ELECTRICITY NETWORK SCENARIOS FOR GREAT BRITAIN IN 2050

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Abstract

The next fifty years are likely to see great developments in the technologies deployed in electricity systems, with consequent changes in the structure and operation of power networks. An important motivation for this transformation will be the increasing development of renewable sources of energy, placing radically new demands on electricity systems. New technologies will be developed and applied to power systems to meet these needs, and existing technologies will be used in novel ways. This paper, which forms a chapter in the forthcoming book "***Future Electricity Technologies and Systems***"[2], develops and presents six possible future electricity industry scenarios for Great Britain, focussed on the year 2050. The paper draws upon the discussions of important technologies presented by expert authors in other chapters of the book to consider the impact of different combinations of key influences on the nature of the power system in 2050. For each scenario, a discussion of the effect of the key parameters is presented, and a description and pictorial illustration is given. Summary tables identify the role of the technologies presented in other chapters of the book, and list important figures of interest, such as the capacity and energy production of renewable generation technologies.

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2 ***Future Electricity Technologies and Systems***
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1. Introduction

This paper attempts to illustrate how the technologies described in the forthcoming book "Future Electricity Technologies and Systems" may be deployed in combination with one another, with other new and developing technologies and with existing technologies in the electricity network of 2050. This task is accomplished through the development of a small number of "high-level" future network scenarios, encompassing different economic and technological possibilities which may arise.

The book discusses a number of technologies which are likely to be important to the development of the electricity network in Great Britain over the coming decades. In part one, four renewable generation technologies, wind, solar photovoltaic, biomass and wave energy are considered. Of these, wind is already gaining a foothold in the British generation mix with a great deal more capacity in development or planning. Biomass is established in a relatively unsophisticated form, while solar photovoltaic generation currently has a very small level of application. Wave energy is also at an early stage of development, with a number of prototype devices under test. In all of these generation technologies significant research and development is in progress aimed at helping them to reach their full potential.

In part two of the book, a number of technologies relevant to more conventional non-renewable generation are discussed. The capture and storage of CO_2 would permit fossil-fuelled generators to continue to contribute to the electricity supply without the release of large volumes of greenhouse gases into the atmosphere. Issues relating to nuclear generation are discussed, together with new technological prospects which might improve its attractiveness and mitigate some of the current barriers to its development in the UK. Microgeneration has the potential to bring about significant change in the electricity industry, through the proliferation of very small generators including micro-renewables and domestic scale combined heat and power systems. Such micro-CHP systems are beginning to see application in the UK; there is scope for very considerable expansion of this market.

Beyond generation, there are considerable advances in prospect in the conversion and transmission technologies covered in part three of the book. Superconductor technology has developed in its capability and its economics in recent years and is beginning to see application in power systems. Power electronics have become increasingly common in many roles related to power systems, from DC interconnectors and large reactive compensation equipment to newer applications such as network integration of small renewable generators, and has the potential to play a variety of important roles in future power systems. Hydrogen has the potential to be a sustainable climate-neutral energy carrier, replacing hydrocarbon-based fuels; the book outlines developments in the production, storage and use of hydrogen which are in prospect, together with challenges, to and strategies for, its widespread adoption. Hydrogen is also a possible medium for the storage of energy in the electricity system, an activity which may become considerably more important in the future. A number of technologies are in development, or already applied which are expected to be suited to the various time and power requirements of future energy storage applications.

Energy use technologies are discussed in part four of the book. Two future directions of development in energy demand in buildings are presented, considering both significant further progress in energy efficiency, and much closer integration and coordination of energy demand and diverse and distributed generation. Future prospects for consumption of electricity by industry are surveyed, covering three important areas of technological development affecting industrial energy consumption. Transport is another major energy area of energy use, to which electricity has the potential to contribute in the form of electrified railways and electric and hybrid road vehicles. The prospects for the application of more advanced or 'smart' electricity meters in the domestic market are reviewed, and alternative customer-supplier relationships which might evolve as a result of their deployment are presented.

The scenarios presented in this paper have been developed by the authors as part of the Supergen Future Network Technologies research effort, which brings together a consortium of researchers from a number academic institutions to consider the application and effects of the application of new and emerging technologies to power systems in the first half of the twenty-first century. The scenarios are intended to permit the analysis of network performance (including economic, technical and environmental measures) under a variety of future circumstances.

Six scenarios have been developed and are presented here, each considering a set of technical, economic, environmental and regulatory possibilities which are felt by the authors to be plausible and achievable. The selection of a relatively small number of scenarios is intended to permit their analysis in reasonable detail, together with consideration of variations of each scenario to determine the influence and importance of individual technologies and external factors. It also permits a relatively detailed presentation in the context of this chapter.

The limited number of scenarios also presents a restriction, in that very radical scenarios and unexpected "wildcard" technologies can only be accommodated at the expense of other, more plausible, possibilities. Such developments are inherently difficult to model and analyse as a result of their very unpredictability, although the influence of such technologies might be estimated to an extent by considering their effects, such as significant changes in demand, reductions in energy costs, reductions in emissions from large generators, or great increases in small-scale energy storage, for example. Such analysis might be incorporated into the study of variations around the six "core" scenarios discussed here. Furthermore, the relatively slow pace at which change generally proceeds in the electricity industry, as discussed below, means that very radical scenarios are much more unlikely to arise than those presented here. Thus, while such scenarios might present very large challenges to the electricity industry, the risk presented is offset by their low likelihood. It is the belief of the authors that the benefits of omitting these more radical scenarios and unexpected technologies from our discussion here outweigh the disadvantages

While the selection of 2050 as a target date for the scenarios may appear to some to be a long way into the future, the electricity supply industry operates under very high expectations of reliability in its product. This gives rise to a tendency towards technological conservatism and incremental development of existing technologies in preference to rapid deployment of revolutionary new ideas. Furthermore, plant lifetimes in the industry are generally long in comparison to other industries – 50 years or more for some types of equipment – and it is likely that existing technologies will survive in strength for a number of decades. These effects mean that the pace of technological change in electricity networks will tend to be relatively slow; therefore 2050 was selected as a suitable date by which significant and wide ranging changes in the British electricity network might have come to fruition.

In this paper, the process by which the six scenarios were developed is described, and the key characteristics which are used to delineate possible "future worlds" are tabulated. The set of six "high-level" scenarios, focusing on the year 2050, of possible future circumstances in which electricity networks will be required to operate is summarised.

Each of the scenarios is then described in more detail, and a description of the network which might be developed by the year 2050 under the scenario is given. Each of these illustrations discusses how the factors inherent in the scenario influence network development, and assess the extent to which the technologies discussed in "Future Energy Technologies and Systems" are applied.

2. Scenario Generation Methodology

The process by which the scenarios discussed in this chapter were generated is summarised in Figure 1.

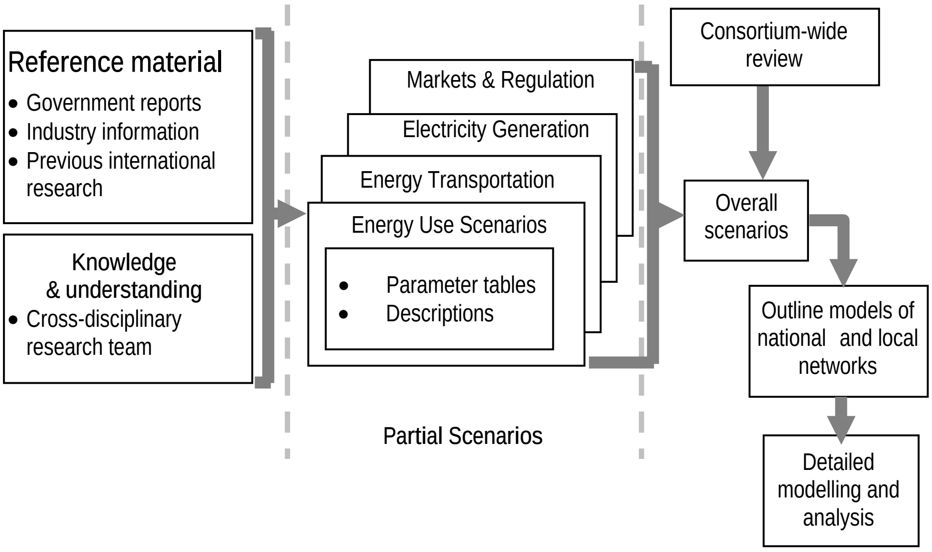

Figure 1: Scenario Identification Process

The starting point in the process is the identification for detailed consideration of four key activities facilitated by electricity networks:

- Energy Use
- Electricity Generation
- Energy Transportation
- Markets and Regulation

Reference material, which is listed in the bibliography, presenting opinions, forecasts and analyses relating to these areas over the coming fifty years was collated and reviewed by those of the authors with particular expertise in each area. Key sources included:

- Department of Trade and Industry (DTI) modelling and projections of future energy demand
- DTI-supported analysis of future generation mix
- Surveys of potential future developments in network technology
- Industry forecasts of future development in specific technology areas
- Material on energy use, electricity generation and network technology presented at the workshop summarised by this book.

Information from these sources about key factors likely to influence the future development of electricity networks was summarised, and possible ranges of variation in these factors were proposed for study. Specific technologies which might be included in the scenarios were identified, together with conditions under which they might see more or less extensive deployment in a scenario. This information was used to generate small sets of five or six possible future partial scenarios focussed on each of the four key areas individually. These partial scenarios were thus based on future combinations of electricity demand, generation and network technology mixes resulting from previously published predictions and forecasts from a variety of sources. In addition to narrative descriptions of these partial scenarios, tables of key parameters covered by the scenarios were generated. As described below, the partial scenarios for each individual area then formed the basis of the "overall" high-level scenarios described in this document, which combine key features of the environment in which networks might operate.

The key inputs to the process of generating the overall scenarios are:

- Narrative descriptions of proposed partial scenarios covering each of the four areas individually:
    - Energy Use
    - Electricity Generation
    - Energy Transportation
    - Markets and Regulation
- Tables of principal scenario parameters and corresponding qualitative ranges of values

Opinions and experience from other work packages within the Supergen Future Network Technologies consortium.

Using this information, the following process was undertaken to better understand the relationship between the scenarios, and to identify drivers for overall scenarios.

1. The scenario drivers from the parameter tables were compared in order to identify common and related themes across the partial scenarios.
2. The scenario descriptions for each area were reviewed to identify further related issues in the scenarios.
3. From the scenario descriptions, the qualitative values of each relevant parameter were identified and tabulated.

4. Partial scenarios were tabulated according to the values given to related parameter groups identified at 2.
5. Partial scenarios were re-tabulated to identify the degree of mutual similarity between pairs of scenarios.
6. Key factors and qualitative ranges were proposed to differentiate overall scenarios.
7. Potential overall scenarios were identified.
8. Using their descriptions, individual partial scenarios were tabulated against potential overall scenarios to evaluate their narrative coverage and identify potential redundancy.
9. The resulting descriptions of the potential scenarios were presented and discussed at a workshop attended by researchers from across the Supergen consortium, at which opinions on the technological, economic, regulatory and social aspects of the scenarios were canvassed.
10. The results of these discussions were used to refine the range of important factors and to make corresponding revisions to the overall scenarios.

The overall scenarios were then used, together with additional technical background material, to generate a corresponding set of descriptions, or outline models, of the electricity network which might develop by 2050 under each scenario. These “network visions” consider the effects of the generation mix envisioned by each scenario, together with important issues such as the range of transmission and distribution technologies likely to have been developed and applied, and the effects of public environmental concern on network development.

In the future, as shown in Figure 1 the scenarios and network descriptions presented in this chapter will form the basis of a set of detailed quantitative models of various aspects of the British electricity system. These models will be analysed to determine the outcomes of each scenario in respect of metrics such as the cost of operating the network, CO_2 and other emissions, and the reliability of electricity supply, as well as the influence on these outcomes of the important uncertainties addressed by each scenario.

3. Principal Factors in Scenario Development

As a result of the analysis described above, the following key parameters on the overall scenarios are proposed:

- **Economic Growth:** This parameter influences factors which include increases in energy demand and levels of investment finance. In these scenarios, the following range of values is considered:
  - ◊ Low growth, whereby economic growth is significantly less than recent levels.
  - ◊ High growth, in which economic growth is somewhat higher than current levels

- **Technological Growth:** The technological growth parameter governs the appearance and application of new technology to electric power networks. The following range of possibilities is considered:
  - ◊ Revolutionary development, in which radical new technologies are developed and applied widely.
  - ◊ Evolutionary development, in which technological advance is restricted to the application and gradual improvement of current and currently foreseen technologies.

- **Environmental attitudes:** Strength or weakness of prevailing environmental attitude determines factors including emissions constraints and incentives and the acceptability of the power network. In these scenarios, the following range of possibilities is considered:
  - ◊ Weak environmental attitudes whereby concern reduces in comparison to the current UK atmosphere to a situation similar to that current in the United States
  - ◊ Strong environmental attitudes whereby popular and governmental concern for the environment strengthen significantly with respect to the current situation.

- **Political and regulatory attitudes:** This parameter concerns the attitudes of government and society in general to the management and development of energy industries in general, including energy use, transportation and electricity generation. Two possibilities are considered:
  - ◊ Liberal attitudes, in which the current preference for relatively light regulation, together with a market-driven approach continues.
  - ◊ An interventionist approach, in which a centrally directed model of management and development is adopted, with greater and more prescriptive government involvement.

Some other scenario-based work, such as that of the UK Government's Foresight Energy Futures Task Force has presented scenarios graphically as quadrants within a "scenario space". While early iterations of the scenarios described in this paper made use of such a representation, further reflection and wider discussion with members of the Supergen research consortium suggested that in this case the approach tended to encourage the consideration of technically uninteresting and mutually similar scenarios, while failing to adequately represent the diversity of issues of interest. Instead, a process of formal presentation, review and criticism of draft scenarios by the consortium has been adopted, in order to assure the relevance and diversity of the final scenarios presented here.

4. Scenarios of the UK Electricity Industry in 2050

4.1. Overview

The parameters described above were combined to yield the six overall scenarios summarised in Table 1 below. They are described in more detail in the subsequent sections. These scenarios capture a range of possible future paths for development of conditions in which energy networks exist.

Scenario Name	Economic Growth	Technological Growth	Environmental Attitudes	Political & Regulatory Environment
Strong Optimism	More than recently	Revolutionary	Stronger	Liberalised
Business as Usual	Same as recently	Evolutionary	As at present	Liberalised
Economic Downturn	Less than recently	Evolutionary	Weaker	Liberalised
Green Plus	Same as recently	Revolutionary	Much stronger	Liberalised
Technological Restriction	More than recently	Evolutionary	Stronger	Liberalised
Central Direction	Same as recently	Evolutionary	Stronger	Interventionist

Table 1: Names and key parameters of UK electricity industry scenarios

These scenarios are described in the following sections, together with the corresponding electricity network which might develop by 2050.

5. Future Energy Technologies

In addition to the technologies discussed in “Future Energy Systems and Technologies”, a number of other existing, developing and future technologies were reviewed which might be form part of power systems in the years leading up to 2050, or influence their development. As part of this process, the authors consulted a number of general and more technology-specific reviews and roadmaps which have been published in technical journals and by government and industry bodies. These sources are included in the bibliography.

As a result of this review, and from the discussion in the book, a set of important technologies and types of devices were identified as being relevant to the six electricity network scenarios. Some technologies are of general interest throughout the set of scenarios, but in differing roles dependent on the particular circumstances. For example, power electronics play a prominent role in all of the scenarios, but in applications such as interconnectors, Flexible Alternating Current Transmission Systems (FACTS), energy storage and microgeneration dependent on the conditions prevailing in the scenario.

Conversely, some technologies feature only in some scenarios, or have some of their possible applications ruled out of all scenarios on technical or economic grounds. For example, while DC network technology is applied to transmission systems in some scenarios, DC distribution is considered to be impractical, since it would either require wholesale replacement of appliances or mass installation of household DC-AC converters as individual local networks are converted. The ability for ageing distribution cables to support DC distribution might also be questionable.

In order to illustrate how new and existing technologies are applied in each scenario, a graphical illustration is provided for each which shows the broad geographical locations within Great Britain in which large-scale generation and network technologies are applied, and identifies smaller-scale technologies which are applied in rural and urban networks. In these diagrams, generation and network technologies are represented using the symbols shown below:

Local rural network	Offshore wind	Tidal generation
Local urban network	Onshore wind	Biomass
Interconnector	CCGT	Photovoltaic generation
Overhead AC transmission	CCGT with carbon sequestration	CHP
Overhead DC transmission	Coal generation	FACTS
Undersea DC transmission	Coal with carbon sequestration	Microgrid
Underground AC transmission	Nuclear	Energy storage
Underground DC transmission	Wave generation	Demand-side control

6. Strong Optimism

6.1. Scenario Background

This scenario takes as its central theme a future in which there is sustained strong economic growth. Over the period to 2050, the overall effect is of growth in excess of recent levels. At the same time, there is a significant increase in interest in, and importance attached to, power generation, transmission and distribution technologies. This results in considerable investment in research and development in these technologies, so that new and improved kinds of equipment, and methods of operation and management are rapidly brought to market and applied. These advances are broadly spread over a wide range of fields related to energy systems and bring benefits in cost, reliability and environmental performance.

A sharpening of current levels of environmental consciousness takes place in this scenario, continuing current trends towards greater popular awareness of these issues. The availability of more capable, newly developed devices permits the replacement or reinforcement of existing equipment in less intrusive form. Additionally, there is significant undergrounding of electricity circuits, supported by the deployment of network and control technologies, such as DC transmission. Environmental concerns, together with increasing prices of fossil fuels, (notably natural gas) also help to increase the adoption of existing and new efficiency measures such as low energy buildings and consumer devices. Carbon trading is extended to industry and individual buildings including the domestic sector.

The current liberalised and market-based approach to regulation and the implementation of government objectives remains in place. However, increases in the share of generation accounted for by renewable technologies, together with improved system control capabilities resulting from technological development, will lead to an increase in the sophistication of market mechanisms to balance the needs and capabilities of a variety of electricity producers and consumers. In addition, standard contractual and technical agreements are developed to streamline the connection of domestic and office CHP and for microgrids, including such aspects as metering, protection and control requirements, automated demand side energy management systems and automated building energy systems.

The success of the UK's system of markets and regulation leads to similar arrangements becoming widespread in Europe. Ultimately, this results in the development of complementary and integrated energy markets at a European scale. Thus, there is increased cross-border trading of energy with correspondingly increased demand for energy transportation between countries, leading to a significant increase in both gas and electricity interconnector capacity between Britain and mainland Europe.

Complementing the development of energy-related markets at a European scale, locally focussed markets in energy and existing and novel energy services (such as the provision of power quality and energy storage devices, and the trading of network capacity) become widespread. These markets serve to focus development of local networks and small-scale generation resources on local needs. Therefore, there will be two types of electricity market in the UK: a sector of many microgrids for small scale demand – homes and offices; and a national, UK-wide, market. Large scale wind, marine, biomass and large 'conventional' plants will participate directly in the UK market, as will larger-scale consumers. Increased interconnector capacity will permit extensive trading between the national market and international markets. Mechanisms are introduced to permit the aggregation of small generators (which would otherwise participate in local markets) to permit them to trade in the UK-wide market.

The increased range of technologies in use, particularly in the form of renewable and/or small-scale generation results in a wider variety of ownership than today. Vertical integration of companies deploying mature technologies tends to develop, with increasing movement of these organisations into energy services products. Smaller scale independent companies will develop, focussing on new markets and technologies such as automated control systems and IT. As these technologies mature and become more widely deployed, their suppliers may become consolidated into larger organisations.

6.2. 2050 Electricity Network

In this scenario, strong economic growth leads to a corresponding increase in the demand for energy services as people become more affluent and able to afford new and improved energy consuming devices which are developed. Equipment such as air conditioning becomes more popular and railway electrification is extended. The resulting increase in demand is offset to a degree by the application of existing and new efficiency measures, but the overall demand for electricity grows at a relatively strong average rate of 1.25% annually to approximately 600TWh/year by 2050 (from approximately 345 TWh in 2003), within current geographical patterns. Variability in electricity demand is reduced, as a result of significant deployment of energy storage systems and demand-side control at small scale, whose technology develops rapidly in the period to 2050. Peak demand is approximately 80GW (from approximately 60GW in 2003).

Renewable generation accounts for around 50% of total generation, of which half is made up of offshore wind. Figure 2 illustrates the location of these renewable generators and other features likely to be important in the “Strong Optimism” scenario. Offshore wind generation is principally located around Scotland (with important concentrations in the Moray Firth), in the Irish Sea and off East Anglia. The size of individual developments will increase, being generally in the hundreds of MW, as will individual turbine size with machines of 20MW being typical. Relatively remote wind farms will be developed, with some in international waters. Onshore wind development is restricted by growing concern over its environmental impact which prevents larger and more cost-effective turbines from being deployed; most onshore wind will be located in Scotland.

Biomass makes up the second largest renewable energy source. In urban areas, this will be in the form of waste-fuelled developments, often allied to district heating schemes in new building projects (promoted through planning regulations and the development of energy service providers) to form relatively large CHP systems. In rural areas, gasification-based biomass generation, fuelled by energy crops will predominate; the size of these plants will be restricted by the costs of transporting biomass and the increasing efficiency of relatively small biomass power plants. There will also be a significant presence of small-scale combustion-based biomass generators. Marine – i.e. wave and small-scale tidal – generation will be located along the west coast of Scotland and in the Western Isles.

Large central generation stations will account for 10-20% of generation. These will be a mixture of gas-fired CCGT systems, which may include liquid oxygen feedstock units, participating in carbon sequestration schemes, and new-technology nuclear power stations, located adjacent to existing nuclear generation sites. Both of these generation technologies are likely to be mainly located in the south; the precise mix will be determined by economic factors, although increases in fossil fuel prices are likely to make some level of new nuclear construction attractive. The remainder of generation capacity, totalling approximately 40%, will be composed of CHP systems as discussed below. The overall effect of this change in generation technologies will be that the proportion of generation in the midlands and south reduces somewhat as large central generating stations are replaced by increases in renewable energy in the north.

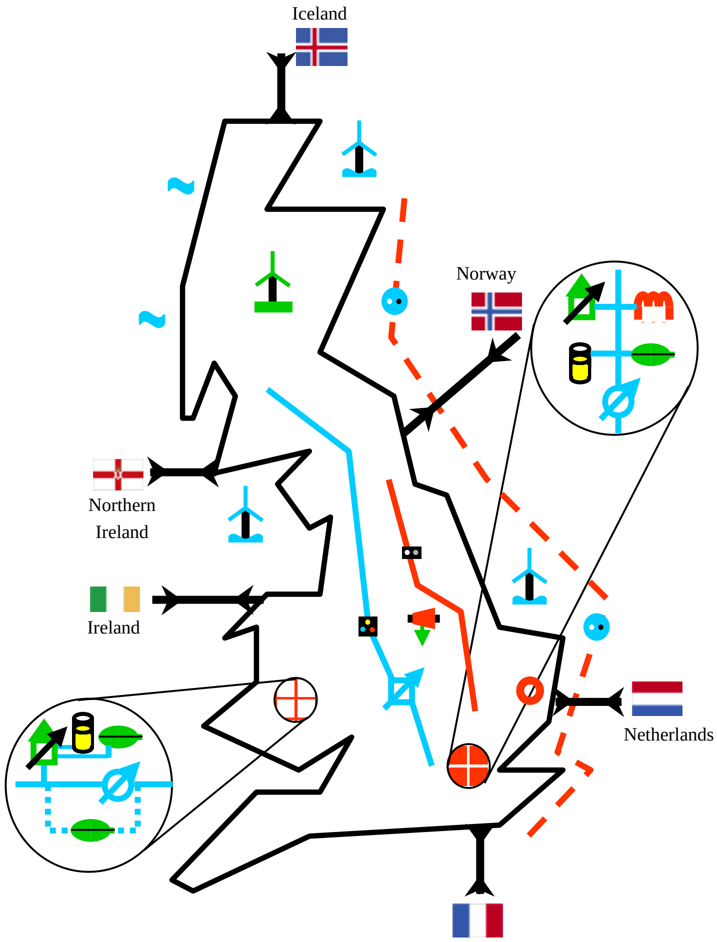

Figure 2: "Strong Optimism" scenario: 2050 electricity network

As shown in Figure 2, interconnectors are constructed to a variety of countries with varying generation profiles. Existing interconnectors to France and Northern Ireland are increased in capacity when major refurbishment or replacement is required. The varying generation and demand profiles of the countries and systems linked by these interconnectors mean that there is likely to be 'through traffic' in the transmission system, as energy from renewable-rich countries such as Iceland and Norway is transported to mainland Europe via the southern interconnectors. It should be noted that the interconnectors to Ireland will provide an additional north-south transmission path.

The overall result of these developments will be in increased demand for electricity transmission, particularly along the north-south axis. At the same time, there will be significant undergrounding of the transmission network, particularly in environmentally sensitive areas, resulting in considerable change to its operational characteristics. Superconductors will be deployed in situations in which it is critical to maximise capacity within a confined space, such as in cities and at river crossings. In order to secure increased capacity from the transmission network, a number of technologies will be applied. Advanced control systems, allied to power electronic-based FACTS systems will be widely deployed. In addition, energy storage systems will be used to provide 'rapid response' capabilities to support the power system during a disturbance event. Such facilities will be closely integrated with advanced network control and protection systems.

Additionally, notwithstanding the reduced variability of electricity demand, large-scale energy storage systems at strategic locations will provide ‘peak smoothing’ capabilities, enabling bulk energy transport to take place in a more controlled manner. These systems are likely to be based on advanced electrochemical technology, although other technologies may be adopted where local conditions are favourable.

Some transmission facilities will be replaced by HVDC circuits when undergrounding is undertaken. These are likely to be strategic north-south transmission paths in which undergrounding of AC circuits cannot provide the required transmission capacity. Superconducting DC cables are likely to be applied in order to minimise losses.

Demand for electricity transmission and available capacity will move closer together. At the same time, the British and European electricity and transmission markets are likely to become more closely connected, and novel mechanisms may be necessary to allocate peak capacity between demands for domestic north-south transmission and through flows from Iceland and Scandinavia to mainland Europe. Under such circumstances, it is possible that new facilities (such as coastal DC transmission) could be developed by investors to support these flows.

As noted previously, local networks will see a considerable penetration of small-scale generation. Small CHP installations, mainly installed and managed by energy services organisations, will account for 30 to 40% of total generation, with strong penetration of the domestic market. By 2050, the majority of such systems will be based on fuel cell technology with integrated conversion of natural gas, but there will be a significant base of older CHP installations including turbine and Stirling Engine systems. In remote rural areas, biomass-based CHP systems will be popular. There will be a mixture of combustion and integrated gasification technologies depending on the particular requirements of the application and the date at which the equipment is installed. In rural communities, community-scale biomass CHP will be developed, based on gasification technology. Photovoltaic generation will be deployed to a limited extent, often integrated into new buildings, but its contribution to the overall generation total will be small.

This increase in small-scale generation will promote the adoption of microgrids in both urban and rural settings, to the extent that their application is very widespread. Power electronic devices similar in concept to FACTS devices will manage the interface between the microgrid and the regional power network. However, as noted below, interaction and co-operation with devices connected to the microgrid will be important and will be facilitated through the medium of wireless communication technology which will be very widely available. Larger embedded generators – for example rural biomass systems, may be connected on one or other side of this boundary depending on local conditions.

Energy storage systems will be widely deployed within microgrids. In rural areas, local or building-focussed storage systems will be strongly applied. In urban areas, these will be supplemented by larger scale systems installed to address the needs of the energy services marketplace.

As noted above, interaction among the generation, storage and energy-consuming devices within microgrids will be important in maintaining local system conditions and in managing the interaction of the microgrid with the regional power system. This will be achieved through large-scale adoption of integrated intelligent control of demand, generation and energy storage. Initially adopted for large industrial and commercial developments, building-scale systems will propagate to progressively smaller applications so that by 2050, there is significant adoption of such technology at a domestic scale. Such systems will permit wide participation in both conventional and novel markets, and will permit significant development of demand-side control schemes. Co-ordination of generation, storage and energy consumption across the microgrid will be facilitated by the development of novel local markets. The widespread metering systems with capabilities such as time of use pricing, automated demand control (often integrated into household or building energy management systems) and automated meter reading, will help to facilitate these developments.

A large-scale transition to hydrogen fuel for road vehicles will lead to the development of fixed hydrogen infrastructure in urban areas. In other areas hydrogen will be distributed by road or rail. Much of the hydrogen will be produced from fossil fuels (with carbon sequestration), but some will be imported, and a small proportion will be produced by electrolysis; hydrogen based energy storage systems will also interact with the distribution system.

6.3. Scenario Summary

The "Strong Optimism" scenario represents a case in which strong economic growth is supported by the availability and application of advanced electricity generation, transport and use technologies. A mix of generation technologies is deployed although there is an increased focus on renewables; other network technologies are developed and deployed to improve environmental outcomes, quality of service and cost effectiveness. The influence in 2050 of each of the technologies mentioned in the introduction to the paper is summarised in Table 2. For each of the generation technologies listed, the table gives the expected installed generation capacity, and the proportion of annual electrical energy demand supplied by that technology.

Technology	Scope of Application
Wind generation	Very strong development of which the great majority is offshore. Total wind generation capacity is 50-60GW, supplying 25% of electricity demand.
Photovoltaic generation	Integrated into many new buildings, deeply embedded in distribution networks. Generation capacity is around 5GW, generating 1-2% of electrical energy.
Biomass electricity generation	Strong application of large and small-scale plants and CHP. Total generation capacity is around 10-15GW, generating 15% of electricity.
Wave generation	Large application in relatively small developments. Including tidal generation, capacity is approximately 15GW, accounting for 10% of electrical energy
CO_2 capture	Applied to about 10GW of new CCGT. Significant role in hydrogen production.
Nuclear generation	Nuclear capacity is 8-10GW of new technology generation, generating 10-15% of electricity.
Microgeneration	Strong fuel cell deployment. Total capacity is 30-35GW, producing 35% of electricity.
Superconductivity	Some network application in constrained locations and onshore HVDC and storage.
Power electronics	Very extensive application in a variety of roles.
Hydrogen	Strong use in transport and as domestic/industrial fuel. Mainly produced from fossil sources.
Energy storage	Considerable application at all sizes and timescales. A variety of technologies are in use.
End-use technologies	Deployment of efficiency measures allied to strong deployment of small distributed generation closely integrated with local networks.
Industrial electricity use	Strong adoption of new technologies to increase efficiency and profitability. Significant integration of electricity generation into production processes, using combustion and advanced fuel cells.
Transport	Increased use of electricity for rail transport; road transport mainly hydrogen-fuelled hybrid vehicles.
Smart metering	Strong application, supported by universally available communications infrastructure. Advanced metering capabilities integrated into demand/generation/storage management systems.

Table 2: Technology application in the “Strong Optimism” scenario

7. Business as Usual

7.1. Scenario Background

This scenario represents a continuation of current trends. Economic growth continues on average at recent levels. As a result, there is an increase in the demand for energy services as people become more affluent and business expands. This trend is countered by the application of energy efficiency, for example in the form of better appliances and machines or improved insulation, largely on economic grounds, particularly in the light of increased natural gas prices, but with some environmental motivation.

Technological development in the energy sector continues at much the same rate as at present, and tends to result in the evolution of existing technologies, and the application of those currently under development, rather than to revolutionary changes in the technology applied to energy systems. Thus, new kinds of power system equipment and generators tend to be recognisably similar to systems which are currently in use or in close prospect for application.

The level of environmental consciousness in this scenario generally remains constant at its current point, or sharpens slightly, but does not impose significant additional restrictions. Resistance to increases in the visual and environmental impact of electricity networks remains relatively strong. Gaining approval for the construction of new transmission infrastructure remains costly and time consuming, and there is pressure for the undergrounding of existing circuits in specific environmentally sensitive areas as refurbishment or replacement becomes necessary. However, there is no pressure for generalised removal or undergrounding. Furthermore, there is less concern over the smaller structures used by distribution systems.

The government remains supportive of current liberalised, market-based approaches to regulation. However, the perceived success of these structures in the current environment means that they are relatively slow to adapt to the needs and opportunities of very small-scale generation, restricting their initial competitiveness. Ultimately, however, increased competitiveness through gradual technological improvement influences the adoption of a favourable regulatory and market mechanisms. An important development in this regard will be the emergence of energy service providers, optimising light, power and ultimately heat provision from national energy markets, a portfolio of renewable and large generators, and as the technology develops, on-site microgeneration.

Liberalisation of energy markets and industries continues across Europe. However, although some new electricity and gas interconnectors are constructed, limited transfer capacity means that UK participation in these markets is limited. Thus, although UK markets become more closely aligned to those of mainland Europe, integration is far from complete. There is however strong development in integrated cross-European markets for emissions trading.

A centralised market remains the principal method of electricity trading in the UK. The market design is gradually optimised to allow participation of a considerable volume of wind and CHP generation and to take account of their implications for generation and load profiles. Energy service providers participate in half-hourly or shorter term markets on behalf of groups of customers; some small-scale and domestic customers participate directly, taking advantage of domestic energy storage systems. Limited incentives for renewables, are available in the early years of this scenario in line with environmental attitudes, but interest in these tends to slacken as network-imposed constraints on the development of renewables are approached. Carbon trading applies mainly to industrial and large commercial users and takes place in a pan-European market; the price of carbon will be relatively low.

Ownership patterns continue largely as at present, with a variety of individual companies with limited vertical integration. There is some decentralisation of the management of local networks, although they are likely to remain closely coupled to the electricity network at large. Development of microgrids is likely to be restricted to specific industrial or commercial settings with a large amount of embedded generation under common control.

7.2. 2050 Electricity Network

In this scenario, economic growth brings about an increase in demand for energy services as people become more affluent and business activity increases. Increasing costs of natural gas leads to a small amount of fuel switching as electricity becomes more attractive in some applications. However, some of this growth is offset by energy efficiency measures. Demand for electricity grows at an average of around 1% to approximately 540TWh/year in 2050. This demand remains distributed within current geographical patterns. Variability of demand reduces somewhat as a result of increased participation in Demand Side Control schemes, but as this is far from universal, peak load continues to grow and at around 80GW remains significantly above average load.

Renewable technologies account for around 30% of generation. Figure 3 illustrates the location of these renewable generators and other features likely to be important in the "Business as Usual" scenario. Of this renewable generation, just under half is found in offshore wind developments, located in the Irish Sea and off East Anglia and north-east Scotland, using machines in the 10-20MW range. There is some additional onshore wind capacity, located in Scotland and the South-West, but this is limited by the greater efficiency offered by the larger turbines acceptable in offshore developments, which preferentially absorb the capacity of the network to accommodate intermittent generation. Onshore wind is restricted to two or three percent of total generation.

A further 10 to 15% of total generation is in the form of biomass-fuelled systems, mainly in the form of gasifiers coupled to combined cycle turbines. Biomass generators are generally relatively small in scale and are often embedded within local networks. The remaining 3 to 5% of total generation from renewable sources is made up of marine generation on the west coast of Scotland and a small amount of photovoltaic generation integrated into new buildings.

Large central generation will account for around 50% of total generation. Large CCGT developments will predominate, with their location being driven by a combination of transmission constraint avoidance and the availability of existing sites for redevelopment. However, increases in the cost of natural gas will make the construction of a small number of advanced coal-fired stations attractive where a supply of suitable fuel can be secured. With a significant concentration of renewable generation in the north in Scotland, it is likely that the majority of these new generators will be located in the midlands and the south. Between a quarter and half of new CCGT units will be equipped for carbon capture; to counter environmental objections, new coal generators will exploit this technology. Coastal sites with easy access to undersea storage facilities are most likely to participate in carbon sequestration. Construction of new nuclear generation is relatively unlikely, but economic conditions may favour the construction of one or two new stations of the next evolutionary design. As noted below, some low-cost generation capacity at strategic locations, in the form of OCGT units may be necessary to relieve transmission constraints under high load conditions. The remaining 20% of generation will be made up of small CHP systems.

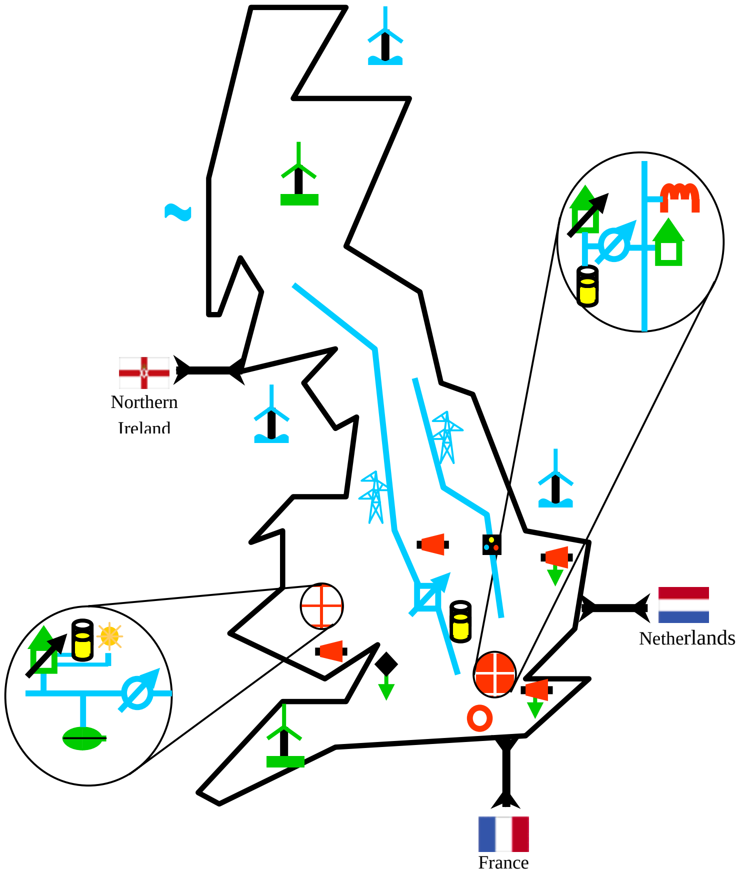

Figure 3: “Business as Usual” Scenario: 2050 Electricity Network

Existing interconnectors will be renewed and refurbished as necessary, and will benefit from increases in capacity as a result of technological improvements. New interconnector construction will be confined to a second relatively short link to mainland Europe of similar capacity to existing facilities. Energy transfer between Great Britain and Europe will be dependent on relative energy prices, and thus on the availability of renewable resources. However, since interconnector capacity will amount to less than 10% of domestic generation, its influence is likely to be limited.

The demand for bulk electricity transmission will increase as a result of demand growth. The increased proportion of electricity generated from intermittent renewable sources means that flow patterns in the transmission network are less predictable beyond the short term. As there is little construction of new transmission facilities, the need arises to increase the effective capacity of existing facilities while increasing the overall flexibility of the system, a situation complicated by the undergrounding of specific environmentally sensitive sections of many transmission circuits. These objectives are met through the deployment of advanced and highly interconnected control systems, together with power electronics-based FACTS-like devices. Additionally, strategic energy storage systems using electrolytic or compressed air technology and strategically located generation will be used to alleviate pressure on the transmission system at times of peak demand. Superconducting technology may be used in particular locations where space for transmission system capacity is at a premium.

As mentioned above there will be a large increase in generation connected to local electricity networks. Most CHP systems will be small-scale units of existing technology (e.g. microturbines or Stirling Engines) fuelled by natural gas; a small proportion of more recently installed systems will use fuel cell technology, mainly using on-site natural gas reformers. This growth will be driven by the emergence of energy service providers. In rural areas, biomass will be an important generation technology. In remote areas, biomass-fuelled CHP will be widely deployed, while larger-scale systems mainly fuelled by waste will be deployed in more populous areas.

Demand and control pressures on relatively lightly constructed rural networks with significant embedded renewable generation may lead to adoption of microgrid technology in such areas. Interaction with the regional network in such situations will remain relatively strong with the likelihood of strong net imports of energy. Domestic generation, including small biomass and photovoltaic technologies, together with larger scale network-connected generation and demand side control capacity will be controlled through local market mechanisms. Energy storage in such networks is likely to be restricted to domestic-scale systems designed to insulate individual consumers from short-term price spikes in the energy market. These systems will be based on flywheel or battery technology. More advanced metering technologies permit consumers to take advantage of these techniques to participate in these local markets.

In urban settings, the application of microgrid technology will be restricted to 'power-parks' – new developments in which energy service providers are responsible for providing heat and electricity to industrial and commercial customers, although some residential and mixed use power parks may develop. In such networks, there will be deployment of relatively large CHP systems linked to district heating, and community-scale energy storage systems serving the entire microgrid. Participation in demand-side control schemes will be facilitated by building management systems furnished by the energy service provider, which will include more advanced metering capabilities permitting variable pricing for energy and services such as demand-side response. Outwith these power parks, urban networks will experience a strong increase in the deployment of small-scale single building CHP systems, but will otherwise see little change.

In this scenario, demands placed on electricity networks will tend to increase. There will therefore be a strong focus on the development and deployment of asset management and condition monitoring systems in order to derive maximum reliability and value from the installed asset base while minimising the overall cost of operating the system.

7.3. Scenario Summary

The "Business as Usual" scenario represents a case in which current economic and technical trends continue largely without change. Conventional generation remains the most important source of electricity, but with a considerably increased contribution from renewables and small-scale plant; other network technologies are developed and deployed to improve reliability and cost effectiveness of supply while delivering some environmental benefits. The influence in 2050 of each of the technologies mentioned in the introduction is summarised in Table 3. For each of the generation technologies listed, the table gives the expected installed generation capacity, and the proportion of annual electrical energy demand supplied by that technology.

Technology	Scope of application
Wind generation	Strong development. 20-25GW of offshore capacity and around 5GW onshore, generating 12-15% of electrical energy.
Photovoltaic generation	Integrated into some new buildings, deeply embedded in distribution networks. Total generating capacity is around 4GW, producing around 1% of electricity.
Biomass electricity generation	Strong application of mainly smaller-scale plants and CHP. Total capacity is around 10GW, supplying 10-15% of electrical energy demand.
Wave generation	Some application in relatively small developments. Total marine generation capacity, including tidal generation, is 6-7GW, of which wave accounts for three quarters. 3-5% of electricity demand is supplied from marine generation.
CO_2 capture	Applied to a proportion of new CCGT and coal generators; 10-20GW plant capacity is equipped. Adopted for hydrogen production.
Nuclear generation	One or two new stations using developments of existing technology, giving a total capacity of 2-4GW, supplying 5-10% of electricity demand.
Microgeneration	Strong deployment, mainly using existing technology; total installed capacity of around 15GW, accounting for 20% of electrical energy production.
Superconductivity	Applied in a few specific constrained locations.
Power electronics	Very extensive application in a variety of roles including transmission control systems. Distributed generation is an important application.
Hydrogen	Little interaction with electricity network; main use is in transport. Almost entirely produced from fossil sources.
Energy storage	Main application is at domestic level with a few large strategic installations.
End use technologies	Microgeneration mainly operates in isolation; a few integrated ‘power park’ developments combining control of demand, generation and heating.
Industrial electricity use	Replacement of existing equipment with more efficient and flexible plant on economic grounds or at life expiry. Increased employment of cogeneration, particularly at large and medium scales using turbine plant. Some small-scale using turbines and reciprocating engines.
Transport	Road transport mainly hydrogen-fuelled hybrid vehicles; little additional railway electrification.
Smart metering	Mainly applied though energy service providers, and in association with small-scale energy storage and generation; most users retain traditional meters.

Table 3: Technology application in the “Business as Usual” scenario

8. Economic Downturn

8.1. Scenario Background

The principal factor driving this scenario is a significant reduction in economic growth from recent levels, as a result of factors such as fuel-price shocks or global recession. As a result of these events, people generally have less money to spend on additional devices and appliances. Thus the growth in demand for electricity occasioned by such purchases is reduced in comparison to other scenarios.

Similarly growth of business, commerce and industry is lower than in other scenarios, limiting the energy demands of these sectors. There is considerable interest in conservation of energy on economic grounds; energy efficiency becomes a strong selling point for replacement appliances where it can be achieved at modest cost.

Limited funding is available for research and development activities, and spending on these activities reduces and becomes focussed on relatively short-term goals. Technological advance in energy systems is mainly confined to the evolution of existing technologies and is focussed on increasing the cost effectiveness of energy supply. Economic concerns tend to divert awareness from environmental issues, and environmental consciousness thus becomes less strong than at present. Energy efficiency is motivated largely by economic drivers; although there is considerable interest in more efficient buildings which incur lower energy costs, moves in this direction are limited by relatively short-term cost pressures and a reduced rate of turnover in the building stock.

Similarly, restrictions on the availability of finance mean that investment is largely limited to like-for-like replacement of life-expired assets, together with limited network extension to connect new generation, unless economic benefits can be realised from the deployment of more capable plant.

Notwithstanding the economic difficulties, the government remains generally committed to liberalised, market-based regulation in the UK, in the belief that this will promote more efficient and cost-effective energy supply than a more interventionist policy. Market structures are directed towards the promotion of cost reduction and efficiency in energy supply. Some financial assistance from the government towards the implementation of such measures is forthcoming where overall benefits can be secured. Liberalisation of European energy markets continues, although the pace of reform tends to reduce as economic pressures become more evident. In any case, lack of interconnector capacity, and uncertainty over the economics of new interconnectors between Britain and mainland Europe continues to restrict the capability to transfer electricity. There is thus little opportunity for UK participation in European electricity markets. New interconnector capacity is focussed on the import of natural gas. There is however strong interest in the convergence of technical standards between energy industries in the UK and Europe in the hope of realising economies in the manufacture and purchase of equipment. However, the economic climate is difficult for manufacturers of power system apparatus.

Market structures are thus likely to remain similar to those currently planned for implementation. Carbon trading will be adopted under the current EU system; however its scope does not expand beyond generators and large energy intensive industrial concerns. Wider economic and political considerations will keep emission allocations large, and prices correspondingly low. With focus being placed on encouraging the most economic generation technologies, incentives for renewable generation will be allowed to expire; future regulatory incentives will promote greater efficiency.

Economically-driven consolidation is likely to be the principal driver of ownership patterns, as amalgamation of existing companies into large, possibly vertically integrated companies takes place. As a result, a few big combined generation and supply companies will dominate the market.

8.2. 2050 Electricity Network

In this scenario a relatively low rate of economic growth restricts the increase in demand for energy services. People tend to postpone the purchase of new devices and appliances and new models tend to emphasise efficiency rather than performance. Adoption of capital-intensive energy efficiency measures, such as the replacement of the building stock with more efficient designs is limited by restrictions on the availability of finance. However, smaller scale efficiency measures, such as improved appliance design, better insulation and progressive improvement and adoption of building control systems is sufficient to lead to electricity consumption remaining constant or to reduce at an average rate of up to 0.5% to approximately 275TWh/year in 2050. The geographical pattern of demand is largely unchanged. There is no adoption of domestic-scale energy storage for economic and technological reasons, and lack of demand growth means that there is no incentive to promote adoption of demand-side control in other than particular local circumstances. Variability of electricity demand is therefore largely unchanged in comparison to today, and peak demand is approximately 45GW.

In this scenario, renewable generation is divided roughly equally between onshore wind and biomass technologies, and accounts for between 10% and 20% of generation. Figure 4 illustrates the location of these renewable generators and other features likely to be important in the "Economic Downturn" scenario. The renewable generation capacity is largely made up of smaller-scale developments of a few tens of megawatts connected to either local or regional power networks dependent on the size of the generation scheme, although older onshore wind farms will be larger, ranging up to 500MW. Onshore wind generation is principally located in Scotland and Wales and makes use of turbines typically in the 2-5MW range on the grounds of environmental impact.

Energy crop fuelled biomass generators using a mixture of gasification and combustion technologies are distributed in many rural areas, with important concentrations in Scotland, Wales and the north of England. Marine and photovoltaic technologies do not develop to the point where their application becomes economically attractive.

Large central plants account for around 75% of generation. CCGT is the dominant technology, although a number of new coal-fired power stations will be built in order to provide an element of fuel diversity and to reduce the potential impact of gas price fluctuations. There is little or no uptake of carbon capture and sequestration technology. New large generators make use of existing power station sites in order to reuse existing transmission network connections. CCGT generation is preferentially located at sites with convenient connections to the national gas transmission network and to gas import facilities, while new coal-fired plants are located close to ports to permit the use of imported coal. No new nuclear plants will be constructed: nuclear generation will have been eliminated by 2050 under this scenario. Small-scale CHP, mainly in industrial and commercial settings will account for the remaining 5–10% of generation.

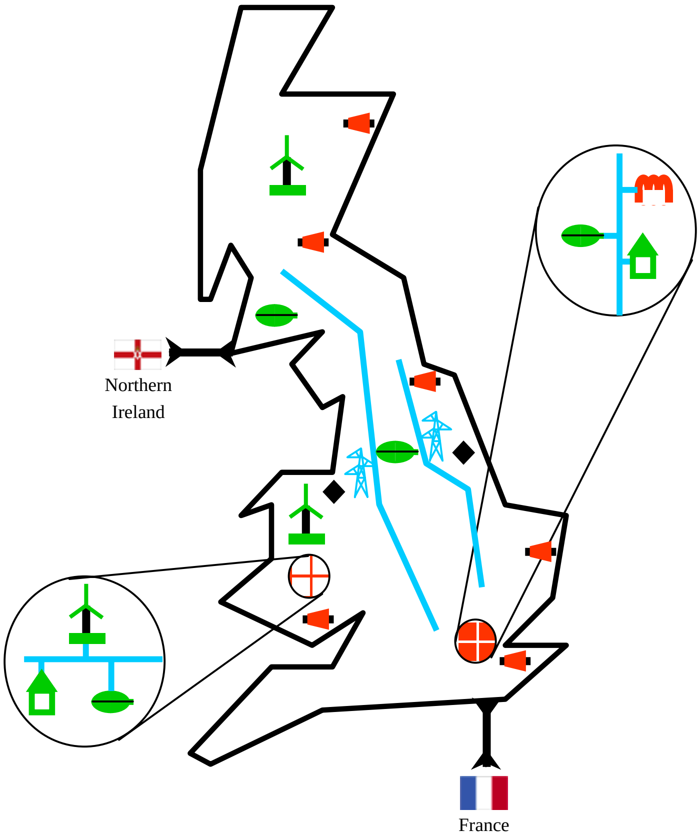

Figure 4: “Economic Downturn” Scenario: Electricity Network in 2050

Existing interconnectors are life-extended, with refurbishment and renewal as necessary. This results in modest increases in capacity as a result of technological development, but no new interconnectors are constructed. Given the likely fuel price issues resulting from a strongly fossil-fuelled generation mix, it is likely that the UK-France interconnector will mainly act as an energy import route, and will also offset fuel security concerns to an extent. Depending on generation development in Northern Ireland and the Republic of Ireland, the Scotland-Northern Ireland interconnector is likely to facilitate energy exchanges to balance the availability of intermittent renewable resources in Great Britain and Ireland.

The development of small-scale embedded generation is driven largely by pressure for cost savings. In addition to embedded renewable sources discussed above, CHP developments will account for between 5% and 10% of total generation. Industrial and commercial sites will be the dominant users of such systems; domestic-scale generation will be largely driven by security of supply concerns and will thus be something of a niche market, confined to more remote areas. CHP technology will remain focussed on small turbines or Stirling Engines fuelled by natural gas.

No new energy storage facilities are deployed. The development of large-scale systems is frustrated by a combination of a lack of suitable sites for traditional technologies such as pumped storage and the high capital costs of such developments. Deployment of smaller scale systems is prevented by their high initial costs and the lack of perceived need. These factors serve to restrict the amount of intermittent renewable generation which can be accommodated by the network while minimising the amount of reserve generation capacity used.

The relatively small penetration of small-scale generation, and the fact that demand side control schemes remain scarce means that there is little pressure for the adoption of microgrid technology. Local power networks remain largely passive systems. Any installation of remote control and monitoring equipment is driven by cost saving and asset management needs rather than the need for improved control of the network.

The slow pace of technological development means that hydrogen is not widely adopted as a fuel or an energy storage medium. Road transport continues to make use of petrol and diesel fuels, with adoption of hydrogen being frustrated by the high cost and technical difficulty of storing sufficient fuel to achieve an acceptable range. There is very limited application to short-range vehicles (such as delivery vans) where a supply of hydrogen is available from other industrial activities. There is some adoption of hybrid vehicle technology on efficiency grounds; however these vehicles are entirely fossil fuelled; there is no adoption of battery charging from the electricity network.

The overall result of these trends is that the technical demands placed on transmission and distribution systems can in general be met by the power network of today. However, economic constraints mean that there is a strong focus on life-extension of existing plant items to avoid the need for expenditure renewal or replacement. Where such a course of action becomes impractical, life-expired assets are likely to be replaced on a least cost like-for-like basis. However, where cost savings could be achieved through rationalisation of the network, it is likely to be undertaken at this point of asset replacement. There may be modest investment in extending the remote control of local distribution networks in order to save on operational expenses associated with manual operation.

The power network of 2050 under this scenario is likely to be very similar to that of today in its structure, technology mix and operational approach. The most important issue of concern to network operators will be the reliability of ageing plant. There will be considerable deployment of asset management and condition monitoring technology and well as research into the behaviour and characteristics of such plant in order to manage this issue and prevent significant degradation of quality of supply to customers without incurring unnecessary expense on maintenance or plant replacement. When replacement of an asset becomes necessary, the least cost modern equivalent capable of performing the task will usually be selected, unless another course of action will yield cost savings in the short-to-medium term.

8.3. Scenario Summary

The "Economic Downturn" scenario represents a case in which the effects of adverse economic events are dominant. Investment for research and development is relatively scarce and as a result renewable technologies develop to only a limited degree. Investment in the electricity network is generally minimised except where relatively rapid economic benefits can be realised. The influence in 2050 of each of the technologies mentioned in the introduction is summarised in Table 4. For each of the generation technologies listed, the table gives the expected installed generation capacity, and the proportion of annual electrical energy demand supplied by that technology.

Technology	Scope of application
Wind generation	Limited onshore application (total installed capacity is approximately 10GW) in relatively small developments. 5-10% of electrical energy is generated from wind sources.
Photovoltaic generation	Minimal application.
Biomass electricity generation	Application mainly in small-scale plants Total generating capacity is around 5GW, supplying 5-10% of electricity demand.
Wave generation	Not economically attractive.
CO_2 capture	Application to one or two CCGT plants, if used at all.
Nuclear generation	No nuclear generation.
Microgeneration	Application of microturbines and Stirling engines in industrial settings. Total installed capacity is around 5 GW, accounting for 5-10% of electricity produced.
Superconductivity	No applications in electricity networks.
Power Electronics	Main applications are in new or replacement compensation and control systems, in refurbished interconnectors and in microgeneration.
Hydrogen	Limited use in specific vehicle applications.
Energy Storage	No additional deployment of energy storage systems.
End use technologies	Strong emphasis on efficiency and reduction in energy use, at reasonable cost.
Industrial electricity use	High efficiency technologies adopted for new facilities and replacement of life-expired plant where capital cost differential allows a short pay-back period. Cogeneration integrated into construction of many new facilities on economic grounds; capital cost pressures favour use of turbines and reciprocating engines.
Transport	Transport remains largely based on fossil fuel sources.
Smart metering	Little application; refurbishment and reuse of electromechanical meters continues strongly. Some application of simple remote-readable meters in new developments on cost-saving grounds.

Table 4: Technology application in the “Economic Downturn” scenario

9. Green Plus

9.1. Scenario Background

This scenario envisions a future in which environmental concerns relating to all aspects of electricity generation, transport and consumption become significantly stronger than today. Factors underlying this sharpening of attitudes include increasingly manifest effects of climate change on this country. Significantly increased constraints on energy use and on the generation and transport of electricity arise as a result of these environmental concerns. In particular, a disproportionate share of ambitious CO_2 emission reduction targets falls upon the electricity industry which is felt to be well placed to contribute to these goals.

Overall, the effect on the economy of this change in environmental attitude is largely neutral as ‘environmentally responsible’ technologies become a significant area of national expertise and output.

Technological growth in energy systems is strong, and focuses on improving environmental performance. Economic growth continues at recent levels over the period of this scenario. As a result, there is continued growth in the demand for energy services, which is offset by strong investment in energy efficiency measures which are supported by government incentives and regulations.

An important effect of the increased level of environmental concern is a strong increase in resistance to the impact of electricity networks. Construction of new transmission facilities is largely impossible and there is strong pressure for the undergrounding or outright removal of existing circuits. New and refurbished distribution circuits are invariably undergrounded. Alternatives to oil-filled distribution equipment are sought in order to avoid an increasing regulatory burden aimed at prevention of environmental contamination.

Local networks tend to become more diverse in this scenario, resulting in an increasing trend towards local management and possibly ownership of networks. The development of microgrids is influenced by the need for local networks to exchange energy with the electricity system at large in response to local surfeits or shortfalls in generation. The scale of adoption of local energy storage devices and the effectiveness of local balancing of generation and load will determine the extent of such energy exchanges and trading.

In general, a liberalised and market-oriented approach to regulation is seen as successful, and is broadly retained. The government uses a combination of direct regulation and market-based mechanisms (analogous to the current carbon trading system) to provide incentives for significantly increased environmental responsibility on the part of energy users and generators and transporters of electricity.

There is widespread liberalisation of energy industries across Europe. Energy is increasingly traded at a European as well as national scale. This process is facilitated by increased interconnection capacity between European energy systems, including the development of a strategic European hydrogen network. These changes permit the development of markets in novel commodities such as various forms of renewable energy in which the UK is able to participate strongly. Markets also develop in various forms of environmentally-focussed permissions, such as emissions permits. This latter group of markets is promoted by the imposition of increasingly stringent limits on emissions.

The centralised national electricity market declines in importance, and is supplemented by a set of regional markets, and European markets. Market structures are optimised for decentralised generation and control and large scale deployment of both continuous sources and intermittent sources which are predictable over a range of timescales. Emissions trading (primarily in CO_2) becomes highly prevalent, extending to households and individuals, with a very high carbon price. Standard contractual agreements for domestic and office CHP and microgrids will be introduced, including such aspects as metering, automated demand side energy management systems and automated building energy systems.

Ownership will be decentralised into many specialist companies in a variety of areas, including energy services, energy and emissions trading, system control and optimisation and local system operation.

9.2. 2050 Electricity Network

In this scenario, strong application of efficiency measures reduces the demand for energy services. However, electricity use increases moderately by 2050, as initial deployment of fossil-fuelled CHP systems on grounds of efficiency gives way to the use of electrically driven heat pumps to meet a large proportion of space and water heating requirements from carbon-free energy sources. The overall result is that electricity consumption increases on average by up to 0.25% until 2050, giving an annual electricity demand of approximately 390TWh. Variability of electricity demand is strongly reduced in comparison with the present situation, as a result of strong deployment of demand-side control and increased domestic-scale generation. Peak load is thus reduced to around 50GW.

Renewable energy accounts for around 80% of generation in this scenario. Figure 5 illustrates the location of these renewable generators and other features likely to be important in the "Green Plus" scenario. Offshore wind is the significant renewable source, accounting for almost half of this total, with major concentrations of generation in the Irish Sea, around the south east of England, including East Anglia and the Thames Estuary, and off the Scottish coast. Large developments of several hundred MW are common, typically using turbines of 30–40MW. Rapid early adoption of onshore wind generation leads to development in more remote rural areas including northern and southern Scotland, central Wales and south-west England. However, this development is subsequently restricted by concern over the environmental impact of onshore wind. Thus, most developments are relatively small, at no more than 200MW and use turbines no larger than the 5-10MW range. By 2050, onshore wind accounts for 5-10% of total generation. At this point, any new onshore wind developments will be small-scale community focussed schemes deeply embedded within local distribution networks.

Biomass, largely in the form of combustion turbines fed by gasification accounts for the second largest share of generation, at around 25%. There is a strong increase in the cultivation of energy crops to support the needs of biomass generation. In order to minimise the requirement for transportation of raw biomass, power plants tend to be relatively small, and will connect to local or regional power networks rather than to the national transmission system.

Marine energy sources account for a further 5-10% of generation. Wave energy is exploited on the west coast of Scotland, in the Western Isles and in south-west England, with tidal generation being sited in the Bristol Channel and the Pentland Firth. In both of these cases, large numbers of small generators are preferred to a few intrusive, high-capacity devices.

Small scale systems will account for 5% of generation from renewable sources in the form of technologies such as photovoltaics and small hydro, with capacity measured in kW. These will be connected either to local distribution networks or integrated at the customer level. The other 20% of generation will be supplied by CHP systems.

Interconnector capacity to mainland Europe will be increased through reinforcement of the existing link, and construction of new capacity. In addition, new interconnectors will be constructed to Iceland and Norway, both rich in renewable resources. In the regulatory environment outlined above, the ability to exploit cheap, reliable and plentiful renewable resources will make construction of these interconnectors attractive to investors; a contribution from government or EU sources in recognition of the environmental benefits of such a scheme is also possible. The scale of energy transfers across these interconnectors will be dependant on the day-to-day availability of intermittent renewable resources and stored energy reserves across the European energy market. It is therefore likely that these flows will exhibit some volatility. Since significant 'through traffic' between Iceland and Scandinavia across these interconnectors is likely, energy flows in this country's transmission network may be similarly volatile.

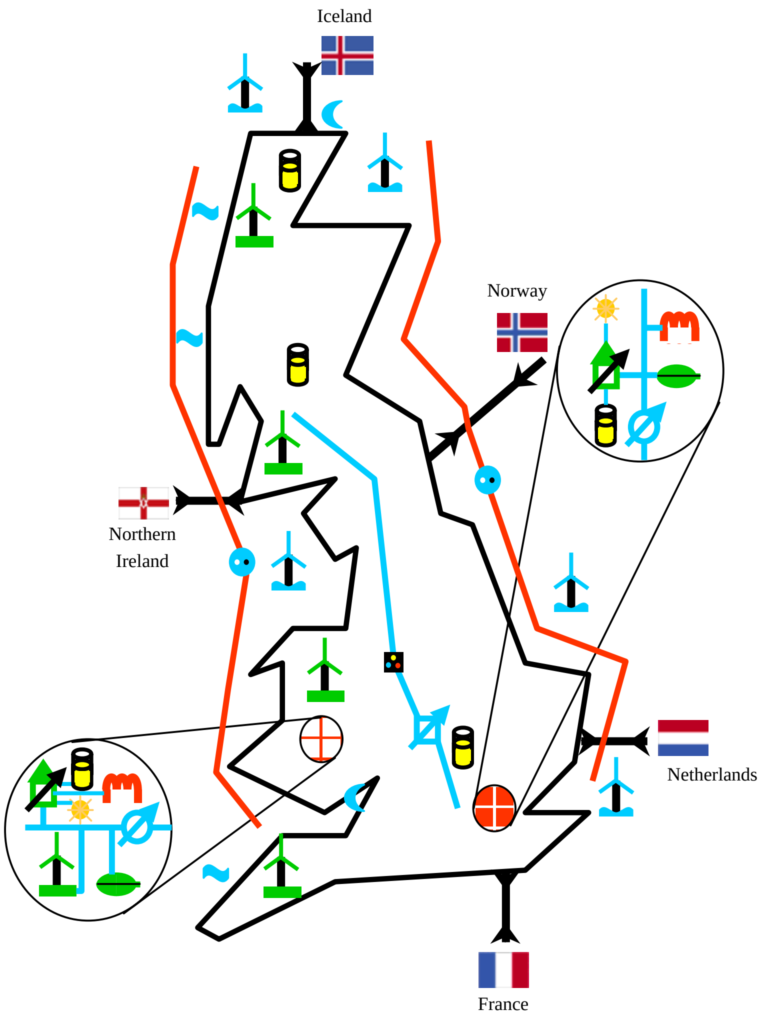

Figure 5: "Green Plus" Scenario: Electricity Network in 2050

The overall effect of these developments will be a strong increase in the demand for electricity transmission from remote renewable sources to urban load centres and to and from interconnector landfall points. As noted above, it will become more difficult to predict energy flows in the electricity system more than three or four hours ahead. At the same time, resistance to the environmental impact of the overhead transmission network will lead to pressure for removal or undergrounding of much of the network. To address these conflicting needs, high capacity DC transmission circuits will be constructed off the east and west coast of Great Britain, connected at strategic points to the onshore transmission network and to interconnector terminal points. DC connections may also be projected inland to major load centres using superconducting technology. These new facilities will take on much of the north-south transmission role of the existing network, resulting in rationalisation of its capacity, and undergrounding of much of the remaining system, which will fulfil the role of onward transport of electricity from a small number of DC terminal points to load centres.

Given the modest load growth, and environmentally-driven pressure for reductions in transmission assets, there will be a requirement to maximise the use of onshore transmission capacity. These needs will be addressed through the deployment of advanced control systems in conjunction with advanced power-electronic devices. Superconductors will be used to provide increased capacity over more conventional systems where space is at a premium, such as in cities. Environmental objections to oil-filled and SF_6-based plant will see conventional transformers and switchgear replaced by power electronic devices incorporating one or both of these roles, together with the provision of fast-acting compensation linked to fast-acting energy storage systems. These developments will be paralleled by developments in substation technology which reduce the environmental impact of the power system while improving capacity and reliability.

Strategic large-scale energy storage systems will be located close to concentrations of generation and near major load centres in order to smooth the flow of electricity over the transmission system. At times of high transmission utilisation, energy will be accumulated close to generation and released from storage systems at load centres. The balance will be restored through additional transfers at "quiet" times. Furthermore, energy storage will increasingly be integrated with remote intermittent generation such as wave, wind and tidal developments in order to optimise utilisation of the grid connection and to enable more effective participation in energy markets. A variety of energy storage technologies will be used. Flow cells are likely to feature prominently, although where there is ready access to a hydrogen transport network, large fuel cell installations are likely to be used instead. Smaller, more cost-sensitive installations, such as those associated with individual renewable energy developments, may use batteries or flywheels. One or two strategic pumped storage facilities may be constructed in remote areas.

As noted previously, small-scale CHP systems, embedded in local networks will account for 20% of total generation. Most of these generators are likely to use fuel cell technology consuming hydrogen. Most hydrogen consumed in the UK will be produced by large-scale natural gas reformation with carbon capture. There will also be significant hydrogen imports, and some will be electrically produced at times of low demand for electricity, often in conjunction with energy storage systems. Biomass and 'dual fuel' CHP will be developed at a 'community-scale' in some rural areas while small biomass CHP will be applied in remote parts of the country. Small gas turbine technology is likely to be used in these latter two applications. In urban areas, waste-fuelled generation may contribute to district heating schemes. As noted previously, significant quantities of small-scale renewable generation, such as photovoltaics, and small wind and hydro generators will be integrated into local networks, amounting to as much as 5% of generation.

There will be widespread deployment of advanced building control systems, integrating control of demand, energy storage and generation systems for new buildings. By 2050, integrated building management systems will have been fitted to the majority of older buildings also. These systems will optimise the environmental outcomes of energy use, and provide information to customers about, for example the current availability of renewably-generated electricity to help in making decisions about electricity consumption. Integration of all forms of energy consumption within these systems will permit participation in household-scale emissions trading schemes

Many new buildings will be designed to accommodate small renewable generators such as photovoltaics and small wind turbines within their structure. Some retrofitting of such generators to existing buildings will also take place. Small-scale energy storage systems will also be integrated with buildings, sometimes forming part of fuel cell-based CHP systems. Participation in demand-side control schemes will take place on a very large scale.

All of these developments will lead to the widespread deployment of microgrid technologies. Power electronic systems will control the interfaces between the microgrid and the regional electricity system and between individual generators, customers and the microgrid. Operation of the microgrid will be facilitated by a novel set of localised markets which will be designed to optimise the use of available generation and storage resources as well as the capacity of the microgrid and its grid connection. Interaction between microgrids and then regional and national electricity systems will be governed by a further set of markets. Microgrid operators may opt to invest in medium-scale energy storage systems in order to serve better the needs of their customers, or to improve their position in regional markets.

9.3. Scenario Summary

The “Green Plus” scenario represents a case in which environmental concerns are paramount. Renewable generation technologies are strongly deployed; other technologies are adopted in order to permit this technological shift while minimising the impact of the electricity network on the environment. The influence in 2050 of each of the technologies mentioned in the introduction to this paper is summarised in Table 5. For each of the generation technologies listed, the table gives the expected installed generation capacity, and the proportion of annual electrical energy demand supplied by that technology.

Technology	Scope of application
Wind generation	Very strong: largest single generation source. Total installed capacity is around 60GW, with the great majority offshore. 45-50% of electricity is generated from wind.
Photovoltaic generation	Significant small-scale application, deeply embedded in distribution networks. Total capacity is around 10GW, producing 3-5% of electricity.
Biomass electricity generation	Strong application of small-scale plants and CHP around 15GW, 25% of energy).
Wave generation	Large application in relatively small developments. With tidal generation, total marine capacity is 10-15GW, accounting for 5-10% of electrical energy output.
CO_2 capture	No application in electricity generation. Significant role in hydrogen production.
Nuclear generation	No nuclear generation.
Microgeneration	Strong fuel cell deployment – total installed capacity around 10GW; micro-renewables are also important. Microgeneration supplies about 20% of electrical energy consumption.
Superconductivity	Application in constrained locations and onshore HVDC.
Power electronics	Very extensive application in a variety of roles.
Hydrogen	Strong use in transport and as domestic/industrial fuel. Mainly produced from fossil sources.
Energy storage	Significant application in large-scale storage systems and integrated with renewable generation; interaction likely with hydrogen system.
End-use technologies	Strong emphasis on efficiency and reduction in energy use, with some deployment of small distributed generation.
Industrial electricity use	Widespread adoption of advanced technologies to improve energy efficiency. Some fuel switching takes place to take advantage of renewably generated electricity and avoid carbon trading costs. Cogeneration, including the use of waste heat and waste products from industrial processes is integrated into the design of all new plants using turbine and advanced fuel cell technologies.
Transport	Increased use of electricity for rail transport; road transport mainly hydrogen-fuelled hybrid vehicles.
Smart metering	Strong application promotes awareness of the environmental consequences of electricity consumption and permits optimisation of electricity use to minimise emissions; commonly integrated into building control systems, but ‘standalone’ smart meters also exist.

Table 5: Technology application in the “Green Plus” scenario

10. Technological Restriction

10.1. Scenario Background

This scenario shares with the “Strong Optimism” scenario a sustained level of strong economic growth above recent levels. However, in this scenario, there is much less importance attached by investors, researchers and technologists to the creation and development of power generation, transmission, distribution and end-use technologies. Research funding and effort is instead channelled preferentially into other areas of innovation such as biotechnology or advanced computing and communications technology, where greater opportunities for innovation and returns on invested effort and money are perceived. Technological advance in energy systems is therefore mainly confined to the evolution of current technologies and the deployment of those currently in development.

Environmental consciousness strengthens somewhat in comparison to current levels, but not to the extent of the “Green Plus” scenario. As a result, resistance to the environmental impact of electricity networks continues to increase, so that construction of new transmission facilities becomes virtually impossible, and there is significant pressure for undergrounding of existing circuits at all levels of the network.

Strong economic growth leads to a corresponding increase in the demand for energy services, as people can afford to purchase new devices, and their performance expectations improve. Air conditioning of domestic properties becomes more common. This effect is offset to a degree by the increased application of energy efficiency measures, including improved building design the effect of which is supported by the relatively high turnover of building stock which the economy can support. Adoption of energy efficiency is motivated by a combination of economic and environmental factors.

The current liberalised regulatory arrangements remain in force, with the government committed to market-based approaches. However, as the difficulties and costs imposed by rising electricity demand, and increased renewable generation become clear, modifications are progressively made to the regulatory regime to encourage greater installation of small-scale generation and participation in demand-side control schemes. Liberalisation of electricity markets across Europe continues. However, technological constraints means that electricity interconnectors remain costly and development is thus limited, with more focus being placed on gas import. UK participation in European electricity markets is therefore restricted. There is strong development of European markets for emissions trading. Trading of CO2 extends to industrial and commercial users, with a moderate-to-high price for carbon.

As with the “Strong Optimism” scenario, there will be two main levels of electricity market develop in the UK. A series of local markets corresponding to microgrids and local networks with participation by small scale demand and generation. In addition to local energy markets, markets in energy services at the local level are likely to develop. To encourage adoption of small-scale generation and efficient use of the network, these markets may be encouraged by regulators to offer novel services such as portfolio management of domestic scale generation or real-time trading of network capacity entitlements. These local markets will underpin a single national market, in which large scale wind, marine, biomass and ‘conventional’ plants will participate, as will larger-scale consumers and the limited interconnector capacity. Much of the back-up generation capacity to support intermittent renewable sources is provided by participants in this market, although market mechanisms to encourage the use of small-scale generation and CHP for this purpose are progressively developed. Market structures develop to support a high level of renewables, but little storage.

Existing ownership patterns are likely to remain unchanged in relation to networks and large generators, but are likely to be paralleled by the development of energy service companies operating in the domestic/small energy demand market. Local ownership of microgrids and small-scale generation is likely to increase.

Small-scale CHP generation does not show strong development initially as a result of high initial costs. However, constraints on the electricity network as a result of rising demand and renewable penetration become increasingly costly to satisfy, and as it becomes clear that environmental aspirations cannot be satisfied through renewables due to disappointing technological progress, increasing incentives for the adoption of small scale generation and demand-side controls put in place. CHP remains natural-gas fired, with limited development of fuel-cell or hydrogen systems. The management of local networks therefore becomes appreciably more complex, with a trend towards more localised management and in some cases ownership of these networks. Local networks with strong concentrations of embedded generation and demand-side control will become increasingly autonomous and may become able to operate largely in isolation from the electricity network at large.

10.2. 2050 Electricity Network

Strong economic growth in this scenario leads to an increase in business and industrial activity. As described above, new and more capable devices are purchased, and people tend to be able to afford to use more energy to increase the comfort of their daily lives, leading to a corresponding increase in the demand for energy services. These factors are offset to a degree by the increased application of energy efficiency measures motivated by a combination of economic and environmental factors so that demand for electricity grows at an average rate of about 1.5%, within current geographic patterns to around 680TWh/year in 2050. Increased participation in demand-side control schemes tends to divert electricity use away from peak times so that variability of demand tends to reduce somewhat, but growth in the peak load value continues, remaining significantly above average load by 2050 at approximately 100GW.

Renewable generation accounts for approximately 40% of generation. Figure 6 illustrates the location of these renewable generators and other features likely to be important in the “Technological Restriction” scenario. Onshore wind takes the largest share of renewable generation at around 20% of the total. Individual wind farms of up to 1000MW are developed, although turbine sizes are restricted to around 15MW on grounds of technological capability and environmental impact. Offshore wind will remain restricted to relatively shallow-water sites, usually close to land, and will thus be restricted by environmental impact concerns to a few sites. Its economic potential is restricted as turbine sizes reach a plateau. In general, the deployment of intermittent renewable generation, such as wind, is restricted by concerns over the extent to which the transmission network can accommodate it. The risk of significant output constraints being placed upon new development weakens the economic case for their construction.

Biomass is the other major renewable energy source, with between 15% and 20% of total generation, mainly in the form of large combustion based plants in rural areas. Some small, community-focussed biomass generation will also be developed. The market penetration of biomass generation is restricted by the difficulty of producing and transporting biomass to the generation plant. Other renewable energy sources will account for a small proportion of the total generation. Marine and tidal energy will be confined to a few developments on the Scottish coastline, and will not be widely deployed, while photovoltaic technology will remain too costly for wide application.

The majority of generation will be in the form of large CCGT stations, accounting for between 40% and 50% of the total. This generation will be located at existing generation sites, with those preference being given to locations close to load centres. This generation will tend to be concentrated in the midlands and south-east to balance the exploitation of renewable energy resources in Scotland and the north. About 10% of the CCGT fleet in 2050 will be equipped for carbon capture and sequestration. These will be those of the more recently constructed units which are at conveniently locations for access to carbon storage facilities. In the early 21st century, nuclear generation technology remains expensive and continues to suffer difficulties with public acceptance, while the problems of long-term waste storage are not resolved. No new nuclear generation is built in this scenario: by 2050 all nuclear generation capacity has been eliminated.

The remaining 20% of generation will be accounted for by small CHP generation, although initial development is slow, because capital costs reduce only slowly. However, as the constraints on the electricity network brought about by rising demand become increasingly onerous and costly, and it becomes clear that disappointing technological progress means that environmental aspirations cannot be met by large-scale deployment of renewables or carbon capture, incentives and market modification are put in place to encourage greater investment in small-scale generation and CHP. Such plants will take the form of small natural gas fuelled turbines or Stirling Engines. Operationally, CHP will generally be run to meet heat demand, and many new urban development schemes will include larger CHP systems associated with district heating schemes operated by energy service providers. Some small-scale wind and biomass generation will also be connected to local electricity networks.

Existing interconnectors are refurbished and renewed as necessary, but the pace of technological change means that expansion of capacity is unattractive to investors. Thus, there is no large-scale extension of interconnector capacity. A relatively small-capacity to the Republic of Ireland is however developed with support from public bodies in order to better integrate Ireland into the European electricity market.

Demand for electricity transmission increases as a consequence of load growth, this effect being increased at times of year when there is strong availability of renewable energy in the north. At such times, full exploitation of these resources may be prevented by lack of transmission capacity. Transmission capacity will be maximised through extensive application of advanced control systems, in conjunction with strategic deployment of power electronic FACTS-like devices. Some strategic transmission routes may be converted to HVDC in order to increase capacity without unacceptable environmental impact. The geographical location of new generators becomes considerably more important in controlling demands made on the network.

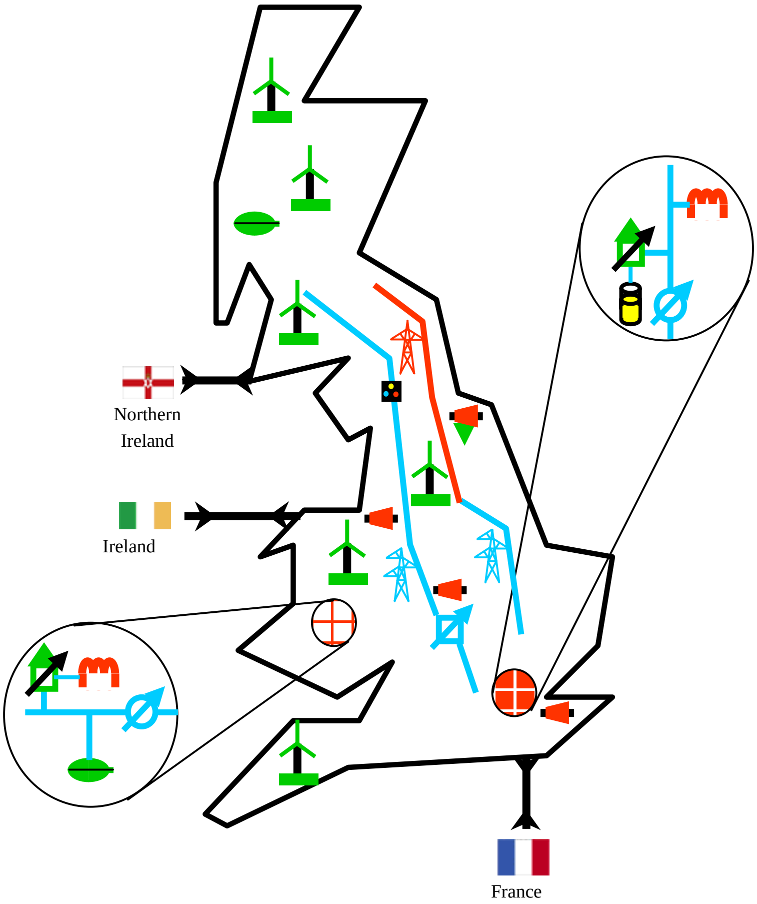

Figure 6: “Technological Restriction” Scenario: Electricity Network in 2050

Superconductors may be deployed in one or two key instances where increased density of power flow in a constrained space is necessary – for example in central London, but will remain too expensive and technically complex for more general application.

There will be increased concern over the potential environmental impact of leaks from oil filled plant, together with the risk of safety hazards. These issues will be applicable at all levels of the power network, but will be particularly acute at transmission level. While there will be some replacement of this plant with oil-free equipment at lower voltages, technical and cost issues will prevent such substitution at the transmission level. Comprehensive condition monitoring systems will therefore be developed and applied to transmission transformers and other large oil-filled equipment in order to detect developing problems.

Energy storage systems will be restricted to devices aimed at improving power quality for specific sensitive customers; any increased requirement for large strategic systems will be met by intelligent generation dispatch systems incorporating reserve management capabilities and demand-side control schemes.

Microgrids will be relatively widely applied, but will use relatively simple devices and control systems. A combination of generation dispatch and local demand side control schemes will attempt to ensure approximate system balance, but as local energy storage systems will be technically complex and to expensive for general application, there will be significant import and export of energy from the microgrid to the national network depending on local loading conditions.

Regulatory policy remains liberalised and market-based, but modifications are progressively made to permit network operators to exert greater control by sending much stronger market signals to electricity generators and consumers in respect of both their location and their day-to-day behaviour. As a result, participation in demand side control schemes is strongly encouraged. There is increasing liberalisation of European markets and regulation along similar lines to the UK, which results in the development of markets in energy and services spanning multiple countries. However, the limited ability to import and export electricity restricts the ability of the UK to participate in these markets. However, there is strong participation in a single European market in CO_2 emissions.

Within the UK, a series of linked local and national markets will co-ordinate the activities of individual customers and generators, local networks and the national transmission network. As with the "Strong Optimism" scenario, there will be two main levels of electricity market. A series of local markets corresponding to microgrid and local networks with participation by small scale demand and generation will underpin a single national market, in which large scale renewables and 'conventional' plants will participate, as will larger-scale consumers and the limited interconnector capacity. Much of the back-up generation capacity to support intermittent renewable sources is provided by participants in this market, although market mechanisms to encourage the use of small-scale generation and CHP for this purpose are progressively developed.

10.3. Scenario Summary

The "Technological Restriction" scenario represents a case in which strong economic growth and growth in the demand for electricity is not matched by strong technological progress. Restrictions in the flexibility and capability of the power network impose significant constraints on the nature and location of generators. Renewable generation technologies are deployed in relatively large absolute volumes, but make up a comparatively small proportion of overall capacity, and use relatively simple technology; other technologies are adopted in order to manage the pressure of increased demand on a technologically relatively electricity network. Market mechanisms are also important in this regard. The influence in 2050 of each of the technologies mentioned in the introduction is summarised in Table 6. For each of the generation technologies listed, the table gives the expected installed generation capacity, and the proportion of annual electrical energy demand supplied by that technology.

Technology	Scope of application
Wind generation	Mainly restricted to onshore wind; large in absolute but not relative terms. Installed capacity around 45-50GW, accounting for 20% of electrical energy generated.
Photovoltaic generation	Little application because of high cost
Biomass electricity generation	Tends to appear as relatively large-scale plants. Moderate contribution to electricity supply, accounting for 15-20% of electrical energy produced. Installed capacity is around 20GW.
Wave generation	Applied in a few niche opportunities. Installed capacity is around 3GW, producing 1-2% of total electrical energy.
CO2 capture	Around 5GW of newest CCGT capacity equipped by 2050.
Nuclear generation	No nuclear generation.
Microgeneration	Becomes more important later in scenario; gas-fired using developments of current technology. By 2050, installed capacity is around 20GW, supplying 20% of electrical energy consumption.
Superconductivity	Very limited network application in a few constrained locations
Power electronics	Applications include advanced network control and compensation systems, renewal or refurbishment of interconnectors and HVDC; also some application in microgrids.
Hydrogen	Little influence on electricity network.
Energy storage	Confined to small-scale systems focussing on power quality improvement.
End use technologies	Energy efficiency develops progressively; distributed generation and community heating schemes develop later.
Industrial electricity use	Improvements in energy efficiency tend to make use of incremental developments of existing technologies; more radical technologies are expensive or present reliability problems. Small-scale generation and cogeneration develops first in industry using turbine and reciprocating engine technology, achieving significant penetration as a means to improve energy efficiency.
Transport	Some increase in rail electrification, but otherwise little influence on electricity network; fossil-fuelled hybrid road vehicles increase in popularity.
Smart metering	Regional application in support of market and tariff schemes reflecting network congestion; automated management of selected devices to reduce consumption when costs are high.

Table 6: Technology application in the “Technological Restriction” scenario

11. Central Direction

11.1. Scenario Background

This scenario takes the replacement of current liberal regulatory attitudes with a more prescriptive approach by central government as its focus. A strongly centralising approach is one possible outcome of an increased level of governmental involvement and intervention in the electricity industry. Other possibilities might include a more regional or local model in which government bodies at those level exercise strong directive control over the industry, or a mixed approach in which different aspects of the industry (such as the exploitation of renewable energy resources, or the planning and regulation of transmission and distribution networks, for example) are controlled at different levels of decentralisation.

The centralised approach presented here has been selected for particular examination since it might be plausibly be presented as an approach which reflects the importance of the electricity system to the UK as a whole, and which would be expected to lead to improved planning processes to give better allocation and deployment of available energy resources and network capabilities in the national interest.

Pressure for more prescriptive government involvement and control may arise as a result of perceived inadequate responses of the liberalised industry to major events or apparently inefficient use of resources, and could be compared to current government attitudes towards the railway industry. Notwithstanding the effects of the triggering events, general economic growth continues at broadly the same rate as in the recent past, and the economy remains liberalised; there is no move towards increased government control over industry in general. As a result, growing personal wealth and industrial activity tends to drive up the demand for energy consuming appliances and energy services. This trend is counteracted by energy efficiency initiatives promoted by government incentives and regulations. Electricity demand therefore increases by a small amount.

Technologically, government policy is to focus on relatively low risk, well-proven technologies, rather than highly innovative strategies. As a result, technical development of is power network equipment is focussed on the evolution of existing technologies and the application of those in development.

Environmental awareness sharpens somewhat in comparison to the current situation and is reflected in government actions. Public acceptance of the environmental impact of electricity networks continues to decline, with corresponding changes in government policy. There is therefore a tendency to invest in higher capacity technology when refurbishing existing facilities and to require undergrounding of existing circuits in environmentally sensitive areas. Government direction is used to concentrate circuits into a smaller number of corridors. The geographical location of new generation becomes increasingly important in managing constraints on the network and becomes the subject of strong government direction in order to balance the direct environmental impact of new generation against its effects on the network.

In addition to directing the development of the electricity network, the government exercises considerable influence and control over the UK's generation mix, and over the technical standards required of generators. Rather than approving or rejecting proposals for new generators which are created and put forward by investors and generating companies, tenders are invited for the construction, operation and ownership of generators of particular types in general geographical locations. Where such a requirement is commercially unattractive, financial support for capital or running costs may be offered. Such schemes may be coupled to initiatives in other areas, such as agricultural incentives promote the farming of biomass feedstocks. The preference of the government is generally for a smaller number of projects at a larger scale. Embedded generation is encouraged through other approaches. CHP at medium scale develops strongly as part of district heating schemes for new office and housing build, driven by planning requirements.

Strong regulation of local electricity networks is a feature of this scenario, with operators being obliged to meet strict quality of supply measures. There are also be targets in relation to the connection of embedded generators to these networks. However, such generators will be regulated so as not to give rise to serious problems of network management since the government will wish to favour simple and well-established approaches, which may include requiring some measure of compulsory participation in demand-side control initiatives. Overall, there will be little scope for increased local network autonomy.

While energy markets continue to exist, they become subject to greatly increased government intervention in both their structure and in the behaviour of participants. As government focus is likely to be on simple and robust solutions which reliably deliver expected outcomes, there will be a simplification of market structures, with a series of markets focused on single commodities or services. Participants in these markets will be subject to compulsory licensing, and behaviour will be closely scrutinised by regulators. Certain participants in some markets may be obliged to also participate in others – for example operators of some generators in an energy market may be obliged to offer balancing services. Companies encountering financial difficulty exchange government financial support for an increased measure of government control.

There is increased EU and bilateral governmental intervention in cross-border European energy transport and trading. There is some government-supported investment in interconnector capacity, but political uncertainty over long-term prospects means that focus is primarily given to gas interconnectors; electricity interconnectors tend to be the subject of EU-supported development. Markets for emissions trading tend to be replaced by prescriptive limits imposed by national governments to meet EU requirements, operating on per-plant and per-company bases.

Changes to market structures favour concentration of ownership into a small number of vertically-integrated companies, each having a diverse portfolio of assets in order to minimise market and regulatory risk. Emerging companies specialising in particular technologies and activities are likely to be short-lived and will either fail or be absorbed into large organisations.

11.2. *2050 Electricity Network*

In this scenario, economic growth tends to cause an increase in the demand for energy services. However, effective energy efficiency incentives and regulations, mean that growth in demand for electricity is more restricted, and averages around 0.5% annually over the scenario period to approximately 430TWh in 2050, mostly within current geographical patterns. Demand-side control schemes do not attract general favour, while CHP tends to operate to meet heat load; thus, variability of electricity demand is largely unchanged. Peak load is approximately 70GW.

In this scenario, renewable generation rises to between 50% and 60% of total generation, and is divided equally between onshore wind, offshore wind, biomass and marine generation. The geographical areas of application of these forms of generation are decided centrally by the government and are illustrated in Figure 7. Offshore wind is mainly located in relatively shallow water in the Irish Sea and off East Anglia. Large developments of between 500MW and 1000MW are favoured with machine size progressively increasing to around 30MW. There is strong development of onshore wind resources in Scotland, together with sites in central Wales. Individual wind farms of around 300MW are preferred, with machines restricted to about 15MW on grounds of environmental impact.

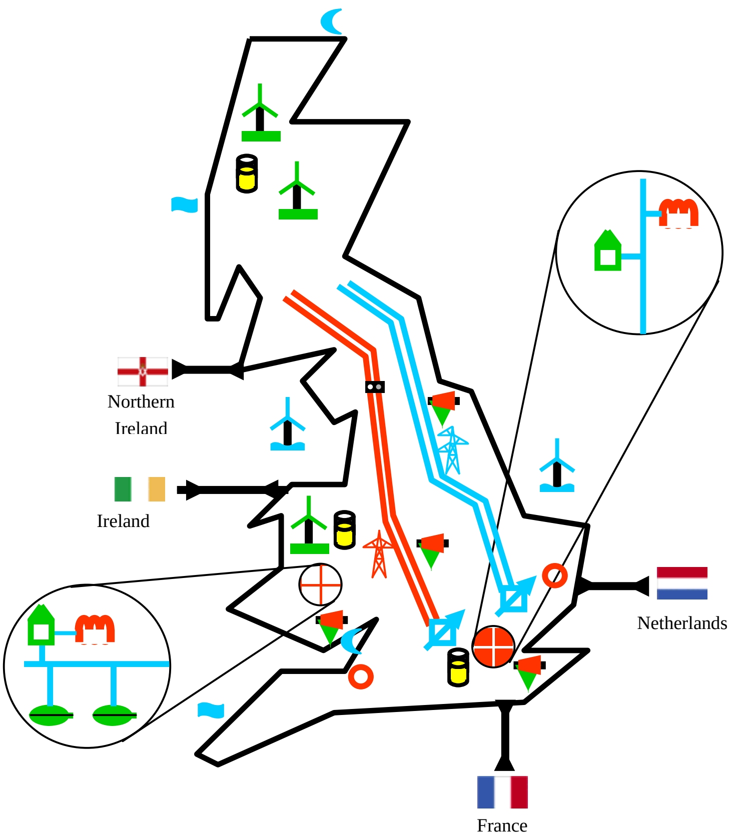

Figure 7: "Central Direction" Scenario: Electricity Network in 2050

Biomass generation is located in rural areas in which the growth of energy crops in encouraged by agriculture policy. In order to limit problems related to transport of biomass, preference is given to small-to-medium scale plants. Initially, combustion-based generation will be preferred, possibly co-firing with fossil fuel. As technology develops most plants operating in 2050 will make use of gasification processes feeding combined-cycle turbines.

Wave generation will be deployed extensively along the west coast of Scotland, in the Western Isles and in south west England. Policy will favour the use of large numbers of small generation systems in preference to expensive and more technically adventurous large units. Tidal generation developments will be located in the Bristol Channel and the Pentland Firth. Other forms of renewable generation are not favoured by government policy on grounds of perceived value for money or technical risk and do not see significant application.

Large central power plants will account for 25-30% of generation. Most of these power plants will take the form of large CCGT generators, which will be required to participate in government sponsored carbon capture and sequestration schemes. Construction of carbon transportation and storage infrastructure will be facilitated by government in harmony with planned generation development, which will in general be located close to major load centres and in areas in which renewable resources are not strongly developed. As new nuclear technologies mature, there is increased interest in the construction of nuclear power stations and a small number of new facilities, promoted on grounds of energy security, are constructed on existing sites, beginning as the last of the current fleet is decommissioned. The remaining 10-20% of generation is composed of CHP systems, as described further below.

Existing interconnectors to mainland Europe will be retained and increased in capacity as renewal is required. A second European interconnector of similar capacity will be constructed to permit increased participation in European energy markets and to gain additional energy security benefits from increased access to a greater diversity of generation. An interconnector of modest capacity to the Republic of Ireland will extent these energy security benefits to that country. Long interconnectors to Iceland and Scandinavia will be eschewed as a result of the technical risk associated with their length and depth.

The result of these changes in the level of demand and the pattern of generation is that there is strongly increased demand for transmission of electricity. Government preference is for this challenge to be met using mature, low-risk technological solutions. Therefore, transmission capacity along existing corridors is increased by the construction of new transmission assets. There may be some rationalisation of transmission corridors in cases of particular environmental impact, but movement in this direction is likely to be very limited as a result of risk-averse attitudes to system security. Undergrounding of sensitive sections of route is regarded as a more appropriate response in most cases.

Large-scale strategic energy storage systems using pumped storage, electrolytic or hydrogen technology according to local conditions will be used to alleviate peak transmission loads, and to enhance system security in conjunction with advanced control and compensation equipment installed at a significant number of substations. With the exception of a few power quality-driven small-scale installations, this is the only application of energy storage technology.

In a few cases, complete transmission routes will be converted to HVDC in order to maximise capacity and to eliminate otherwise unavoidable constraints on the operation of the system.

Superconductors will be used in specific cases where space constraints require particularly high energy transmission densities. However, concerns over their long-term reliability and cost constraints prevent their wider application; installation of addition conventional transmission assets is felt to be a more robust solution.

As noted above, CHP will account for between 10% and 20% of total generation. Planning regulations will require that new commercial and residential developments above a stipulated size in urban areas must either include integrated CHP – which will be relatively large – or participate in a district heating scheme. Smaller developments and those in rural areas will feature domestic-scale CHP systems. There will be modest support for retrofitting such systems to existing properties. Most of these CHP systems are likely to be natural gas fuelled turbine or Stirling Engine units; by 2050 general adoption of fuel cell technology will have begun, but the vast majority of the CHP fleet will use a development of current technology and will be operated to meet heat demand. Many small biomass generators will also connect to local electricity networks.

Microgrid technology will not see widespread deployment, as the government will place strong emphasis on the benefits of an integrated national electricity network. Microgrid deployment will therefore be restricted to ‘power parks’ associated with technology-based companies having particular power quality requirements.

Demand side control schemes will develop in a relatively small number of cases where local demands rapidly outstrips the capacity of the distribution network. However, the preferred approach in such cases will be limited network reinforcement in combination with more generalised incentives to reduce consumption. Plant recovered from network reinforcement schemes will be deployed elsewhere, either to replace life-expired equipment or to provide further reinforcement.

Government policies on social inclusion and fuel poverty are supported by novel energy pricing strategies and tariffs, facilitated by advanced metering. Such tariffs feature automated management of ‘essential services’ such as space and water heating; these benefits are available to all at a reduced cost in exchange for a reduction in energy use at peak times. Smart meters also provide improved information to support responsible use of energy for other purposes and in other pricing plans. Metering becomes a nationally regulated monopoly.

Extension of railway electrification is promoted by the government to achieve environmental benefits and improved quality of service. However, while main routes benefit, cost constraints preclude universal electrification. The effect on the electricity system is in any case relatively small. Increasingly stringent emissions regulations for road vehicles are addressed by the development of more efficient and flexible fossil-fuelled hybrid vehicles.

11.3. Scenario Summary

The “Central Direction” scenario represents a case in which central government imposes a strongly interventionist regulatory regime on the electricity industry. A mix of generator types, in which renewables are strongly represented, is deployed with generation technologies being concentrated in specific geographical areas. Network reinforcement, careful siting of generation and large strategic energy storage systems are the preferred approached to accommodating the increasing demands on the electricity network. The influence in 2050 of each of the technologies mentioned in this introduction is summarised in Table 7. For each of the generation technologies listed, the table gives the expected installed generation capacity, and the proportion of annual electrical energy demand supplied by that technology.

Technology	**Scope of application**
Wind generation	Strong application. Total wind generation capacity is 35-40GW, equally divided between onshore and offshore, and supplying 25% of electrical energy generated.
Photovoltaic generation	Not favoured by government policy: very little development.
Biomass electricity generation	Many small-to-medium sized facilities plus small CHP. Total capacity is around 8GW accounting for 10-15% of electrical energy produced.
Wave generation	Strong application in many relatively small developments. Including tidal generation, total installed capacity is around 15GW, meeting 10-15% of electrical energy demand.
CO_2 capture	Applied to all new CCGT plant (around 15GW, 20-15% of energy)
Nuclear generation	A small number of power plants, using new technology if feasible. Installed capacity is approximately 5GW, accounting for 5-10% of electricity produced.
Microgeneration	Applied for rural CHP and small or retrofit developments. Most CHP in the form of large multi-user systems. Total microgeneration capacity is around 10-15GW, and supplies 10-20% of electricity demand
Superconductivity	Little application: seen as poor long-term value in network applications.
Power electronics	Applications include advanced network control and compensation systems, interconnector upgrading and microgeneration. Little application in microgrids.
Hydrogen	Primary application is energy storage.
Energy storage	A few large strategic hydrogen and pumped storage facilities are built. Little small-scale storage.
End use technologies	Energy efficiency promoted by government; distributed generation and community heating schemes encouraged by planning regulations.
Industrial energy use	Government and European incentives and regulations promote the adoption of technological measures to increase efficiency. Planning and economic incentives to integrate cogeneration with wider community heating schemes where possible.
Transport	Some increase in rail electrification, but otherwise little influence on electricity network; fossil-fuelled hybrid road vehicles promoted by government.
Smart metering	Strong application in support of policies on fuel poverty and responsible energy use. Metering activities undertaken by regulated monopoly.

Table 7: Technology application in the “Central Direction” scenario

12. Conclusions

The development of the electricity network in Great Britain over the years to 2050 will be influenced by a number of uncertain factors. Some of these factors are economic in character, such as the rate of growth or reduction in demand for electricity, or the availability of finance for investment in electricity infrastructure. Others, such as the system of regulation or the level of environmental consciousness in society, are of a more political nature. A third group of influences is technological – the rate at which the technologies mentioned in this paper are developed and applied.

This paper has presented six scenarios of possible future electricity systems which may develop in Britain in the years to 2050. The main features of each are presented in Tables 8 and 9:

Scenario	Average annual demand growth[1]	2050 Electricity Demand (TWh)[2]	2050 Peak Electricity Demand (GW)[3]	Important network technologies
Strong Optimism	+1.25%	600	80	Advanced control and FACTS Energy storage Superconducting transmission Microgrids
Business as Usual	+1%	540	80	Advanced control and FACTS Strategic energy storage Asset management
Economic Downturn	-0.5%	275	45	Remote control of local networks Life extension Condition monitoring
Green Plus	+0.25%	390	50	Interconnectors and offshore HVDC Network control and compensation systems Large and small scale energy storage Microgrids Demand-side participation
Technological Restriction	+1.5%	680	100	Advanced control and FACTS HVDC Simple microgrids Condition monitoring
Central Direction	+0.5%	430	70	Large-scale energy storage HVDC Network control and compensation systems Demand-side participation

Table 8: Summary of electricity consumption and network technologies

[1] 2005 trajectory is approximately +1.5% (National Grid GB Seven Year Statement 2005)
[2] 2004/2005 value is approximately 355TWh (National Grid GB Seven Year Statement 2005)
[3] 2005 value is approximately 60GW (National Grid GB Seven Year Statement 2005)

Scenario	Total Generation Capacity (GW)	Renewable generation (% of Total Capacity)	Renewable generation (% of Total Energy)	Central generation (% of Total Capacity)	Central generation (% of Total Energy)
Current Situation	74[1]	7%	4%[2]	84%	10%
Strong Optimism	145	60-70%	50%	10-20%	10-20%
Business as Usual	110	40-50%	30%	45%	50%
Economic Downturn	55	20-30%	10-20%	65%	75%
Green Plus	110	90%	80%	0%	0%
Technological Restriction	135	50-60%	40%	30%	40-50%
Central Direction	100	60%	50-60%	20-25%	25-30%

Table 9: Summary of electricity generation in each scenario

While these scenarios might not appear to be particularly radical or adventurous, many of them nonetheless represent a significant but plausible shift away from current network structures and practices. Given the long life and relatively high cost of electricity network plant, particularly at transmission level, it is likely that considerable and sustained effort may be required over the coming decades for electricity networks to meet some of the possible challenges of the twenty-first century. The technologies discussed in this book will have an important role to play in these changes.

13. REFERENCES

As noted previously, a large number of information sources have been consulted in the preparation of the scenarios described in this paper. While they are not individually referenced in the text, this section lists the principal documents which have contributed to the development of the scenarios.

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