System Level Cost and Environmental Performance of Integrated Energy Systems: An Assessment of Low-Carbon Scenarios for the UK

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Abstract — **Driven by the need for actions to successfully fight and prevent the consequences of climate change, the concept of integrated energy (or multi-energy) systems is receiving increasing interest across the world. This concept includes optimal integration of multiple energy infrastructures such as for electricity heat, gas, and so on, partial electrification of heat and transport, and a shift of energy sources from fossil fuels to renewables. However, while several low-carbon integrated energy scenarios are being proposed, there is often a lack of clear assessment of their true cost and environmental performance when also considering the multi-energy infrastructure implications. In this light, this paper investigates the system performance of different UK future scenarios that have been proposed for 2035 from technical, environmental and economic points of view. To do so, a model that can simulate these different future scenarios with detailed analyses of the integrated energy interactions has been created in the EnergyPLAN tool. In addition, in order to truly understand the infrastructure techno-economic implications, which are often overlooked or not dealt with in sufficient depth, EnergyPLAN has been coupled to a tailor-made tool that assesses multi-energy (electricity, heat and gas) infrastructure requirements. The results are used to comprehensively illustrate the impact of integrated energy planning strategies with a broad range of low carbon technologies.**

Index Terms — **Multi-energy systems, Energy system integration, EnergyPLAN, Infrastructure planning, Low carbon technologies.**

I. INTRODUCTION

Following the need for reducing greenhouse gas emissions (GHG) and achieving a low-carbon energy system, a number of environmental targets have been set up in many countries around the world and relevant future scenarios have been put forward. In the UK, in particular, the targets set by the Department of Energy and Climate Change (DECC) [1] are to reduce greenhouse gas emissions by 80% relative to the 1990's level by 2050, with a massive shift from fossil fuels to renewables. While there are numerous discussions around the challenges of achieving this goal, several paths can be investigated to reduce GHG emissions such as increasing rapidly the renewable energy sources (RES) installed capacity, electrifying heat and transport, building Carbon Capture and Storage (CCS) facilities, exploiting combined heat and power (CHP) at different levels, and so on. It is likely that a combination of these technologies will eventually be needed to provide the necessary operational and planning flexibility to meet the targets. In this context, integrated energy systems (or multi-energy systems [2]) planning as opposed to considering separate energy sectors (electricity, gas, heat, transport) as mostly currently done will play a key role in order to ensure a cost effective deployment of the most appropriate low carbon technologies (LCT) for the whole system. It is also likely that the flexibility gained by interaction of electricity with other energy vectors and heat in particular will improve the business cases for LCT [3][4][5] while also facilitating the integration of RES [6].

Amongst the various scenarios proposed in the UK, two sets of pathways were created by National Grid (the UK transmission system operator) and DECC in order to investigate the consequences of different decarbonisation strategies. More specifically, a 2050 Pathways Calculator that can estimate different scenarios performance was created by DECC [1], and in order to satisfy the government requirements, six pathways were eventually identified. At the same time, four scenarios created by National Grid [7] show the progression from now to 2035 in terms of possible system evolution depending on various boundary assumptions.

In this work we will focus on the scenarios proposed by National Grid, as they may be of particular interest from an infrastructure perspective. However, although they provide substantial information about possible futures of the UK energy system, economic aspects are not sufficiently discussed in the analysis. In particular, as a number of combinations of LCT can yield plenty of choices to meet the government requirements, economic aspects and infrastructure utilization and need for investment become an important decision factor to compare available pathways. In spite of this, no analysis is available that assesses the overall techno-economic and

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environmental performance of the proposed integrated energy systems scenarios, including the implications for the multi-energy infrastructure.

In the light of the above, this paper aims to develop an analysis of the proposed scenarios for the UK system as a whole which takes both environmental and economic aspects into account, and considering multi-energy operational and infrastructure implications. This is done by using the well proven EnergyPLAN software tool [8] for integrated energy systems analysis. However, since the tool does not take into account networks and the relevant technical and economic implications of different scenarios, a specific model, implemented in Matlab-Excel VBA, has been developed which based on EnergyPLAN's operational results estimates the relevant infrastructure (electricity, heat and gas, in the specific case) requirements and the associated costs. The final results, which will be fed back to National Grid, will thus allow a more comprehensive quantification of how different LCT can contribute to deliver low carbon energy systems at an affordable cost and while minimising infrastructure impact or changes.

This paper is organised as follows. First of all, the methodology introduced to estimate the environmental and economic performance is presented. Following the methodology, the four pathways modelled after National Grid's 2035 Future Energy Scenarios are simulated and the case studies are detailed and discussed.

II. Methodology

To investigate the integration of LCT into the UK system under various scenarios, a techno-economic assessment model was developed. Both economic and environmental performances are modelled to analyse the UK energy system. As indicated before, EnergyPLAN is interfaced with a Matlab-Excel VBA model and the framework is shown in Figure 1. In particular, the interface gathers the output from EnergyPLAN as the input of the Matlab-Excel VBA Model for the infrastructure cost analysis.

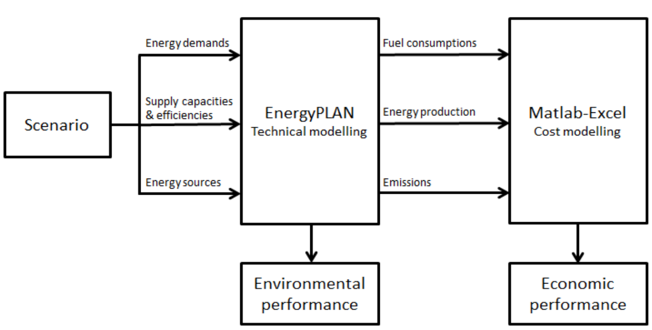

Figure 1. EnergyPLAN/Matlab-Excel Framework

A. Technical analysis

EnergyPLAN is an integrated energy system tool [9] which incorporates a broad range of technologies (biomass conversion, RES, carbon capture storage, combined heat and power and heat pumps) for multi-energy system simulations. EnergyPLAN was chosen for the technical and environmental assessment due to its well-proven suitability for system-level analysis [10]. The inputs to EnergyPLAN consist of the demand time series for different energy sectors, RES energy production time series, and generation capacities and efficiencies of energy production units and resources [8]. Detailed energy production levels, fuel consumptions and carbon dioxide emissions constitute the outputs of EnergyPLAN model and are subsequently used as the Matlab-Excel VBA model inputs. The results are generated for one year of simulation with a one-hour resolution.

The 2012 UK energy system was modelled as a reference case and, in order to validate the model, the results were compared against the DECC statistics of the real system [11]. Table I shows the comparison of the energy production results obtained from EnergyPLAN and DECC's real data. The differences between simulated and real data are minor, which indicates that the model developed in EnergyPLAN is suitable to represent the technical operations of the UK energy system.

TABLE I. Comparison of Modelled and Actual Energy Production, UK 2012 case.

Production type	*Energy Production (TWh/year)*		
	EnergyPLAN	***DECC***	***Difference***
Wind power	20.32	19.58	0.74 (3.78%)
Hydro power	5.27	5.28	-0.01 (0.19%)
Photovoltaics	1.26	1.18	0.08 (6.78%)
Conventional power-plants	265.63	264.40	1.23 (0.47%)
Nuclear	71.52	70.05	1.47 (2.10%)

B. Economic analysis

A Matlab-Excel VBA model was purposely built to estimate the required infrastructure for different scenarios. The technical analysis from EnergyPLAN provides required input data (fuel consumptions and electricity generation for different technologies) to the economic analysis model.

1) Investment cost modelling

Investment cost modelling is done separately for electricity generation, building insulation, individual heating technologies, and multi-energy network infrastructures. To estimate the annuitized investment costs, the total investment costs for each technology needs to be calculated first.

For electricity generation, individual heating technologies and electrical transmission network investment, the required inputs are the new installed capacities and their capital costs. The capital costs are taken from [12] [13] [14] for different technologies, including RES, CHP, CCGT, nuclear, pumped storage, individual gas boilers, individual heat pumps, and electrical interconnector and transmission network. For each technology, the investment cost is given by the required new capacity, which is found from [7] [15], multiplied by the capital cost. Similarly, for the building insulation investment, the required inputs are the dwellings' different types of wall insulation [7] and their respective investment costs, which are taken from [1].

For heat network assessment, the investment costs are highly dependent on the types of dwelling and areas [13][16]. The required input data for the heat network costs modelling is the number of different dwellings that will be connected to district heating in each scenario and the investment costs for each house type [13]. As the UK dwelling type share is expected to remain steady in the long term, it can be assumed that the house type shares [17] will remain similar as today in 2035. For each dwelling type, the investment cost is calculated using the number of houses multiplied by the relevant specific capital cost.

In general, the annuitized cost for each technology is calculated as:

$$A = \frac{I \times i}{1-(1+i)^{-n}} \quad (1)$$

Where i is the interest rate which is assumed to be 9% in this paper, while n and I are the assets lifetime (in years) [18] and the investment costs, respectively, which vary by technology.

Concerning the gas network, the current supply capacity is considered as sufficient to satisfy current and future gas peak demand and there are currently no plans to increase pipeline interconnection in any of the pathways [19]. The gas distribution network costs are not included in the model as there is no clear visibility whether new households' connection will require significant network upgrade.

Although all the four scenarios require significant electricity generation investment, as there is not sufficient information concerning the distribution network required upgrades and investment costs, their calculation is left out for a future study.

2) Operation costs modelling

a) Operation and maintenance costs modelling

For electricity generation technologies, the Operation and maintenance (O&M) costs consist of both fixed and variable operation and maintenance costs. The fixed O&M cost depends on the generation installed capacity while the variable O&M cost depends on the quantity of electricity generated. The O&M costs for different technologies are taken from [12] [13]. For individual heating, the fixed O&M costs are calculated similarly using the numbers for different individual heating technologies [13]. It is important to note that the O&M costs exclude the fuel costs, which are calculated separately and presented below.

b) Fuel costs modelling

The required inputs are fuel consumptions and fuel prices. The fuel consumptions, which include gas, oil, coal, nuclear fuel and biofuel consumed by the whole system, are obtained from EnergyPLAN. The fuel costs for each type of fuel are defined as the annual consumption multiplied by their respective market price [20]. The emissions costs are considered endogenous to both the fuel prices and generation dispatch, they are consequently not detailed here.

III. CASE STUDIES AND RESULTS

A. Description of the pathways under analysis

Four pathways for 2035 have been analysed based on National Grid's UK Future Energy Scenarios [7]. More specifically, the four scenarios (shown in Figure 2) developed for the year 2035 are associated with different sustainability and affordability levels as follows:

- Pathway 1: Uses assumptions from National Grid's "Gone Green" scenario. In this scenario, more money is available for energy infrastructure investments and the system has the highest levels of renewable energy generation.
- Pathway 2: Uses assumptions from National Grid's "Low Carbon Life" scenario. In this scenario, the system shares same economic conditions as Pathway 1. However, instead of developing more RES, nuclear and CCS are preferred options for decarbonisation.
- Pathway 3: Uses assumptions from National Grid's "Slow Progression" scenario. In this case there are similar policy and regulation as in Pathway 1, but less money is available, which leads to lower levels of LCT and RES compared to Pathway 1.
- Pathway 4: Uses assumptions from National Grid's "No Progression" scenario. It is a scenario with a slow economic recovery and the lowest renewable uptake. Natural gas is the preferred choice for electricity generation.

Due to different progresses assumed, each scenario has distinct economic and environmental performance. Therefore, studies have been run to analyse each scenario environmental and economic performance, as discussed below.

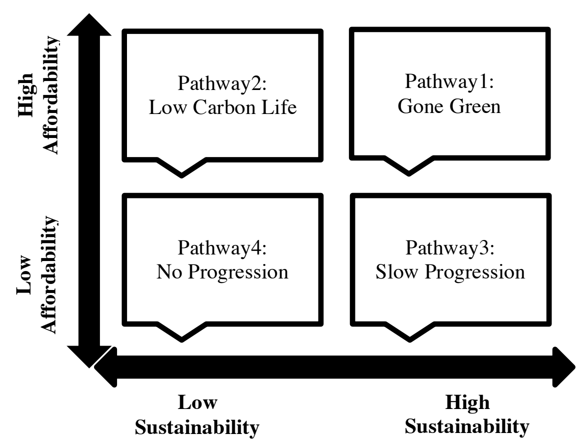

Figure 2. Comparison of different sustainability and affordability levels for the four pathways

B. Environmental performance

The results of the technical modelling from EnergyPLAN are used to analyse the environmental performance. Table II shows the results of the technical analysis performed in EnergyPLAN for the four pathways compared with the reference system (2012) results. The total electricity production, RES, nuclear, and fossil fuels generation, and carbon dioxide emissions are shown. The carbon dioxide emissions are expressed in percentage of the reference year (2012), and the electricity production for different technologies is expressed as a percentage of the total electricity generation for each pathway.

As expected, the carbon dioxide emissions have decreased for all the pathways compared to 2012. Pathway 1 and Pathway 2 see a reduction of more than 60% of 1990's level and meet the 2035 GHG emission targets. Although the emissions in Pathway 3 are only slightly higher than Pathway 1, the carbon target is likely to be missed. Finally, for Pathway 4 the carbon target is clearly missed.

The RES generation varies significantly across the scenarios. As expected, Pathway 1 has the highest renewable energy generation with the lowest carbon dioxide emissions, while Pathway 4 has the highest emissions with a small shift from fossil fuel to renewables.

According to the 2009 Renewable Energy Directive (RED) [21], the UK should meet the 15% of the total energy consumption delivered by RES by 2020 target and only Pathway 1 meets that target. For Pathway 3, due to a slow economy recovery, the target is likely to be missed and RES is not highly developed compared to Pathway 1. As shown in Table II, Pathway 3 has a similar RES share as Pathway 2 while having higher emissions. Although in Pathway 2 RES are not prioritized, the high development of nuclear and CCS makes the GHG reduction target achievable.

TABLE II. ELECTRICITY GENERATION AND ENVIRONMENTAL PERFORMANCE FOR THE FOUR PATHWAYS

Parameter	*Base case (2012)*	*Pathways*			
		1	*2*	*3*	*4*
Electricity Production (TWh/year)	365	369	392	349	368
RES electricity production (%)	10	59	41	46	25
Nuclear electricity production (%)	19	19	23	15	8
Fossil fuel electricity production (%)	71	23	35	40	67
Carbon dioxide emissions (%)	100	52	54	56	69

C. *Economic performance*

Figure 3 illustrates the detailed annuitized costs for the four pathways. As shown in Figure 3, Pathway 1 has the highest annuitized costs while Pathway 3 has the lowest. It is worth highlighting that although Pathway 4 has a low affordability level with less infrastructure investment, the total cost is still high due to high fuel costs.

Compared to the energy generation operation costs, the infrastructure costs take a less significant role in the total costs for all the pathways. The fuel costs, which account for 56% to 80% of the total annuitized costs in all pathways, is a key factor in analysing the economic performance, particularly in the light of potential uncertainty in fuel costs (not modelled here).

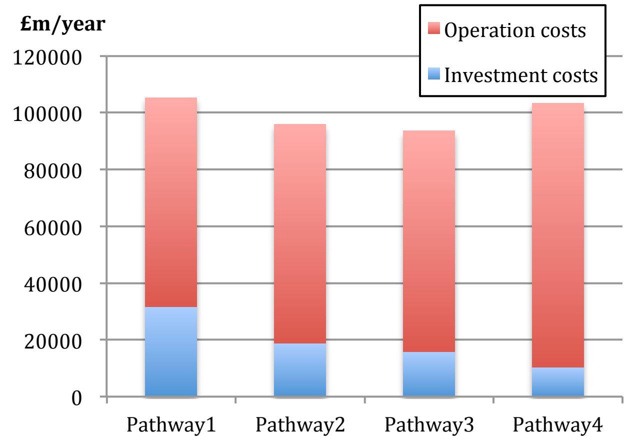

Figure 3. Annuitized costs for the four pathways

1) Annutized investment cost

Table III and Figure 4 show the breakdown of investment costs for each sector. It can be noticed that the investment costs, which are added in the Matlab-Excel VBA model, allow quantifying each pathway total annuitized cost. Pathway 1 has the highest investment costs and the smallest operation costs, making it no more slightly expensive than Pathway 4. Pathway 2 and 3 both share lower annuitized costs with investment costs being significantly lower than Pathway 1.

To reduce GHG emissions, Pathway 1 has highly developed RES and electric heat pumps for individual heating. Thus, it has the highest investment costs in electricity generation, individual heating and transmission networks. In addition, Pathway 1 has a high growth in wall insulation, which increases significantly efficiency. Compared with Pathway 1, Pathway 3 has a lower investment costs due to lower levels of RES and heat pumps. Pathway 2 has the highest developed DH networks compared with others. Pathway 4 has the lowest investment costs with the lowest level of LCT and RES.

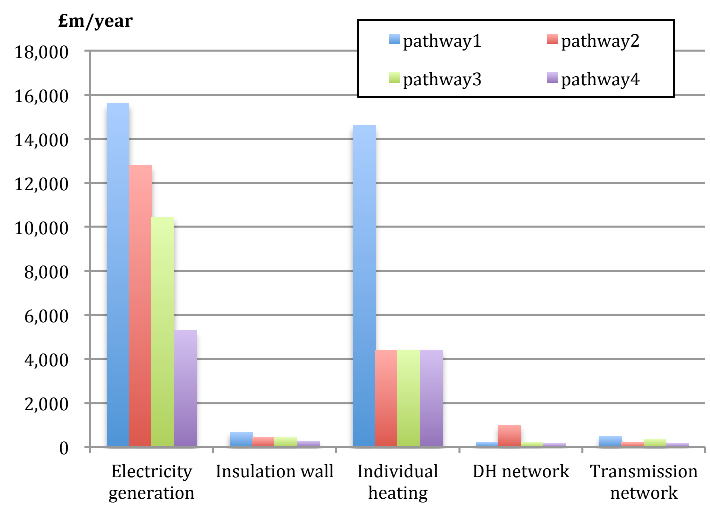

Figure 4. Annutized investment costs for the four pathways

TABLE III. ANNUITIZED INVESTMENT COSTS

Cost type		*Pathway 1*	*2*	*3*	*4*
Generation (£m/year)	Pumped storage	111	34	2	2
	Wind onshore	2227	1817	1792	1109
	Wind offshore	8868	4362	6222	1765
	PV	3819	4238	2195	1735
	Hydro Power	29	77	29	0
	Nuclear	351	1953	0	0
	CCGT	0	0	0	539
	CHP	216	325	216	142
Wall Insulation (£m/year)	Solid wall	350	111	111	111
	Cavity wall	173	173	173	71
	Loft wall	149	149	149	98
Individual Heating (£m/year)	Gas boilers	3750	3750	3750	3750
	Heat pumps	1087 8	668	668	668
Heat Networks (£m/year)	Small terrace	23	101	23	16
	Medium/large terrace	47	204	47	31
	Semi-detached (dense)	70	304	70	47
	Semi-detached	62	268	62	41
	Converted flats	6	24	6	4
	Low rise flats	21	90	21	14
	High rise flats	2	11	2	2
Transmission Network (£m/year)	Interconnections	360	165	360	165
	Transmission	117	38	0	0

TABLE IV. OPERATION COSTS FOR FOUR PATHWAYS

Cost type		*Pathways 1*	*2*	*3*	*4*
Operation and Maintenance Costs (£m/year)	Pumped storage	49	34	27	27
	Wind onshore	927	808	801	603
	Wind offshore	2713	1462	1972	724
	PV	401	441	245	201
	Hydro Power	217	217	159	151
	Nuclear	977	1288	721	416
	CCGT	787	610	843	1070
	CHP	265	302	263	238
	Heat pump	986	73	73	73
	Interconnector	4	2	4	2
Fuel Cost (£m/year)	Coal	4005	3915	3274	5846
	Oil	29819	30023	32033	33629
	Natural Gas	31801	37255	36564	49335
	Biomass	704	262	721	764
	Nuclear	917	1208	677	390

2) Operation costs

Table IV and Figure 5 summarise the results of operation costs modelling. Contrary to the investment cost results, Pathway 4 has the highest operation costs while Pathway 1 has the lowest. For Pathway 4, over 97% of the operation costs are inputted directly to fuel costs. The proportion of the fuel costs in Pathway 1 is 15% lower than that in Pathway 3, which means that Pathway 1 will be less dependant on potential fuel prices variations than Pathway 3.

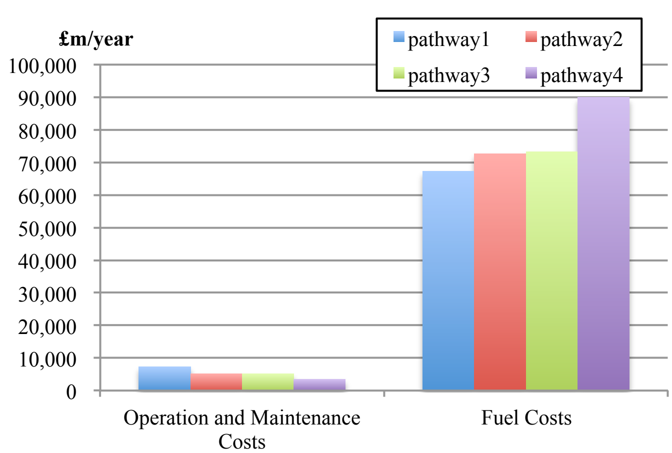

Figure 5. Operation costs for the four pathways

D. Discussion

The results show the environmental and economic performance for each pathway. In the light of developing sustainable energy strategies, Pathway 1 should be more efficient than other pathways from an environmental perspective, even though it has the highest annuitized costs. Pathway 3 is the most cost efficient option being about 27% cheaper than Pathway 1 but its GHG emissions are slightly higher (~8%). However, the fuel costs for Pathway 3 are higher than those in Pathway 1, meaning that if fuel prices were to be higher than assumed in this study, the cost difference between Pathway 1 and Pathway 3 is likely to decrease. Compared with Pathway 1, although Pathway 2 has lower annuitized costs, the fuel costs in Pathway 2 are 8% higher than Pathway 1. The annuitized costs of Pathway 4 are much higher than Pathway 2 and Pathway 3 while having the highest emissions, thus it becomes the least cost efficient pathway and the least interesting pathway overall.

Compared with EnergyPLAN, the new model added the insulation wall, DH network and transmission network investment costs. The system level costs, including investment and operation costs, which are presented in annuitized costs for the four pathways, correspond to the National Grid's assumptions while providing more insights into the economic costs of the different options under investigation. The environmental performances were also found to be consistent with National Grid estimates.

IV. CONCLUSION

To decarbonise the UK energy system and meet the carbon reduction targets, an integrated energy system planning is required. In this paper, a comprehensive model to assess the system level techno-economic and environmental performance for different integrated energy systems scenarios has been presented. The model is based on the EnergyPLAN tool and a Matlab-Excel VBA interface. The developed model for economic analysis includes infrastructure costs for multi-energy generation and networks, and operation costs. After developing and validating the model against the current system, four pathway scenarios put forward for 2035 by National Grid were tested. The simulation results highlight the importance of accounting for the operation costs and investment costs. Investment costs in infrastructures are usually not properly considered in scenario-based studies and in many system analysis tools currently available. The results consisting of total annuitized costs are critical to gain true insights into future options in a comprehensive manner to cover technical, environmental and economic aspects.

Future work aims at improving the model developed, including cost impact on electrical distribution networks [22] (for instance due to electrification of heating [23]), and analysis of different storage technologies.

REFERENCES

[1] DECC, "2050 Pathways Analysis," London.UK, 2010.

[2] P. Mancarella, "MES (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1–17, Feb. 2014.

[3] T. Capuder and P. Mancarella, "Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options," *Energy*, vol. 71, pp. 516–533, Jul. 2014.

[4] E. A. Martinez-Cesena, T. Capuder, and P. Mancarella, "Flexible Distributed Multi-Energy Generation System Expansion Planning under Uncertainty," *IEEE Trans. Smart Grid*, accepted for publication, February 2015.

[5] Y. Kitapbayev, J. Moriarty, and P. Mancarella, "Stochastic control and real options valuation of thermal storage-enabled demand response from flexible district energy systems," *Appl. Energy*, vol. 137, no. 1 January 2015, pp. 823–831, 2014.

[6] H. Lund and B. V. Mathiesen, "Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050," *Energy*, vol. 34, no. 5, pp. 524–531, May 2009.

[7] National Grid plc, "UK Future Energy Scenarios," 2014.

[8] H. Lund, "EnergyPlan Advanced Energy Systems Analysis Computer Model," no. August. Aalborg University, Denmark, 2012.

[9] D. Connolly, H. Lund, B. V. Mathiesen, and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems," *Appl. Energy*, vol. 87, no. 4, pp. 1059–1082, 2010.

[10] R. K. Edmunds, T. T. Cockerill, T. J. Foxon, D. B. Ingham, and M. Pourkashanian, "Technical benefits of energy storage and electricity interconnections in future British power systems," *Energy*, vol. 70, pp. 577–587, 2014.

[11] DECC, "Digest of United Kingdom Energy Statistics 2014," London, 2014.

[12] DECC, "Electricity Generation Costs (December 2013)," no. December, pp. 1–62, 2013.

[13] Pöyry Energy Consulting and Faber Maunsell, "THE POTENTIAL AND COSTS OF DISTRICT HEATING NETWORKS," no. April, 2009.

[14] D. Connolly, "EnergyPLAN Cost Database," no. January, pp. 0–15, 2015.

[15] National Grid plc, "Electricity Ten Year Statement," 2014.

[16] A. Ahmed and P. Mancarella, "Strategic techno-economic assessment of heat network options for distributed energy systems in the UK," *Energy*, vol. 75, no. 1 October 2014, pp. 182–193.

[17] DECC, "English Housing Survey," 2012.

[18] M. MacDonald, "UK electricity generation costs update," *Mott MacDonald*, no. June, 2010.

[19] National Grid, "Gas Ten Year Statement: UK Gas transmission," 2014.

[20] J. I. Utley and L. D. Shorrock, "Domestic energy fact file 2008," *Energy*, pp. 1–99, 2008.

[21] DECC, "National Renewable Energy Action Plan for the United Kingdom: Article 4 of the Renewable Energy Directive," *Renew. Energy*, p. 189, 2009.

[22] C. K. Gan, P. Mancarella, D. Pudjianto, and G. Strbac, "Statistical appraisal of economic design strategies of LV distribution networks," *Electr. Power Syst. Res.*, vol. 81, no. 7 July 2011, pp. 1363–1372.

[23] A. Navarro-Espinosa and P. Mancarella, "Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks," *Appl. Energy*, vol. 127, no. 15 August 2014, pp. 249–266.