Assessing the future security of the UK electricity system in a low-carbon context

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Abstract

In order to meet legislated targets for mitigating climate change, future energy systems will need to become secure, affordable and low-carbon (the energy 'trilemma'). As part of a growing body of research into potential ways of achieving this transition, this project seeks to assess the future security of the UK electricity system in a low-carbon context. A new mixed-method indicator framework for assessing security of both supply and demand has been developed; the framework uses a 'dashboard' approach to security analysis which employs both quantitative and qualitative indicators, and is capable of identifying potential red flags for the future security of a low-carbon electricity system. The framework has been applied to a set of three transition pathways, all of which seek to reduce carbon emissions by 80% by 2050. The choice of transition pathways aims to compare and contrast options for market-centric, centrally-controlled and decentralised systems. This paper presents the initial results from the security assessment, and uses these results to highlight some of the key risks and trade-offs which may emerge under different routes to a low-carbon electricity transition. In particular, serious concerns are raised regarding trade-offs between system adequacy and redundant capacity. The results indicate that a core challenge may be the feasibility of achieving a secure, low-carbon electricity system whilst simultaneously incentivising sufficient investment. It is argued that energy policy should pay immediate attention to flexible demand, increasing consumer participation, and maximising indigenous biomass supply. Finally, it is the contention of this paper that policies should be designed to reward flexibility on both the supply-side and demand-side, rather than simply focusing on generation capacity.

Key words: energy security; low-carbon transition; electricity systems

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1. Introduction

In recent years, energy security has taken a central place on the policy agenda, both in the UK and globally. Two consecutive Gulf Wars and the Arab Spring, the emerging issues of non-renewable resource depletion and climate change, increasing tensions in and around Russia, and rapidly growing global energy demand have all contributed to a rising awareness of the importance of securing energy supplies (Barrett *et al* 2010; Bielecki 2002; Cherp and Jewell 2011; Jansen and Seebregts 2010). In the UK, energy security and climate change have become a central feature of energy policy discussions (Chaudry *et al* 2011), and in 2012 the Department for Energy and Climate Change published the UK's first ever Energy Security Strategy (DECC 2012a). This resurgence of interest in the UK has been induced by two main drivers (MacKerron 2009; POST 2012; Winstone et al 2007):

- Domestic production of oil and gas from the UK Continental Shelf, and of coal from domestic mines, has declined. In 2013 the UK imported 47% of all energy used, and was a net importer for all three major fossil fuels (DECC 2013a). Steadily increasing import dependence has combined with rising and volatile wholesale fossil fuel prices (Sauter and MacKerron 2008).
- Increasing concerns over anthropogenic climate change may force a shift to a low-carbon energy economy. The UK has agreed to legally-binding carbon-reduction targets of 80% on 1990 levels by 2050 under the Climate Change Act 2008 (DECC 2008). This shift means that dependence on cheap, abundant and flexible fossil fuels may need to be significantly reduced.

In the UK, it is seen as imperative that the energy system can deliver affordable energy in the volume and quality required at any given moment. However, policy recommendations are frequently given on the basis of 'improving energy security', without an attempt to actually assess future energy security empirically in the context of a low-carbon transition (DECC 2011; 2012a). As such, this paper seeks to identify a set of indicators and metrics which are appropriate for assessing the relative security of electricity system transition pathways, and uses this framework to carry out an empirical assessment using a set of recognised carbon-reduction scenarios.

The following section of this paper reviews the existing literature on energy security, with a focus on conceptualising energy security and the challenges of achieving security in a low-carbon context. Section 3 outlines the methodology which has been employed for an empirical energy security assessment. Section 4 presents the results of the analysis; section 5 then discusses the results, drawing attention to some of the key trade-offs which have been highlighted and some key uncertainties which arise. Finally, section 6 concludes, and offers policy recommendations arising from the research.

2. Energy security in a low-carbon context

2.1 A broader approach

The term "energy security" has become commonplace in academic and policy discussions; however, there is no generally accepted definition of the term. There has been a common tendency in the energy literature to focus upon supply-side dynamics (Bielecki 2002; Bohi and Tohman 1996; Bordhoff *et al* 2010; Lefèvre 2010), in some cases becoming even more specific and concentrating on the physical fossil fuel resources alone (Bradshaw 2010; Frondel and Schmidt 2014). Much of the literature focuses on large-scale, long-term dynamics such as global markets and geopolitics (Chester 2010). On the other hand, when discussing security of *electricity* supplies, the literature seems to lean in the opposite direction, to a short-term focus on aspects such as reliability and capacity availability (Boston 2013; Chaudry *et al* 2011; Creti and Fabra 2007). This divide can be conceptualised as a differentiation between gradual 'stresses', such as resource depletion or geopolitical tensions, and sudden 'shocks', such as a technical fault at a plant or a powerline failure (Stirling 2014; Hoggett *et al* 2014). Such disparity within the literature on this topic suggests the need for a broader approach which comprises both long and short-term dimensions.

Conceptions of 'energy security' have recently become linked to environmental issues, in light of an emerging new paradigm of environmental and social concerns (Elkind 2010; Hughes 2012; Mitchell *et al* 2013; Frances *et al* 2013). The inclusion of climate change mitigation into the energy security agenda has led to the development of the energy 'trilemma' (shown in *Figure 1*). A sustainable energy system needs to balance the three elements of security, cost, and carbon reduction. This trilemma illustrates a fundamental facet of the energy security discussion – that there may be certain trade-offs between objectives, and that effective policy should work to identify these trade-offs (Brown and Huntingdon 2008; Froggatt and Levi 2009; Sovacool and Saunders 2014).

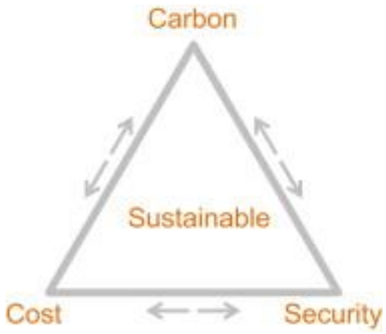


Fig. 1: The 'Energy Trilemma' (Boston 2013)

2.2 The policy challenges of low-carbon electricity

Electricity will be at the heart of policies to reduce emissions, because technology for producing electricity from low-carbon sources is advanced compared to technology for producing low-carbon fuel for heating or transport. Indeed, some sectors such as aviation are hardly expected to reduce their emissions over the coming decades (DECC 2012b). As such, electricity will need to decarbonise more quickly and deeply in order to make up the difference; it has been widely suggested that in order to put the UK on a trajectory to meet its carbon reduction commitments, the electricity sector will need to be largely decarbonised by 2030 (DECC 2011; UK CCC 2013).

In order to meet the challenges of the trilemma, the UK electricity system will need to undergo a fundamental transition. As outlined in a recent DECC White Paper entitled "Our Electric Future" (2011), the electricity system in the UK is facing a number of unprecedented challenges, including:

- <u>The closure of existing generation capacity</u>: Around 19GW of power generation (around a quarter of existing capacity) is due for closure over the next decade.
- <u>The challenge of decarbonisation</u>: The UK has legally-binding targets to reduce its emissions, and the electricity sector will be key to meeting these targets. Decarbonising the electricity supply will result in challenges due to intermittent generation sources.

- Increasing demand for electricity: Even with planned improvements in energy efficiency, demand is still projected to rise, due to increased electrification of transport, heat and other carbon-intensive sectors.
- Expected rises in electricity prices: Increases in wholesale gas prices, as well as carbon prices and environmental policies, are likely to lead to higher electricity bills in the future.

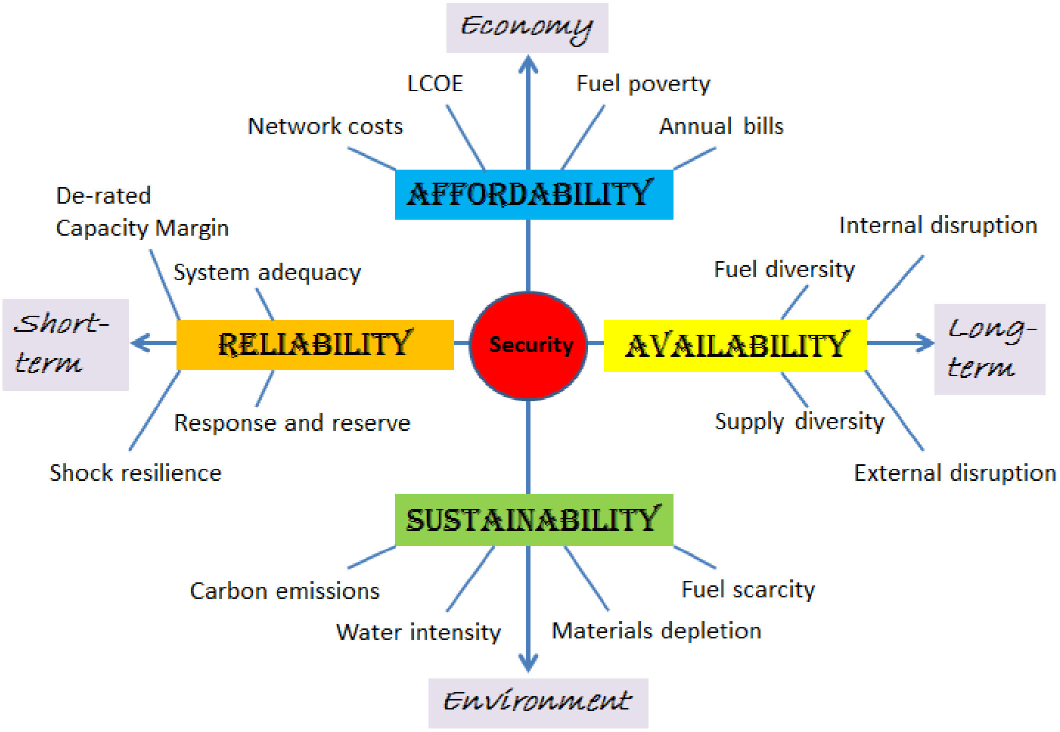
3. Framework and Methodology

3.1 A framework for the assessment of low-carbon electricity security

As noted in Section 2, vulnerabilities can be conceptualised in terms of long-term 'stresses' and short-term 'shocks'. This conceptualisation can be used as the basis for a framework which can assess the security of the UK electricity system in a low-carbon context. The ability to withstand longer-term 'stresses' can be thought of in terms of electricity availability, encompassing aspects such as geopolitical tensions and domestic opposition. Meanwhile the ability to respond to short-term 'shocks' can be thought of in terms of system reliability, encompassing aspects such as capacity margins, hour-by-hour system adequacy, and short-term system resilience. Further to this, it is important to consider a price dimension, which is widely recognised as being fundamental to the pursuit of energy security; this can be thought of as affordability. The term 'affordability' is more useful than 'price', because it raises the question 'affordable to whom?', and thus encompasses issues such as consumer bills and effects on fuel poverty. Finally, the previous discussion on broadening conceptions of energy security suggests that a fourth dimension must be added, that of sustainability. Assessing 'sustainability' rather than just carbon emissions allows the inclusion of wider aspects such as resource depletion. Thus a four-way framework of key characteristics is arrived at – a secure electricity system must ensure that the electricity is 'available', 'reliable', 'affordable' and 'sustainable'.

There is still much debate over the best means of assessing energy security, and indicator approaches are not immune from shortcomings (see for example Jewell *et al 2014;* Gracceva and Zienewski 2014). However, some of the drawbacks can be overcome by avoiding the temptation to attempt to create a generalisable indicator framework which is applicable to any situation; instead, the research should identify its specific aim (in this case, assessing UK low-carbon electricity security), and indicators should be developed which are 'fit for a purpose' (Axon *et al* 2013). As pointed out by Mitchell and Watson (2013) and Gracceva and Zienewski (2014), the choice of security indicators is subjective and often highly political and contested, and therefore a 'one size fits all' approach is undesirable. Instead, it is preferable to offer a 'dashboard' of indicators, which can be used as a whole set or individually, depending on the purpose of the study. This approach is useful because it allows the incorporation of a broader range of indicators, as suggested above; moreover, it permits the inclusion of both quantitative and qualitative methods, without limiting the study to one or the other. The 'dashboard' approach enables the identification of areas of potential concern or vulnerability for the security of a system by highlighting areas of concern with a 'red flag'. This can also assist in the identification of trade-offs and synergies between objectives; for example, if one indicator generates a red flag, whilst a separate group of indicators appears to be very secure, this could point to a trade-off which may require policy attention.

Fig. 2: A framework for the assessment of low-carbon electricity security



3.2 Detailed overview of indicators, calculation methods and data sources

	Indicator	**Metric**	**Overview of methods and data sources**
AVAILABILITY	Internal disruption	Diversity of fuel types in the electricity mix	Shannon-Wiener diversity calculation: $-\sum Pi*(Ln(pi))$
		Public acceptability of generation types	Results from a nationally-representative public survey (Demski et al 2013) are extrapolated to show proportion of scenario (in GW and %) which is ‘approved’ and ‘opposed’ by the general public
		Likelihood of disruptive opposition	Examines specific factors which could cause disruptive opposition: local impact (level of new generation and transmission infrastructure required); domestic resource extraction; carbon emissions; levels of public participation in the energy system
	External disruption	Diversity of fuel imports	Current (2010) fuel import diversity is measured using Shannon-Wiener index Import diversity projections are made on BAU trajectory basis
		Stability of fuel exporting nations	High uncertainty r.e. import projections necessitates 2 methods used in conjunction: #1: Neumann-Shannon-Wiener Index NSW1 applied to BAU trajectory: $NSW1= -\sum Pi*(Ln(pi))*b$ *(where ‘b’ represents a stability parameter, derived from the Fragile States Index)* (SECURE 2009); #2: Qualitative scoring framework using literature on fuel supplies and national stability
		Dependence on fuel imports	Pathways data used to show % of fuel mix from imports Neumann-Shannon-Wiener Index NSW2 used to include a measure of domestic supply as an addition to the previous NSW Index: $NSW2= -\sum (Pi*(Ln(pi))*b)*(1+g)$ *(where ‘g’ represents the proportion of total fuel supply which comes from domestic sources)* (SECURE 2009)
		Supply chains and choke points	Qualitative approach uses colour coded ‘red-flag’ table to highlight potential disruption in supply chains and at supply route choke points
AFFORDABILITY	Generation costs	Levelised Cost of Electricity (LCOE)	LCOE calculation includes CAPEX (pre-development, construction), fixed OPEX (O&M, connection charges, insurance), variable OPEX (variable O&M, fuel) Cost data from DECC (2013b) and Mott Macdonald (2010)
	Network costs	Transmission upgrade costs	Onshore upgrade costs calculated using Electricity Networks Strategy Group estimates of upgrades required for different levels of new capacity (ENSG 2012) Offshore upgrade costs calculated using estimated unit costs (from National Grid 2013, Technology Appendix)
		Distribution upgrade costs	Distribution upgrade costs for the pathways modelled by Pudjianto *et al* (2013)
	Costs to households	Annual retail bills	Wholesale prices added to a ‘consumer uplift’: 19% of bill for supplier costs and margins, 9% social and environmental policies, 20% network charges, 5% VAT (DECC 2013c)
		Impact on fuel poverty	Qualitative analysis carried out using annual bills estimates, existing literature on levels of fuel poverty in the UK (especially Hills 2012), and the pathways storylines, to generate ‘red flag’ analysis

SUSTAINABILITY	Emissions	Carbon intensity & cumulative carbon emissions	Scenario carbon intensity = Fuel-type intensity * (fuel-type generation TWh/y / Total generation TWh/y) Baseline estimate from the pathways data; high and low estimates from IPCC global power station data (Moomaw *et al* 2011) Cumulative carbon emissions calculated by summing 5-yearly carbon emissions (available in TP data)
	Depletion and resource scarcity	Primary fuels depletion	Qualitative scoring approach from the existing literature, which scores each fuel from 1 to 10 (1 = no risk of depletion) Scores are applied to the fuel mix in the pathways
		Secondary materials depletion	32 crucial materials are identified from the literature and listed from ‘highly critical’ to ‘not critical’ (Moss et al 2011) Qualitative scoring approach from existing literature: generating types are scored from 1 to 10 based on quantity and criticality of secondary materials required
	Water	Water consumption and withdrawals	Data on water withdrawals and water consumption of different types of power generation (Davies et al 2012) Projections on types of cooling to be employed in UK thermal powergen in future (Kyle et al 2013) These are extrapolated to scenarios to show water consumption and water withdrawals (in m3 and m3/MWh)
RELIABILITY	System adequacy	Generation adequacy	TP scenarios have been modelled to meet generation adequacy requirements; supply is sufficient to meet demand on hour-by-hour basis (Barnacle *et al* 2013)
		Network adequacy	Cost of transmission and distribution upgrades (see ‘Affordability’) used as a proxy for network adequacy
		De-rated Capacity Margins	Indicative fuel-type margins from National Grid (2012) are applied to the generation mix in the scenarios. Fuel type margin is weighted according to generation mix, and subtracted from peak demand
		Load factors and oversupply	Load factors (from the TP data) and plant margins are used to highlights areas of oversupply
	Shock resilience, response and reserve	Frequency Response capability	Power station data from National Grid (available on request) is used to calculate average FR capability of types of powergen; this is extrapolated to the fuel mix in the scenarios. Maximum and mean FR capability shown for primary FR (<30 seconds) and secondary FR (30 seconds to 30 minutes)
		Short-term Operating Reserve and black-start capability	Calculates percentage of power generation in the scenario which would be capable of providing STOR and black-start capability (see National Grid 2011). STOR results shown for short-term STOR (<45 minutes) and long-term STOR (45 minutes to 4 hours)
		Response and Reserve requirements	Increasing requirements for FR and STOR are calculated on the basis of decreasing system inertia, increasing impact of wind forecasting error, and increased credible in-feed loss due to increase of unit size. All data from National Grid (2011)
		Flexible supply and demand	Levels of storage and interconnection used to as a proxy for flexible supply Levels of heat pumps and electric vehicles used as a proxy for flexible demand

3.3 Applying the framework

The aim of this paper is to apply the framework illustrated above to a set of existing low-carbon transition pathways for the UK electricity system. Transition pathways are especially useful because they generally take a whole-systems view, which explores how all parts of the wider energy system work together. The pathways used for the initial analysis were developed by the Transition Pathways to a Low-Carbon Economy consortium (TP);[1] see Appendix A for further information on the pathways and the rationale for choosing this set. The TP consortium asked what kinds of socio-political governance systems could emerge over the next 40 years, and how the overriding 'governance logic' of the system could affect the transition options taken.[2] From this, the consortium developed three pathways, each of which corresponds to a different governance logic:

- **Market Rules (MR):** continued dominance of a market-led system in the UK, in which the government sets high-level goals but otherwise interferes little in the market. Reliant on coal and gas CCS, some nuclear, some large-scale wind. Electricity demand increases significantly, driven by electrification of heat and transport.
- **Central Coordination (CC):** landscape pressures lead to a stronger role for government to deliver carbon reductions, leading to a top-down, government-led transition. Reliant on nuclear and large-scale wind. Electricity demand increases, but is constrained somewhat by efficiency improvements.
- **Thousand Flowers (TF):** a decentralised, bottom-up transition led mainly by civil society and consumers. Reliant on CHP, biomass and decentralised renewable energy sources (RES). Despite electrification of heat and transport, electricity demand remains stable due to demand reduction and increasing consumer engagement.

4. Results

4.1 Availability: domestic disruption

Figure *3* below shows public acceptability in GW and % of total scenario capacity. The figures show the weighted proportion of the generation mix which would be 'approved of' by the public, minus the weighted proportion which would be 'actively opposed' (source: Demski *et al* 2013). Figure *4* shows the level of public participation, under the assumption that greater levels of participation usually lead to higher levels of public acceptance.

Fig. 3: Acceptability and diversity

	Market Rules (MR)			Central Coordination (CC)			Thousand Flowers (TF)		
	GW	%	Fuel diversity	GW	%	Fuel diversity	GW	%	Fuel diversity
2010	4.912	5.7%	1.948	4.033	4.6%	1.921	4.077	4.8%	1.92
2030	32.327	26.1%	2.438	29.491	26.2%	2.486	48.031	38.1%	2.407
2050	49.043	30.1%	2.261	42.269	32%	2.315	69.963	50.4%	2.084
Mean	**28.761**	**20.7%**	**2.216**	**25.265**	**21.0%**	**2.241**	**40.690**	**31.1%**	**2.137**

Fig. 4: Likelihood of disruptive opposition: public participation (from pathways storyline)

MR	CC	TF
Very low	Low	High

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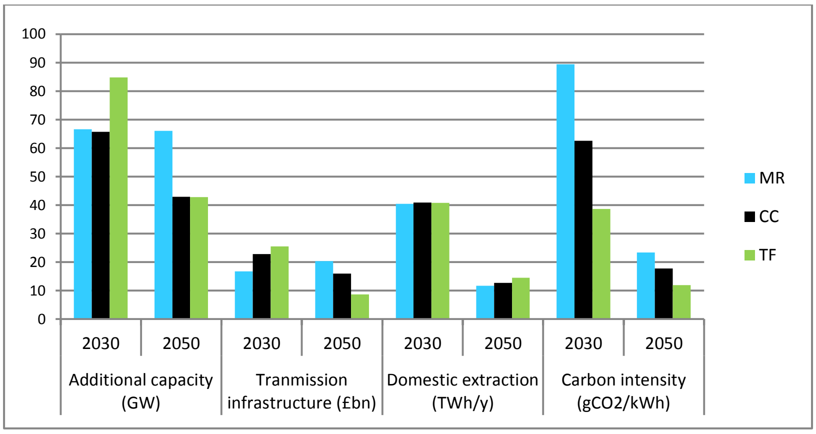
[1] http://www.lowcarbonpathways.org.uk/

[2] 'Governance' is defined as the structures and processes influencing the decisions made by various actors, and how these choices give rise to changes within the system (Foxon 2013; Smith 2009)

The results from Figure *3* show that public acceptability and diversity both improve greatly on 2010 levels for all pathways; both of these factors reflect the positive impacts of increasing penetration of RES. Public acceptability tends to be much higher for RES than for fossils; this is reflected in the extremely positive acceptability score for the TF pathway. This pathway scores lower than the other two for diversity, reflecting a considerable reliance on biomass as a back-up for intermittent sources. The main cause for concern here is the low levels of public participation in the MR pathway, as shown in Figure *4*; however, when taken together with the increasingly positive acceptability score, the risk doesn't appear to be too high. Finally, Figure *5* shows the likelihood of disruptive opposition due to local, community and environmental impacts; a rather mixed picture emerges, with all three pathways raising some concerns for some of the measures, but no clear vulnerabilities emerging for any of the pathways. Potential risks include the environmental impacts of the MR pathway, and the large amount of infrastructure required to realise the TF pathway before 2030 (reflecting the scale of the transition required for this pathway). A potential concern would be the feasibility of the TF pathway to realise this transition, considering that the public and the politics are likely to be split on many important issues.

Fig. 5: Likelihood of domestic disruption due to local, community and environmental impact



4.2 Availability: external disruption

Fig. 6: Import dependence and stability of exporting nations
'Risk score' assessed on the basis of major importing nations to the UK, likely major import trends, and stability index (SECURE 2009)

Market Rules	Coal	Gas	Uranium	Biomass	Electricity Imports
Risk Score	**7**	**7**	**3**	**5**	**2**
2010	72.5%	54.2%	23.2%	42%	4.96%
2030	91.72%	81.71%	23.2%	53.9%	4.99%
2050	99.16%	98.15%	23.2%	71.9%	3.76%

Central C	Coal	Gas	Uranium	Biomass	Imports
Risk Score	7	7	3	5	2
2010	72.5%	54.2%	23.2%	42%	4.97%
2030	82.28%	80.12%	23.2%	58.8%	5.98%
2050	95.5%	97.53%	23.2%	32.01%	5.02%

Thousand Flowers	Coal	Gas	Uranium	Biomass	Imports
Risk Score	7	7	3	5	2
2010	72.5%	54.2%	23.2%	42%	4.98%
2030	75.92%	63.97%	23.2%	91.8%	7.16%
2050	82.73%	86.36%	23.2%	93.1%	4.38%

Fig. 7 (left): Import diversity (SW), import stability (NSW1) and import dependence (NSW2) index results, based on BAU import trajectory

Fig. 8 (below): risk of disruption in supply chains and at transport choke points

MR	LNG supply
	Offshore wind supply chain choke points
	Longer supply chains
	Marine energy supply chains
CC	LNG supply
	Nuclear supply chain choke points
	Longer supply chains
	Marine energy supply chains
TF	Biomass supply
	Marine energy supply chains

The tables in Figure *6* are based on the results from the qualitative assessment of risk of non-domestic disruption to supplies; the qualitative method makes an attempt to project likely global fuel sources. It shows that all three pathways raise serious concerns in some areas regarding fuel imports. The TF pathway performs slightly better for fossil fuels, but much worse for biomass. The best performer overall is probably the CC pathway, which has more areas of 'minimal concern' (yellow and green squares).

Figure 7 shows the results from the quantitative method, which uses current fuel supply routes and a BAU supply trajectory in order to allow for the high uncertainties in projecting future supply routes. There is consistency between the quantitative and qualitative results. The graph in Figure *7* shows that the preponderance of coal and gas in the MR pathway creates risks for import stability and dependence; this combined with a lower diversity score due to high reliance on CCS and nuclear power raises some concerns for all three quantitative metrics. The low scores for the TF pathway, especially in 2050, reflect a significant dependence on biomass and a lack of assured biomass supply to meet fuel requirements, which raises serious concerns. However, it is worth noting that a lack of data necessitated the use of a BAU supply trajectory; therefore, if the TF pathway were to develop a strategy for sourcing more biomass indigenously (for example, using more waste and residues) then it would be far more secure for this indicator. This highlights the need for a strong UK strategy for the sourcing of indigenous biomass. This is supported by the 'supply chains and choke points' results *(Figure 8),* in which the Market Rules and Central Coordination pathways suffer from key vulnerabilities in LNG, large-scale offshore wind, and nuclear supply chains; the Thousand Flowers pathway is the most resilient in this respect, although considering that much of the biomass requirement for this pathway will need to be imported, it is plausible that supply chain bottlenecks could emerge.

4.3 Affordability

The various results from the 'affordability' indicator shown below are highly interesting when viewed as a group. Figure *9* shows spiralling generation costs for the TF pathway; this reflects the enormous scale of the transition which would be required for such an ambitious phase-out of fossils and nuclear in a relatively short period of time, and raises the possibility that this pathway may be too ambitious economically. Network costs increase significantly for all three pathways *(Figure 10)*, but are lowest for the TF pathway due to smaller installations and fewer large wind arrays and nuclear plants; this could point to an interesting trade-off between costs to the generators and costs to the networks.

Fig. 9: Levelised cost of electricity generation

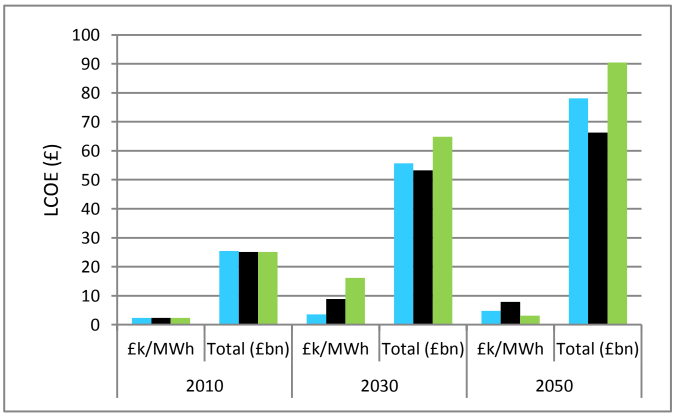


Fig. 10: Cumulative network upgrade costs

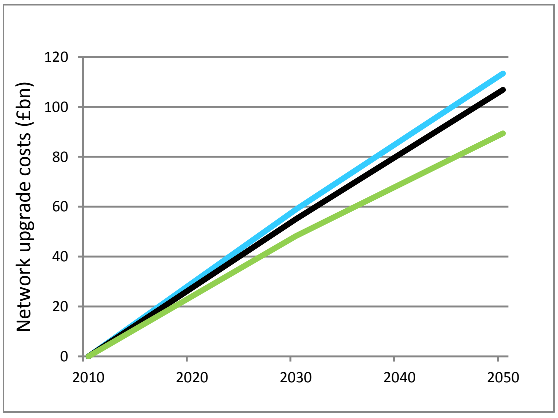


Fig. 11: Annual bills and impact on fuel poverty

	2010	**2030**	**2050**		
	Baseline	**Baseline**	**Baseline**	**High**	**Low**
MR	£1280.09	£1300.02	£1980.81	£2483.93	£1790.02
CC	£1323.04	£1231.46	£1804.00	£2301.91	£1585.72
TF	£1319.98	£1507.49	£1513.37	£1923.49	£1367.60

	2030			2050		
	Bills	% increase from 2010	Storyline	Bills	% increase from 2010	Storyline
MR	**£1300**	**1.56%**	**Most risk**	**£1980**	**54.68%**	**Most risk**
CC	**£1231**	**- 6.96%**		**£1804**	**36.35%**	
TF	**£1507**	**14.17%**	**Least risk**	**£1513**	**14.62%**	**Least risk**

A highly interesting comparison comes when levelised costs of generation and network costs are extrapolated out to annual bills *(Figure 11)*. Unsurprisingly, in all cases, annual electricity bills are set to increase considerably, reflecting the demands of a transition to a low-carbon electricity system. Once again, the TF pathway looks highly ambitious out to 2030; the bill increases are much higher in the shorter-term for the TF pathway, which could raise severe feasibility issues.

However, these results also clearly illustrate the impact of reducing demand; in 2050, the TF pathway has the lowest bill increases and much lower potential impact on levels of fuel poverty, despite having higher generation costs. This illustrates clearly the importance of the demand-side when attempting a transition: the most effective means of ensuring that the costs of achieving sustainable energy are not borne by struggling consumers is to reduce household demand. It is worth noting that the level of demand reduction in the TF pathway and the low risk score for fuel poverty are both achieved through high levels of engagement and participation from the general public. Therefore, the results from the 'annual bills' and 'fuel poverty' indicators show that in order to keep consumer spending on energy manageable, consumers

must also undergo a transition, from passive consumers to active participants in the energy system.
It should be noted that there are high levels of uncertainty surrounding affordability projections; in order to reflect this, extensive sensitivity analyses have been carried out to highlight the impact of the assumptions made. The results of these tests will be available for later publication.

4.4 Long-term environmental sustainability

Fig. 12: Carbon intensity

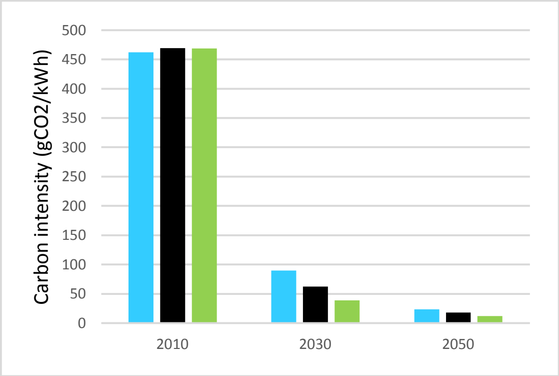


Fig. 13: Water consumption and withdrawals

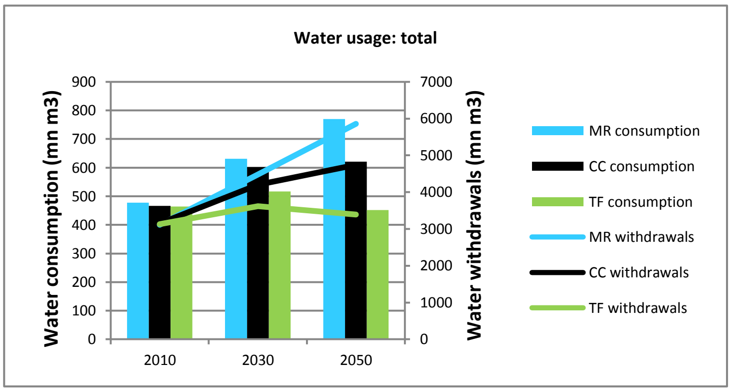


Fig. 14: Depletion risk of major generation types

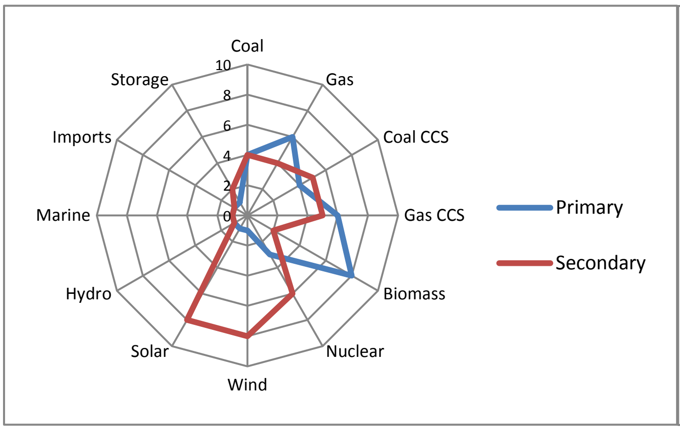
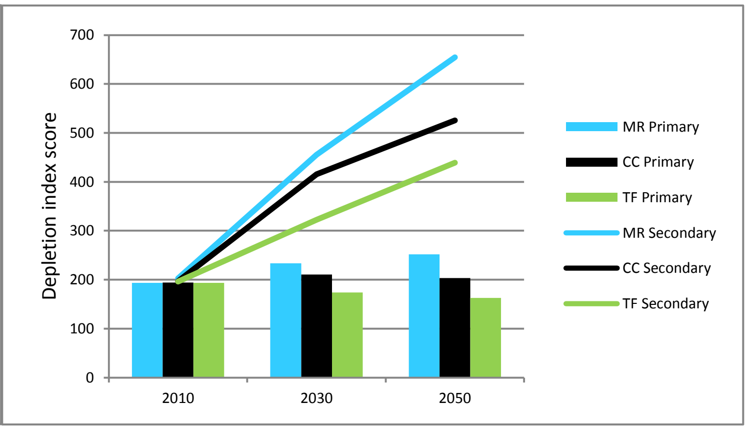


Fig. 15: Primary and secondary resource depletion



Rather unsurprisingly, the TF pathway is clearly the most sustainable for all the metrics above. The increasing penetration of small-scale, decentralised energy and RES and a steep decline in the share of fossil fuels and nuclear in the generation mix all act to reduce pressures on the atmosphere, water resources, fuel resources and materials. Moreover, the considerable use of biomass in this pathway results in lower levels of secondary materials depletion. The results from this set of indicators are interesting when viewed alongside the other indicators, because the clear result here may help to highlight potential trade-offs between environmental sustainability and other aspects of energy security.

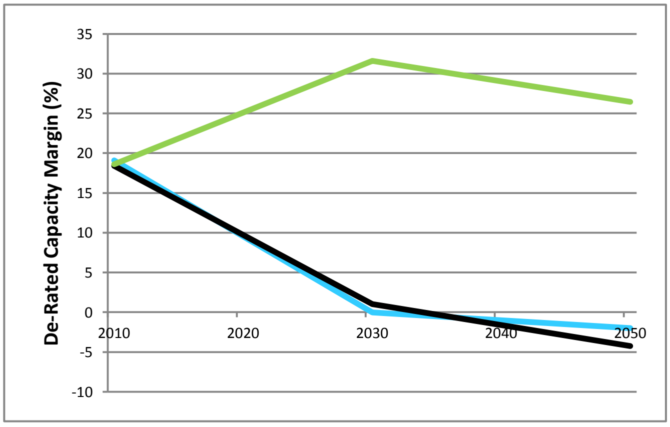
One important caveat is that this indicator illustrates high uncertainties around biomass. There is very little research into the sustainability of biomass, in particular on life-cycle emissions, levels of global resources, and life-cycle water requirements. It is therefore the contention of this paper that more research needs to be done, both in accounting for the impacts of the biomass we currently use, and into the advancement of more environmentally friendly sources such as energy-from-waste.

4.5 Reliability: system adequacy

Generation adequacy, network adequacy, and oversupply

The three transition pathways were all developed with hour-by-hour generation adequacy in mind; as such, they are all capable of meeting peak demand at all times. However, achieving this in the context of increasing RES penetration means that considerable spare capacity is required. Load factors for conventional generation need to be low; in some cases, the load factors for fossil generation are so low that there are concerns raised for the feasibility of the pathways, because low load factors mean less of an incentive to invest in power generation capacity (although DECC is currently trying to address this with the inclusion of capacity payments in the EMR). A similar issue occurs with network adequacy: as shown in the 'affordability' indicator, the cumulative network upgrade costs required to maintain network adequacy could reach into the hundreds of billions. Therefore the really interesting conclusion from this indicator is that the impacts of the transition may be felt not through decreasing ability for supply to meet demand, but through decreasing ability for the system to actually attract enough investment in generation and networks. This is of high concern for all three pathways.

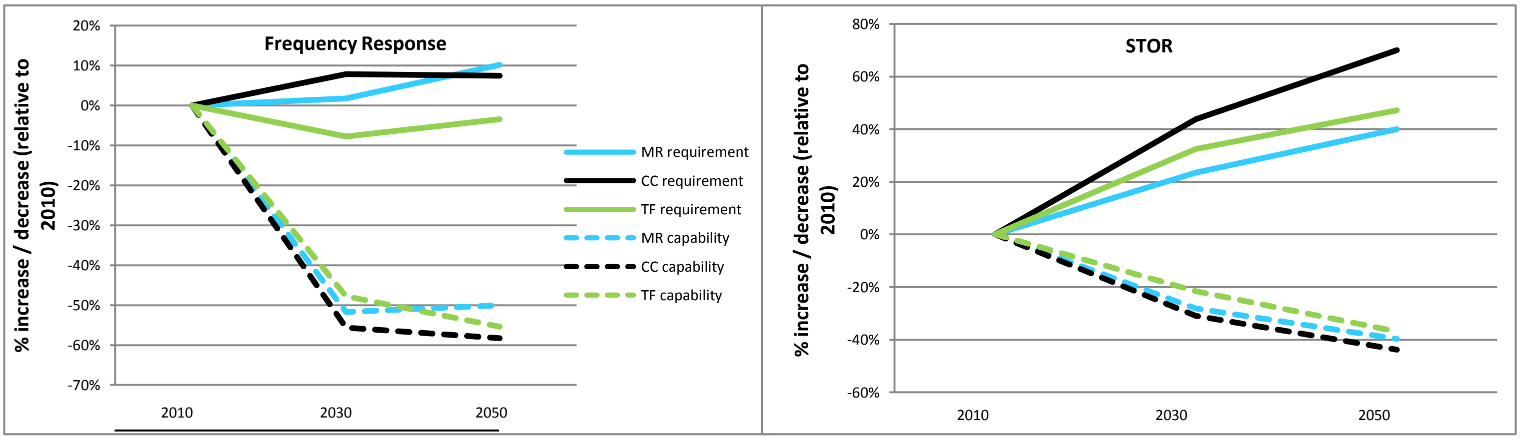
Fig. 16: De-rated capacity margins



The results from the DRCM indicator *(Figure 16)* show a large disparity between the TF pathway and the other two. The MR and CC pathways both raise serious concerns for DRCM, in both cases seeing negative margins by 2050. The TF pathway, on the other hand, shows a very high margin throughout, reflecting the need for large amounts of spare capacity to back up intermittent RES. Once again, it seems that the real issue may be in the feasibility of attracting investment in this spare capacity, especially considering that such high margins may result in excessive curtailment.

4.6 Reliability: shock resilience

Fig. 17: Response and reserve capabilities and requirements[3]



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[3] Frequency response = the ability of the system to respond to unexpected fluctuations in electricity frequency, over very short timescales (<30 minutes). Short-Term Operating Reserve (STOR) = the ability of the system to return to normal operating conditions, under slightly longer timescales (30 minutes to 4 hours)

Figure *17* shows a clear disparity between declining capabilities and increasing requirements for response and reserve, for all three pathways. The declining *capability* reflects the increasing penetration of inflexible sources such as RES and nuclear, and also the impact of low load factors; if a plant is switched off at the time of the response or reserve request, it cannot come on-line quickly enough to provide backup services. The increasing *requirement* reflects the impact of increasing wind generation (leading to bigger impact of inevitable wind forecasting errors), decreasing system inertia, and an increase in the credible potential in-feed loss due to an increase in (nuclear) unit size. The STOR estimates *(Figure 18,* below*)* show these issues in more detail, reflecting declining availability of both short-term and long-term STOR, and of black-start capability. These concerns are greatest for the CC pathway, reflecting the impact of increasing penetration of wind and nuclear.

Fig. 18: STOR and black-start capabilities

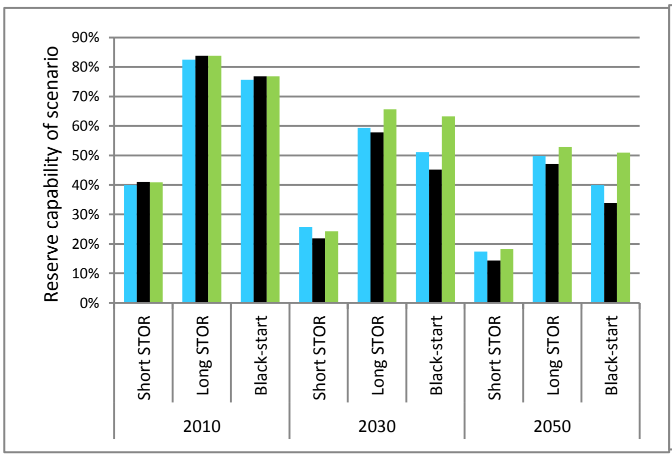
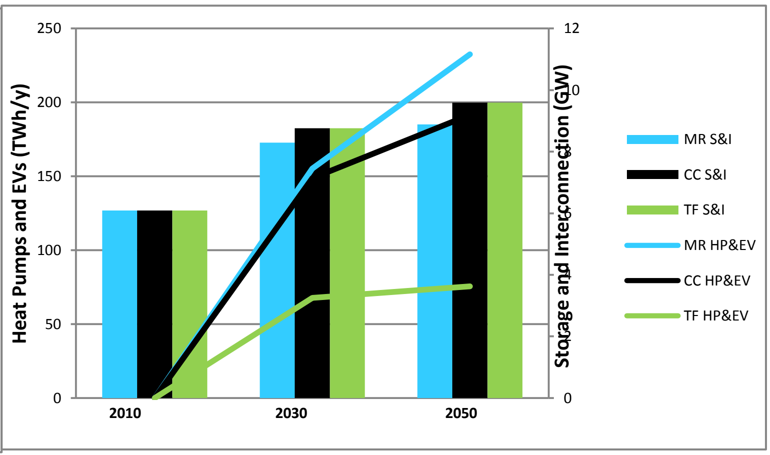


Fig. 19: Flexible supply and demand



The one positive message from this indicator is the increase in flexible supply and demand, shown in Figure *19.* These results merely represent a rough proxy estimate, as the data required to project the existence and efficacy of complex systems such as smart demand-side response are not easily available; however, the concerns raised in Figures *17* and *18* suggest that flexible demand-side measures should be a policy priority.

5. Discussion: risks, trade-offs and uncertainties

The results from a broad assessment of electricity security can help to reveal some important trade-offs which may be experienced when attempting to resolve the 'energy trilemma'. The results show that there are no clear winners; all routes to a low-carbon transition involve vulnerabilities in certain areas, and one of the challenges will be to identify the areas in which we are most prepared to accept costs and compromises.

One of the most immediate and noticeable trade-offs which emerges from the analysis is a potential high-level conflict between long-term and short-term energy security. All of the pathways perform worst for short-term reliability and for affordability, whilst in general, fewer serious concerns are raised for longer-term availability and sustainability. However, the Thousand Flowers pathway performs well in most of these areas, raising fewest concerns regarding likelihood of internal or external disruption (long-term), environmental sustainability (long-term), system adequacy and margins (short-term), and shock resilience (short-term). A considerable factor in this is the lower levels of electricity demand in this pathway compared to the others.

An important outcome of the analysis is that a more sustainable pathway does in fact result in higher generation costs; however, reducing demand can mean that this cost is not borne by consumers, and that therefore sustainability does not have to be regressive. However, this raises the difficult question of "affordable to whom?" If generation and network costs are set to increase, then a key trade-off emerges between avoiding spiralling fuel bills and maintaining profitability and competitiveness for the utilities. The Thousand Flowers pathway attempts to achieve this by making a dramatic shift towards decentralisation and community ownership, and significantly reducing demand; this succeeds in driving down network costs, but generation costs are the highest of the three pathways in both 2030 and 2050. It appears therefore as if there may be a key trade-off between delivering affordable, sustainable electricity, and the feasibility of somehow still managing to pay for the generating capacity necessary to drive such an ambitious transition. The affordability trade-off is an issue for all three pathways, but in rather different ways: the Market Rules pathway may struggle to avoid a serious fuel poverty problem arising from high retail bills and a market-oriented system, the Central Coordination pathway could struggle with attracting private investment whilst maintaining the political legitimacy to pass the costs of this onto consumers, and the Thousand Flowers pathway could see community groups and householders struggling to develop the capital necessary to build infrastructure. In all these examples, concerns are raised regarding the feasibility of attracting and delivering investment in generation and network infrastructure.

This issue with feasibility is also evident in the concerns raised by the various 'short-term reliability' indicators (sections 4.5 and 4.6). Both of the top-down pathways perform particularly badly, suggesting serious concerns for the reliability and shock resilience of a centralised low-carbon electricity system. The only example of secure capacity margins in the three scenarios is in the TF pathway, where is it achieved via reduced running hours for conventional generation and large amounts of spare capacity on the system. Therefore the feasibility of realising this is called into question, as investors would be less willing to build spare thermal capacity or to endure significant curtailment of RES. This project aims to carry out further research in the near future to explore whether other sets of transition pathways may be capable of achieving system adequacy without such high levels of spare capacity. It is also worth noting that increased flexibility of demand and peak shaving could significantly mitigate the trade-off between secure capacity margins and excessive spare capacity; the pathways assessed here do not contain enough data to make an accurate assessment of the ability of the system to support significant levels of demand-side innovation, but this represents an important area for future research.

5.1 Uncertainties and limitations

Two major areas of uncertainty in the analysis stand out as worthy of note:

- **Biomass**: the TF pathway especially is highly reliant on biomass, and this will be a crucial aspect of sustainable yet flexible electricity generation. But how sustainable is biomass? What are its life-cycle resource requirements, costs and emissions? And, in the context of increasing demands globally for the resource and the current lack of an established global supply market, where is it all going to come from?
- **Costs:** it is notoriously difficult to project costs, and like all previous projections, the cost projections here will probably prove to be wildly inaccurate. This reinforces the

importance of focusing on reducing demand, which is a relatively fail-safe means of ensuring that the brunt of higher costs doesn't get passed on to struggling consumers.

The results above show a very high-level view of the future security of the UK electricity system in a low-carbon context. Clearly, this produces limitations of the analysis, both in terms of subjectivity and uncertainty. Multiple assumptions must be made, which in some cases tend to stack up on top of each other. These uncertainties will be explored through the use of multiple sensitivity analyses for several of the indicators, the results of which should provide fruitful ground in future for discussions on the impact of assumptions in energy security assessment.

It is important to note that the choice of indicators will always be subjective. As such, the next stage of the research will seek to explore the assessment framework and the results by opening up the discussion to a range of expert stakeholders. The aim will be to interrogate the diversity of stakeholder perspectives and attempt to explain the origins of their differences. Their views will be used as the basis of a transparent and much-needed discussion on energy security, which recognises the fact that 'security' always means different things to different people, and which seeks to explore the ways in which subjectivities influence the debate.

6. Conclusions and Recommendations

This paper has presented the initial results from a high-level, broad assessment of the security of the UK electricity system, in the context of a set of three low-carbon transition pathways. A new framework for the assessment of future low-carbon electricity security has been developed, which explicitly addresses the importance of different timescales when discussing system security, and which seeks to widen the security discussion to include social, economic and environmental aspects. The aim has been to create a 'dashboard' of indicators using both qualitative and quantitative methods, which can be used either individually or as a whole set. This indicator framework is designed to be broadly applicable to the security assessment of any set of transition pathways, provided that the raw data is available. The use of these indicators as a whole set has helped to identify key issues and trade-offs which could occur when undergoing a transition to a low-carbon electricity system.

Some important policy recommendations emerge from the analysis. Firstly, the analysis reinforces the fact that a transition must involve significant effort on both the supply-side and the demand-side. On the supply-side, it is clear that there will be high economic costs, whichever route to transition is taken. This research has raised some serious concerns regarding the feasibility of attracting and delivering ambitious levels of investment in generation and network infrastructure, due to the scale of the transition required. However, rising costs to consumers can be managed through ambitious demand reduction programs; this will necessitate a policy focus on increasing consumer engagement and participation, for instance by increasing support for decentralised and small-scale community projects and microgeneration. Increased flexibility on both the demand-side and the supply-side will be imperative to mitigate the impact of increasing penetration of intermittent generation. As such, policy should immediately recognise the future importance of biomass in providing renewable yet flexible power generation; in particular, more sustainable indigenous forms of biomass, such as energy-from-waste, should be prioritised. Moreover, policy should act now in support of system flexibility, including smart DSR, storage and interconnection. It is the contention of this paper that current UK energy policy displays a worryingly pervasive focus on large-scale centralised generation assets, with the emphasis on providing capacity rather than flexibility, and therefore runs the risk of prioritising solutions which may be more expensive and which may lock the UK into a less flexible and less resilient electricity system.

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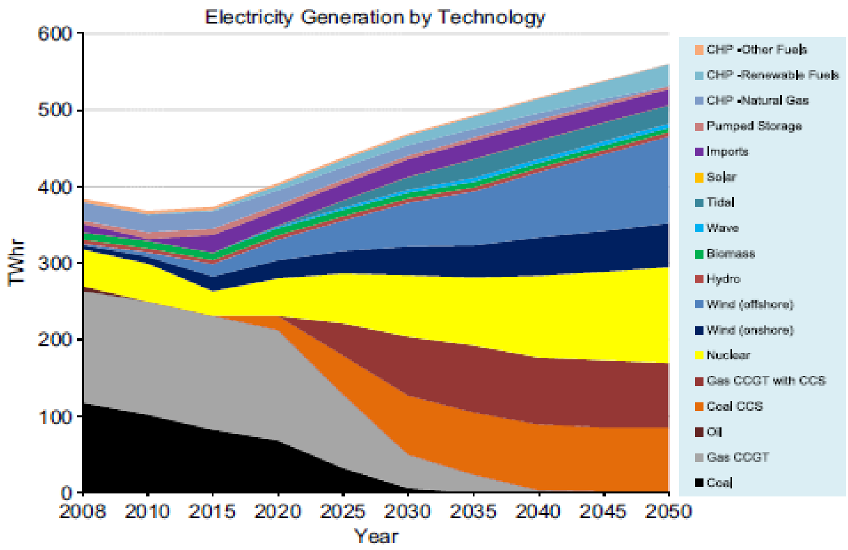
Appendix A: Transition pathways to a low-carbon economy

The development and design rationale of the TP pathways is described in detail in the Special Issue of *Energy Policy,* Volume 52 (2013). The theoretical background is elaborated in Foxon (2013); more detailed technical development can be found in Barnacle *et al* (2013). The Transition Pathways were chosen largely because they represent a departure from the technological or economic modelling methodologies usually used for creating transition pathways. Energy systems do not emerge on the basis of economic rationality; rather, they are the result of a messy combination of socio-technical, political and economic drivers.

All the pathways aim to reduce UK carbon emissions by 80% by 2050. However, the consortium did not assume that all the pathways succeed in doing this; in fact, only the CC and TF pathways succeed, with the MR and CC pathway reducing overall emissions by 72% in 2050. All pathways assume some electrification of heat and transport; for this reason, despite improvements in efficiency, electricity demand increases in both the MR and CC pathways.

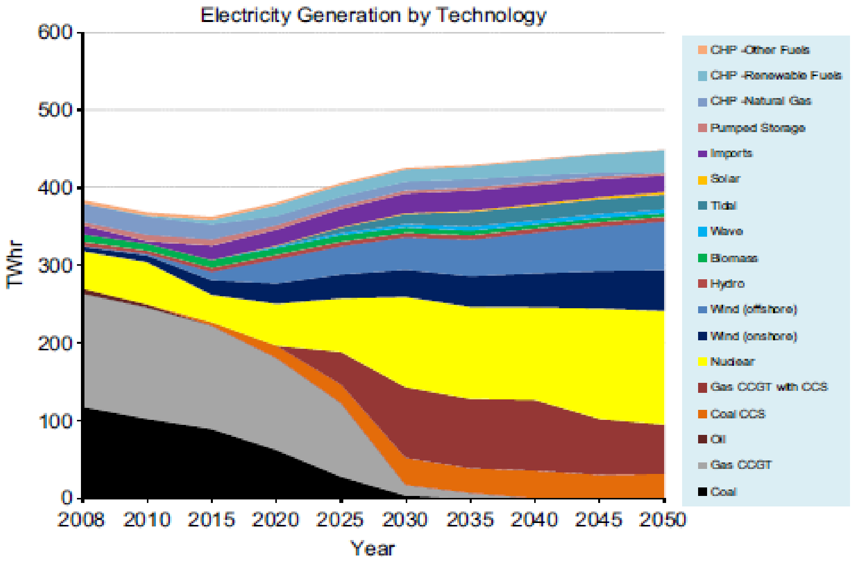
The fuel mix for the pathways is illustrated below. A clear dichotomy emerges between the two pathways which are dominated by centralised, top-down approaches, and the third pathway which envisages a much more participatory, bottom-up logic. This is particularly interesting, because it opens up the space to discuss energy security issues in the context of the normative question of how the emerging system *should* look, if we are to achieve a low-carbon, affordable and secure electricity system.

Market Rules:



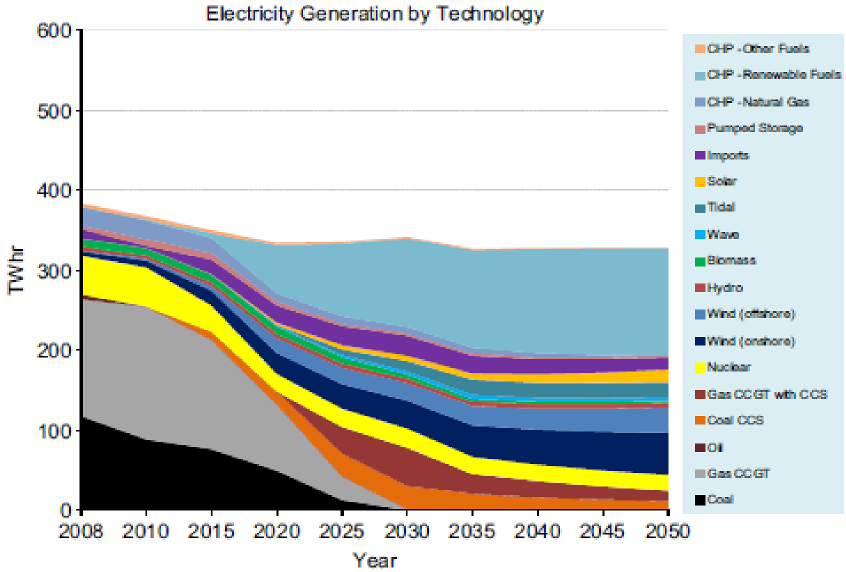
- Large-scale
- Centralised
- Offshore wind
- Fossil fuels
- CCS
- Rising electricity demand

Central Coordination:



- Large-scale
- Centralised
- Nuclear
- CCS
- Energy efficiency
- Slight demand increase

Thousand Flowers:



- Decentralised
- Small-scale
- Biomass CHP
- Micro RES
- Behaviour change
- Demand reduction