	23,292	23,292	23,292	23,292	23,292	23,292	23,292
Uranium	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000

Table 4. The capital and operational cost inputs for the different technologies in the UK electricity generation mix.

Electricity generating technologies	Medium capital investment (£/kW)	Medium operation & maintenance (£/MW/y)	Data source
Wind Onshore (Nth of a kind)	1,596	75,396	
Wind Offshore (Nth of a kind)	2,851	181,773	
Renewable (Biomass) CHP	4,272	222,371	DECC, 2011
Hydroelectricity	2,417	88,462	
Biomass	2,532	152,289	
Pumped Storage	1,958	12,570	Parsons Brinckerhoff, 2011
Nuclear (1st of a kind)	4,428	94,688	
Biomass with CCS	4,118	131,092	
Gas CCGT (Nth of a kind)	599	22,655	
Gas CCGT with CCS (1st of a kind)	1,369	39,674	Parsons Brinckerhoff, 2013
Conventional CCGT CHP	618	47,214	
Coal(Pulverised Fuel, ASC with FGD)	1,954	60,602	
Coal CCS (Pulverised fuel, ASC, FGD-CCS)	3,354	120,383	Mott MacDonald, 2010
Wave	3,610	200,000	
Tidal	2,750	37,200	DECC, 2011
Solar PV (New built 250-5000kW	780	20,400	DECC, 2012

Table 5. Sensitivity study results on the impact of varying the cost of future investment and fuels.

Technologies	2025	2030	2035	2040	2045	2050
Gas CCGT baseline (scenario) capacity	29.8	28.7	26.4	24.1	24.1	24.1
Gas CCGT sensitivity capacity	32.7	28.7	26.4	24.1	24.1	24.1
Nuclear baseline (scenario) capacity	7	10.8	13	12.8	13.8	13.9
Nuclear sensitivity capacity	7	10.8	13	12.8	13.8	13.9
Offshore Wind baseline (scenario) capacity	27.1	31	30.7	30.7	31.7	31
Offshore Wind sensitivity capacity	27.1	31	30.7	30.7	31.7	31

Total CCS baseline(scenario) capacity	4	9.2	13.6	14.8	14.7	15.7
Total CCS sensitivity capacity	4	9.2	13.6	14.8	14.7	15.7

1.10 Figures

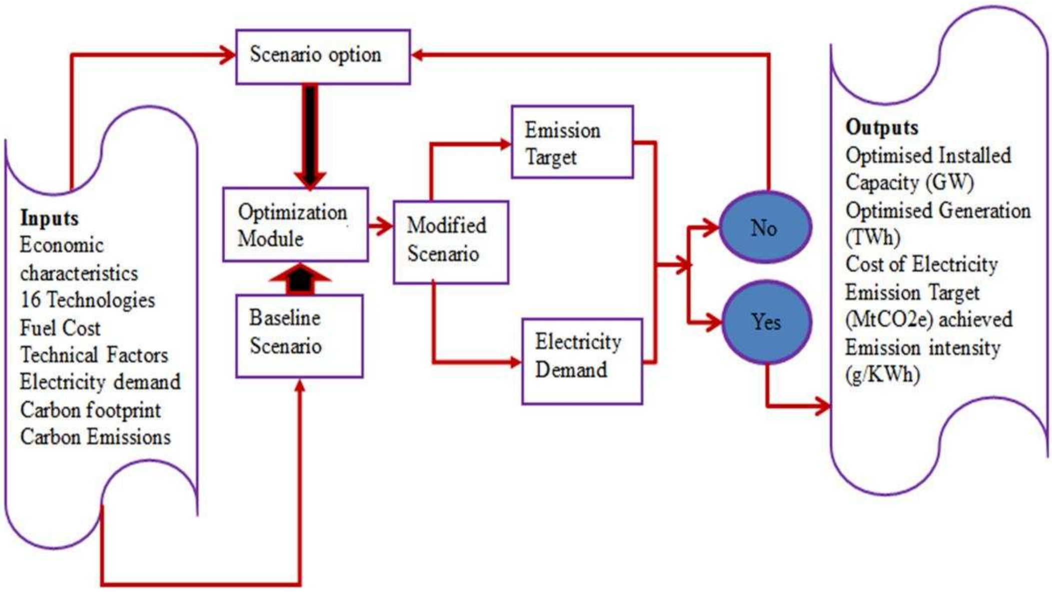

Figure 1. The main components in the process flow of the 'Energy Optimisation Calculator'.

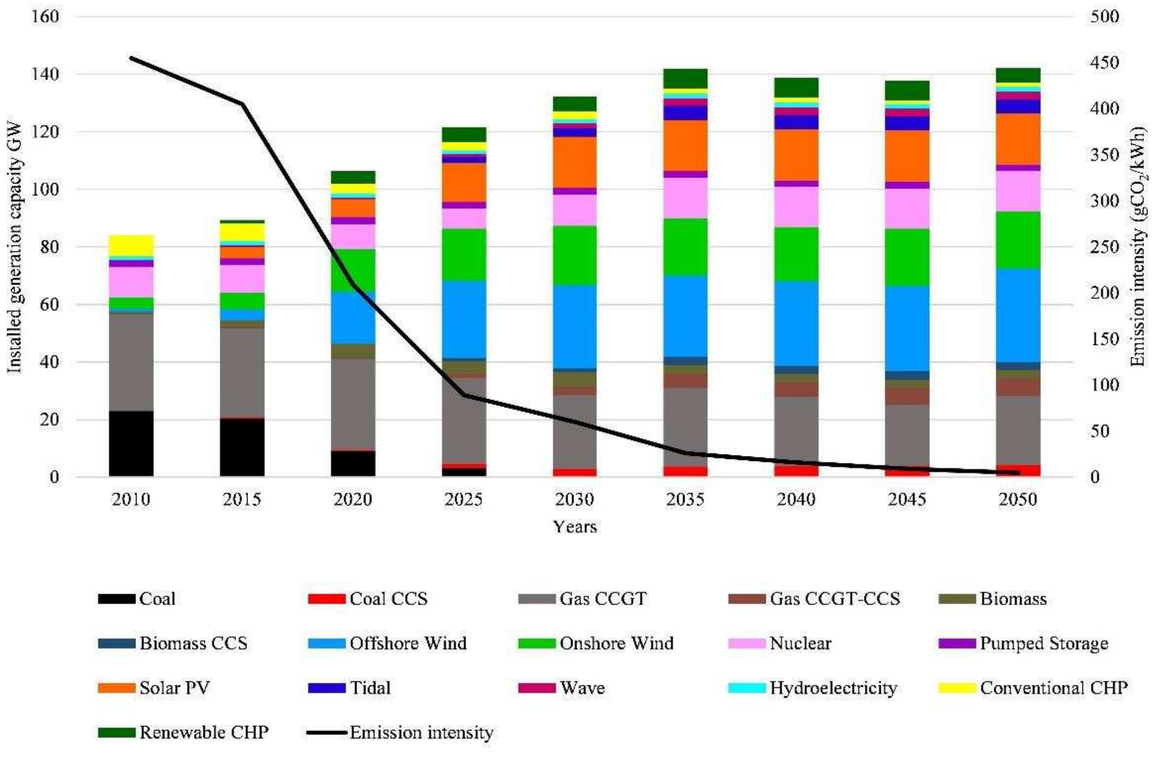

Figure 2. The installed electricity generation capacity for the SPP from 2010 to 2050.

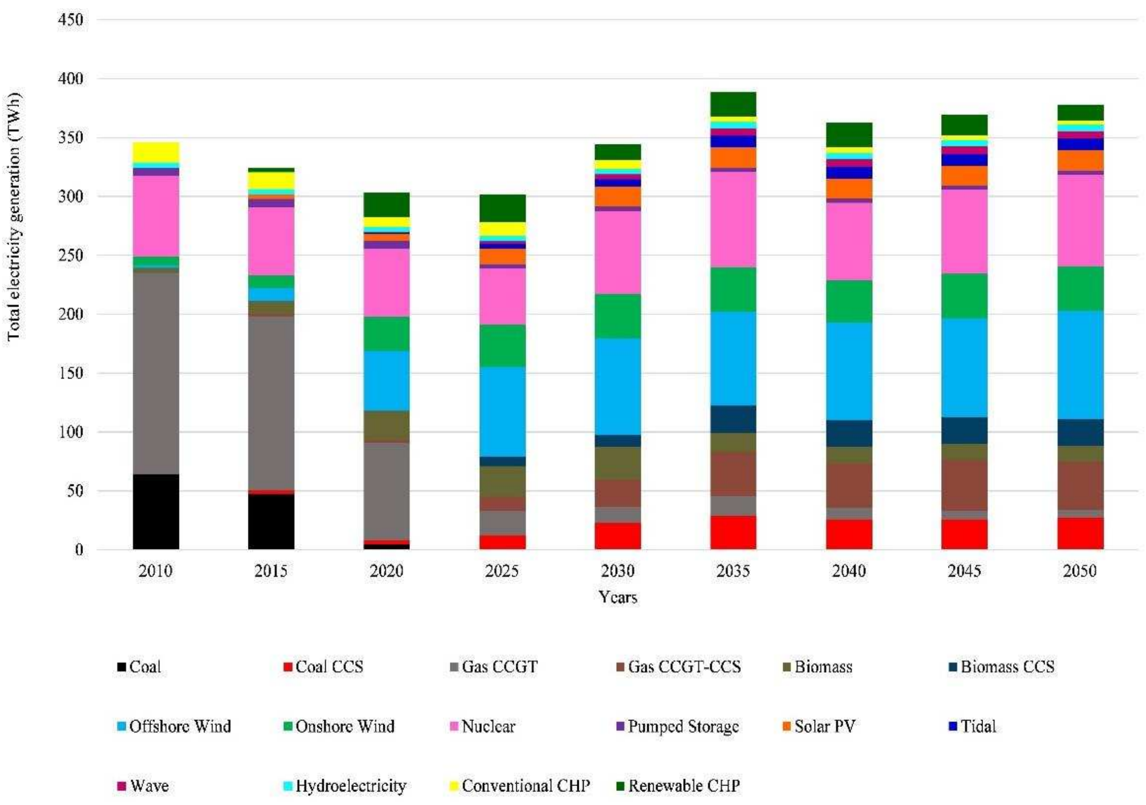

Figure 3. The electricity generation profile for the SPP from 2010 to 2050.

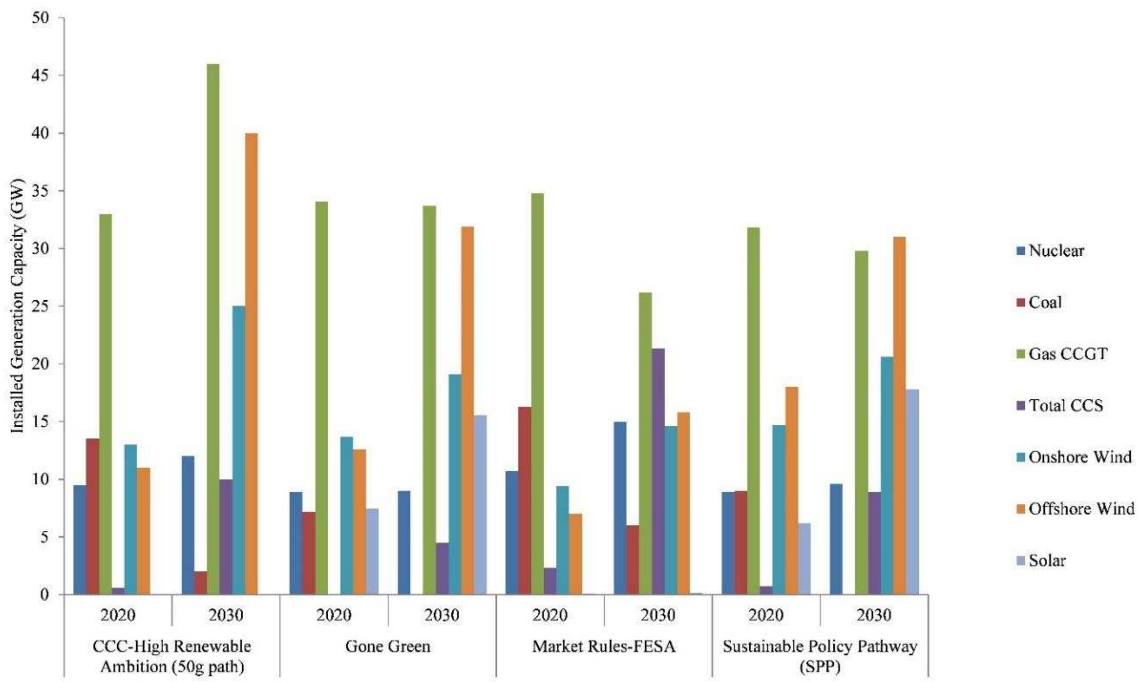

Figure 4. A comparison of the projected installed capacity for the SPP and other scenarios from 2020 to 2030 [10], [46], [64]**.**

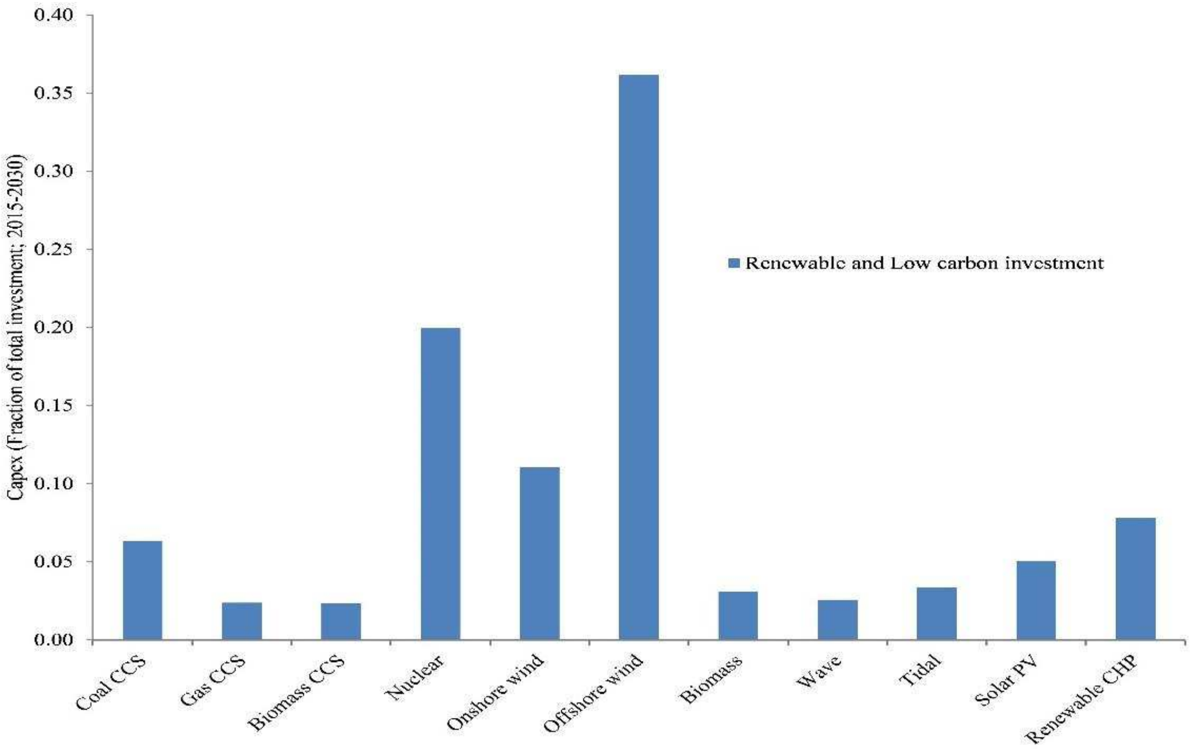

Figure 5. The capital investment outlay for the low-carbon technology deployment in the period 2015 to 2030.