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Article

Projecting the UK's future electricity supply mix: A tool for generating future energy scenarios

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Abstract: This paper explores the features and choices available to decision-makers through the development of an Excel-based 'future scenarios' tool. The tool acts as a database for existing energy supply/demand scenarios and allows the user to look up existing scenarios or mix and match existing scenarios for the UK leading to a range of new possibilities. The benefits of creating and using the developed tool are explored within the paper and it is concluded that this approach begins to address the complex issues of projecting the most appropriate electricity supply mix and electricity demand by using a range of existing energy studies. In so doing it facilitates greatly decision-makers in beginning the process of further assessing the risks that might be involved. An example of using the tool for developing three very different supply mix scenarios for the UK (including one with high share of interconnections) is provided.

Keywords: demand projection; electricity supply mix scenarios; Excel-based tool; interconnections

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1. Introduction

Growing energy demands and climatic changes are two major global issues facing developed and developing nations. Anthropogenic concentrations of CO_2 in the atmosphere have been increasing over the past century; the 2005 concentration (379 ppmv) was about 35 % higher than in the mid-1800s (OECD/IEA 2012) and there is consensus amongst scientists that this is linked directly to our warming climates. Continually growing world energy demands and the combustion of fossil fuels has undoubtedly been a major source of CO_2 in the atmosphere and this thirst for energy is projected to increase by one-third between 2010 and 2035 (OECD/IEA 2011). Undoubtedly this is due in no small part to the world's rate of population growth and substantial global economic development in new emerging markets (Yusaf, Noor et al. 2013). In the UK alone, electricity demand is projected to increase by up to 40 % by 2030 (CCC 2011). The question remains as to how these demands will be met when so many nuclear power stations are reaching the end of their design life and being decommissioned (all but one of UKs' currently operating plants will be closed by 2023).

In part fulfillment of this requirement, ongoing research is being conducted looking at supply/ demand scenarios that seek to match future energy demands with energy supply mixes. This requires energy providers to foresee the impact of various electricity generation scenarios on CO_2 emissions and to assess the sustainability of, and risks involved with, each so that an attitude of energy provision 'whatever the cost' does not prevail. Various notable UK projections exist which look at this area of scenarios analysis (e.g. DECC (2011), Cambridge Econometrics (2011), Poyry (2008), CCC (2011), Dagoumas and Barker (2010) and National Grid (2011)). Decision-making in the face of a plethora of electricity supply mixes and/or energy demand predictions is a complicated procedure which requires in depth consideration of the various scenarios that are being developed. This requires a high level of knowledge that is available only within a team of experts that are well versed on the various techniques of future scenarios analysis. For decision-makers what is missing is a tool that allows switching between a range of supply/demand scenarios (for direct comparison) and a 'cherry picking' option to allow alternative approaches together with associated CO_2 emissions and costs to be considered.

In part fulfillment of this requirement an Excel-based tool has been developed, which will be explored further, through the use of carefully selected examples, within this paper.

2. Methods and Implementation

This section describes the 'input' (Section 2.1) and 'output' (Section 2.2) features within the tool and elucidates further on the choices which are available to end-users. A detailed overview of the tool with appropriately selected figures is given throughout.

2.1. Inputs

The input requirement within the excel tool consists of six distinct steps as shown in Figure 1 and described below. Drop down menus are used throughout and these are indicated by the ▾ symbol.

STEP 1 - This step allows the user to select the year of projection; three options (i.e. 2020, 2030 and 2050) are available that are sufficiently far enough in advance of today to allow for short medium and long term decisions to be made. Moreover they are in line with where national and international policy requirements have been drawn up.

Figure 1. STEP 1 to 6 in excel based scenarios tool.

STEP 1 - Select year of projection:

Year: 2020

STEP 2 - Select scenario(s) for supply:

Technology:	Reference (Year)
Marine	NG3 (2012)
Nuclear	ENSG (2012)
Offshore Wind	Butler1 (2012)
Onshore Wind	Barnacle2 (2012)
Hydro	Dagoumas1 (2010)
Pumped Storage	Chaudry1 (2011)
Biomass	Energynautics3 (2011)
Gas	DECC1 (2011)
Gas+CCS	Dagoumas4 (2010)
CHP	Poyry1 (2010)
Coal	Grubb (2006)
Coal+CCS	Mott MacDonald1 (2011)
Oil	Barnacle (2012)
Interconnections	OFGEM (2010)

STEP 3 - Select scenario for demand:

Demand: Energynautics2 (2011)

STEP 4 - Rank priority (1 to 14) then select % contribution:
(equal priorities cannot be assigned to technologies).

Technology:		2020	2030	2050
Marine	2	0%	0%	4%
Nuclear	11	14%	17%	0%
Offshore Wind	14	0%	12%	36%
Onshore Wind	4	12%	15%	16%
Hydro	5	2%	2%	1%
Pumped Storage	6	2%	1%	1%
Biomass	10	3%	6%	0%
Gas	12	15%	11%	0%
Gas+CCS	7	0%	12%	16%
CHP	9	11%	10%	1%
Coal	1	34%	0%	0%
Coal+CCS	8	4%	8%	17%
Oil	13	0%	0%	0%
Interconnections	3	4%	5%	7%
Sum		100%	100%	100%

STEP 5- Select criteria for capital cost:

Capital Costs: Renewable

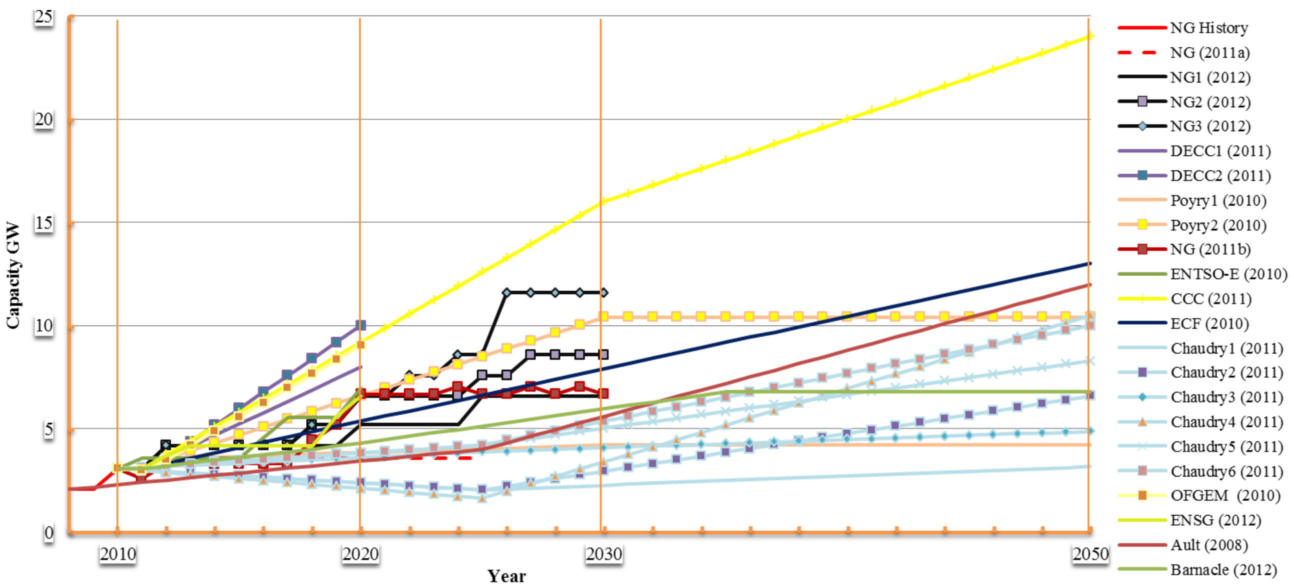
STEP 6 - Select criteria for CO emissions:

CO_2 Scenario: High-end

STEP 2 - The step allows the user to select a scenario for each of 14 likely future macro-scale technologies based on categories stipulated by National Grid (2011). PV systems are excluded from the list as they are considered micro-scale for domestic use in the UK and there is no solar farm in the country at the moment. The selection(s) can be from one source or multiple sources (Figure 1).

In total some 50 scenario sources are currently available to the end-user and this list can be added to as more scenarios become available. In so doing the tool can remain relevant and upgradeable for decision-makers both now and in the future. In terms of interconnections over 23 scenario studies are included within the tool (Figure 2).

Figure 2. Considered studies for projecting the share of interconnections



It is possible through the use of the tool to identify the highest achievable share of interconnections within the UK up to 2050. As it is shown in Figure 2 the highest capacity of interconnections is projected by CCC (2011) and this is more than twice other projections – this is because they declare relatively small costs associated with interconnection compared to generation costs and they perceive increased interconnection, even in scenarios with low renewable generation, with European and Scandinavian systems. The current capacity of interconnections in the UK is around 4 GW (National Grid 2011 Table F.13).

STEP 3 – This step allows the user to select the scenario for energy demand (up to the year being considered).

STEP 4 – In this step the demand option is balanced with the supply option (this includes additional spare capacity required within the network – see later). In order to do this efficiently the technologies must firstly be prioritized (by use of drop down menus) according to their relative importance – in other words a technology with high priority (1) would be considered to be the preferred option for UK (Coal is assigned 1 in Figure 1). Likewise a technology with low priority (14) would be considered the least preferred option for UK. The table automatically indicates % share of supply that is available / required from each technology for 2020, 2030 and 2050. The % assignment is based on two criteria:

1. Firstly, its availability, which depends on the selected scenario study chosen in STEP 2; Equation (1) is applied to each technology previously selected in STEP 2:

   $$\text{Technology (\%)} = \text{(Projected capacity)} / \text{(Selected demand projection} \times \text{Plant Margin)} \qquad (1)$$

2. Secondly, the percentage selected *ibid*. For example if coal is Priority 1 with a 34 % share selected (Figure 1), 66 % is then available for Priority 2 to 14. If marine is then selected as Priority 2 with 0 % then 66 % is still available for Priority 3 to 14 etc.

[Plant margin is defined as: the amount by which the total installed capacity of directly connected power stations and embedded large power stations and imports across interconnections exceeds the demand and is often expressed as a percentage of the peak demand (National grid 2013). The plant margin is used in a grid to meet any demand fluctuation, scheduled and unscheduled maintenance of power plants and also the renewables intermittency. Therefore, the estimation of plant margin is complicated and requires consideration of various parameters and will change according to the overall share of renewables. For simplicity in this research a fixed value of 40 % is selected based on historical values from the National Grid.]

STEPS 1 to 4 help ascertain (based on existing scenario studies) what possible future mixes of supply might be available in order to meet projected demands. To further help decision-making two vital parameters for future performance are considered, namely; Level of CO_2 emissions (STEP 5) and Capital cost (STEP 6). Table 1 shows the associated references used for each technology adopted:

STEP 5 – This step allows the user to select options for capital cost; based on the work of Mott MacDonald (2011); these are referred to as 'Renewable', 'Balanced effort' or 'Least cost'. Table 2 shows the respective costs according to technology type. [The reported costs are largely driven by differential learning rates and deployment projections. This contrasts with fuel and carbon costs, both which are generally projected to be on upward trajectory. The cost estimates include contractors' contingencies but not developers' own contingencies. In addition they exclude land costs and any additional site preparation costs. Interest during construction is excluded but includes any market "congestion premium" or discount in the case where prices deviate from level that would return a normal profit to equipment and service providers.]

STEP 6 – In this step the user can select options for CO_2 emissions; based on the work of (Kharecha et al. (2010) the choices are 'high-end' and 'low-end'. The High-end scenario gives higher life-cycle emissions compared to the "low-end" scenario. Table 1 shows the associated references used for each technology adopted. In order to select and rank the technologies in terms of Carbon emitted per GW produced a Pollution Factor (Equation 2) is required for each (Table 3).

$$\text{Pollution Factor} = \text{Life-cycle GHG emissions } (tCO_2eq/\ GWh) \times \text{Load Factor} \quad (2)$$

The life-cycle greenhouse gas (GHG) emissions are 'cradle to grave' (i.e. from construction to decommissioning and therefore includes maintenance periodic component replacement plus machinery use). The initial "emergy" (intrinsic energy stored in raw materials) also known as embodied energy has been excluded (Kharecha, Kutscher et al. 2010).

Load factor refers to the typical % of time that energy can be sourced, this is only 30 % for wind (as wind speeds can fluctuate by the second – and when wind speeds are low, no energy is produced – likewise if speeds are too high electricity production is halted to safeguard wind turbines). For power stations there is no reliance on wind speeds just fuel – hence values are high. Where technologies have the same Pollution Factor (e.g. offshore and onshore wind) the technology with the higher projected capacity is typically selected to have the higher share of meeting demand and therefore achieving reduced levels of CO_2 emissions.

Table 1. Performance indicators used within scenarios tool

Performance Indicator	Technologies	References adopted
CO_2	Coal, Oil, Gas, Hydro, Geothermal, Biomass, Onshore and offshore Wind, Solar, Nuclear,	(Kharecha, Kutscher et al. 2010)
	CHP	(Matthes, Graichen et al. 2005)
	Pumped storage	(Weisser 2007)
	Marine	(Reeves and Watson 2011)
	CCS (Gas and Coal)	(Kharecha, Kutscher et al. 2010)
Capital Cost	Onshore and offshore Wind, Marine, Hydro, Solar, Geothermal, Nuclear, CCS (Coal and Gas), Biomass	(Mott MacDonald 2011)
	Gas, CHP, Coal	(Mott MacDonald 2010)
	Oil	(Kannan 2009)
	Pumped storage	(Parsons Brinckerhoff 2011)
	Interconnection	-
Risk and uncertainty	Scenarios	(Palisade Corporation 2012)

Table 2. Technologies ranked according to projected capital costs in 2020 (References in Table 1).

Technologies	Capital costs (£/kW)	Rank
Gas	90	1
CHP	110	2
Coal	270	3
Interconnections	480	4
Oil	650	5
Gas + CCS	870	6
Onshore Wind	1,190	7
Hydro	1,850	8
Pumped Storage	1,870	9
Offshore Wind	2,110	10
Coal + CCS	2,230	11
Nuclear	2,450	12
Marine	2,630	13
Biomass	3,390	14

Table 3. Technology pollution factors

Technology:	Life-cycle emissions (tCO_2-eq/GWh)	Load Factor (%)	Pollution Factor	Ranking
Onshore Wind	9.5	30	3	1
Offshore Wind	9.5	30	3	1
Pumped Storage	36	15	5	2
Marine	20	25	5	2
Biomass	48	53	26	3
Hydro	86	40	34	4
Nuclear	57	90	51	5
Gas + CCS	110	90	99	6
Coal + CCS	118	90	106	7
CHP	474	92	436	8
Oil	771	90	694	9
Gas	1100	90	990	10
Coal	1180	90	1062	11

For references related to emissions see Table 1

Load factors are adapted from (ENVIROS Consulting Limited 2006; Douglas, Harrison et al. 2008; Ipakchi and Albuyeh 2009; DECC 2011)

The format of the tool means that additional steps can easily be developed for decision-makers depending on local priorities and local conditions (Hunt, Lombardi et al. 2008) – a key thread of any sustainability policy. For example, STEP 7 could help decision-maker assess 'risks' and 'uncertainties' associated with various scenario choices and be linked with capital cost(s) and CO_2 emission(s), as possible risk impacts. The Excel add-in '@Risk' provides a robust platform for such purposes. [As part of this research project a methodological approach is being developed to help quantify risk (through one-to-one interviews with key energy stakeholders). It is hoped that this will identify the key risks associated with each particular technology and provide a framework for assessment of its appropriateness either for direct adoption or interconnection (and the appropriate nation for this to take place).]

2.2. Outputs

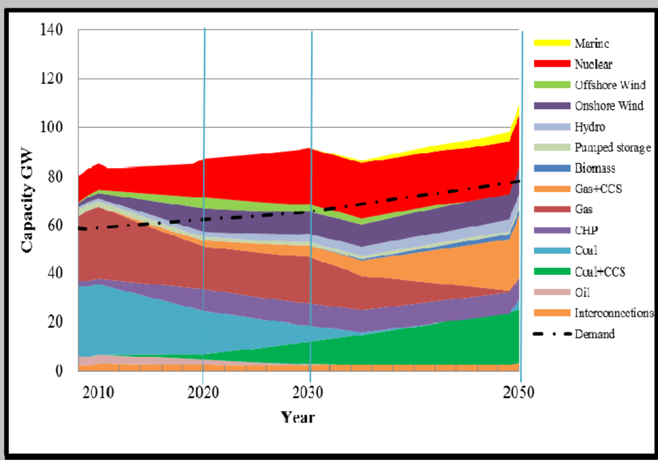
The advantages of using excel is that outputs (Figure 3) that will facilitate decision-making for both supply and demand of energy can be displayed instantaneously without the need for analysis time. Output 1 provides a summary of the supply potential (in GW) for each technology, the total demand, related emissions and cumulative capital costs in 2010, 2020, 2030 and 2050. The trends can then be seen in Stacked-Area charts in Output 2 to 4. The 1990 level of CO_2 emissions is presented in Output 3 for direct comparison.

Figure 3. Scenarios tool outputs

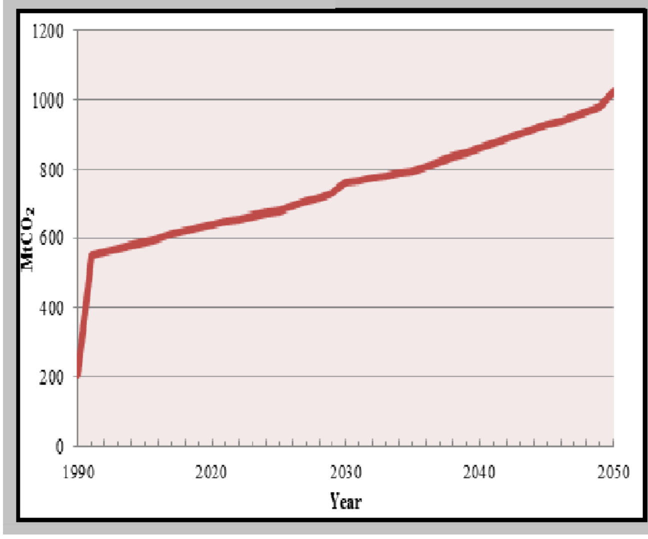
OUTPUT 1: Summary

		2010	2020	2030	2050
Capacity (GW)	Marine	0.00	0.00	0.00	4.00
	Nuclear	10.84	15.84	23.00	21.57
	Offshore Wind	1.20	4.47	3.01	0.00
	Onshore Wind	2.29	9.40	9.15	10.92
	Hydro	1.12	2.27	3.42	5.00
	Pumped Storage	2.30	1.72	1.39	1.22
	Biomass	0.00	0.00	0.00	2.38
	Gas	29.60	17.41	19.00	0.00
	Gas+CCS	0.00	2.40	4.80	26.00
	CHP	2.24	9.00	9.00	8.90
	Coal	28.80	17.68	6.56	4.00
	Coal+CCS	0.00	2.30	9.15	22.00
	Oil	3.64	2.18	0.73	0.00
	Interconnections	3.07	2.38	2.27	3.17
Demand (GW)		59.03	62.18	65.33	77.97
CO_2 Emissions (tCO2-eq)			363.62	285.03	126.47
Capital Cost cumulatively (£ bn)			44.42	81.37	140.09

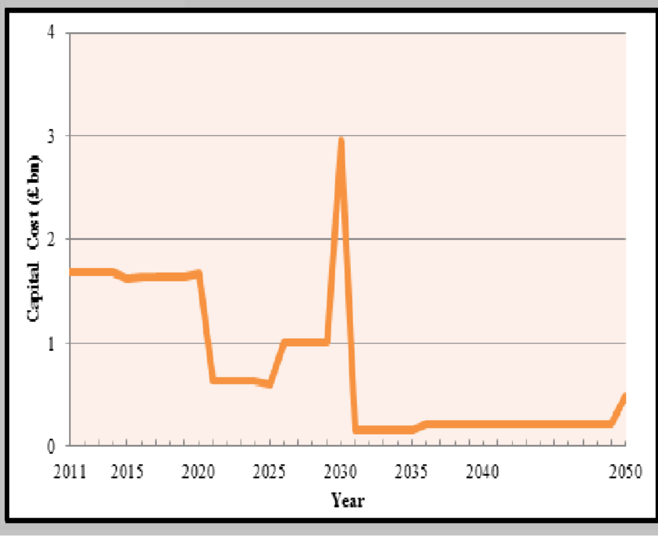
OUTPUT 2: Supply and Demand mix



OUTPUT 3: CO_2 emissions



OUTPUT 4: Capital costs



3. Example: Using the future scenario tool to generate 3 new scenarios.

In order to investigate the outcomes and implications of the developed tool, three new energy scenarios are developed for the UK namely;

- Scenario 1- High share of renewable energy achieving low CO_2 emissions.
- Scenario 2 - High share of fossil fuels with low cost.
- Scenario 3 - High share of interconnections.

Figure 4 shows the references selected within STEP 2, these are then applied to all three scenarios. Figure 5 shows the different prioritization given in STEP 4 for each of the three scenarios. The graphical output for each scenario is shown in Figure 6a to 6c. A discussion of each scenario is given:

3.1. Scenario 1

As this scenario seeks to maximize use of renewable(s) whilst reducing low CO_2 emissions technologies are prioritized in STEP 4 (Figure 5) according to the pollution factors and rankings given previously in Table 3.

Figure 4. STEP 2 in Scenario 1 to 3

STEP 2 - Applicable to scenarios 1 to 3

Technology	Reference (Year)
Marine	UKERC1 (2009)
Nuclear	Butler2 (2012)
Offshore Wind	UKERC1 (2009)
Onshore Wind	Barnacle1 (2012)
Hydro	Dagoumas2 (2010)
Pumped Storage	Barnacle (2012)
Biomass	Energynautics3 (2011)
Gas	Dagoumas1 (2010)
Gas+CCS	Butler (2012)
CHP	Barnacle3 (2012)
Coal	Chaudry1 (2011)
Coal+CCS	UKERC4 (2009)
Oil	Dagoumas2 (2010)
Interconnections	CCC (2011)

Figure 5. STEP 4 in Scenarios 1 to 3

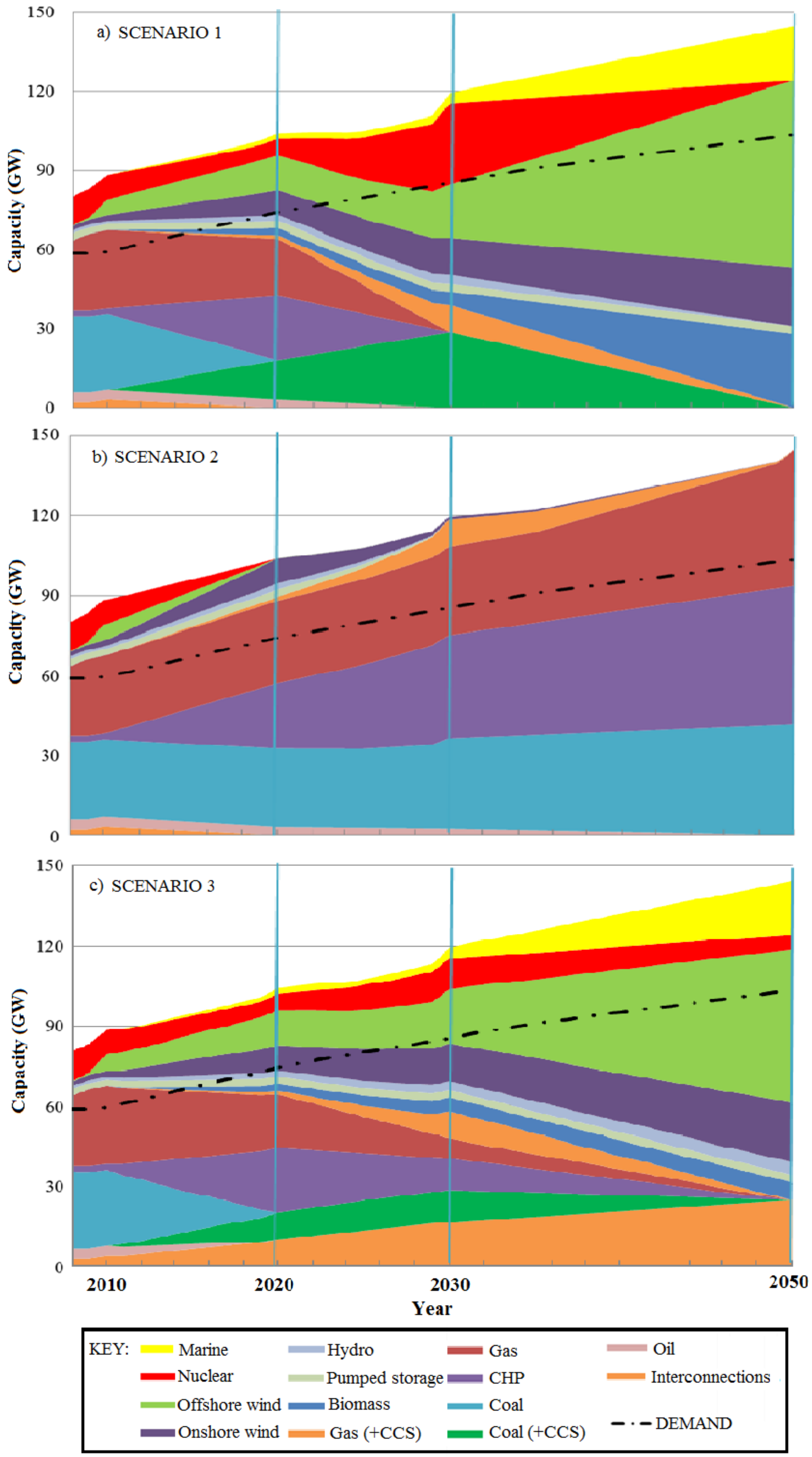
	STEP 4 - Scenario 1				STEP 4 - Scenario 2				STEP 4 - Scenario 3			
Technology		2020	2030	2050		2020	2030	2050		2020	2030	2050
Marine	3	2%	3%	14%	12	0%	0%	0%	5	2%	3%	14%
Nuclear	7	6%	26%	0%	11	0%	0%	0%	8	6%	10%	4%
Offshore Wind	1	13%	17%	49%	9	0%	0%	0%	2	13%	17%	40%
Onshore Wind	2	9%	12%	16%	6	9%	1%	0%	3	9%	12%	16%
Hydro	6	2%	3%	0%	7	2%	0%	0%	6	2%	3%	3%
Pumped Storage	4	3%	2%	2%	8	3%	0%	0%	7	3%	2%	2%
Biomass	5	3%	4%	19%	13	0%	0%	0%	4	3%	4%	5%
Gas	12	21%	0%	0%	1	30%	28%	35%	12	19%	6%	0%
Gas+CCS	8	1%	9%	0%	5	1%	9%	0%	10	1%	9%	0%
CHP	10	23%	0%	0%	2	23%	33%	36%	9	23%	10%	0%
Coal	13	0%	0%	0%	3	28%	28%	28%	13	0%	0%	0%
Coal+CCS	9	15%	24%	0%	10	0%	0%	0%	11	10%	10%	0%
Oil	11	3%	0%	0%	4	3%	2%	0%	14	0%	0%	0%
Interconnections	14	0%	0%	0%	14	0%	0%	0%	1	9%	13%	17%

It can be seen that the market share of offshore and onshore wind power is gradually increased from 21 % (combined) in 2020 to 65 % (combined) in 2050. At the same time Biomass is increased to 19 % by 2050 whilst phasing out all fossil-related fuel supplies. Figure 6a shows more clearly this gradual change in use of supply technologies from fossil based fuels to renewable in the forty year period 2010 to 2050. In this scenario interconnections are not considered highly desirable in terms of ensuring a security of supply for the UK and hence they are ranked 14 and not adopted. In all cases plant margin has been factored in to ensure the supply-demand balance is maintained.

3.2. Scenario 2

The main driving force for developing this scenario is low capital cost. Hence the technologies in STEP 4 (see Figure 5) are preferentially adopted and therefore ranked in line with meeting this aim (i.e. cheapest option is ranked 1 and most expensive option is ranked 14). This scenario draws its ideology from the study by Mott MacDonald (2011) and costs are drawn directly from Table 2. It can be seen that two fossil fuel supply options (gas and coal, Figure 6b) are used to power the UK's electricity through existing and new gas and coal powered stations. These are supported by localized initiatives for district heating and electrical power generation in the form of CHP – which due to widespread policy-based initiatives sees a tremendous boost in its market share. When considering that most CHP units are gas fired the reliance on gas dominates in 2050. The share of offshore and onshore wind fails to gain any substantial market share, due to many local and external factors. Once again interconnections are overlooked as being a cost-effective means of meeting demands.

Figure 6 – OUTPUT 2 – Scenario(s) 1 to 3



3.3. Scenario 3

Figures 6c presents the share and mix of technologies for a scenario that seeks to adopt a much higher market share of interconnections (highest priority with a ranking of 1 in STEP 4, see Figure 5). It can be seen that in 2050 offshore wind has the highest market share with 40 % followed by interconnections with 17 %. This assumes that the share of interconnections grows steadily from 9 % market share in 2020 to 17 % share in 2050. This is based on the projections from CCC (2011) which assumes 24 GW interconnected supply is possible by 2050. This is the highest possible capacity of interconnections found within any of the scenario studies considered here. Moreover, it assumes that all fossil fuel supplies are phased out and are replaced by renewable, which become more widely accepted (in-particular wind) and hence adopted. The positive impact of developing new interconnections is expected to have played a significant role in incentivizing increased renewable adoption.

3.4. Comparing developed scenarios

The key comparison of the three example scenarios are presented in Table 4. It can be seen that the demand in all three scenarios is assumed identical and only the supply options have been changed. In this specific case the lowest cumulative capital cost (£31 billion) for the time period considered is in Scenario 2. However, the trade-off is that the emissions are not kept in check and are > 1000 times that of Scenario 1. Whilst interconnections are not considered as an option for reducing UK emissions in Scenario 1 it is surprising then that Scenario 3 actually has the lowest annual emissions of any scenario considered here. In addition it has lower capital cost compared to Scenario 1.

Table 4. Comparing three developed scenarios

Scenario	**Annual Demand (GW)**	**Annual CO_2 Emissions ($MtCO_2$-eq)**	**Cumulative Capital Cost Up to 2050 (£ bn)**
Scenario 1 – Renewable(s)	103.30	9.65	402.21
Scenario 2 – Fossil Fuel(s)		1025.39	31.02
Scenario 3 – Interconnection(s)		8.98	254.78

Ironically the reduction in CO_2 emissions within this ‘Interconnections’ scenario could be very misguiding as it can be argued that emissions are just being transferred to other member states. Alternatively perhaps it highlights important considerations for another scenario, not yet considered. This scenario perhaps should adopt only interconnection that enhance overseas renewable adoption.

The examples presented here show how an energy-based scenario tool can be used by decision-makers to contrast and compare scenario choices depending on the factors they consider to be most important. It also highlights the trade-offs that may have to be made along the way. The examples could just have easily looked at any of the following, and these are not meant to be an exhaustive list.

1) A scenario which strongly incentivizes only new markets;

2) A scenario which provides maximum storage capacity;

3) A scenario which addresses renewable intermittency issues.

4. Conclusions

This paper described briefly research into the development of an Excel-based tool for generating energy scenarios for the UK. The developed tool shows great potential as a research tool, firstly because it provides a database for selecting projections of future electricity demand and electricity supply mix within the UK. Secondly, as shown in this paper, it can be used to generate new electricity supply mix scenarios (by cherry picking previously developed scenarios) whilst considering the implications on (i) CO_2 emission and (ii) Capital cost. These attributes, in particular the technology ranking system, are extremely valuable for decision-makers within the energy sector who wish to compare / contrast the plethora of energy related scenarios that are in existence and select a viable supply demand mix.

Conflict of Interest

The authors declare no conflict of interest.

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