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Getting to zero: impacts on local electricity distribution systems arising from UK 2050 carbon pathway scenarios

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The electricity sector worldwide is facing considerable pressure arising out of climate change issues, depletion of fossil fuels and geo-political issues around the location of remaining fossil fuel reserves. Electricity systems are also facing technical issues of bi-directional power flows, increasing long-distance power flows and a growing contribution from fluctuating generation sources. There is a concern that these systems are vulnerable. Investigation of vulnerability has focussed on shocks to the system associated with weather risks, equipment failure, supply (fuel) failure and price shocks, and analysis has been primarily based on financial measures such as the value of lost load.

As the UK electricity system makes the transition to a low carbon future, it is unclear what this new future will look like. Transition pathways research using a multi-level perspective has identified a general picture of the drivers in future systems architecture. In such futures, vulnerability becomes multi-dimensional, and security becomes a more complex issue than that of supply of fossil fuels. These issues are not specific to the UK. Electricity systems across the globe face the same issues of multi-dimensional vulnerability and complexity of security. There are also issues around governance of energy, particularly for those scenarios that involve a significant proportion of energy needs being met locally.

Research into the transition to a low carbon electricity system has, to date, been primarily focussed on the national scale in the UK. The aim of this work is a critical analysis into the 2050 pathway scenarios for the UK with respect to their impact locally on the distribution network in a case study urban area in the North East of England. The case study shall examine the proposed national low carbon scenarios, what this means in domestic and non-domestic buildings for the case study area, and the nature of the stress on the electricity distribution system which may result from the expected growth in electrical load. The significance of these findings shall then be discussed with respect to transitions and local governance.

Key words: Electricity distribution, low carbon transitions.

1. INTRODUCTION

The electricity sector worldwide is facing considerable pressure arising out of rising global demand for energy services (Barrett *et al.*, date unknown; Ipakchi and Albuyeh, 2009), geo-political issues around the location of remaining fossil fuel reserves (Vivoda, 2012; Valentine, 2011; Coaffee, 2008; Nuttal and Manz, 2008), in addition to climate change issues (Eyre and Baruah, 2011; Grubb *et al.*, 2006).

The International Energy Agency (IEA) predicts a doubling in world energy demand from 2009 to 2035 (IEA, 2011). The most significant percentage growth in demand for energy occurs in the Middle East (growth of 1100%), China (growth of 432%), Asia (growth of 327%) and Africa (growth of 223%). Energy reserves are currently concentrated in relatively few nations around the world. In 2010, the top 5 oil exporting countries were responsible for 47% of global oil exports, 4 of which are members of the Organization of the Petroleum Exporting Countries (OPEC) (OPEC 2011). Middle East and North Africa (MENA) countries are home to 60% of world oil reserves and 49% of world gas reserves. Widespread political and social instability in this region, particularly the 2010 and 2011 “Arab Spring”, led to oil price increases during that period (MENA-OECD Investment Programme, 2011).

With respect to climate change, the only legally binding international agreement to tackle greenhouse gas emissions is the Kyoto Protocol, developed in 1997 and ratified in 2005. Whilst international agreements on carbon emissions reductions have faltered at recent Conference of the Parties (COP) meetings, in 2009 the European Commission created legally binding targets for 20% reduction in greenhouse gas emissions and 20% contribution of renewable energy sources to overall energy consumption by 2020. The UK Government has a legally binding target to reduce greenhouse gas (GHG) emissions by 80% by 2050, compared to 1990 levels (Climate Change Act 2008). Associated with this target is a plethora of Government reports and legislation produced by the Department of Energy and Climate Change (DECC) which consider how this challenging target can be achieved (for example: DECC, 2009a; DECC, 2009b). The 2050 pathways report (DECC, 2010) demonstrated that scenarios achieving the 80% target involved significant electrification of the heat, transport and industry sectors in parallel with considerable decarbonisation of the electricity sector. Therefore, regardless of relatively slow growth predicted in the UK population, the growth in demand for electricity is predicted to be significant over the next 40 years.

Growth in demand may not be universally distributed throughout the whole of the UK however. Actions taken at a regional and local level will influence the degree to which demand changes. In the UK national climate change targets are devolved to the regional and local level voluntarily through a Memorandum of Understanding (MoU) between DECC and the Local Government Group (LGG) (Bale et al, 2012; DECC, 2011). The result is that UK local authorities take responsibility for cutting carbon from their own estate whilst reducing per capita CO_2 in their areas, reducing fuel poverty and adapting to climate change (Akcura et al, 2011). One example is Newcastle City Council in the north east of England who set a target to reduce the city’s carbon emissions by 34% (from 1990 levels) by 2020 (Newcastle Partnership, 2010). Other city and municipal authorities worldwide have set similar carbon and GHG emission reduction targets to be met through measures such as energy demand reduction strategies, energy efficiency programmes and the deployment of decentralised renewable energy systems. It is therefore necessary to understand the potential impact locally on the distribution network in order to plan for a future low carbon electricity system.

UK total inland energy production and consumption have not changed significantly in the 30 years between 1980 and 2011, as indicated in Figure 1 (DECC, 2013a). Industrial consumption has fallen from 48.3 million tons of oil equivalent (mtoe) in 1980 to 27.1 mtoe in 2011 as the UK has reduced involvement in industrial production, domestic consumption has risen slightly (remaining in the region of 40mtoe) and services have continued to consume some 20mtoe. The major increase has been in the transport sector where consumption has risen from 35.5 to 55.2 mtoe in the period (DECC, 2013a).

As shown in Figure 1, the primary sources of UK energy have changed between 1980 and 2011. There has been a large rise in gas consumption that has offset the reduction in the use of coal. Oil consumption has fallen, and primary electricity (mostly nuclear) has risen by about the same amount. Bioenergy and waste appears in the 2012 data but was not significant before 2008.

Figure 1. UK inland energy production and consumption 1980 – 2011.

Prior to 1980, the UK was a net importer of energy. For the next quarter of a century up until 2004, the UK was self sufficient in energy. However, as the North Sea reserves of oil and gas have been consumed, the UK has returned to a position of energy dependence, importing 36% of its requirements in 2011 (DECC, 2013a).

The 2011 and 2012 fuel mix supporting the production of electricity is shown in Figure 2 (DECC, 2013a). Traditional fossil fuels such as coal, oil and gas, are the primary energy carriers for almost three quarters of UK electricity generation.

Figure 2. UK energy sources for generation of electricity 2011/2012.

1.1. Electricity system resilience

What is meant by resilience?

Historically, the security of supply discussion has been around supply side (e.g. Cohen *et al.*, 2011; Jamasb and Pollitt, 2008) and technology performance (Chiaradonna *et al.*, 2011; Grave *et al.*, 2012). However, several research groups are investigating a wider concept of security (for example, Stirling (2009), Jansen and Seebregts (2010), O'Brien and Hope (2010), Goldthau and Sovacool (2012)). Included in these wider concepts is consideration of terms such as robustness, diversity, stability, durability, adaptability, sustainability, vulnerability, redundancy and resilience.

The UK government has focussed on security of supply with respect to reduced reliance on imports and robust supply chains and partnerships. One electricity sector service currently at risk of under-delivery in the privatised UK electricity system, and hence a market failure requiring intervention, is the issue of generation capacity margin. Whilst the target for capacity margin is 20%, capacity margins in the winter of 03/04 fell to 16.5% (Hammond and

Waldron, 2008) and to 16% in 2009 (OFGEM, 2010). The regulator OFGEM has recognised that increased use of intermittent generation means that capacity margin becomes a less reliable measure of the ability of the electricity system generation to meet demand. De-rated capacity is to be used for reporting capacity under new requirements in the Energy Bill 2010 (OFGEM, 2011). De-rated capacity is the excess of available generating capacity when compared to demand. With 12GW of coal and oil to close by 2015 and 7.1GW of nuclear to close by 2020 (Department of Energy and Climate Change, 2011c), modelling of the UK electricity system indicates that the de-rated capacity margin could fall to as low as 5% by 2020 (Department of Energy and Climate Change, 2011b), down from 16% in 2009 (OFGEM, 2010). Capacity margin has been such a concern that the issue has been addressed in the 2011 Electricity Market Reform proposals, which recommend a Capacity Market be created.

For electricity in particular, the engineering focus has been on a robust system able to operate under loss of components, the “N-k” approach. Regulation for security is through the GB Security and Quality of Supply Standards (SQSS). The SQSS states that the GB electricity transmission system must cope with simultaneous outages of “k” elements from a total “N” elements of generation, network elements or the demand side, without unsupplied demand and without violating operating limits. The document was issued in 2004, with updates in 2009 and 2011. The emphasis in the document (National Grid, 2011) is on the re-instatement of the system to its pre-event operation levels, should an outage occur. Normally, systems are required to operate such that they are able to withstand N-1 without any loss of service. Research has shown that cascade failure is not always due to failure to operate at N-1 security, and not always due to N-2 failure. More often, cascade failure is the result of an initial N-1 incident followed by a protection malfunction which removes healthy network from service. The cost of this “N-k” security approach is complex to assess since it depends upon the system component under consideration (cable/wire, transformer, power station). For example, considering the UK electricity generation capacity margin of 14% in 2012/13 (OFGEM, 2012), and assuming the spare capacity of 7,948MW is combined cycle gas turbine technology with an average capital cost of £691.3/kW (PB, 2011), then the estimated capital cost associated with the 2012/13 UK electricity generation capacity margin is £5,494m.

With changes to the electricity infrastructure and reduced national self-sufficiency in oil and gas, it is no longer technical risk of outage, but geo-political uncertainties, price shocks and homeland security that have recently entered the vocabulary when discussing the UK electricity sector (Coaffee, 2008). Following the terrorist attacks on the USA World Trade Centre on 9/11, the US expanded it’s list of critical infrastructure (CI) to 17 (O’Rourke, 2007). Homeland security became a key priority for the White House and security was ramped up at airports around the world following the incident. The threat of terrorist activity is seen by some as a fundamentally different type of disruption to CI, with characteristics such as large scale disruption over large areas, mass media coverage of events, and a lack of historical precedent (for some nations) on which to base solutions (La Porte, 2006). al-Qaeda’s most deadly European attack was the Madrid train bombing in 2004 which killed 190 people (known in Spain as 11-M). London’s own experience of an al Qaeda-claimed attack on 7/7 2005, involving the bombing of the London underground and a London bus and leaving 37 dead, is not the UK’s only experience of terrorist attack. In the 1980’s and 1990’s a number of terrorist attacks by the IRA took place in the UK, predominantly in Northern Ireland but also in London, Brighton, Bristol and Manchester. The single terrorist attack resulting in the highest number of British deaths was 9/11 (67 British lives lost), whilst the greatest number of lives lost on UK soil due to a terrorist attack was the Lockerbie bombing in 1988 (270 lives lost).

Whilst there is increased concern regarding the threat of terrorism, and the potential for CI such as electricity systems to be the target for such attacks, analysis of global data on terrorist activity indicates just 1.5% of world terrorist incidents from 1998 to 2007 had targeted energy infrastructure, with attacks concentrated in Columbia, Iraq, Pakistan and India (around 70% of all energy-related terrorist activity in these four countries) (Toft et al, 2010). The concern for the UK, therefore, is more likely to be based around disruption to supply as a result of terrorist activity overseas, than terrorist activity on home soil leading to supply disruption. Whilst reliance on fossil fuels from unstable parts of the world is highlighted in the Government's National Security Strategy (2010), the UK Government has identified international terrorism, cyber attack, major accident or natural hazard, and an international military crisis priority risks.

It is therefore timely to consider indicators which go beyond the supply focus and financial focus (such as value of lost load (Chaudry *et al.*, 2009)). Given the historical focus on security as an issue of supply of primary fuel, alongside more recent developments in the way we view issues of terrorism, interconnected infrastructure and smart grids, "security" as a term no longer seems appropriate. **Resilience** is proposed as an alternative appropriate term.

Resilience has been used in ecology to define the magnitude of disturbance which an ecological system can absorb before the system structure changes, described in work by Holling in 1973. Holling (an ecologist) described ecological resilience as the magnitude of the disturbance which can be absorbed before the system structure changes and a new equilibrium is reached (Davoudi, 2012). So the concept is not a return to the status quo, but the ability to adapt, change and transform. Holling's work has been expanded upon, for example Walker *et al.* (2004) define resilience as the ability to reorganise during change, to enable continued functionality.

Within resilience thinking, the concept of change and evolution of systems is represented by the "adaptive cycle". The cycle comprises four stages.

1. There is a period of growth, with an abundance of resources, and an accumulation of structure.
2. There is a period of conservation, with a slowing of net growth, greater system interconnection and less flexibility.
3. There is a stage of release of bound-up resources where disturbance leads to accumulated structure collapse.
4. Finally there is a reorganisation stage where novel practice or technology can take hold (Walker *et al.*, 2006).

Stages of the cycle are not necessarily sequential and one system may have elements with nested adaptive cycles operating at different scales and timeframes.

Resilience as a term therefore enables a discussion of the electricity system's ability to adapt, change and transform rather than an ability to return to "normal" within some prescribed range of operating conditions. Resilience as a concept can be applied to much more than the supply side and hardware. Instead, it enables a holistic approach to the system which is the electricity sector, and about the components which make up that sector. It brings in to the discussion a richness which addresses the social and the technical. Resilience provides a new definition of a healthy system.

Within the adaptive cycle concept, where do the disturbances originate which lead to change? Multi-level perspectives in transitions theory are complementary to resilience theory in this regard. A multi-level perspective considers niche technologies at the micro scale putting pressure on the incumbent system at the meso level, and macro level pressures from the overall socio-technical landscape (Geels, 2002). This concept of a multi-level perspective enables an electricity sector resilience dialogue to incorporate global and local issues.

In considering resilience and transitions theories, we propose a nested resilience model comprising environment, society, political processes and electricity infrastructure, incorporating global, national and local issues. This is shown in Figure 3. Note that in the UK, generation (ownership and operation of power plant), transmission (long distance transportation, at 400kV, 275kV and in Scotland 132kV, of electricity from large generation plant to distribution networks), distribution (short distance transportation, at 132kV and below, of electricity to end users) and supply (metering and billing of electricity end users) have been separated and privatised, and so each subsection of the electricity sector is shown separately in Figure 3. Different sub sectors may be appropriate in different contexts.

Qualitative and quantitative measures within each element of the resilience model can then be chosen, appropriate to the context under consideration. For example, in considering indicators of resilience for the UK electricity system an appropriate national scale societal indicator may be the number of households in fuel poverty. For the Sudan, it may be the number of households without a supply of electricity. The collection of qualitative and quantitative indicators can then be presented as a score card. Amalgamation of indicators to provide one measure of resilience relies heavily on quantitative measures and subjective weighting of components, and so is not recommended.

Figure 3. Representation of three scales, applied to a nested system to represent the electricity sector and its relationship to politics, society and the environment.

1.2. The Smart Grid concept

Between 1945 and 1973 the developed world grew, and many costly capital projects were undertaken. Much of the existing UK electrical infrastructure, such as turbine generating plant, nuclear reactors, transformers and power lines, date from this period. The equipment had a finite lifetime, which has in many cases elapsed. The problem now facing energy planners in the UK, for instance, is that the cost of replacing the capital equipment is very high. Owing to the very long ‘lead time’ before new projects can be completed, system operators are facing the task of operating power systems without reliable components; power failures and blackouts are to be expected in this situation.

In order to be able to achieve the target reduction in CO_2 by 2050 and improve energy security, a number of proposals have been suggested regarding the primary energy fuel mix, including nuclear, wind power, wave power, geothermal, solar PV, combustion of biomass and tidal energy. The UK Renewable Energy Strategy (DECC, 2009c) has set a target by

2020 of 30% of UK electricity generation from renewable energy sources, including 32GW of offshore wind generation. These targets influence choices regarding electrical infrastructure development.

A common feature of renewables is that they typically have lower relative energy density; a large wind turbine might have a rated capacity of 3MW as opposed to 1GW for a large coal fired power station. A change in electricity generation from few large central generators to many smaller distributed generators means that power flow will, in some cases, be from lower voltages to higher voltages, which will create problems for protection and control systems. The coordination of the numerous sources of generation to achieve adequate levels of power quality requires new technology and processes. Given that the existing power infrastructure requires extensive investment due to the age of its equipment, the Smart Grid concept can channel this investment into new and improved performance levels.

A Smart Grid carries flows of information between electricity consumers and producers, and also controls the multi directional flow of power to ensure that all Power Quality standards are met, and that the supply is reliable. A Smart Grid should have the ability to carry on despite breakdowns in components within the system, much as the Internet is able to do. A Smart Grid's prime purpose is to respond to changes in supply and demand conditions, both of a technical nature such as normal changes in power flow, voltage and frequency, and environmental, such as the fluctuations in supply of renewable energy. The secondary purpose is to deal with commercial considerations, such as setting price levels for power such that supply is brought in line with demand. At the same time the Smart Grid should be capable of automatically dealing with faults in a self healing manner.

1.3. Governance of the grid

The question of effective governance of energy systems internationally has been labelled a "mega-issue" (Lesage et al, 2010) in part due to the fact that energy is deeply embedded in other sectoral and policy contexts. As such energy system governance represents a significant challenge for policy makers at all levels. In most regions the organisation of public administration structures were designed in an age when fossil fuel prevailed, as such today's governance structures were not designed to cope with the decentralised, locally deployed renewable energy systems required to transition to a low carbon economy (Radzi & Droege, 2013). Governments are poorly placed to govern local or national energy issues, let alone participate in effective global energy system governance (Florini & Sovacool, 2009).

This is the case in the UK where the tensions between international, national and local energy governance are currently being played out. Here it is increasingly being recognised that established carbon reduction targets require strong, co-coordinated efforts from a variety of different stakeholders including both 'institutionally driven' (i.e. local government) initiatives, and more organic or 'grassroots' community based approaches (Fudge et al, 2012). The UK Energy minister, Ed Davey highlighted this in a speech to the Local Government Association (LCA) where he stated, "*…national government can't deliver on its energy and climate change policy without local government*" (Davey, 2012). Local authorities recognise that ambitious early action can pre-empt future central government regulation, whilst also contributing to regional economic regeneration, increased employment, improved energy security, lower energy costs, improved local environments and stronger connections between people and communities (Akcura et al, 2011). It is necessary then to consider the implications energy demand and supply in the context of local level policy and governance issues.

2. MATERIAL AND METHODS

The UK in 2050 – A local perspective

In investigating the impact of 2050 scenarios (DECC, 2010) on the local distribution network, the public domain EXCEL 2050 pathways calculator was used (DECC, 2012) along side details of the seven UK Government pathways, to find the mean electricity consumption for households, based on heating, cooling, lighting, appliance and personal electric car loads (Table 1). The 2050 scenarios bring together possible scenarios for several energy supply and demand sectors: heating and cooling, lighting and appliances, transport, industry, nuclear, renewables, coal and gas with carbon capture and storage (CCS), bioenergy, agriculture and waste. Each of these categories has four possible scenarios or levels. Combining these, the report outlines six scenarios and a reference case, which are the scenarios which are studied here in order to identify their local impacts on the electricity distribution network.

Table 1. Electricity consumption scenarios, 2050 pathways.

These consumption figures for domestic households, for the seven 2050 scenarios, are a mean for the whole of the UK. However, household electricity consumption in the north east is lower than average, typically 85-87% of the average for Great Britain (DECC, 2013b). In addition, the network model which was used for this research allows steady state analysis of network conditions under a summer and winter load profile. There was therefore a need to produce seasonal load profiles which are appropriate to the north east for 2050, in order to use within the network model.

Growth in energy demand may not be universally distributed throughout the whole of the UK as actions taken at a regional and local level will influence the degree to which demand changes. The demographic profile of the north east of England is very different from other parts of the UK, with the region producing the highest per capita carbon emissions of all of the English regions, despite being the smallest region outside of London in terms of area (DECC, 2013c). There is also a wide variation in the amount of renewable energy generating capacity by region both in terms of installed capacity and plans for further deployment (DCLG 2009). The difficulty lies in how to accurately model energy demand at the local level; all of the existing UK energy demand models to date have been created at the national level. In attempting to refine these models to a finer spatial resolution, the predictions do to some degree become increasingly speculative (Cheng & Steemers 2011; Shorrock & Dunster 1997).

Previous work on high-resolution energy demand models has highlighted discrepancies between national UK profiles. Many such discrepancies are believed to be due to socio-economic factors, employment profiles and individual attitudes to energy consumption (Richardson et al. 2010). Such factors are likely driven by the decisions made by local government as well as the historical socio-economic context. As such there are clear benefits of adopting a more localised approach to modelling and planning energy pathways where such local factors can be incorporated into models and be used to inform future energy demand and supply decisions.

Load profiles for the region were not available for this research. A normalised load profile (UKGDS project) was therefore scaled to provide a seasonal load profile which matched the total mean electricity consumption per household, for the north east, based on 2011 consumption data. The resulting 2011 north east mean seasonal load profiles are shown in Figure 4. This stage of the method could be improved if regional domestic mean seasonal load profiles were available.

To approximate the UK 2050 scenarios to the north east, at this initial stage a simple scaling factor was applied to the 2011 north east mean seasonal load profiles, based on the data from the 2011 UK domestic mean annual load and the 2050 UK domestic mean annual loads. Further research should be undertaken, to determine regionally specific 2050 scenarios, which contribute to the overall UK picture but which account for the regional context. Figure 5 shows an example of some of the winter 2050 load profiles for the north east of the UK, for the reference, gamma and zeta scenarios (2011 is also included for comparison). Where 2050 national scenarios included household scale generation by photovoltaics (PV) and small scale wind, the average installed capacity per household for the national scenario was applied. Some technologies will be more appropriate for the north east region and, therefore, further research is required to develop local 2050 scenarios which have appropriate local generation profiles in addition to appropriate local load profiles.

Figure 4. Mean seasonal electricity load profile, for the north east of the UK.

Figure 5. Mean winter electricity load profile, for the north east of the UK, 2050 scenarios.

A group working at Northumbria University, which includes two of the authors, has developed an Excel based modelling tool primarily designed to assess the impact of electric vehicles (EVs) on the low voltage distribution system. The various components of a 230V system may be modelled, including the 11kV step down transformer, cables, and location of consumers such as houses, shops and small businesses. It is possible to model the effects of renewable generation such as wind, combined heat and power (CHP) and photovoltaics (PV), and the effects of various types of EV chargers and heat pumps. Vehicle to Grid (V2G) operation may be studied, and the tool gives an indication of the effects of various charging regimes upon EV battery life. Interested potential users of the tool should contact the corresponding author.

The network model is based on a section of electricity distribution grid in an urban town in the north east of England, comprising a 400V 3-phase distribution system supplying 59 domestic properties (17 at node 2, 13 at node 3, 11 at node 4, 12 at node 5 and 6 at node 6). This model of the low voltage distribution system was used, along with scenarios for north east electricity load profiles and scenarios for distributed generation on the distribution network, for household loads only. The results indicate the potential impacts of national 2050 low carbon scenarios on the local distribution grid.

4. RESULTS

3.1. Reference scenario

Figures 6, 7 and 8 show the outputs of the model using data from a suburban area of Newcastle upon Tyne using the north east 2050 load profile for the reference scenario, (a) winter load profile and (b) summer load profile. The UK 2050 reference scenario is a baseline scenario with little or no attempt at decarbonisation for the UK. The 80% emissions reduction target is not achieved and the demand profile is slightly increased compared with 2011, as shown in Figure 5 which shows the north east demand profile for this scenario.

Figure 6 shows the 24 hour cycle of loading on the transformer, Figure 7 shows the voltages at various points on the network over 24 hours, and Figure 8 shows the currents flowing at various points on the network over 24 hours. Points on the network are assigned node numbers, such that lower node numbers are closer to the low voltage transformer. In accordance with electrical engineering practice, the results are shown in pu (per unit) where 1 pu =100% of the rated value for a component. The operating limits are included in Figures 6 and 8 as a horizontal dashed line. The dashed horizontal lines on Figure 7 are the upper and lower acceptable voltage limits as defined in network quality and security of supply standards.

Figure 6. Transformer loading during 24 hour cycle, 2050 north east reference scenario, (a) winter; (b) summer.

Figure 7. Line voltages at various points (nodes 2 to 6), 2050 north east reference scenario, (a) winter; (b) summer.

Figure 8. Line currents at various points (nodes 2 to 6), 2050 north east reference scenario, (a) winter; (b) summer.

Results show that transformer loading, node voltage and node current are all within acceptable limits for this scenario. The result closest to an operating limit is for the line current at 6pm at node 2, which reached 0.986pu (Figure 8).

4.2. Alpha scenario

The 2050 UK alpha scenario assumes that the sectors (heating and cooling, lighting and appliances, transport, industry, nuclear, renewables, coal and gas with carbon capture and storage (CCS), bioenergy, agriculture and waste) are balanced in their contribution towards carbon reduction, and the 80% reduction is achieved. This scenario includes significant effort to reduce energy demand and to use bioenergy, with relatively equal effort in development of renewables, nuclear, coal and gas with CCS.

Figure 9. Transformer loading during 24 hour cycle, 2050 north east alpha scenario, (a) winter; (b) summer.

Figure 10. Line voltages at various points (nodes 2 to 6), 2050 north east alpha scenario, (a) winter; (b) summer.

Figure 11. Line currents at various points (nodes 2 to 6), 2050 north east alpha scenario, (a) winter; (b) summer.

Results show the transformer experiences reverse power flow between 10am and 12pm, with load exceeding the transformer rating between 4pm and 8pm, in winter (Figure 9a). In summer the reverse power flow is more significant and lengthy, lasting from 5am to 5pm with a peak of -0.6pu at 9am (Figure 9b). This reverse power flow can give rise to problems for power system operators since the transformer may not be capable of reverse power flow and protection settings will be incorrect. Voltages remain within statutory limits for summer and winter, with a peak of 1.08pu at 9am in summer (Figure 10). Line currents exceed cable ratings at node 2 between 4pm and 10pm in winter (Figure 11a).

4.3.Beta scenario

For the beta scenario it is assumed that carbon capture and storage is not developed. Other sectors have to make a greater contribution in order for the UK to achieve the 80% reduction target. This includes offshore wind, imports of biofuels, energy storage, and demand reduction efforts.

Figure 12. Transformer loading during 24 hour cycle, 2050 north east beta scenario, (a) winter; (b) summer.

Figure 13. Line voltages at various points (nodes 2 to 6), 2050 north east beta scenario, (a) winter; (b) summer.

Figure 14. Line currents at various points (nodes 2 to 6), 2050 north east beta scenario, (a) winter; (b) summer.

Whilst the transformer load profile shows power flow does not exceed the transformer rating in the forward direction, there is reverse power flow in both winter (between 10am and 3pm) and in summer (between 5am and 6pm), as shown in Figure 12. Voltages remain within statutory limits for summer and winter, with a peak of 1.09996pu at 9am in summer, which almost exceeds the maximum voltage limit of 1.1pu (Figure 13b). Line currents exceed cable ratings at node 2 between 4pm and 7pm in winter (Figure 14a).

4.4. Gamma scenario

For the gamma scenario it is assumed that nuclear is not developed. Other sectors have to make a greater contribution in order for the UK to achieve the 80% reduction target. With no nuclear build, there is a significant amount of distributed and central renewable energy generation, and energy demand reduction for lighting, appliances and cooking. This means that the gamma scenario includes the maximum amount of local generation for any 2050 scenario; the average domestic household installs 2.52kW of solar PV and 40.9W of wind energy.

Figure 15. Transformer loading during 24 hour cycle, 2050 north east gamma scenario, (a) winter; (b) summer.

Figure 16. Line voltages at various points (nodes 2 to 6), 2050 north east gamma scenario, (a) winter; (b) summer.

Figure 17. Line currents at various points (nodes 2 to 6), 2050 north east gamma scenario, (a) winter; (b) summer.

Whilst the transformer load profile shows power flow does not exceed the transformer rating in the forward direction (the peak in apparent power is 0.986 at 6pm), there is reverse power flow in both winter (between 10am and 3pm) and in summer (between 4am and 6pm), as shown in Figure 15. Voltages remain within statutory limits for winter. In summer there is a voltage rise issue with voltages at nodes 3 to 6 exceeding the maximum statutory limit between 8am and 3pm (Figure 16b). Line currents exceed cable ratings at node 2 between 4pm and 8pm in winter, and between 8am and 10am in summer (Figure 17). Issues of reverse power flow, summer voltage rise and summer high line current occur when solar irradiance is at its peak during the middle of the day.

4.5.Delta scenario

For the delta scenario it is assumed that renewable energy is used to a minimal extent. Other sectors have to make a greater contribution in order for the UK to achieve the 80% reduction target. With minimal renewable energy uptake, there is a significant amount of nuclear generation in this scenario, and a significant increase in the amount of biofuel imports. The scenario also assumes there is a significant effort to improve energy efficiency across sectors.

Figure 18. Transformer loading during 24 hour cycle, 2050 north east delta scenario, (a) winter; (b) summer.

Figure 19. Line voltages at various points (nodes 2 to 6), 2050 north east delta scenario, (a) winter; (b) summer.

Figure 20. Line currents at various points (nodes 2 to 6), 2050 north east delta scenario, (a) winter; (b) summer.

Transformer load remains within the transformer rating for summer and winter with no reverse power flow (Figure 18). Line voltages remain within the statutory limits for both summer and winter (Figure 19). Line current also remains within cable rating for summer and winter (Figure 20). The delta scenario, with its reliance on central power generation and reduced load, results in no issues of concern regarding performance of the distribution network.

4.6.Epsilon scenario

The Epsilon scenario assumes very low levels of bioenergy are incorporated into the energy mix. Other sectors have to make a greater contribution in order for the UK to achieve the 80% reduction target. In comparison to other pathways, the shortfall is made up with a greater contribution from solar thermal installations for hot water supply, with very high levels of electrification for space heating and transport loads. This scenario includes significant effort to reduce energy demand.

Figure 21. Transformer loading during 24 hour cycle, 2050 north east epsilon scenario, (a) winter; (b) summer.

Figure 22. Line voltages at various points (nodes 2 to 6), 2050 north east epsilon scenario, (a) winter; (b) summer.

Figure 23. Line currents at various points (nodes 2 to 6), 2050 north east epsilon scenario, (a) winter; (b) summer.

Figure 21a shows that the transformer load profile exceeds the transformer rating in winter between 4pm and 7pm. There is no reverse power flow for this scenario. In summer, the transformer load profile remains within the transformer rating (Figure 21b). Line voltages remain within the statutory limits for both summer and winter (Figure 22). Figure 23a shows that in winter, at the time of peak transformer loading, there is a corresponding peak in line current. Line current exceeds cable rating for node 2 between 4pm and 10pm. Line currents remain below cable rating for summer conditions in the epsilon case (Figure 23b).

4.7.Zeta scenario

The UK zeta scenario assumes very little behaviour change occurs by 2050. There is no efficiency effort in appliances and lighting, or space and water heating, and continued growth in private car transport. In order for the UK to achieve the 80% reduction target the scenario assumes high levels of electrification in the heating, appliances, industry and transport sectors, with a contribution from all generation technologies to achieve decarbonisation of the electricity sector. As a result, this scenario shows a significant increase in electrical load.

Figure 24. Transformer loading during 24 hour cycle, 2050 north east zeta scenario, (a) winter; (b) summer.

Figure 25. Line voltages at various points (nodes 2 to 6), 2050 north east zeta scenario, (a) winter; (b) summer.

Figure 26. Line currents at various points (nodes 2 to 6), 2050 north east zeta scenario, (a) winter; (b) summer.

Figure 24a shows that the transformer load profile exceeds the transfer rating in winter between 7am and 9am, and 4pm and 11pm. In summer, reverse power flow occurs between 5am and 5pm. For the zeta 2050 line voltages remain within statutory limits for summer and winter (Figure 25. Line currents are in excess of cable ratings in winter for node 2 between 7am and 10am, and for nodes 2, 3 and 4 between 4pm and 11pm (Figure 26a). Line currents remain below cable rating for summer conditions in the epsilon case (Figure 26b).Results indicate a need to increase the transformer rating by approximately 60%, to double the cable rating for node 2 and to increase cable ratings for nodes 3 and 4 by approximately 25%.

4.8.Results summary

A summary of all scenario results is shown in Table 2. The results show forward power flow exceeds the transformer rating in winter for the alpha, epsilon and zeta scenarios. Reverse power flow occurs in summer for the alpha, beta, gamma and zeta scenarios. Line voltages exceed statutory limits in summer for the gamma scenario. Line currents exceed cable ratings in winter for the alpha, beta, gamma, epsilon and zeta scenarios, and in summer for the gamma scenario.

Table 2. Summary of 2050 low carbon pathway impacts on the local distribution grid.

5. DISCUSSION

The results of the study show clearly that under the 2050 assumptions for growth of electricity demand and renewables uptake, problems arise for the present day electrical distribution system which go beyond the ability of existing control structures. For the reference and delta scenarios, the investment in the distribution grid would focus on replacement of assets at end-of-life.

For the gamma scenario, the network experiences significant reverse power flow, currents exceed cable ratings in summer and winter at node 2, and voltages are outside statutory limits in summer. Network protection would need to be reconfigured for reverse power flow, the transformer may need replacement if it is unable to cope with reverse power flow, cables would need replacement with higher rating cable between the transformer and node 2, and the tap settings at the transformer may need adjustment to lower the voltage on the network. These network adjustments and their cost could be mitigated through time of day tariffs to encourage peak shifting, through storage, and smart communication to both load and generation to ensure better matching. There could be system wide problems if many areas produce a power surplus during the same period, since under present arrangements there is no means of storing the surplus power, and no means of coping with the resultant imbalance except for curtailment of renewable generation. The cost and market mechanism of curtailment is not yet fully understood, since it has not been widely implemented at the distribution network level.

The epsilon and alpha scenarios result in very similar network problems. The power flow exceeds the transformer rating in winter by 10%, and the line current at node 2 exceeds the cable rating by 24%. Therefore, a reinforcement approach would result in transformer replacement and replacement of cables between the transformer and node 2. These network adjustments and their cost could again be mitigated through time of day tariffs to encourage peak shifting, through storage, and smart communication to both load and generation to ensure better matching.

For the zeta case, the network experiences significant transformer and cable overload in winter due to high load, and reverse power flow at the transformer in summer. The power flow exceeds the transformer rating in winter by56%, and the line current at node 2 exceeds the cable rating by 71%. The transformer may need to be replaced with a higher capacity unit, capable of reverse power flow. Cables may also need to be replaced to provide higher thermal ratings to cope with the higher currents. Again, these network adjustments and their cost could be mitigated through time of day tariffs, through storage and through smart communication. The extent and duration of the network overload for the zeta case makes the need for reinforcement much more likely, unless a reduced load profile is ensured through greater engagement in energy efficiency.

Given the target to transition to a low carbon pathway, and the evidence shown that the existing distribution system is not capable of accommodating power flows in future low carbon scenarios, there is a window of opportunity during which resilience of the distribution network can be considered. The framework contained in Figure 3 recommends consideration of local, national and global resilience issues for the environment, society and the electricity sector. A more resilience distribution system may be possible if considering smart meters, load shifting and use of storage, for example, rather than proceeding down an N-k network reinforcement pathway.

6. CONCLUSION AND POLICY IMPLICATIONS

A smart grid which includes energy storage and which monitors generators and consumers, issuing appropriate control signals, would enable electrical supply and demand to be equilibrated even with the projected rise in the contribution of renewables to the energy mix. Given that much of the UK energy infrastructure is in need of updating, the opportunity to use the opportunity to build an adaptive smart grid should not be missed.

In moving to a network management model which is more proactive and dynamic, there are issues associated with technology transitions in moving to a smart grid. Regional electricity networks connect to the National Grid and there is a desire for compatibility of the approach to regional smart grids to ensure National grid operability with the 12 distribution networks. In specifying and trialling these smart grid technologies, there is a difficulty in the government and regulator approach to "not picking winners" and the inherent market uncertainty which therefore remains for technology suppliers.

With respect to the smart grid and governance, there are conflicts between distribution network owners, suppliers and generators in, for example, agreeing time of use tariffs to encourage load shifting. Such agreements will need to take into account local considerations such as daylight hours and cultural preferences such as meal times and working practices. There are also conflicts of commercial interest for the parties concerned. The regulator OFGEM is limited in terms of regulatory powers, to consider gas and electricity markets and networks only. It does not currently have a remit to create policies with respect of electric vehicles for example, or heat networks, although electrification of transport and heat loads are key issues for the 2050 scenarios. In this respect a more localised approach to energy demand planning would allow the consideration of such policies and thus be better placed to respond to, and feed in to, the development of future strategic planning decisions. The result would be a more holistic approach to energy supply and demand planning, one which would result in a smarter, adaptive and more resilient energy system.

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