

A Climate Change Report Card For Infrastructure

Working Technical Paper

Power Systems, Transmission & Distribution

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HIGHLIGHTS AND KEY MESSAGES

The risk of flooding is very likely to increase. This will have the greatest effect if substations are inundated. The industry has an ongoing programme to improve the resilience of electricity infrastructure to flooding.

Considerable uncertainty in the seasonal, regional and absolute changes to wind-speed results in corresponding uncertainty in the contribution of wind generation—which could have substantial impact on the optimal size and location of electricity transmission corridors.

It is unlikely that a step change in the performance of network assets will take place as a direct result of climate change. Equipment is already designed to operate in the future conditions anticipated under climate change. There will however be marginal changes to the capabilities of equipment and this may need to be accounted for in some parameters used in network planning procedures.

The indirect effect of climate change, created by the political response designed to minimise greenhouse gas emissions, will be more significant than the direct impact of a changing climate. This will dramatically change the generation mix, overall demand and both seasonal and diurnal demand profile. A significant factor in this response is the decarbonisation of the transport and heat sectors.

An industry with a wider range of tools and technical solutions for planning and operation will be more prepared to manage capacity, stability and reliability at lower cost than if present methods do not evolve. Adaptation in the face of climate change and broader trends in the electricity supply industry will be necessary throughout the coming decades.

INTRODUCTION

Power is transmitted and distributed across Great Britain (GB) from a wide range of generation plant types to industrial, commercial and domestic customers. These networks are composed of assets comprising; overhead lines and underground cables which connect substations containing transformers, switches and control equipment. The transmission network transfers bulk quantities of power at voltages of 400kV and 275kV in England and Wales, with 132kV additionally used in Scotland. The transmission system operators are responsible for balancing supply and demand, while also maintaining reserves in case of exceptional events. Distribution networks take power from the transmission network at Grid Supply Points and then cascade through a series of voltage transformations at substations to the final customer connections.

The parts of the system at higher voltage levels are built with more redundancy so they are able cope with equipment failures and maintenance periods without interrupting supplies to customers. These networks are meshed, so that there are a number of paths through which power can be routed, which provides redundancy, flexibility and resilience. At the lowest voltage levels (domestic supply) there is often no redundancy, but far fewer customers are affected if a fault occurs. The variety of network types also varies more at the further reaches of the distribution network, at one extreme there are dense urban areas where the quantity of customers demands the highest levels

of reliability and the compactness of the network means that it can be built to achieve this. At the other extreme, sparse, radially fed, rural populations can experience interruptions to supply from time to time.

The effects brought about by climate change will have a substantial impact on the electricity supply system. Of at least equal weight to the direct impacts of climate change, political decisions will be a major factor in the evolution of the power system in response to climate change [1]. The Climate Change Act of 2008 [2] declared legally binding targets for the UK's contribution to climate change requiring fundamentally, an 80% reduction in 1990 levels of greenhouse gases by 2050. This is a significant decrease in the UK's overall emissions and achieving such a reduction presents real challenges to the operation, planning and investments of a power system that will effectively require complete decarbonisation.

As a backdrop to climate change considerations, since the start of deregulation in 1990, the transmission and distribution (T&D) systems have been in a state of considerable change. Challenges have emerged from: the need to manage ageing infrastructure (some substation equipment from the 1950s and steel towers and underground cables from the 1930s remain in service) and the political response to climate change, typified by significant increases in generation capacity installed in the distribution network. When examining the broader or 'indirect' effects of climate change on the power system, the substantial interdependence of electricity systems with their physical, social, environmental and political surroundings, rapidly becomes apparent [3].

To identify the effects of climate change on the power system this report continues with a brief review of several climate change adaptation reports. The potential effects of climate change on T&D networks are considered from the existing records of weather related faults. The specific effects of anticipated climate variation on relevant assets are then described. Next, trends in the evolution of the power system, in large part driven by actions designed to minimise climate change, are discussed. A summary closes the report.

CLIMATE CHANGE ADAPTATION REPORTS

In response to the Climate Change Act, a number of organisations have produced Climate Change Adaptation Reports; for transmission and distribution system operators their industry body, the Energy Networks Association (ENA), produced a Climate Change Adaptation Report in 2011 [4]. Focussing on factors that affect electricity networks, this report identifies the main impacts from climate change projections to be increased temperature, increased winter rainfall, summer drought, sea level rise and storm surge. They do not find firm evidence for increased wind intensity or ice storms. Increasing temperature will reduce the current carrying capacity of network assets by up to 10% (3%) for overhead lines in distribution (transmission) networks, 4% (5%) for underground cables in distribution (transmission) networks and 7.5% (5%) for distribution (transmission) transformers. In response to recent flooding incidents and increased risk in future, engineering technical report ETR138 [5] has resulted in a ten year programme of work to improve substation resilience to flooding.

The ENA has worked with the UK Met Office to produce the EP2 report which seeks to better understand the impact that predicted climate change will have on the electricity networks. One published branch of this work [6] has determined that the risk of lightning faults to the network is projected to increase in the future. Wind and gale faults occur frequently, but uncertainty in future climate projections of wind means that how this risk may change in the future cannot be quantified. Snow and ice accretion may decrease in the future due to less days of snow, but when it does snow the intensity of the event may be the same or increase.

PricewaterhouseCoopers' Adapting to Climate Change in the infrastructure sectors report [7] summarises key findings for the power transmission and distribution sector. Risks to the resilience of transmission and distribution infrastructure are likely to increase with predicted climate change. In the current regulatory environment, investment decisions are linked to the price control periods, previously five years (increasing to eight years from 2015) which tends to limit the horizon over which decisions are made. To incorporate adaptation planning into capital programmes and asset management processes, alternative incentive and accounting practises may be necessary.

In the Royal Academy of Engineering's Infrastructure, Engineering and Climate Change Adaptation report [8] a range of future vulnerabilities were identified for power systems. Flooding from rainfall, sea level rise and storm surges are a key risk. Heat could reduce transmission efficiency and storms could cause overhead line faults. It is suggested that wind and wave generation systems could be negatively affected by extreme stormy conditions. It is highlighted that behavioural change will have a significant impact on the power system, with summer peaks increasing from air conditioning demand. The benefits from smart meters and smart grids in enabling demand response to manage the expected increases in demand peaks are noted.

The UK government's Climate Change Risk Assessment [9] identifies the key risks of relevance to electricity networks as flooding, higher cooling demand, and heat damage. An opportunity in reduced demand for heating is acknowledged.

POTENTIAL IMPACTS OF CLIMATE CHANGE

Alongside reports of the type summarised above there is a growing body of work aiming to understand the risks and impacts of climate change on power systems. Before detailing the potential effects of projected climate change, we consider how the existing climate and weather in the UK affect transmission and distribution networks.

The impact of future climate change on national transmission and distribution networks can be assessed and measured from a number of perspectives. Most directly, there is a possible increase (or decrease) in the number and severity of fault incidents on the network, a proportion of which can be attributed to weather and the environment.

These incidents are potentially most severe when they affect the higher voltage (400kV, 275kV) transmission network, or the highest voltage (132kV) of the distribution network. However, such incidents are infrequent, because of the relative robustness of construction of higher voltage

networks. They are also less likely to cause customer disconnection, as there is generally a wide choice of alternative routes. For example, cross-border transmission between Scotland and England consists of a double circuit on tower lines down the West coast, and a similar double circuit down the East coast, shortly to be augmented by a direct undersea cable between Scotland and North Wales, and the possibility of a further undersea cable off the East coast [10].

Incidents on the distribution network are more frequent, and increasingly frequent at lower voltages. For example, during a typical year (2009-10) the number of incidents on the 132kV network (transmission in Scotland, distribution in England and Wales) was 751 [11]. This can be compared with 2583 incidents at distribution high voltages (HV, 66kV, 33kV), 28313 incidents at medium voltages (MV, typically 11kV) and 145203 incidents at low voltages (LV, 0.4kV) [12]. Moreover, the lower the voltage, the more likely it is to disconnect customers, and the longer that disconnection is likely to last because of decreased alternative supply routes. These data are shown in Table I [12]. In terms of overall impact (the product of the four middle columns) it can be seen that MV has the greatest impact, and subsequent analysis will apply to that voltage level alone. This is further justified in that the proportion of incidents caused by weather or environmental factors (25%) is greater than the proportion at HV (20%) or at LV (9%).

Table I: Customer disconnections and durations at different voltage levels

<i>Voltage</i>	<i>No of incidents</i>	<i>Proportion of incidents disconnecting customers</i>	<i>Average number of customers disconnected</i>	<i>Average disconnection time (mins.)</i>	Product (million customer minutes lost)
HV	2583	25%	2314	38	57
MV	28313	92%	539	76	1067
LV	145203	98%	20	205	583

Of 7134 incidents per year at MV caused by weather or the environment, the class with greatest frequency was incidents caused by lightning strike (2185). This was followed by wind, including windborne materials (1535), trees (1320), and snow and ice (1285). Relatively infrequent were incidents caused by rain or flooding (165) or by solar heat (50) [12]. However, these relative frequencies must be multiplied by likely severity. A lightning strike will usually cause no permanent damage, and power to customers can often be restored by automatic switch reclosing within a few minutes. By contrast, supply following flooding cannot easily be restored, and may cause customer disconnection for several days. The highest impact would arise from flooding of a major 400/132 or 132/33kV substation, as the network design standards relate to redundancy of circuits not substations, making substations vulnerable under single failure. Recovery time from such a loss could extend into weeks, with permanent repairs taking many months. Emergency interventions might need to include mobile generation or construction of temporary circuits.

One way to reduce the number of incidents could be undergrounding. While 48% of the MV network is underground, only 27% of incidents occur on underground cables. The 52% of the MV network which is overhead, however, accounts for 41% of incidents, around half as much again (the other 32% of incidents occur at substations) [12].

However, the duration of incidents is at least as significant as their frequency, particularly at the high duration extreme. Around 40% of customers are reconnected within 20 minutes following an HV or MV incident, and just over 90% of customers are reconnected within 3 hours [12]. Arguably, it is the other 10%, who are disconnected for over 3 hours, who should be the focus of the present study, although it is not easy to disaggregate them from the rest of the data. In particular, climate change could affect this extreme of the distribution (for example, if extensive flooding also prevents repair crews from attending the incident).

Finally, the question arises of how to cost any increase (or decrease) in climate-related incidents. Earlier analysis [13] suggested a metric of total network risk (TNR), measured in expected £k at a given location or section of the network [14]. This metric includes direct repair costs following an incident, indirect costs including possible shortening of asset lifetimes, and customer disconnection costs (based on frequency and duration) as levied by the regulator on the distribution network operators (DNOs). This metric, and others like it, have proved useful in enabling DNOs to determine which of a number of possible mitigation strategies would be cost effective.

Electricity infrastructure has a long operational lifetime, often at least 30-40 years. It is important therefore to understand how assets will perform over these durations. Assets built now, and those already in place, will be expected to operate long into the future, potentially in a different environment to the one in which they currently operate. UK climate projections [15] indicate that mean temperatures are likely to rise by 2-3°C by 2050. It is suggested that this could lead to reductions in conductor ratings, particularly during the summer [16]. There is strong evidence linking climate change to extreme weather events [17], and that extreme weather has an adverse effect on power system reliability [18].

Climate change predictions are subject to a considerable degree of uncertainty. However, it has been argued that this uncertainty is reducing, and that in any case the changes in climate are more stable and less uncertain than the equally important prediction of political response to anticipated climate change [14]. Before considering the indirect political dimension of climate change, the direct effects on power systems will be addressed.

CLIMATIC VARIATION

EXTREME EVENTS

An increased frequency of extreme weather events is a consequence of climate change [17], and one with potentially severe implications for power systems. Different extreme weather events can impact the power system in different ways, and some events are easier to mitigate than others.

FLOODING

The UKCP09 predictions suggest that, in all emission scenarios, there is a reasonable likelihood of increased rainfall, which could lead to increased flooding [15]. Abi-Samra [19] suggests that flooding is the most significant extreme weather event, because of its long term consequences. Flash floods are particularly troubling, because they occur with little warning; experience from Boscastle in 2004 shows the impact that can result. River floods, which are more common in the UK, are more gradual and consequently responsive action can be taken to mitigate their impact. The major concern is flooding of substations, where sensitive equipment can come into contact with flood waters. Suggested measures include waterproofing the substation and ensuring that there is sufficient drainage. In coastal areas rainfall will be compounded by sea-level rise, particularly when combined with storm surge.

HEAT WAVES

Heat waves are currently not common in the UK, but if temperatures increase in both their average value and variability, it is likely heat waves will increase in frequency and severity. A study in California suggests that heat waves can cause distribution transformer failures [20]. The study shows that more transformers failed during a heat wave than had failed during the entire preceding year. Higher temperatures also lead to de-rating of overhead lines, as the maximum sag is determined by legally binding minimum ground clearances. Climate predictions suggest that the UK will have a reduced level of precipitation during the summer. Soil moisture reduces soil thermal resistivity, which results in increased heat transfer from underground cables. Droughts, caused by a reduction in precipitation, would lead to an increased likelihood of underground cables overheating [20]. Both of these predictions are less worrying for transmission networks in comparison to distribution networks; in transmission circuit redundancy means that normal (non-fault) loadings are substantially less than maximum ratings, while in distribution, the large number of components means it is difficult to monitor these effects. Distribution network monitoring may increase in light of emerging system trends.

Earthing systems will be effected by reduced soil moisture. This will reduce conductivity of the soil and so require reassessment of the assumptions made in earthing system design. This is discussed in the ENA's Climate Change Adaptation Report [4].

WIND SPEED

UKCP09 wind projections suggest that average summer wind speeds are likely to decrease, while average winter wind speeds may increase, but are as likely to decrease or remain the same [21]. However, this projection comes with a 'health warning' due to the high levels of uncertainty. A study based on regional climate models of northern Europe, with boundary conditions informed by a global climate model, indicates that in the North Sea region wind energy density, which is dependent on wind speed, is likely to increase both on average and in winter, but decrease in summer [22]. The study also found that wind energy density is already highly variable, with changes of up to 19% annually, a result that is verified by other wind resource studies looking at large scale phenomena [23]. It is suggested that climate change could further increase this variability [22, 24].

Wind speed affects the power system in a number of ways: when the wind blows conductors and transformers are cooled by forced convection [25] and wind generation produces electricity. If the wind generation is connected at distribution level, this can result in customers being supplied by the local generation, alleviating the congestion on the network [26]. Conversely, if the wind farm is much larger than the local load, this can result in reverse power flow, which could increase congestion. At high wind speeds (usually 25 m/s), wind generation cuts out to avoid damage to the turbines [27]. This could result in a sudden deficit in generation, which would need to be resupplied using conventional plant or interconnection. Because the conventional generation and DG are likely to be in different areas of the network, this could result in power flow volatility [10].

High winds are likely to result in damage, though usually due to wind-blown debris interfering with the system, rather than lines and towers themselves being damaged by the wind directly [19]. The increased failure rate on overhead lines with large numbers of trees nearby, is being mitigated by a resilience vegetation management programme legislated in the 2006 amendment to the ESQC regulations [28]. The ENA [4] highlight that increased temperature and sunlight will cause increased vegetation growth, so the management task will become more significant.

CLOUD COVER

The UKCP09 climate predictions [15] indicate that the amount of cloud is likely to increase in winter, while it may decrease in summer. A decrease in cloud cover during the summer could lead to greater energy yield from Photo Voltaic (PV) panels. This can provide benefits to the network, by supplying customers directly and hence reducing the load on circuits. However, it can also provide problems, such as rising voltages at the end of distribution feeders, and undesired harmonics arising from the use of power electronic converters. The impact of PV on distribution systems is discussed in detail by Thomson [29].

SPATIAL VARIABILITY

The UKCP09 projections [15] suggest that changes in climate will not occur uniformly across the UK. Increases in temperature are expected to be more prevalent in the south of England, increasing the already present temperature difference across the country. Changes in precipitation, both increases in winter and decreases during the summer, are also expected to be more pronounced in the south of England. Conversely, changes in mean wind speed, particularly in the winter, seem more likely to occur in the north of Scotland, although the predictions have a high level of uncertainty as to which will occur, suggesting an increased level of variability. An increase in the variability of wind speeds in Scotland is likely to be detrimental to power system operation, given that much of the UK's wind generation is situated in Scotland. More extreme temperature changes in the south of England imply that there is likely to be an increase in the volume of electric power transmitted from north to south.

SYSTEM TRENDS

Of the three central categories [30] in which climate change can produce impact, the direct impact of climate change on the frequency and severity of fault incidents on power system components has already been discussed. The remaining two categories of policy impacts, such as market

reforms and regulation, and the uncertainties surrounding climate change predictions are the focus of this section. This will affect patterns of electricity generation and consumption in response to mitigation strategies adopted to reduce the emission of greenhouse gases.

Emissions reduction targets across the world have led to the decommissioning of conventional fossil-fuel generating plant and an increase in the installed capacity of renewable generation sources. In the UK the majority of these new sources have been in the form of wind power [31], however since deregulation, generation has no longer been the sole concern of the transmission network. The geographic location of renewable generating capacity, in combination with the Government's Feed in Tariff (FIT) policy and other incentives has led to a significant increase in installed capacity within the distribution network. The FIT policy will be discussed in greater detail later in this paper.

Managing a transmission system with a high penetration of such generation presents significant challenges to maintain reliable and secure services to customers. It has been suggested that in some scenarios, with high penetrations of wind generation for example, that traditional 'base-load' generation may be forced to operate at lower efficiencies, affecting asset lifetimes and leading to an increased risk of faults [32].

A significant body of work has been developed in investigating the UK's transition to a low carbon economy. The DECC 2050 Pathways project [33], LENS 2050 [34], UKERC's Energy 2050 project [35], SuperGen Networks 2050 [36] and the analysis of Barnacle et al. [37] are just some of the analyses available. A core theme is that of 'scenario modelling'. Each of these analyses typically employs a reference scenario where networks, generation and demand evolve in a 'business as usual' (BaU) manner. The remaining scenarios show greater flexibilities in, market reform, generation technologies and demand side engagement.

All of these scenarios have differing impacts on the T&D systems in the UK. The more BaU scenarios display reliance on increasing efficiencies of conventional plant such as coal and gas combined with carbon capture and storage (CCS). Such scenarios have a strong influence on capacity at the transmission level, as well as increased interconnection. At the other end of the spectrum, consumers are more likely to become 'prosumers' (producers and consumers) where domestic level generation is combined with highly integrated demand side participation (DSP) schemes, resulting in further shift of the generation bias towards the distribution networks.

Under the 'Transition Pathways' narratives of Barnacle et al.[37], the 'Market Rules' BaU scenario has been shown to have significant impacts on the balancing of supply and demand, with a generation surplus of 19 GW on the UK system in a scenario with no DSP. This number reduces to 9 GW with the presence of DSP, though this remains significantly larger than the predicted 2050 interconnection capacity of 6.81 GW. This scenario also generates the highest peak demand at around 83 GW, far greater than that shown in the most socially inclusive scenario 'Thousand Flowers' with a peak demand of around 38 GW. Both these values are reduced to 73 and 27 GW respectively when DSP is employed. The 'Thousand Flowers' scenario does however generate

significant generation surplus values of around 44 GW and 28 GW for non DSP and DSP situations, again far higher than the predicted capability of interconnection [37].

The adoption of low carbon technologies (LCTs) on the demand side also has a role to play in both the development of the power system and the nature of supply and demand balancing. In each of the scenarios differing adoption rates for technologies such as Electric Vehicles (EVs), Heat Pumps (HPs) and Combined Heat and Power units (CHPs) are studied. Increasing adoption of EVs and HPs with their respective charging and high demand characteristics will affect the size of the network peak power significantly. However they can provide DSP services, helping to offset the negative aspects of their high power consumption. The adoption of CHP units as opposed to HP devices can help to reduce peak consumption by generating electricity on-site at the same time as meeting heat demand. Adoption rates for all these low carbon technologies will affect future development, sizing and investment decisions for the power system.

In order to prepare for the low-carbon transition and with increasingly likely expansion of the role for distribution network operators (DNOs), the energy regulator OFGEM has established the Low Carbon Networks Fund to provide funding for DNOs to trial various responses to the need for decarbonisation. A number of demonstration projects are currently underway in the UK.

The wider power system, in response to these challenges has developed a number of possible pathways for evolution [38]. In an effort to manage increasing system complexity, distributed control techniques have been developed, centring on local measurements to inform decisions. The advance of artificial intelligence and machine learning techniques has led to the concept of an autonomic power system [39]. The smart grid philosophy aims to improve reliability and efficiency, reduce costs, and increase network capacity whilst maintaining the same level of system security.

A commitment central to the uptake of a smart grid in the UK is the installation of smart meters, with the UK's Low Carbon Transition plan [40] stating that by 2020 a smart meter will be installed in all homes within the UK. Half hourly monitoring has been almost ubiquitous for larger demand customers for some time, however the introduction of smart meters allows, for the first time accurate electrical consumption profiling of domestic customers. This is expected to increase energy efficiency through increased visibility of consumption and facilitate innovative energy supply tariffs.

Whilst electricity supply companies may focus upon the fact that smart meters ensure that customers cannot be overbilled for their supply, there are a number of additional pros and cons from their introduction into the power system for other participants in the electricity supply chain. At present, distribution network planning at low voltages in the UK is carried out through the use of historically monitored data and various statistical tools [41], however with increased information from smart meters, the planning process, infrastructure requirements, and investment strategies for distribution circuits are likely to change as a result.

As smart grid alternatives are implemented the network is likely to become more complex, and more interconnected. This complexity brings its own increase in risk. One of these, in particular at transmission level, is an increasing likelihood of cascading failure, where one incident has rapid knock-on effects across an entire network leading to widespread blackouts [42, 43]. Another possible increased risk, as the network becomes increasingly reliant on whole-network control systems, is of communication or control system failure, either accidental or as a consequence of malicious cyber-attack.

GENERATION

It is forecast that there will be an increased proportion of nuclear generation, and a greatly increased proportion of renewables, at the expense of fossil fuels, in particular of coal. This may be affected by the use of clean coal, if the technologies can be proved effective. As regards transmission and distribution, the substitution of nuclear or clean coal generation for coal and gas is unlikely to have a significant overall effect. It is unlikely to be possible to site new large generating stations in optimal locations (for example, close to demand). Rather, they are likely to be in remote locations (for example, on the sites of previous nuclear generation) for political reasons, so the transmission of large amounts of electricity over long distances ('coal by wires') is likely to continue unchanged.

This is likely to be exacerbated by the location of large wind farms in remote locations, both onshore (e.g. in northern Scotland) and offshore (e.g. in the North Sea). Construction of new transmission lines and undersea cables will be required to move electrical energy from where it is produced to where it is consumed. The same would apply to any large marine schemes such as tidal barrages.

However, the expansion of large scale plant is likely to be mitigated by the proliferation of small-scale generation, in particular wind and PV. The amount of such proliferation will probably be affected more by political decisions (e.g. level of feed-in tariffs) than by climate change itself [14]. However, increasing temperatures (and probably associated decreased cloud cover) is likely to increase the level of adoption of small scale PV. Less certain is whether wind speeds would increase, leading to increases in the level of penetration of small-scale wind. These questions are addressed in a number of papers accessed via a particularly useful summative paper on mitigating the effects of climate change [44].

DEMAND

While the focus of this paper is the impact of Climate Change on the electricity transmission and distribution systems, power systems are heavily influenced by the connected demand and generation. Consequently, it is important to understand how these are likely to change, and how this could affect electrical networks. This section briefly describes the likely changes in electricity demand as a result of climate change, and what this means for the transmission and distribution systems.

There is likely to be extensive electrification of transport (electric vehicles replacing diesel and petrol driven) and of space heating (ground and air sourced heat pumps replacing natural gas). The extent of this substitution could be as great as a tripling of overall electrical energy demand, although this depends to a great extent on inherently unpredictable political decisions [44-47]. As well as the electrification of existing loads, new types of load can be expected, which may be essentially independent of climate change (e.g. digital applications), but may be a direct consequence, in particular space cooling. This substantial increase in demand would, on its own, require extensive reinforcement of distribution networks across the country and at all voltage levels.

Electricity demand in the UK currently peaks during the winter months [10, 48], in most parts of the UK winter peak loads are up to 50% higher than summer peaks. This is helpful to the system operator because conductor ratings are set seasonally, with the winter rating being the highest due to the low ambient temperatures [10, 49]. In addition to making best use of the varying asset capacity this also allows network maintenance to be carried out in summer months at lower risk. However, as temperatures increase, increased use of space cooling may cause the peak to shift into the summer. In some city centre areas this difference has already disappeared, and there may even be a summer peak due to space cooling requirements. In warmer climates, a significantly higher summer peak is seen for this reason [50]. This would be detrimental to system operation, because there is strong evidence that in summer peaking power systems, demand is highly correlated with ambient temperature [51-53]. Consequently, assets would be most heavily loaded during the hottest periods, increasing the chances of equipment failures.

At present, the technique of demand side response (DSR) is only possible for large customers who are capable of providing a demand curtailment (or a generation increase) when called upon. Smart meters will allow engagement at the domestic level for the first time. Domestic prosumers are incentivized to install low-carbon generation sources to aid both the overall decarbonisation of UK generating plant, and offset their own consumption.

The initial FIT rollout led to a significantly biased increase in the uptake of PV generation at the domestic level, with both personal and 'rent-a-roof' schemes. Similar experiences have been observed in Italy [54]. The pricing points of this policy had a significant effect on the uptake of generation at the distribution level, again demonstrating the impact of climate change policy on the electricity networks.

ADAPTATION OPPORTUNITIES

Within the UK, supply and demand can be balanced more effectively by the use of storage, either electrical in the form of batteries [44, 50], or using other media such as hydrogen [55] or thermal [56]. There are system benefits to be gained across the transmission and distribution networks from energy storage, ranging from offsetting the need for peaking plant to preventing over-voltage in LV networks. Realising these benefits under the current market, regulatory and cost conditions is challenging, but will become easier as the understanding of the role for storage and the market and regulatory conditions improve [57].

Reference has already been made to the potential of smart grid installations and operation to smooth system imbalances and enable the existing grid to cope more effectively and efficiently with the pressures of climate change, both direct and indirect. Possible interventions which could assist include real-time thermal ratings [16, 58], smart buildings, demand side management, network automation, and operational ingenuity [44]. On the transmission side, high voltage direct current, Flexible AC Transmission Systems (FACTS), and superconductor cables are a medium-term possibility [59]. And, looking to the distant 2080 horizon, technologies which are at present only conceptual could become a reality, including nuclear fusion, geo-engineering, solar energy from outer space, and a world-encircling hydrogen super grid [60].

Other possible interactions with the potential to balance energy generation and load are commercial rather than technical, and include emissions trading [44]. Besides the technical balance between supply, storage and demand there is a parallel management or political balancing act between security of supply, energy costs, and environmental protection [61]. Again, this highlights the sensitivity of the overall energy system to the decisions of overall policy-makers

THE COST OF IMPACTS

The cost for decarbonisation represents an enormous proportion of the European energy budget. It has been suggested that between 2010 and 2035, 70% of Europe's energy investment will be made in the electricity sector [62].

One aspect of the smart grid philosophy, which is relevant to the aspect of network costs, is to maximize the use of existing assets through smart technologies and techniques. Latent network capacity can be unlocked through techniques such as real-time thermal ratings [16, 58, 63], deferring or negating the need for high capital cost replacement of components. New assets represent a significant investment, incorporating raw materials, removal of the existing asset(s), construction and commissioning costs and at lower voltage levels of the distribution network, are likely to result in loss of supply to customers. Whilst weather effects have been shown to be the most significant aspect when considering power system failures, the second highest contributor has been found to lie in maintenance or in asset management [64].

Again, due to the interdependent nature of the electricity system, only considering the result of installing assets does not represent the complete carbon impact. The manufacturing and transport of new assets must also be taken into consideration. Since climate change scenarios are being evolved and developed constantly, coupled with the fact that power system components typically have long operational lifetimes, the installation of new assets also represents a 'locked-in' investment decision, with limited possibility for re-sizing once installed. Environmental and planning issues have been found to delay infrastructure installation, as in the case of the Beaulieu-Denny transmission circuit upgrading in Scotland [65]. This particular circuit is of high interest due to the overwhelmingly negative reaction to the initial planning proposal. Despite a significant number of objections and a considerable timeframe, the plan was given consent, showing that attempts to alter the national decarbonisation framework on a local or national basis will be difficult [65].

Traditional investment as part of the Revenue Price Index (RPI-X) regulation mechanism has been altered with the introduction of RIIO (Revenue=Incentives+Innovation+Outputs) mechanism, which places innovation at the heart of investment for the distribution network operators. This reflects the emerging system trends with power networks evolving to smart grids with increased decentralization.

INTERCONNECTIONS

Interconnection between wide-area power systems can help to improve overall system stability and reliability, ensuring that customers' supplies are maintained even with increased quantities of variable generation [66]. However it has also been shown that whilst emissions are potentially reduced within one system, the knock-on effect could increase emissions in another, resulting in a net stalemate with regards to emissions [66]. Although helping manage demand and generation variability, interconnection can bring the potential for substantial disruption from cascading blackouts such as those seen in 2003 in Italy, the USA and Canada [67, 68].

The UK has electrical interconnectors to France, Ireland and the Netherlands, with planned interconnectors to Belgium and Norway, and possible future interconnectors over greater distances, such as to Iceland. In conjunction with transcontinental interconnectors elsewhere, this permits both import and export energy transfers, that could potentially connect the UK to systems including PV generation in North Africa [69, 70]. This could well become a significant component of the national energy balance in a world responding to climate change.

Each year the Transmission System Operator (TSO) for the UK, National Grid, publishes a statement of their projections for the electrical transmission grid in the following 10 years. These statements contain information on the present and future trends of national demand and generation within the UK. Within this statement, operational and planned interconnections between countries are also discussed. For example, on the 3rd of December 2010, 10 countries from around the North seas signed a Memorandum of Understanding to establish a co-ordinated path for development of an offshore transmission system. This work is now under the control of the North Seas Countries' Offshore Grid Initiative.

Smart grids, and power systems in general will develop and evolve in different ways in different countries [62], they will be used to achieve different targets therefore it will be crucial to manage the competitive environment correctly in order to achieve successful wide-scale interconnection across Europe and beyond.

SUMMARY

There is a growing body of work by industry and academia on the likely impacts of climate change on the electricity transmission and distribution systems. The indirect effect of climate change, created by the political response designed to minimise greenhouse gas emissions, will be more significant than the direct impact of a changing climate. This will dramatically change the generation mix, overall demand and both seasonal and diurnal demand profile. Complete decarbonisation of

the electricity supply chain will change the characteristics of the generation plant and switch demand from fuels for transport and heating to the electricity networks.

Direct effects from climate change are expected to be gradual and it is unlikely that a step change in the performance of network assets will take place. Equipment is already designed to operate in the conditions anticipated under future climate change. However, DNOs do exploit the greater peak and cyclic ratings that can be achieved at lower ambient temperatures. To maintain these enhanced ratings, additional cooling or conductor cross-section in transformers and greater line clearances will be required. These changes to the capabilities of equipment will need to be accounted for in some parameters used in network planning procedures.

A more immediate concern is that the risk of flooding is very likely to increase. This will have the greatest effect if substations become inundated any more than very infrequently as is the case at the moment. Because this is a problem that is already apparent, the industry has an ongoing programme to improve the resilience of electricity infrastructure to flooding. The long asset lifetime associated with civil works and major plant items necessitate consideration of future flood risks both at time of new build and when undertaking asset replacement.

Extended periods of low rainfall in the summer months will lead to drier soil that is less able to dissipate heat from underground cables. This could lead to a need to reduce the current carrying capacity in network design.

The number of lightning strikes is expected to increase, with a corresponding increase in overhead line faults. This could be addressed by undergrounding circuits, but the capacity issue from drier soil noted above would reduce the favourability of this solution.

Considerable uncertainty in the seasonal, regional and absolute changes to wind-speed results in considerable uncertainty in the contribution of wind generation, both spatially and temporally. Wind installations are necessarily distant from load centres, so this could have a substantial impact on the optimal size and location of major electricity transmission assets.

The principle direct climate effect on demand that affects the networks is the move from a winter peaking system, when asset capacities are highest, to a summer peaking system due to air conditioning, when asset capacities are lower. This also creates problems in maintenance regimes that rely on extended periods of low demand to take circuits out of service.

Adaptation in the face of climate change and broader trends in the electricity supply industry will be necessary throughout the coming decades. An industry with a wider range of tools and technical solutions for planning and operation will be more prepared to manage capacity, stability and reliability at lower cost than if present methods do not evolve. The objective of transitioning to smart grid is undergoing considerable research and demonstration at the moment. Further development of techniques including customer participation through demand side response, energy storage, real-time thermal ratings, phasor-measurements and increased use of power electronics all have potential to increase network flexibility and release latent capacity.

CONFIDENCE IN THE SCIENCE: BRIEF ASSESSMENT

Sea level rise – high confidence and agreement

Storm surge – high confidence and agreement

Flooding – high confidence and agreement

Increase in OHL damage due to extreme wind – low confidence, med agreement

Increase in OHL faults due to lightning strikes – med confidence, med agreement

Reduction in OHL faults due to snow/sleet/blizzard – med confidence, med agreement

Heat effects on assets – med confidence, high agreement

Changing demand – med confidence, high agreement

Changing generation – high confidence, med agreement

RESEARCH GAPS AND PRIORITIES

Climate science and adaptation: The latest information on anticipated outcomes for weather trends due to climate change must be fed into plans for the build of network equipment. This will ensure, as far as possible, that the bounds of duty expected from an asset, given the anticipated climate change, will allow for adaptation during the long lifetime of the asset..

Fault data: The frequency of faults on the networks can be extrapolated from the historical record in the National Fault and Interruption Reporting Scheme (NaFIRS). However, this assumes the causal links between weather and faults are not substantially shifted as future climate change scenarios become the reality. Investigation into fault records, causal links and final impact on customers would increase the usefulness of this information.

Tools and technical options: Solutions that provide network flexibility at a lower cost and greater speed than traditional reinforcement methods will provide the ability to anticipate the effects of climate change. Flexible solutions aim to reduce the risk of being unexpectedly short of capacity or left with stranded assets build for demand or generation that does not materialise. The components and systems that give this flexibility are what is often called the smart grid.

Regulatory environment: The way in which electricity network operators are rewarded for their performance will shortly be based on an eight year cycle (from five). Climate change will take place over a much longer timescale and the ability of the regulatory system to encourage the uptake of long term adaptation strategies needs to be considered. A rigid adherence to net present value cost benefit will not encourage the necessary measures to respond to climate change, given that it may take more than 30 years to accrue the benefits.

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