# Future Network Technologies

## *Report to DTI*

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# 1. Executive Summary

### *Scope of work*

1.1. The overall aims of this work are to review the key characteristics and limitations of the existing network operation and design philosophies and examine possible future developments of electricity transmission and distribution network technology in the context of alternative (extreme) electricity generation scenarios in the medium and long term. This work also includes quantitative analysis of benefits and costs of the integration of distributed generation in the operation and development of the future UK electricity system.

### *Key findings and recommendations*

1.2. **Limitations of transmission and distribution network technology will not prevent the UK energy goals being met**. However, future developments in the network technology could contribute to further improving the efficiency of future system operation and investment. Improvements in grid technology could facilitate the implementation of a range of alternative future electricity system developments, from centralised to distributed, by reducing the system operation and investment cost. Application of advanced network technologies will help the grid to flexibly adapt to alternative future developments of electricity generation systems.

1.3. The security, environmental and economic performance need to be examined for both the present system based as it is on large scale generation and an **integrated energy system** supplied by distributed medium and small size **CHP**, together with various forms of **renewables** generation. **Making use of rejected heat from medium and/or small size CHP** to supply space and water heating demand could become attractive given **very high energy prices and the need to reduce fossil fuel consumption**[1]. It is not clear if the present regulatory and energy market framework would provide sufficient incentives for an integrated energy system to be developed, even if this was shown to be efficient.

1.4. In the **short to medium term** it will be critical to ensure that adequate **transmission capacity** is made available to **integrate on-shore and off-shore wind generation**. The determination of the required network capacity and delivering it in a cost effective manner will be major challenges. Government should support the development of **new standards** for the electricity transmission network **design** and changes in the present **network**

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[1] Heat that is provided by CHP can be used in heat-to-cool process for air-conditioning and refrigerating.

**access** and **network pricing**[2] arrangements to reflect the effects of variable renewable generation.

1.5. In the **longer term**, **technology that enhances the flexibility of future networks will be important** for keeping open the options for future development. Real-time network analysis and control (and more broadly a move from preventive to corrective control) are widely indicated as key technologies for all scenarios. Network technologies such as Flexible AC Transmission or demand side management and storage could help with relieving power transfer problems and congestion, deferring new network investment, reducing system operation cost and increasing the amount of on- and off-shore wind generation and other plant that can be accommodated in the existing grid infrastructure. The Government should support OFGEM in their efforts to expand on the existing Innovation Funding Initiatives (IFIs) developed for distribution network operators to also incentivise transmission operators to engage in RD&D.

1.6. Our analysis shows that **demand side participation** in particular has the potential to make a significant contribution **in all futures**, although the magnitude of the benefits and costs is yet to be quantified.

1.7. At the electricity distribution level, it is important to ensure the existing distribution system is maintained and replaced at the appropriate rate. Although this is obviously a key responsibility of OFGEM, determination of appropriate rates of replacement is not straightforward, as evidenced by the differing replacement policies adopted by the various Distribution Network Operators. Further work should be commissioned to determine the state of distribution network assets and **if like-for-like replacement** is the best option. Particular attention should be paid to the staff and skills required for replacement programmes. The Government should **support RD&D on distribution systems including OFGEM's IFI and RPZ initiatives**. This initiative needs stability over at least two Distribution Price Controls as the DNOs rebuild their RD&D capacity. Furthermore, research into the integration of various forms of distributed generation including micro-generation with the distribution network should be supported.

### *Overview of the report*

1.8. In Section 2 of this report we describe the key features of the existing UK power system and provide some fundamental statistics associated with its major segments; Section 3 identifies and discusses drivers for change. Section 4 provides an analysis of the future development of the UK electricity network in the medium term to long term, based on the present system dominated by large conventional power plant, with contributions from

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[2] Present planning standards are developed for conventional plant. This is important as variable wind generation will impose different demand for transmission capacity and hence network access and pricing arrangements should be reviewed.

large renewbales (wind), micro-generation and MW size distributed generation; Section 5 discusses the operation of an integrated energy system based on CHP an other forms of small scale renewables; Sections 6 gives a review the developments in transmission and distribution technology and discuss its role in further improving the efficiency of operation and development of the electricity system; Our recommendations for Government actions are presented in Section 8.

1.9. The **traditional electricity system** has four main sectors: generation, bulk transmission, distribution and consumption. The key characteristics of these are:

- Relatively **low generation capacity utilisation levels (about 55%),** as generation must be sufficient to meet peak demand, given that demand is uncontrollable and power curtailments are unacceptable. In the process of generating electricity, **significant amount of heat energy** is produced that **is wasted**. The overall thermal efficiency of modern type gas fired technologies (CCGT) is approaching 60%, while the coal based generation operates at less than 35%. An alternative policy, adopted by some European countries has been to build smaller power stations nearer to load centres and use these to supply both electricity and heat to consumers (such as district heating) which allows greater use of the available heat and achieves overall efficiency for the supply of heat and electricity loads together of around 80% of the fuel burnt.

- **Transmission networks** are designed with **planned redundancy** in capacity to allow the network to continue to operate after outages of circuits. Due to these network security related considerations circuits in the interconnected transmission network are generally **loaded below 50%**.

- Three characteristics of the transmission network will define its performance and associated operating costs: (i) **levels of congestion** (ii) **losses** and (iii) **interruptions** caused by outages of transmission circuits. The GB transmission network is characterised by significant north-south power flows as there is more generation in the north and more load in the south. In order to keep the north-south power flow within permissible limits it may be occasionally required that northern generators with lower marginal costs are constrained off, and southern generators with higher marginal costs are constrained-on[3], which increases the cost of operation. **At present these transmission congestion costs are relatively small**, but an increase in generation capacity in the north and a reduction in generation capacity in the south would increase these costs. Costs of congestion are managed in the long run by appropriate investment in network capacity. Annual **energy losses in the GB transmission system**

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[3] Flows on the transmission network are primarily controlled by modifying outputs of generators.

**are below 2%.** In the very large majority of cases, faults on the transmission network causing outages of circuits, do not go on to cause interruptions to end customers. Although low in probability such interruptions, when they occur, could have a very high impact.

- **The performance of distribution networks has a dominant effect on the overall quality of service seen by end customers**. The vast majority of interruptions (about **90%**) have their cause in lowest two voltage levels: 11kV and 400V. **Annual losses in distribution networks in the UK are about 7%**. The control of distribution networks is resolved at the planning stage and no real time control is used beyond network reconfiguration.

- **Demand is largely uncontrollable** and varies with time of day and season. A key feature of demand is the diversity in usage of appliances. The capacity of an electricity system supplying several thousand households would be only about 10% of the total capacity that would be required if each individual household were to be self sufficient (individually supplied by its own generation). Hence, **balancing demand and supply at the household level is clearly inefficient**.

1.10. Four key drivers for change have been identified:

- **Aging assets** and the need to develop an alternative asset replacement strategy because a like-with-like replacement is unlikely to be optimal

- Connection of new forms of generation in response to the **climate change challenge and security of supply concerns**.

- New developments in **information and communication technologies** that can be used to improve efficiency of system operation and development and facilitate development of a more distributed system

- Developments in **transmission and distribution plant technologies** to increase efficiency of network operation and investment

1.11. Major issues associated with the operation and development of two different supply systems are analysed: (i) one dominated by a relatively small number of large conventional generators with modest contributions from large scale renewable generation and other distributed generation technologies and (ii) a fundamentally different integrated energy system, supplied by a large number of small and medium scale distributed generation technologies, primarily CHP, with a significant contribution for various forms of renewables and an absence of large scale central generation.

1.12. For system (i) we focused on the questions of integration of various forms of new generation technologies into this system, including: (a) onshore and offshore wind, (b) micro-generation and (c) MW size distributed generation.

Two major components of system costs and benefits are analysed: first, impact of new generation on the operation and development of the conventional generation system and second, the impact of new generation technologies on the operation and development of transmission and distribution networks.

1.13. We point out that the disproportion between capacity and energy that is displaced by a new generation technology (wind, nuclear, domestic CHP, PV, etc) as it penetrates into an incumbent generation system is the key cause of the additional system costs associated with development of that new technology. We quantified the additional (generation capacity related) cost of integrating wind to be in the range of 6-10£/MWh, for nuclear about 5£/MWh, for PV 14£/MWh while domestic CHP could create benefit to the system of about 20£/MWh.

1.14. Regarding the impact on the transmission network, we single out the question of integration of wind power because the provision of an adequate transmission infrastructure will be critically important if the massive onshore and offshore wind resources (and other marine renewables) in the UK are to be exploited. We point out that this will require development of new standards for electricity transmission network design and will require changes in the present network access and pricing arrangements, if variable renewables are not be disadvantaged.

1.15. Using our UK generic distribution network model, we estimated the benefits of domestic CHP (DCHP) in terms of network losses and investment costs. The analysis revealed that some 25%-45% reduction in losses could be achieved in areas with high density of this generation, which is very significant (in case of PV this could be in the order 15%-25%). Furthermore, additional value of about 100£/kW can be attributed to DCHP due to savings on distribution network reinforcement. However, these system-related benefits (savings in generation and network operation and investment costs) created by micro-generation cannot be captured within the current pricing regime. The lack of recognition of this benefit adversely impacts the competitiveness of micro-generation.

1.16. We have also examined the potential benefits of applying active distribution management techniques in accommodating increased amounts of MW size distributed generation within 11kV networks. The analysis shows that the application of active management techniques in rural networks could reduce the cost of network reinforcement from about £50-60/kW to about £20/kW. These benefits will be lower in case of low density and low volume of generation. Similarly, savings from actively managing fault levels in urban networks could be very significant, up to £100/kW, due to avoided replacement of switchgear. Our studies also show that, in general, active management in 33kV networks would be less beneficial.

1.17. It is important to recognise that the present UK generation portfolio creates a significant amount of heat that is wasted. Hence, we have discussed the design and operation of an alternative integrated energy system, scenario (ii), supplied by distributed medium and small size CHP together with various forms of renewable generation. Making use of rejected heat via medium and/or small size CHP, to supply space and water heating demand, could become very attractive given high energy prices and the urgency to reduce carbon emissions.

1.18. We have discussed the role of electricity and heat networks and the need for a design approach that takes into account both heat and electricity demand and characteristics of generation systems. Application of storage and demand response in managing the balance of demand and supply of both heat and electricity is also discussed.

1.19. Our conclusion is that comprehensive assessments of alternative supply systems would be required to establish their costs and benefits. Furthermore, it is not clear if the present regulatory and energy market framework can provide sufficient incentives for an integrated energy system to be developed.

1.20. In section 6 we review the developments in transmission and distribution technology and discuss its role in improving the efficiency of operation and development of the electricity system. In section 7 we have proposed a set of recommendations for the government to consider as potential actions.

## 2. Key features of the present system

2.1. Figure 2.1 shows a schematic diagram of the structure of the traditional electricity system with its four main sectors: generation, bulk transmission, distribution and consumption.

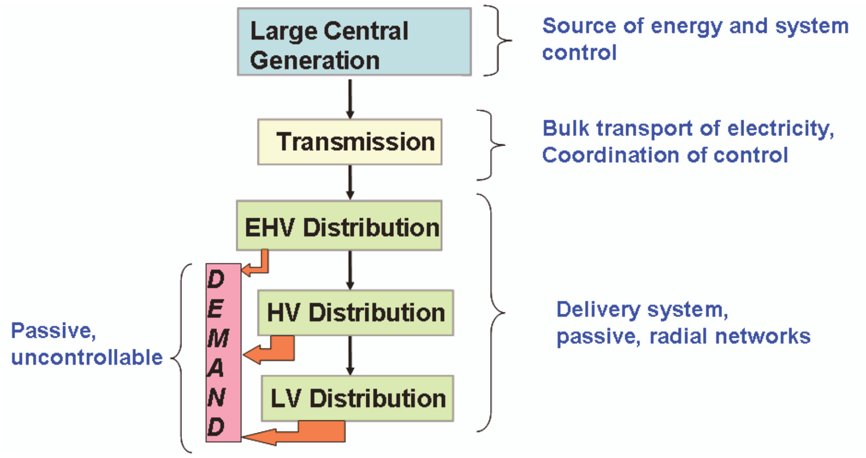

*Figure 2.1*: Schematic diagram of the power system with four main power sectors: generation, bulk transmission, distribution and consumption.

2.2. In common with most industrialised countries, the UK system has been design to support the post world war II economic growth and the development in generation technology. The system is characterised by small numbers of very large generators, mainly coal, oil, hydro and nuclear, and more recently gas based generation. Typical power station ratings would be from a few hundred MWs to a couple of thousand of MWs. These stations are connected to a very high voltage transmission network (operating at 275 and 400 kV). The structure of the electricity transmission and distribution networks was driven by an overall design philosophy developed to support large-scale generation technologies[4]. Networks are predominantly overhead while underground cable networks are used in urban areas.

2.3. The role of the transmission system is to provide bulk transport of electricity from these large stations to demands centres, cities. The electricity is then taken over by the distribution networks that, through a number of voltage transformations (typically Extra High Voltage (132kV, 33kV), High Voltage

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[4] It is important to stress that the key function of a network is to provide secure and efficient transport of electricity from generation (production) to demand (consumption). Hence, the position of generation relative to demand and the amount of power to be transported, are the key factors driving the design and operation of electricity networks.

(11kV)) and Low Voltage (400/230V) provide the final delivery of electricity to consumers. The flow is unidirectional from higher to lower voltage levels.

## Key features of the present generation system

### *Generation capacity and plant utilisation*

2.4. In order to supply demand that varies daily and seasonally, and given that demand in uncontrollable and interruptions very costly, installed generation capacity must be able to meet maximum (peak) demand[5]. In addition, there needs to be sufficient capacity available to deal with the uncertainty in generation availability and unpredicted demand increases. Historically, a capacity margin of around 20% was considered to be sufficient to provide adequate generation security. Given the average demand across the year, the average utilisation of the generation capacity is below 55%[6]. This relatively low average plant utilisation opens a significant scope for demand side management as shifting load from peak to off-peak periods would reduce the need for generation capacity and increase the utilisation of generating plant and hence increase the efficiency of generation investment.

### *Fuel efficiency*

2.5. The UK generation system is dominated by large size fossil fuel generation. In the process of generating electricity, a significant amount of heat energy is produced that is wasted. The overall thermal efficiency of modern gas fired technologies (CCGT) is approaching 60%, while the coal based generation operates at less than 35% efficiency[7].

2.6. An alternative policy, adopted by some European countries, notably Sweden, Denmark and Germany, has been to build smaller power stations nearer to load centres and use these to supply both electricity and heat to the consumers. Such schemes are less efficient from the point of biew of the production of electricity only, but the overall efficiency considering both useful heat and electricity outputs is around 80% of the fuel burnt.

### *Role of generation in balancing demand and supply*

2.7. One of the key distinguishing features of the electricity system is that the balance between demand and supply must be maintained at all times. Given that the demand is not controllable (or not responsive), the only source of control is the generation system. Any changes in demand are met by almost instantaneous changes in generation.

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[5] In the UK peak demand hours occur in evenings of winter working days usually in December or January.

[6] There is a significant spread in utilisation among different generators. The lowest marginal cost plant would operate at abut 85% load factor (e.g. CCGT), while plant with high fuel cost (e.g. old OCGT) would operate only a few hours per year.

[7] The UK electrical output in 2003 was some 398.8 TWh, and fuel inputs totalled 1,031.1 TWh—thus no less than 632.3 TWh of energy were lost, largely in the form of heat dispersed via cooling towers (House of Lords Select Committee on Science and Technology, Second Report 2005)

2.8. In order to deal with unpredicted changes in demand and generation availabilities, various forms of generation reserve services are made available to ensure that demand and supply can be matched on a second by second basis. Inability to satisfactorily control demand-supply balance would potentially lead to black outs. Interruptions of electricity services caused by insufficient generation to meet demand have historically been extremely rare.

2.9. Overall contribution of generation (and supply) cost in the final electricity bill received by domestic customers is above 60%.

## Key features of the transmission system

### *Network design and performance characteristics*

2.10. Historically, the design and structure of electricity transmission (and distribution) networks was driven by an overall design philosophy developed to support large-scale generation technologies. Design in accordance with the GB Security and Quality Supply Standards that specify minimum requirements for transmission capacity, taking into account both network security and economics. The network must be able to continue to function after a loss of a single circuit (or a double circuit on the same tower). After a loss of a circuit due to fault (e.g. lightning strike) the remaining circuits that take over the load of the faulty line, must not become overloaded. This means that under normal operation (during the peak load conditions), circuits in the interconnected transmission network are generally loaded below 50%.

2.11. Three characteristics of the transmission network will define its performance and associated operating costs: (i) level of congestions (ii) losses and (iii) interruptions caused by outages of transmission circuits.

2.12. The GB transmission network is characterised by significant north-south power flows as there is more generation in the north and more load in the south. In order to keep the north to south flow within permissible limits it may be occasionally required that northern generators with lower marginal costs are constrained off, and southern generators with higher marginal cost are constrained-on, which increases cost of operation. At present these congestion related costs are relatively small, but increase in generation capacity in the north and reduction in generation capacity in the south would increase these costs. Costs of congestions are managed by appropriate investment in network capacity[8].

2.13. Annual energy losses in the GB transmission system are below 2%.

2.14. In the very large majority of cases, faults on the transmission network causing outages of circuits, do not result in any supply interruptions to end customers. Although low in probability such interruptions, when they occur, could have a very high impact.

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[8] In fact, through a cost benefit based transmission network design, costs of network congestions are to be balanced with cost of network reinforcement.

*Control of flows on the transmission network*

2.15. Flows in the transmission network need to be maintained within limits to ensure that equipment is not overloaded and that the system is operated stably and securely. The primary source of control of transmission network flows are the large central generators themselves, i.e. the transmission network flows are controlled by varying output of generators. This is because the transmission network operates with fixed topology and the impedance of the network is determined by the electrical characteristics of the circuits used.

2.16. Overall contribution of transmission system related cost in the final electricity bill received by domestic customers is less than 10%.

### Key features of the distribution system

*Network design and performance*

2.17. The level of security (redundancy) in distribution networks is defined in terms of the time taken to restore power supplies following a predefined set of outages. Security levels on distribution systems are graded according to the total amount of power that can be lost. In general, networks have been specified according to a principle that the greater the amount of power which can be lost, the shorter the recommended restoration time. This philosophy is formalised in the Distribution Network Security Standards. This network design practices have effectively determined the characteristics regarding quality of service as experienced by end customers. The performance of 11kV and 0.4kV networks has a dominant effect on the overall quality of service seen by end customers. The vast majority of interruptions (about 90%) have their cause in these networks. This is primarily driven by the radial design of these networks, as any fault on a circuit leads to an interruption to some customers (unlike transmission and higher voltage level distribution networks that operate interconnected)[9].

2.18. Not much generation is present in the distribution networks and hence these are not controlled in a real time. According to the historical principles of the electricity distribution network design, the real time control of distribution network is resolved through the robust specification of primary network infrastructure and hence, these networks traditionally operate as passive systems (i.e. the network control problem resolved at the planning stage). This philosophy may need to change if DG is to be effectively integrated in the system operation and development. This has been long recognised by both DTI and OFGEM and this area of work has been supported by DTI / OFGEM Energy Networks Strategy Group and its predecessor, the Distributed Generation Coordinating Group.

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[9] On average electricity consumers in the UK experience less than one interruption per year lasting about an hour. Consumers in urban area have on the whole fewer interruptions than rural customers.

2.19. Annual losses in distribution networks in the UK are about 7%. Studies performed on our UK generic distribution network model[10] should that 11kV and low voltage networks are responsible for about 75% of the total energy lost in distribution networks. Given that losses are a quadratic function of loading, a significant proportion of losses are made in winter months during heavy loading conditions.

2.20. Overall contribution of distribution network related cost in the final electricity bill received by domestic customers is below 25-30%, with the contribution of low voltage networks being dominant.

Key features of demand

2.21. Demand is largely uncontrollable and varies with time of day and season (there have been insufficient incentives for demand to become responsive). Minimum demand occurs in summer nights and is about 30% of the winter peak. A key feature of demand is the diversity in usage of appliances. This is fully exploited both in system design and operation. The capacity of an electricity system supplying several thousand households would be only about 10% of the total capacity that would be required if each individual household were to be self sufficient (provide its own generation capacity). Distribution electricity networks are essential for achieving this significant benefit of load diversity. However, no material gains in the capacity of the electricity supply system would be made from increasing further the number of the households. This phenomenon is illustrated in Figure 2.2, which shows how the demand coincidence factor changes with the number of households. The coincidence factor is the ratio between maximum coincident total demand of a group of households and the sum of maximum demands of individual consumers comprising the group. In other words, the coincidence factor represents the ratio of the capacity of a system required to supply a certain number of households, and the total capacity of the supply system that would be required if each household were self sufficient.

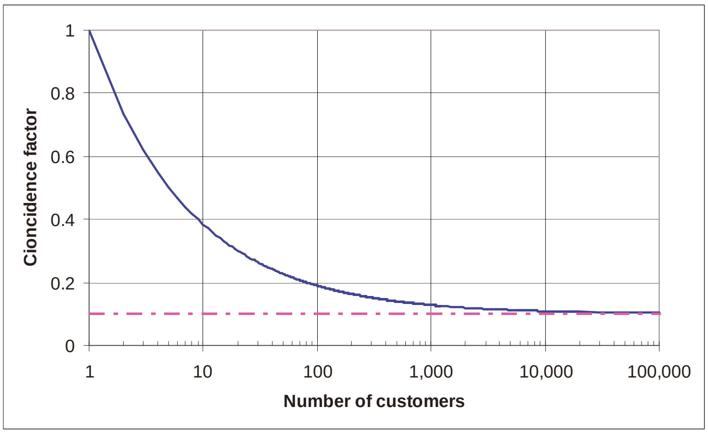

*Figure 2.2* Load coincidence factor as a function of the number of typical households

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[10] These models can be found on www.sedg.ac.uk

# 3. Drivers for Change

3.1. As discussed, the position of generation relative to demand is the dominant factor driving the design and operation of electricity networks. Furthermore, the type of generation technology used, together with the pattern of usage, will make an impact on the actual network operation and development. Finally, advances in technology may open up new opportunities for achieving further improvement in efficiency of operation and investment in transmission and distribution networks. These are discussed in Section 6.

3.2. With this in mind, we have identified four main drivers that may change the conventional philosophy system operation and development.

3.3. First, UK generation, transmission and distribution systems have been considerably expanded in late 1950s and early 1960s. These assets are now approaching the end of their useful life. It is expected that a significant proportion of these assets will need to be replaced in the next two decades.

Second, the UK is committed to respond to climate change challenge and the energy sector, and in particular the electricity, sector will be required to deliver the changes necessary. In the last decade, the UK has supported deployment of DG (distributed generation) of various technologies (particularly renewables and CHP) to reduce carbon emissions and the need to improve system efficiency. These generation technologies range from kW size domestic PV and micro CHP systems to several hundred MWs of wind generation connected to EHV (extra high voltage) distribution networks (132kV), as shown in Figure 2.3[11]

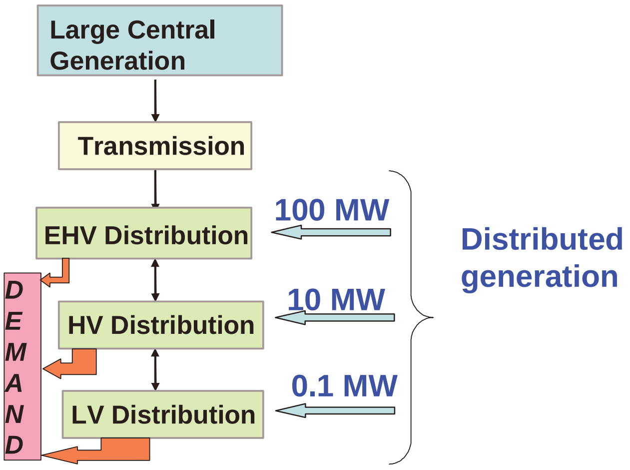

*Figure 2.3* Connection of various forms and sizes of distributed generation to distribution networks

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[11] Some of the very large wind farms may be connected directly to transmission networks

3.4. Figure 2.3 also illustrates the fact that locations and sizes of future generation will have an impact on network design and investment.

3.5. Developments in distributed generation are in line with the need to improve security of supply since an increase in the penetration of different forms of generation increases fuel diversity. Furthermore, a number of DG technologies would generally improve efficiency of operation of the system by reducing the amount of fuel that needs to be imported and burnt. This trend is likely to accelerate in the next decade and beyond as a key part of future energy policy.

3.6. Third, there have recently been some major advances made in information and communication technologies (ICT), that in principle, could enable the development of significantly more sophisticated approaches to control and management of the system and hence increase the efficiency of operation and utilisation of network investments.

3.7. Finally, there has been significant research and development effort invested in the development of a number of control devices and concepts, such as FACTS (flexible AC transmission systems), storage and demand-side management which could be used to provide real time control of power flows in the network increasing utilisation of transmission circuits. Similarly, greater automation of distribution network control could facilitate increase in utilisation of network circuits.

3.8. In summary, the need to respond to climate change, improve efficiency of the system and increase fuel diversity and enhance security of supply, coupled with rapidly aging assets and recent development in ICT, opens up the question of the strategy for infrastructure replacement in particular the design and investment in future electricity networks. This coincidence of factors presents a golden opportunity to re-examine the philosophy of the traditional approaches to system operation and design and develop a policy that will provide secure, efficient and sustainable future energy supply. This however does not necessarily require a radical change in the system, although like-with-like replacement at the distribution network level is unlikely to be optimal.

2.1 Our resent work show that, in the majority of cases, low and medium voltage circuits with a five to ten- fold greater capacity than needed is more economical over 20 years – because of the reduced losses – compared to the minimum size of cable that can still carry the load. These findings suggest that the present network design and replacement strategy, which follows a minimum network investment principle, may not be optimal particularly in the context of the UK efforts to reduce the environmental impact of its commerce and industry, including meeting its obligations for $CO_2$ reductions. Furthermore, it is important that low-loss transformers are appropriately considered in the asset replacement. The main concern here is whether the short term objectives of the network developers, coupled with currently inadequate regulatory incentives for investment into high efficiency distribution plant, may result in the installation of inefficient plant which will then be in operation for the next 30-40 years.

3.9. It is important to stress that an efficient electricity network infrastructure may help with keeping open the options for sustainable development of the UK electricity supply system. Appropriate design of circuits (based on the overall life cycle costs) leads to a strong network that is able to deal with the inevitable uncertainties in future generation, types, sizes, locations and performance.

3.10. In the next two sections, some of the key issues associated with the operation and development will be examined for two supply systems: (i) one dominated by a relatively small number of large conventional generation with modest contributions from large scale renewable generation and other distributed generation technologies and (ii) an fundamentally different integrated energy, supplied by a large number of small and medium scale distributed generation technologies, primarily CHP, and significant contribution of various forms of renewables (with absence of large scale generation).

# 4. Supply system dominated by large conventional generation

4.1. The first example system would be, from an electricity network perspective, structurally and operationally quite similar to the present one. The system would be dominantly supplied by large conventional generation with modest contributions from (a) large scale variable renewables, (b) micro-generation and (c) MW size distributed generation.

4.2. There has been a significant interest developing and integrating of new forms of generation technologies into the overall system operation and development. The key issues involve understating and quantifying costs and benefits of integration. There are two major components of system costs and benefits that need to be analysed for each of these types of new generation. These are the impact of new generation on the operation and development of (i) the conventional generation system, and (ii) the transmission and distribution networks.

### *(a) Integration of large scale variable renewable generation*

4.3. One of the key challenges in this future would be to integrate renewable generation cost effectively in the network operation and development in accost effective manner. In the short term this will focus on wind power and other forms of renewables will feature in the medium and long term. Wind power, both on- and offshore, is presently the principal commercially available and scaleable renewable energy technology. It will hence deliver the majority of the required growth in renewable energy and continue to be the dominant renewable technology out to 2020.

4.4. Potential operational problems stem from two principal causes, namely, the variable nature of the output of wind generation and the location and remoteness of the resource relative to centres of demand[12].

4.5. Although penetration of wind generation may displace a significant amount of energy produced by large conventional plant, the ability of this technology to displace capacity of conventional plant will be more limited. This is important as it will be necessary to retain a proportion of conventional plant to ensure that the security of supply is maintained. We have demonstrated that the disproportion between capacity and energy that is displaced by a secondary technology (wind in this case) that penetrates into the incumbent

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[12] It is also be important to recognise that, in contrast to conventional synchronous generation technology, wind generator technology uses induction generators and various forms of power electronic interfaces, and further work is required to understand the impact that this may have on the stability of the network.

system is the key cause of the additional system costs[13]. The values of these additional costs are not dependent on the level of penetration of wind (provided that all of wind power generated can be absorbed by the system when it arises), but are functions of the capacity credit[14] of wind generation (% of conventional plant displaced by wind power) and the load factor of wind , as shown in Table 4.1

*Table 4.1: Additional system cost of wind power technology (£/MWh)*

| | Capacity Credit (%) | | | |
|---|---|---|---|---|
| Load Factor (%) | **0** | **10** | **20** | **30** |
| **20** | 14.07 | 10.24 | 6.42 | 2.60 |
| **30** | 14.07 | 11.52 | 8.97 | 6.42 |
| **40** | 14.07 | 12.16 | 10.25 | 8.33 |

4.6. We can see that increase in capacity credit significantly reduces the additional system costs. We also see that an increase in load factor for a fixed capacity credit increases additional cost, which is caused by the reduction in the utilisation of primary technology. Taking an extreme position by assuming that wind has no capacity value the additional system cost of wind would amount to 14.07£/MWh. It is important to mention that any base load plant that penetrates into the system (e.g. base load CCGT or nuclear) would also impose additional system costs. Such a plant running at higher load factor (say 85%) than the average primary plant (say 55%) will displace more energy than capacity of the primary technology (similar to wind), causing a

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[13] The following expression can be used for quantification of these additional system costs (G Strbac, A Shakoor (2006), Framework for determining system capacity costs of intermittency, March 2006, www.sedg.ac.uk)

$$\Delta C_{Sec} = (1 - \frac{D^C_{Pr}}{D^E_{Pr}}) \cdot C^{I_0}_{Pr}$$

Where,

$\Delta C_{Sec}$ - additional per-unit system costs of secondary technology (£/MWh)

$D^C_{Pr}$ - percentage displaced capacity of primary technology (due to penetration of secondary technology)

$D^E_{Pr}$ - percentage displaced energy of primary technology (due to penetration of secondary technology)

$C^{I_0}_{Pr}$ - per-unit *cost of capacity* of primary generation technology (£/MWh) in the original system when supplied with the primary technology only. This per-unit cost is simply equal to the annuitised investment capacity cost of the original system (£/annum) divided by the total annual energy produced (MWh/annum). For a CCGT only based system, with a capacity of 84GW (required to meet peak demand of 70GW) generating 400TWh per annum, the per-unit cost of generation capacity will 14.07£/MWh (with the annuitised capacity cost of CCGT of 67£/kW/annum).

[14] Capacity credit is defined as, “The reduction, due to the introduction of wind energy conversion systems, in the capacity of conventional plant needed to provide reliable supplies of electricity” (British Wind Energy Association (BWEA), http://www.bwea.com). This reduction is generally expressed as a percentage of the total wind capacity in the system. The concept of capacity credit can be applied to any generation technology.

reduction in the (average) utilisation of the primary technology. This gives rise to the additional system cost of base load plant of about 5£/MWh.

4.7. The other two system cost components associated with integration of wind power, i.e. cost of additional reserves and transmission network reinforcement costs, tend to be smaller in magnitude. The studies carried out in the UK and abroad, suggest that the total cost of integration of variable renewable sources, for a modest penetration levels (below 30%) are not likely to be very high[15]. However, there are a number of major areas of concern that need to be addressed further and are summarised below.

4.8. Regarding the variability of output, the key issues include the requirements for additional generating capacity and reserve that is needed to maintain security of supply. Also the technical and economic benefits of alternative technologies, such as storage, Demand Side Management (demand participation) and interconnections with Europe are yet to be quantified[16]. In the longer term, further decarbonisation of the electricity system with possibly larger contributions of relatively inflexible nuclear generation and variable renewable generation supplying uncontrollable demand, could make the task of balancing demand and supply significantly more challenging. In this case, storage and demand side response will play an increasingly important role. If however Carbon Capture and Storage technologies are used, it is anticipated that these would be as flexible as present fossil fuel plant and hence would ease considerably the demand-supply balancing task. A wider participation of demand side and/or application of carious storage technologies (heat and electricity based) could bring significant benefits in balancing demand and supply in such systems, enhancement of the efficiency of system operation, security of the system and reduction of carbon emissions. However, comprehensive assessments of such proposals would be required to establish their costs and benefits.

4.9. Another area of key importance is associated with the transmission infrastructure requirements, which will be critically important if the massive onshore and offshore wind resources (and other marine renewables) in the UK are to be exploited. This raises questions regarding (i) reinforcements of the existing transmission and distribution networks and (ii) development of offshore transmission network infrastructure. Integration of variable renewable generation will require development of new standards for electricity transmission and distribution network design.

4.10. Determining the transmission requirements to accommodate variable renewable generation technologies in the north of the country while maintaining cost effectivness of the transmission system will be a major

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[15] Penetration of wind energy to 20% would not increase the electricity prices form more than 5%. This could be contrasted by recent increases in electricity prices caused by the escalation of fuel costs (Dale, L., Milborrow, D., Slark, R. and Strbac, G. (2004), Total cost estimates for large-scale wind scenarios in UK, Energy Policy**,** 1949-1956.)

[16] ESTIGS report, DTI 2005, UKERC report on Intermittency

challenge in the short to medium term. Furthermore, given that renewable generation imposes different requirements on the network infrastructure than that of conventional generation, an efficient integration of renewable generation in the GB electricity transmission and distribution networks may require changes in the present network access and pricing arrangements[17].

4.11. In the longer term, greater flexibility in transmission control could reduce operating and development cost of transmission further and enable more effective management of the uncertainty over the future locations and characteristics of generation and demand. Real-time network analysis and control and more broadly a move to corrective control are widely indicated as key technologies for all scenarios. This could contribute to further improving the efficiency of future system operation and investment and help the grid to flexibly adapt to alternative future developments of electricity generation systems. In general, technologies such as FACTS or DSM and storage could bring a spectrum of potential benefits including

- relieving power transfer problems and congestion,
- deferring new network investment,
- reduce system operation cost,
- increasing the amount of on and off-shore wind generation and other plant that can be accommodated in the existing grid infrastructure

### *(b) Integration of micro-generation*

4.12. In this section we analyse the impact (i.e. system costs and benefits) on on system operation and development of domestic CHP and other domestic renewables (such as PV or domestic wind).

4.13. Regarding the impact on the main generation system, the key parameters are the capacity value (credit) of DCHP and its energy production. Assuming that DCHP will operate during winter peak demand condition, its contribution to capacity is likely to be significant. On the other hand, energy displaced by DCHP will not be significant. Assuming that 5million of DCHP units can displace 5.5 GW peaking plant (about 6% of installed capacity) and will generate 12TWh (about 3% of the annual consumption), the benefits of DCHP in the context of its integration in the GB generation system could reach about 20£/MWh. This is because the percentage energy displaced is smaller than the percentage capacity displaced (see footnote 13). Furthermore, the output of this form of generation would be fairly predictable (given the averaging across a large diverse population of units) and hence it will not impact greatly on the cost of reserve. However, given that DCHP

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[17] Recent work on the update of the existing transmission and distribution security standards has demonstrated that the demand for network capacity driven by variable (wind) generation is smaller than that driven by conventional generation. This finding requires an investigation into the appropriateness of the existing network charging mechanisms.

would not normally be controllable[18], this could increase the need for flexibility although the impact on cost is not expected to be significant.

4.14. In contrast to DCHP, PV would have no capacity value as it cannot displace peak generation (it is dark at the time of national peak demand, in the evenings of December or January). PV will hence create additional cost to the system of 14£/MWh, as opposed to DCHP that makes a contribution to cost reduction for up to £20/MWh (with the difference is system cost of up to £34/MWh). With appropriate storage, PV generation could make more significant contribution to capacity. However, this would further increase the cost of PV generation that is already significant.

4.15. Regarding the impact on the distribution network, the density of DCHP will have a major influence. For very high densities (such as new housing estates) it would be useful to review network design practices for local low voltage networks and possibly also for 11kV feeders. Recognising that new housing development may include new network provision, the design of those specific networks could be tailored to DCHP and the materiality of the issue significantly reduced[19].

4.16. However, the existing network could absorb significant amounts of domestic generation without a need for major reinforcements. The key area of concern is the impact of reverse power flows that may occur during low demand and high generation periods which for DCHP would be in the early mornings)[20]. PV generation during the daytime in the summer holidays could be critical for exactly the same reasons.

4.17. The correlation between load and generation will drive losses and impact future network investment costs (this cost would be positive if generation increases demand for network capacity and negative, i.e. beneficial, in the opposite case).

4.18. DCHP is likely to reduce losses in distribution networks. In this context it is important to remember that losses are a quadratic function of load, and the vast majority of losses are generated in winter evening periods as this is the most heavily loaded time for the majority of networks. This is a period of expected DCHP operation, and the loading on the network will, therefore be reduced and the losses significantly reduced also.

4.19. Using our UK generic distribution network model we have estimated the impact of DCHP on network losses. We assumed that 10% of all customers

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[18] It could be possible to switch off DCHP units when required for a short periods of time, at the expense of reducing the temperature in the house. However, in order to operate DCHP when there is no need for heat would require heat dump facilities to be installed.

[19] This could simply and cheaply be resolved by installing thicker conductors (increased capacity). This change in design would contribute to reduction in losses in distribution networks.

[20] One of the solutions that is being discussed but not investigated is the use of water heaters to absorb this “surplus” of electricity locally.

have a DCHP unit, but that these customers are concentrated in only 20% of the entire network. The results show that the reduction in distribution network losses could reach between 25-40%, which is very significant[21]. The coincidence of peak DCHP generation and peak load conditions is critical for such a large reduction in losses.

4.20. There are some parts of local urban networks, those supplying predominantly commercial and public buildings, in which power flows peak in summer during office hours (due to increased air-conditioning load). In this case, application of PV could produce significant savings in losses and potentially postpone investment in local network reinforcement. Our analysis suggests that potential savings in losses could reach a level of 15-25%, which is significant.

4.21. Regarding the impact on network assets we used our UK generic distribution network model to investigate the savings in future network reinforcement and replacements enabled by DCHP (by reducing peak flows). Our preliminary work suggests that savings in the distribution network assets at higher voltage levels that can be attributed to micro-generation could be worth 100£/kW (or about £100 per unit) for low densities of the units. In the case of very high DCHP densities reverse power flows could become very significant and reduce the benefits created.

4.22. However, the system-related benefits (savings in generation and network operation and investment costs) that are created by micro-generation, are not currently captured within the current pricing regime, and this lack of recognition hence adversely impact the competitiveness of microgeneration. The significance of these savings needs to be investigated further.

### *(c) Integration of MW size distributed generation*

4.23. Regarding medium size distributed generation, the impact on the generation system will be determined through the ratio of the capacity and energy displaced as discussed above. Correlation of generation and peak demand will be of key importance in this context.

4.24. Regarding the impact on the distribution network, it is important to remember that security standards have been updated to take into account the benefits that (medium size) DG can bring to enhancing network security. These standards quantify the ability of various forms of DG to displace network assets[22].

4.25. It is however also worth pointing out that connecting a significant amount of DG to existing 11kV networks may require considerable reinforcement of

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[21] This refers to reduction in distribution network losses (these are about 7%). DCHP would also reduce transmission losses, but the estimates of the reduction are yet to be evaluated.

[22] R Allan, G Strbac, P Djapic, “Developing P2/6 Methodology”, Report to DTI (May 2004)

distribution networks. It is well known that voltage rise is the key cost driver in rural areas, while increased fault levels cause reinforcements in urban systems[23]. These costs could be reduced if an appropriate form of active network management is implemented (see below).

4.26. Estimates of the cost to reinforce GB rural distribution networks for four different penetration levels and two extreme density levels are presented Table 4.2 (cost are given in m£). We observe that the cost increase with increases in both the penetration level and the density, as expected. The cost of this distribution network reinforcement can be attributed to the DG and hence increases the cost of this technology by up to about 56£/kW.

*Table 4.2* The total cost of GB rural network reinforcement driven by DG connected to 11kV networks (in m£).

| Density →<br>Penetration<br>↓ level | Low density | High density |
|---|---|---|
| 2.5GW | 0 | 0 |
| 5GW | 0 | 238 |
| 7.5GW | 100 | 359 |
| 10GW | 243 | 560 |

4.27. By applying active management techniques for voltage control the cost of reinforcement can be reduced, and this is shown in Table 4.3

*Table 4.3* Cost of rural network reinforcement under active voltage control (in £m)

| Density →<br>Penetration<br>↓ level | Low density | High density |
|---|---|---|
| 2.5GW | 0 | 0 |
| 5GW | 0 | 84 |
| 7.5GW | 0 | 253 |
| 10GW | 0 | 376 |

4.28. Clearly, there would be significant benefits of implementing active distribution network techniques for voltage management. As the costs of implementing basic active management are expected to be £40-80m in total (for the entire UK distribution network), in the majority of cases there will be some benefits from changing the philosophy of network operation from passive to active.

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[23] An Investigation of Network Splitting for Fault Level Reduction , Xueguang Wu, Joseph Mutale, Nick Jenkins and Goran Strbac, January 2003 (Tyndall Centre)
G Strbac, N Jenkins, P Djapic, M Hurd, G Nicholson, Benefits of active management, DTI 2003.

4.29. This analysis shows that the active management techniques could reduce the cost of network reinforcement from about £50-60/kW to about £20/kW. These benefits will be lower in case of low density and low volume of generation.

4.30. Similar analysis is performed for urban distribution networks and results suggest that savings from actively managing fault levels could be very significant, up to £100/kW, due to avoided replacement of switchgear.

4.31. Our analysis also shows that cost of connecting DG at 33kV and above will be significantly smaller and the introduction of active network management may be more difficult to justify.

### *Case for closer integration of distributed generation*

4.32. In systems with a significant penetration of distributed generation, such as Denmark, there is a clear need to make the next step, which is to move away from connecting generators under the “fit and forget” basis (with the objective to merely absorb their energy production) and move toward integrating this generation in the overall system operation and development. In Denmark there is already a strong need to use this distributed generation to actively control the system operation (distributed generation can no longer be treated as negative load).

4.33. In order to effectively integrate new resources in the system operation and development, DG and demand will need to takeover the responsibilities from large conventional power plants and provide the flexibility and controllability necessary to support secure system operation, and it must possess an adequate degree of robustness to withstand disturbances.

4.34. If DG (and demand side management ) is not integrated into system operation then conventional generation will continue to be necessary for provision of system support services (e.g. load following, frequency and voltage regulation, reserves) that are required to maintain security and integrity of the system. Given that a significant proportion of DG is likely to be connected to distribution networks, maintaining the traditional passive operation of these networks and centralised control at the transmission level will necessitate increase in capacities of both transmission and distribution networks.

4.35. Although transmission system operators have historically been responsible for system security, integration of DG will require distribution system operators to develop active network management in order to participate in the provision of system security. This will however present a radical shift from traditional central control philosophy (which is presently used to control typically hundreds of generators) to a new more distributed control paradigm (applicable for operation of large number of generators and controllable loads).

4.36. There are a number of alternative approaches that lead to closer integration of DG in the system operation and development and these are briefly elaborated below.

### ***Basic Active Management of Distribution Systems***

4.37. This approach is attractive in order to accommodate increased amounts of Distributed Generation on 11 kV and 33 kV networks networks. Typical examples are Voltage Control in rural systems and Fault Level control in urban systems through network switching. Pilot voltage control schemes are presently being developed through OFGEM IFI/RPZ schemes.

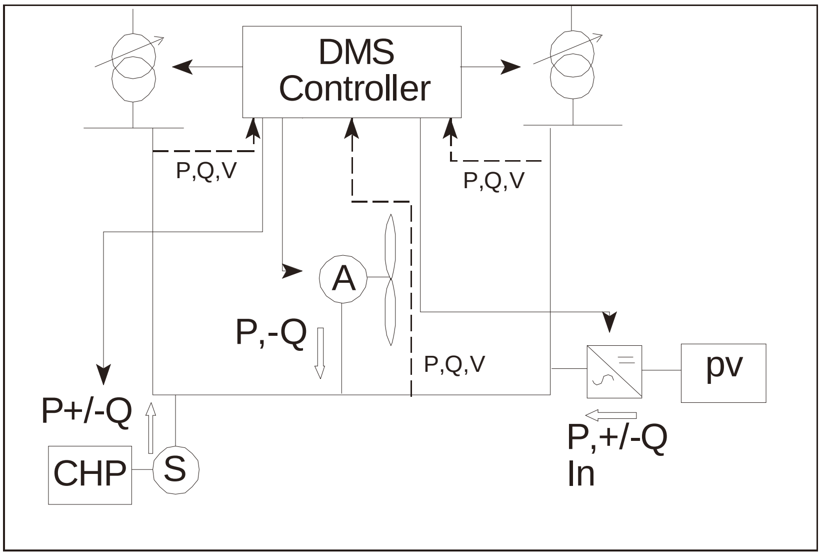

Fig 4.1 Active Management Scheme

### ***Virtual Power Plant/Cell***

4.38. High numbers of small generators pose problems to system operators as they displace large central generation which presently is used for system control. The Virtual Power Plant concept is to aggregate small generators either for the purposes of trading electrical energy or to provide system support services.

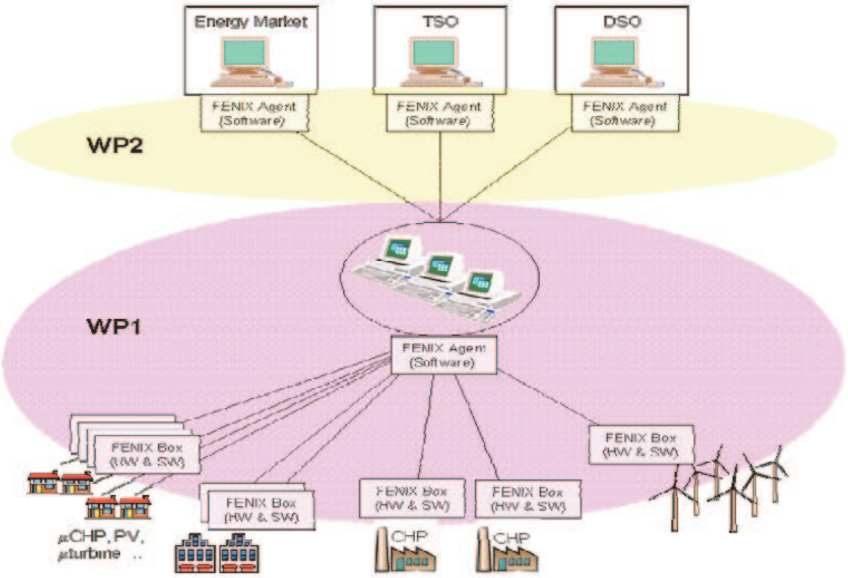

Fig 4.2 Virtual Power Plant (FENIX project)

4.39. A particular manifestation of this concept is being investigated in Demark where sections of Distribution Network are being controlled autonomously particularly to provide black-start capability. A key reason is the displacement of central power plants that would normally be equipped for this duty.

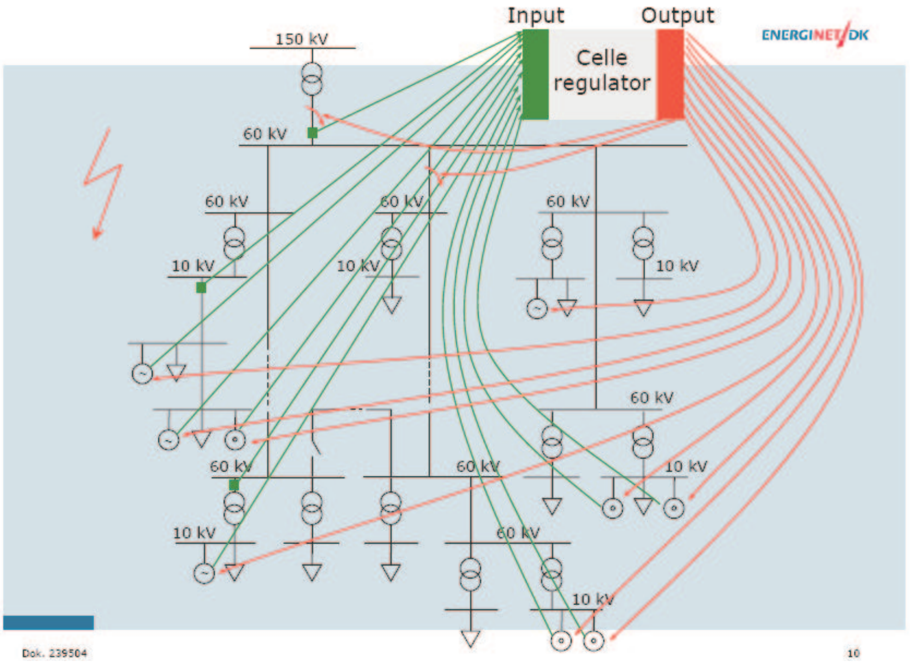

Fig 4.3. Cell concept (Energinet.dk)

## ***Micro-Grids***

4.40. The micro-grid concept is based on the assumption that large numbers of micro-generators are connected to the network and that these can be used to reduce the requirement for Transmission and High Voltage distribution assets. The individual micro grids are arranged to be able to operate autonomously in the case of loss of supply from the higher voltage networks.

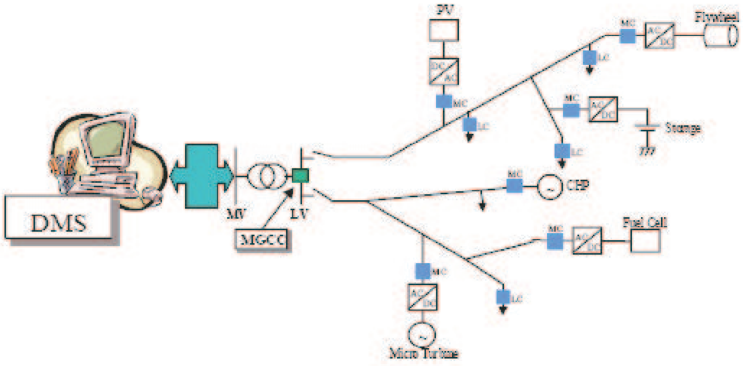

Figure 1.2 Micro-Grid control architecture

Fig 4.4 MicroGrid (MoreMicroGrid project)

4.41. The next section is devoted to the question of operation of a integrated energy system that may lead to the development of a distributed system in which the above concepts may be extended further.

## 5. Integrated energy system

5.1. A radical shift from the present large scale based generation system to a system supplied by distributed medium and small size CHP, together with various forms of renewable generation, would be driven by the prospect of significantly increasing the efficiency of the overall energy supply system. This would be primarily achieved, in the main, by making use of rejected heat from medium and/or small size thermal based electricity generation, i.e. CHP, to supply space and water heating demand (i.e. CHP). It should be stressed that high energy and carbon prices make such an integrated energy system more attractive.

5.2. As stated in the Second Report of the House of Lords Select Committee on Science and Technology, demand for low-grade heat that is, energy delivered at temperatures between ambient and the boiling point of water for space and water heating represents about 25% of the UK energy demand.

5.3. This “dual purpose” based operation is very difficult to realise with units of very large sizes. Generating electricity from large plant is accompanied with the production of a very significant amount of waste heat that is difficult to make use of locally, and transporting it over long distances is inefficient.

5.4. We recognise that the design of distributed power supply systems that involves CHP technologies should need to consider the interaction between heat and electricity production and demand and, in future, the relationship with the transport sector. However, we will first briefly discuss the role of the electricity and heat networks separately and than highlight some of the key issues for the design and operation of a combined system.

### *Role of distribution and transmission electricity networks*

5.5. As discussed earlier, there are significant benefits of electricity distribution networks because the alternative of balancing electricity demand and supply at a household level would be very inefficient. As discussed in Section 2, the capacity of an electricity system supplying several thousand households would be only about 10% of the total capacity that would be required if each individual household were to be self sufficient. Clearly, distribution networks are essential for achieving this significant benefit of load diversity.

5.6. Notwithstanding the case made for distribution networks, the need for transmission networks may reduce. In a system with largely self-sufficient regional power networks, the national transmission network would not have the role of transmitting power from remote large generators to demand centres, but instead would be used to enable demand-balancing energy flows between the regions which are out of balance[24]. It is important to bear in

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[24] A generic vision of such a system based on distributed energy is also described in recent report commissioned by Greenpeace

mind that having a transmission network that is used for backup rather than for transporting bulk power may be more difficult to justify. .

5.7. This is however very unlikely to be case in the context of the UK situation. This is because significant transmission infrastructure will be required in any case to facilitate the transport of massive amounts of power produced by remote large on and offshore wind farms and, in future, by other marine technologies. If several (tens) of GWs of wind power produced in Scotland and from offshore wind farms (and other renewables) is to be efficiently transported to remote load centres (e.g. South East), high voltage transmission network will be required, as these large amounts of power cannot be transported at lower voltage levels (e.g. distribution networks).

### *Role of heat networks*

5.8. There are practical examples of the application of heat systems ranging from a single house heat system (based on a micro CHP with no heat distribution network) to a building or town / city sized CHP schemes with ratings from a few tens of kWe to several tens of MWe with appropriate heat distribution networks. It should be pointed out however, that the UK has an extensive gas network that provides gas supplies to households but, unlike a number of European countries, has no very widely spread heat networks[25].

5.9. The key benefit of heat networks is in facilitation of trade in heat energy. If the heat, that accompanies electricity production, cannot all be used locally, the surplus can be injected in the heat network and the heat energy made available to others. Potentially, therefore, the development of effective markets for such low-grade heat could thus deliver very significant carbon savings[26]. Although new construction technologies can greatly reduce the demand for space heating the demand for low-grade heat will continue for the foreseeable future. The diversity of heat demand, although area specific, may not however be as favourable as that of electricity networks supplying similar number of consumers[27].

### *Balancing of electricity, heat demand and supply*

5.10. Balancing of electricity demand and supply in a distributed supply system dominated by various forms of renewable generation including various forms

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[25] UK policy has not traditionally developed much interest in heat. Thermal solar energy, for example, which, though offering significant efficiency gains when compared with the conversion of solar energy into electricity by photovoltaic cells, enjoys neither the same public recognition nor the same fiscal support through the Renewables Obligation, as pointed out by the Select Committee. They remark that the Royal Commission on Environmental Pollution (RCEP) has also argued for initiatives that are interested in heat to be explored.

[26] The most important practical and economic barrier to the development of heat networks is the initial capital cost.

[27] As pointed out in the report by the Select Committee, the size of the area covered by heat distribution is not in itself a technical constraint, the key technical issue is the density of heat demand (for example, in Gothenburg the network is some 700 km long, with a radius of 20-30 km).

of CHP will be challenging. This is because the output of renewable generation (such as wind and PV) vary with weather conditions and it is not generally easy or desirable to modulate the output of renewables to follow particular load shape. Similarly, the electrical output of domestic CHP schemes is expected to be driven by demand for heat. Generating electricity from DCHP units in order to supply electricity demand, when no convenient use can be found for the rejected heat is not efficient (efficiency of DCHP considering electricity only about 15%). In addition, a heat dump facility would need to be installed to support such a mode of operation[28].

5.11. In this context, having heat networks would generate benefits from diversity amongst the heat loads (commercial, industrial and domestic heat demand). In addition, heat storage could be beneficial as it can assist in decoupling of production of heat and electricity from consumption of these energies[29]. For example, pre-stored heat could be used when the need for heat is high while the need for electricity is low (in this case the CHP plants would be switched-off due to the low electricity demand). Alternatively, it would also be possible to produce additional heat from the electricity output of a CHP plant through simple heater. Similarly, heat networks supported by heat storage/dump facilities would assist in dealing with surplus of heat when CHP plant is needed to supply electricity load while there is no local need for heat.

5.12. The value of “load-generation following” in this system is likely to be very significant. In a distributed energy system, instead of only generation following demand, demand is required to take significantly more active role in following generation. This will require application of various forms of storage to provide flexibility by decoupling energy production from usage. This storage can take the form of thermal, chemical or mechanical energy or intermediate products.

5.13. However, it is important to appreciate some fundamental features of demand management when considering its contribution to system balancing. The issue is that demand response / management redistributes the load but it does not reduce the total energy consumed. This implies that load reduction periods (e.g. reductions in load to meet reductions in generation) will be followed or preceded by load recovery periods[30]. There will be limits to the extent that consumption can be preponed or postponed and this would need to match available generation. Another issue is that demand management tends to reduce load diversity, and avoiding this would require careful design of the entire system. It should be emphasised that experience with demand

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[28] Production of electricity will be accompanied with significant amount of heat (given the low efficiency of DCHP) and if this heat is not needed (e.g. in summer periods) some heat dump facilities will be required to dispose the unwanted heat that is being generated.

[29] Heat is relatively simple and cheap to store, for example in the form of hot water. This can be used to balance heat demand from across a few hours to a number of days.

[30] The amount and duration of the load recovery periods will depend on the requirements of the interrupted process and the nature of storage. In some case the amount of energy recovered may exceed the amount of load curtailed because of losses in the storage or energy conversion process.

management is relatively limited and more work is required to understand the potential of this technology and cost.

5.14. Another important challenge in such a system would be balancing demand and supply across seasons, given seasonal nature of load (and some renewables) and difficulties associated with seasonal storage.

5.15. Comprehensive, quantitative analyses of the economic and technical performance of alternative implementation options of such highly distributed power systems would need to be carried out before firm recommendations can be made.

### *Security performance*

5.16. Distributed architectures should provide a better quality of service and a higher level of security than centralised or hierarchical arrangements. This could be achieved with a distributed power systems because a very large number of generators would be available and accessible through multiple paths through the network. Traditional network operation philosophies are not designed to take advantage of the improvements in quality and security of supply potentially offered by the introduction of highly distributed energy systems. However, balancing demand and supply in such systems, as discussed above, will be a major issue.

### *Standardisation*

5.17. By its very nature, the development of a distributed energy system will require the interaction of devices and subsystems designed, owned and operated by a large number of independent parties. This development will be successful only if it is based on a broad consensus. The importance of standardisation in the development of small scale generation has already been recognised. Current efforts are, however, focussed on the standardisation of the physical interfaces between small scale generator and the distribution network. This standardisation of the hardware represents only a small proportion of the effort required to make the operation of a highly distributed power system possible. A considerable amount of work will be required to develop various communication protocols and facilitate access to energy and services markets, networks etc.

### *Markets for distributed power systems*

5.18. In order to efficiently allocate resources to facilitate balancing of both electricity and heat it would be critical to establish some form of real time pricing arrangement so that users can be fully informed about the value of heat and electricity at each point in time (and location). This would also stimulate the development of appropriate demand side solutions.

5.19. This will require introduction of much more sophisticated energy metering (e.g. half hourly metering) and trading functions and would lead to deployment of information and communication systems to facilitate control of generators and loads. Current economic orthodoxy assumes that the economic optimum can only be achieved through negotiations in a free market environment. Since energy is a complex commodity, a sophisticated commercial structure is needed so that each generator can trade in markets with purchasers of energy and ancillary services. A market with hundreds of thousands or even millions of active participants is clearly a major challenge. All participants will need to access various markets to set up long and short term energy transactions, secure access to the network and provide ancillary services to operate the system in a satisfactory manner (if this is to be done in heat energy, heat networks that would facilitate operation of markets for heat would be required). In order to facilitate trading of energy among very large number of distributed generators and loads, an electronic energy market system, supported by the internet, would need to be developed (extension of Power Exchanges type markets). Some laboratory and pilot schemes that use multi-agent systems technology[31] have already been demonstrated[32].

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[31] Agents are pieces of software that would, in this context, represent a device or household and could be design to automatically negotiate production or consumption of energy. .

[32] EU Project CRISP (Distributed Intelligence in Critical Infrastructures for Sustainable Power) – ENK5-CT-2002-00673.

# 6. Future Network Technologies

6.1. In this section we review the potential and future development of transmission and distribution technology and discuss its role in the improvement of efficiency of operation and development of the electricity system.

6.2. From the discussion in previous sections it is clear that the **limitations of transmission and distribution network technology will not prevent the UK energy goals being met**. However, future developments in the network technology could contribute to further improving the efficiency of future system operation and investment. Improvements in grid technology could facilitate the implementation of a range of alternative future electricity system developments, from centralised to distributed, by reducing the system operation and investment cost. Future technologies will help the grid to flexibly adapt to alternative future developments of electricity generation systems.

6.3. In the longer term, technology that enhances the flexibility of future networks will be important for maintaining the options for future development open. Real-time network analysis and control (and more broadly a move to corrective control) are widely indicated as key technologies for all scenarios. This includes development of analysis and control techniques to support the application of various forms of Flexible AC Transmission Systems and High Voltage DC. Furthermore, demand participation is an area that could bring savings in capital expenditure in future generation and network assets and increase the efficiency of operation of future systems. Our analysis shows that demand side participation has the potential to make a significant contribution in all futures, although the magnitude of the benefits and costs is yet to be quantified.

### *Flexible AC transmission Systems (FACTS)*

6.4. Power flowing from generators to loads divides over various transmission circuits in accordance with the impedances of the circuits. The most common way to change the power flows is to change the pattern of generation, i.e. increase generation at some locations and decrease it at others. As the outputs of generators cannot be changed fast enough (following outage of a line), security is usually provided in preventative mode. This is achieved by dispatching the generation “out-of-merit” to ensure that network security limits are not violated for any credible disturbance.

6.5. As discussed earlier, the GB transmission network is characterised by significant north-south power flows. Traditionally, in order to keep the north-south flow within permissible limits it may be occasionally required that northern generators with lower marginal costs are “constrained-off”, and southern generators with higher marginal costs are “constrained-on”, which increases the cost of operation. Although these transmission congestion costs are relatively small, an increase in generation capacity in the north and a reduction in generation capacity in the south would increase these costs. In other words, the system is run with generation being out-of-merit in order to withstand infrequent disturbances, because there is insufficient flexibility provided in the system to allow it to respond to an event after it occurs. This mode of operation, therefore, could incur relatively high generation costs, i.e. costs of congestion. The costs of congestion are key to informing the need for investment decisions in network capacity[33].

6.6. The concept of FACTS (Flexible AC Transmission Systems) opens up a new future in power system control. FACTS was a proposal for increasing the role of electronic power converters in the operation and control of transmission systems. The power converters would provide control of power flows in lines and control of voltages at nodes in a more flexible, responsive and rapid way than traditional systems. The benefits are the increased ability to manage congestion and other constraints and thus operate the basic infrastructure to transmit more power. As discussed in Section 2, an effect of the need to meet security requirements is that the traditional infrastructure is, under normal conditions, operated below its thermal limits in order for the circuit to be able to take on additional load immediately after an outage of one of the neighbouring circuit. In other words, significant transmission facilities must be held in reserve. The average peak flow on the GB transmission system is at about 50% of the capacity[34].

6.7. Some elements of FACTS (particularly those that control reactive power) have found use but others (those that are able to re-distribute active power flows) have had a slow uptake or none at all[35]. There are two major

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[33] Note that the strength of the transmission network depends not only on the capacity of lines and transformers but also on the position of generation relative to loads. For example, relocation of some generation from the south of the country to the north (away from the load centres) would make the GB transmission network weaker. This is because the north-south flows would increase, which would tend to increase the stress on the network. In order to keep the network operation secure, operation cost of the system would increase as the system would become more congested. Such operation would require northern generators with lower marginal costs to be constrained off, and southern generators with higher marginal cost to be constrained on more frequently. If these costs are to be reduced, the network would need to be reinforced.

[34] Commercial interest in flexibility, rather than in capacity, increased after the privatisation. In the new paradigm, transmission has no direct role in deciding generation locations and patterns of operation, both in the short and long term, as generating companies are free to choose both the technology and location of their generating facilities including the timing of commissioning and decommissioning of plants. Co-ordination of transmission and generation investment as exercised in vertically integrated power utilities has become a thing of the past. The main consequence of this state of affairs for the transmission business has been a marked increase in the level of uncertainty associated with future transmission investment. One response to this challenge would be to introduce more flexibility in the way the transmission system is operated. This could be achieved by applying various forms of FACTS devices (in addition to making demand and generation more controllable)

[35] It should be pointed out that, on the overhead transmission system, the costs of solutions to voltage problems tend to be significantly less than the costs of solutions to thermal (load related) problems.

impediments at present: the capital cost of this equipment and the electrical power losses in operation (giving rise to high running costs). These impediments could be overcome where there is a compelling case for the flexibility and control on offer but other cases which would bring technical benefits are not economic. Both the capital costs and the electrical losses are well known problems and industry will have made attempts to overcome them. However, a research breakthrough in device technology could be very influential. The commercialisation of silicon carbide switching devices will make progress in this regard but further breakthroughs look to be necessary.

6.8. The philosophy of preventative control may become complemented and maybe even replaced by corrective control which can make better use of basic infrastructure by adopting a less conservative approach. This control then enables better utilization of existing facilities and therefore reduces the demand for new investment. The ability to exercise this control will rest on high resolution feedback measurement, control computation and new means of actuation. The actuation will come from FACTS devices and special transformers that could impact distribution of power flows over the transmission network (Quadrature Boosters). A number of such transformers have already been implemented in the GB system, but are not used to redirect power flows in real time.

6.9. Evolution of feedback technology is already in progress in the form of Phasor Measurement Units (PMUs) which make time-stamped measurements of the key electrical quantities in magnitude and angle form and can sustain this at a high sampling rate. (Present monitoring does not achieve the same sample rate and crucially does not provide the accuracy of time-stamping need to resolve this information when used for control).

6.10. PMU technology could potentially increase the control capabilities of the network that could lead to an increase in utilisation of the existing network capacity, reduction of generating cost (due to reduced congestion) and reduction in investment for network reinforcement.

6.11. However, while satisfactory hardware solutions to the feedback problem are necessary part of the implementation of corrective control, much else is also required. The problem of coordinated control of multiple control devices[36] and its automatic execution has not yet been fully resolved.

6.12. Very little work has been conducted on the quantification of the benefits of flexibility so that these can be compared with competing solutions, i.e. network capacity expansion. An analysis of this question[37] showed that the benefits of FACTS tend to be significant when network reinforcement is

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[36] Coordinated control could include actions a number of network control devices (including demand and generators) with the objective to improve system performance while respecting network technical constraints (e.g. voltage and thermal constraints)

[37] J Mutale and G Strbac, Transmission Network Reinforcement Versus FACTS: An Economic Assessment, IEEE Transactions On Power Systems, Vol. 15, No. 3, August 2000

extremely expensive[38]. Clearly, more work is required to a develop framework and some techniques to understand and quantify the value of the flexibility that FACTS devices will bring.

### *Storage and demand response in managing demand-supply balance in system with intermittent renewables*

6.13. To achieve a significant reduction in CO2 emissions, renewable and other low carbon energy sources will become major contributors to the UK electricity generation system. Although growth of these sources through to 2020 (and beyond) is envisaged, there are many concerns about the flexibility, variability, non-controllability of the sources and the impact this has on the ability to maintain the balance between demand and supply.

6.14. Energy storage systems (and demand side management) appear to be an obvious solution for dealing with the variability of renewable sources: during the periods when variable renewable generation exceeds the demand, the surplus could be stored (with storage appearing as an increase of demand) and then used to cover periods when the load is greater than the generation (with storage appearing as an increase of generation).

6.15. In order to deal with the increased uncertainty due to penetration of wind generation, the system will need to apply increased amounts of reserve. This will be generally provided by a combination of synchronised and standing reserve.

6.16. In order for synchronised conventional plant to provide reserve it must run part loaded. Thermal units however operate less efficiently when part loaded, with an efficiency loss of between 10% and 20%. Since some of the generators will run part loaded to provide reserve (in case the output of wind generation reduces), some other units will need to be brought onto the system to supply energy that was originally allocated to the plant that is now running at reduced output. This usually means that plant with higher marginal cost will need to run, and this is another source of additional system cost. In addition to synchronised reserve, which is provided by part-loaded plant, the balancing task will also be supported by standing reserve, which is supplied by plant, such as OCGTs (open cycle gas turbines) with higher fuel costs or through new techniques such as storage facilities or demand side management.

6.17. Application of standing reserve could improve the system performance through increasing the amount of wind power that can be absorbed as fewer generating units are scheduled to operate, which is particularly relevant when high wind conditions coincide with low demand. In this context, DSM and

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[38] Planning issues associated with transmission network reinforcement may be very significant (obtaining new corridors for high voltage overhead transmission lines is extremely difficult). The Yorkshire 400kV line was put in operation 15 years after the decision was made to carry out the project.

storage would allow more wind energy to be absorbed and hence reduce fuel burnt. The value of storage and DSM when providing standing reserves can hence be determined by the evaluation of the improvements in the performance of the system (fuel cost and CO2 emissions).

6.18. Our recent study demonstrated that one of the key factors determining the additional value of storage and DSM when involved in system balancing is the flexibility of conventional generation mix. We showed that only in cases of a system combining inflexible generation with significant amounts of unpredictable wind generation might storage and DSM techniques become competitive. More work is required to fully understand the benefits and costs of storage and DSM in this context.

### *Improving grid investment and operation efficiency through demand side management and storage*

6.19. In addition to controllable types of generation and FACTS, a spectrum of enabling technologies such as storage and demand side management (DSM) can be used to provide transmission and distribution network support services, such as voltage and flow control. These will use a real-time corrective control approach for optimising the utilisation of the existing network capacity, deferring network reinforcement, enhancing security of supply and improving power quality.

6.20. As was the case with FACTS, it may be desirable use using demand-side management and storage to reduce congestion costs through increasing the flexibility of system operation instead of increasing the capacity of the transmission network,. This could be achieved by allowing an increase of the loading of the network under normal operating conditions (e.g. above 50% of the capacity), provided that the overloads that would occur after a line outage could be quickly eliminated by curtailing some loads at appropriate locations. Clearly, this would allow generation to operate at lower costs (as the congestion is reduced) and hence transmission network investment can be differed while maintaining the existing levels of security. This is based on the assumption that some customers may agree to curtail or interrupt their load (for a fee) to help correct an emergency situation[39]. Such schemes have been implemented for some time to handle system level problems but have not been widely used to handle local transmission problems. Although costs and benefits are yet to be quantified, our initial studies indicate that the value of corrective control could be significant[40].

6.21. Similarly, demand side management and storage could be used to manage network constraints at the distribution level. Figure 6.1 shows a schematic

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[39] The value of DSM in this case is bounded by the operating and investment cost of the conventional preventive control approach.

[40] G Strbac, S Ahmed, D Kirschen, R N Allan, "A Method for Computing the Value of Corrective Security", IEEE Trans. Power Systems, Vol.13, No3, August 1998. (1096-1102)

example of how DSM and energy storage systems could be applied for distribution network congestion management associated with peak wind outputs. Flow through the overhead (OH) circuit between busbars 1 and 2 can be maintained within the acceptable limits if excesses in wind power production are used to charge the storage device and/or by increasing consumption of the load connected to busbar 1 (DSM). Further, benefits could be obtained from determining the real-time rating of this circuit given that the rating changes dynamically depending on the actual weather conditions and the fluctuations in line flows. In general, this will allow increased transfers of power and will lead to an increase in the utilisation of wind energy while minimising the required network reinforcement. The Figure also presents the application of an ice-cooling storage facility aimed at increasing the short-term substation transformer rating at busbar 2.

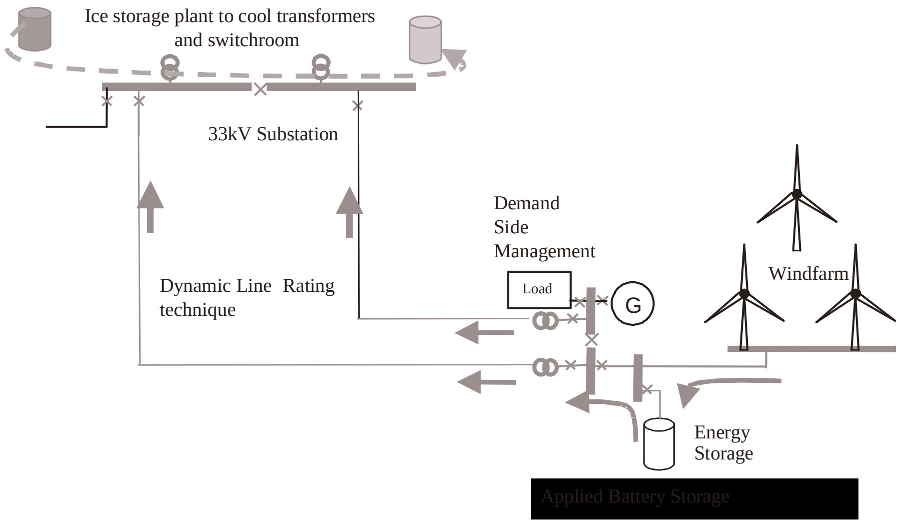

Figure 6.1. An example of demand side management and storage for managing congestion. Generation at busbar 1 faces congestion in the lines between it and the substation at busbar 2.

6.22. Traditionally, energy storage and DSM have been considered for energy arbitrage. The use of these technologies for unlocking unused network capacity and the provision of system support services has barely been considered. Our recent initial studies[41] demonstrated that the commercial value of energy storage can be considerably increased when used for managing intermittency, particularly in systems dominated by inflexible generation.

6.23. In general, storage and DSM could bring a spectrum of potential benefits in terms of (i) deferring new network investment, (ii) increasing the amount of on-shore wind generation, off-shore wind generation and CHP power plant that can be connected to the existing network infrastructure, (iii) relieving

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[41] Strbac, G., and Black, M., "Future Value of Storage in the UK-Final Report", UK Government (DTI) website, 2004

voltage constrained power transfer problems, (iv) relieving congestion in distribution sub-stations, (v) enhancing quality and security of supply to critical load customers, (vi) reducing the requirement for standby and peak generation, and (vii) providing corresponding carbon reduction.

6.24. There is at the moment a significant interest in the development of various storage devices, particularly fuel-cell based concepts, in addition to improving performance of the conventional storage systems. Significant cost reductions are expected in the next several years, which would than make storage applications potentially financially viable. Furthermore, demand side participation is also conceptually attractive but more work is required to examine the practicalities of its implementation. The value of the benefits of energy storage and DSM technologies in releasing latent network capacity is not yet well understood and quantified (our initial studies demonstrate that the potential may be significant[42])

### *Distribution Network Automation*

6.25. It is widely recognised that the present distribution network is much less automated and much less actively controlled than the transmission network. There are three reasons to increase the degree of automation and control. First, areas of high penetration of DG already face constraints both on new DG connections and on power export from DG sites. This stands in the way of increasing uptake of renewable energy. Coordinated control of DG output, transformer tap settings and other equipment on the basis of real-time information on network performance could yield greater DG capacities and avoid or defer expansion of the network with more network infrastructure. The second reason for addressing automation is the increased reliance consumers place on electricity services free from interruption. The structure and the length of lines of distribution networks makes them more vulnerable than transmission systems to occasional equipment failures, lightning and storm damage. The high reliability of the highly interconnected and redundant transmission system can not be replicated at distribution level. Instead, automation can bring rapid restoration post-fault through real-time assessment of reconfiguration options. There is also a growing body of expertise in condition monitoring of distribution equipment that can lead to pre-emptive reconfiguration around equipment judged to be likely to fail. The third reason for increased automation is the network operators' own interests in making best use of available assets and in making strategic asset renewal decisions. An under-automated network relies on conservative design to provide security and quality of supply. Automation can run assets closer to the real-time limits identified from feedback.

6.26. Several of the key technologies required for distribution network automation are being researched at present and solutions leading to offerings from

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[42] A Jayantilal, G Strbac, " Load Control Services in Management of Power System Security Costs", IEE Proc, Gen.Trans.Dist , Vol 146, No.2, May 1999. (269-275)

equipment manufacturers can be expected if the support for these initiatives continues. The technologies are:

- Real-time estimation of network state information from limited actual measurements (since full instrumentation of large networks is expensive)
- Real-time computation of security and quality indicators
- Condition monitoring of cables, overhead lines and transformers
- Real-time, automated selection of re-configuration options post fault
- Look-ahead optimisation of network configuration based on predicted load and generation
- Automated deployment of demand-side management and storage options
- Multi-objective optimisation of network security, DG export capacity, power quality and network power losses.

6.27. Widespread adoption of these technologies would enhance the capacity of the network to connect DG and improve customer service quality at what are expected to be lower costs than traditional network expansion. However, this amounts to a change in operating philosophy and needs targeted investment and needs new skills to be brought to network operations.

### *Electronic Sub-Station*

6.28. Substations which provide the link between distribution voltages and consumer voltages and which house much of the protection equipment for managing fault conditions are presently based on electro-magnetic devices for the power processing. Electronics has replaced (or at least is replacing) much of the information processing for monitoring and remote operation. It is conceivable that electronic (that is, semiconductor) means of actually processing power might replace electro-magnetic means. Such power electronics has already become commonplace in control of electric motors (from the very small to the very large). The advantages of such an approach are largely in the flexibility of use and inherent controllability of such an approach. Thus, one could expect better quality of supply, faster restoration post-fault and better utilisation of other assets. These electronic substations would probably use DC as an intermediate step between different AC voltages and would thus facilitate easier connection of DC energy storage and DC forms of renewable energy generation. They would also be better suited to managing the quality of supply for single-phase customers.

6.29. The electronic substation might use several sub-systems, some of which have counterparts in the transmission network (such as reactive power compensators and series voltage compensators) but a key element is the power electronic transformer (also known as the universal transformer). This devices uses switch-mode electronics (and high frequency magnetic components) to transform voltages. The projections are that it will have a smaller footprint (and thus is useful for up-rating existing urban substations) and will incorporate multiple outputs in a modular fashion for serving closely controlled and high quality voltages to a variety of customers. The flexibility inherent in the design is projected to bring benefits in reducing replacement times and stock holding costs since fewer standard designs are needed. The intention is also to avoid the use of materials that are hazardous and need special precautions. The most pressing examples are the insulation materials of existing electromagnetic transformers such as electrical oils.

6.30. There are two key issues which require research and development if realistic practical devices are to emerge. The efficiency of the electronic transformer is in question. The hope is to greatly reduce the power losses associated with the magnetic materials of conventional transformers. The question is whether the losses in the small, ferrite-based, high frequency transformer plus the power losses in the semiconductors can be kept low enough. The second question is whether the power electronics being used can break into commodity pricing and therefore become cost effective. If prices of traditional and electronic transformers are comparable then the added advantages of the electronic version will carry the case. Both the cost and the power loss issues are generic issues for high-power power electronics and need to be researched at a fundamental level (such as a search for new materials and manufacturing approaches).

### *Fault Current Limitation*

6.31. Accurate detection, location and isolation of faults is key to reliable operation of an electricity network. The approach to the issue is deeply embedded into the design of every element of the system. When a fault occurs, a large fault current flows. The fault current must be large enough to be easily and quickly distinguished from normal currents and be localised enough to indicate the position of the fault. However, this must be carefully judged such that the current remains within the operating limits of the circuit breaker that must interrupt the current. Adding DG tends to increase the current and confuse the locational signals. Interconnecting the distribution network to increase reliability also increases the fault current. There is a need therefore to look at ways of limiting fault current to the safe maximum. The devices must be fast acting, cost effective, controllable and suited to being a critical component in a safety system. Superconducting materials have some intrinsic properties that increase circuit impedance once a critical current is passed. This has long been recognised as the potential basis for an advanced fault current limiter. The remaining questions are whether the balance of plant (mostly the refrigeration system) can be made cost effective, whether the limiter can be fitted in the substation due to space limitations and whether the safety case can be established. (Problems with complying with existing safety approaches have cause take-up problems with other recent fault current limitation devices).

6.32. A converse issue exists which is that power electronic equipment (interfaces for DC forms of DG or the electronic substation) must be designed to self-protect (because the semiconductors are vulnerable) and thus they tend to provide insufficient fault current for the conventional network protection system. It is clear that conventional protection systems are going to be challenged from several directions at a time when customer expectation is for an ever more dependable electricity supply. This may well become an area of skills shortage. Some fundamental rethinking of approach is also indicated. Research and training are going to be key to ensuring continued safe and reliable network operation.

### *Underground and Submarine Transmission*

6.33. Transmission of alternating current through underground or submarine cables at Extra High Voltage (e.g. 400 kV) is limited principally by the capacitive charging current of the cables. Even applying shunt reactors at each end of a cable circuit to absorb the charging current, the maximum distance over which alternating current can be transmitted at EHV cost effectively will be measured in tens of kilometres. Hence for high power submarine cable transmission it is usual to use direct current (as is used for the interconnectors from England to France and Scotland to Northern Ireland). High voltage direct current transmission requires sophisticated and extensive converter stations at each end of the circuit and only point-to-point transmission is generally implemented.

6.34. Underground or submarine cables generally use XLPE (cross linked polyethylene) or paper pressurised with oil as their insulation. XLPE is a solid insulation material and so avoids the environmental difficulties of pressurised oil systems. However, XLPE is only presently available up to a voltage rating of 245 kV in a 3-core construction and up to 420 kV as single-core cable. The costs of laying submarine cable are very high and the greater simplicity of handling 3-core cable makes its use preferable to single-core. The maximum available transmission capacity of 3-core XLPE cable is around 340 MVA (800 Amps) and, if higher ratings are required, parallel circuits must be installed.

6.35. Gas insulated lines (GILs) were developed using the technology of gas insulated switchgear and consist of an outer enclosure, an insulating gas (usually a combination of $SF_6$ and $N_2$) and a rigid inner conductor. GILs have much lower capacitance than cables and can be constructed with much high current ratings (e.g. 2500 Amps). This compares with a typical 400 kV overhead circuit current rating of 2000-3000 Amps. Thus, a GIL circuit rated at 400 kV, 2500 Amps will be capable of transmitting around 1750 MVA. GIL technology has been developed for more than 30 years but not widely used. Circuit lengths up to 10 km are presently being evaluated[43].

6.36. High power submarine transmission remains challenging. Rectification to direct current and subsequent inversion to alternating current is expensive with sophisticated converter stations required at each end of the circuit.

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[43] Schoffner G and Oswald K "Gas insulated transmission lines (GIL) with spare phase – new concepts for investment reductions". Proceedings of ACDC 2006, 8th International Conference on AC and DC Power Transmission, London, 28-31 March 2006, pp 99-104.

XLPE submarine cable in 3-core construction is only available up to ratings up to around 340 MVA. Although higher 3-core ratings may be possible, even 800 Amps at 400 kV would only provide a circuit rating of 550 MVA. Gas insulated lines have been used for more than 30 years but mainly to replace short sections of overhead circuits. There is no experience of using this technology offshore. In conclusion, if very high power submarine transmission is required either for offshore renewables or to interconnect the UK at alternating current to some form of "North Sea grid", then advances in transmission technology will be required.

### *Role of Information and communication technologies*

6.37. Advanced communications, control methods, and information technologies are largely absent from electricity systems, leaving system operators and planners without valuable information for integrating dispersed resources, loads into grid operation and development.

6.38. In order to support the development of corrective real time control of networks and increase in flexibility in network operation, much more significant deployment of various sensors and advanced measurement and control devices will be required, accompanied with much more sophisticated energy metering and trading functions. This will lead to lead to wide ranging deployment of information and communication systems to facilitate control of generators, loads and various network devices and development and implementation of more intelligence distributed to control locally network primary plant.

6.39. Furthermore, information management, wide-area measurement, disturbance recognition, and visualisation tools are beginning to be used by grid operators to process real-time information, accelerate response times to problems in system voltage and frequency levels, and achieve compliance with reliability and security standards. These are considered to be critical to ensure that appropriate responses to disturbances are created before widespread blackouts can occur. This also includes the development of interconnection technologies and standards to enable seamless integration of distributed energy and loads with the local distribution system.

6.40. Implementation of ICT for control of electricity netwotks will lead toi the development of an integrated energy and communications system architecture that is intended to integrate two systems in the power industry: the electrical delivery system and the information system (communication, networks, and intelligence equipment) that controls it. In order to keep the options open by building flexibility (given the uncertainty in future development), the power delivery systems should increasingly rely on the information system. Primary energy plant and system together with the information systems could be developed in parallel in order to allow advanced communications and networking technologies to work with intelligent equipment to execute increasingly more sophisticated system functions. This will also enhance the ability of the existing infrastructure to absorbe various forms of DG with minimized network reinforcements.

6.41. There has been a number of initiatives (such as "GridWise" and “IntelliGrid”) in the US and “SmartGrids” in EU) intended to encourage the use of real-time information, integrating distributed intelligence using sensors with demand response programmes to maximise reliability and system efficiency while providing customers with new choices. The information architecture that incorporates new information technologies in grid operation in order to accelerate market acceptance and optimise system performance is yet to be developed. Although the key ingredients of the technology exist, targeted trials are required to gain more experience with it the context of energy networks.

### *New tools and methodologies for design and control of electricity networks in future*

6.42. As discussed in the Technical Architecture Report[44], distribution networks have traditionally had spare capacity for a number of reasons including standardisation of equipment. The additional capacity and security provided cover for the uncertainties of demand predictions. The acceptance of generous margins also made it possible to apply rules of thumb and use prepared tables and charts in design. However, the excess capacity built into the networks of the past has been taken up by load growth, and reduced expenditure in recent years means the excess capacity has not been replaced. As indicated above, this requires the development of more sophisticated network control, operation and investment strategies.

6.43. Existing tools and methods are optimised for large-scale transmission systems and distribution systems with little or no power generation. The proliferation of energy storage, distributed generation, solid-state equipment (converters, switches and transformers to name a few) and greater demand-side participation are not addressed well in today’s software applications and there will be requirement to enhance the ability to analyse the system in a more integrated manner covering large time scales from real time control to long term planning. To enable power system analysts and planners to evaluate new technologies and recommend effective and efficient developments to power systems requires a rethink of the analysis tools that provide the foundation to executive decision-making.

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[44] http://www.iee.org/OnComms/PN/powersysequip/ta_about.cfm

## 7. Recommendation for Government Actions

*Supply and demand*

7.1. Security, environmental and economic performance of the present large scale based generation system and an integrated energy system supplied by distributed medium and small size CHP, together with various forms of renewable generation needs to be examined. Making use of rejected heat from medium and/or small size CHP, to supply space and water heating demand, could become attractive given very high energy prices and the need to reduce fossil fuel consumption. However, comprehensive assessments of alternatives would be required to establish their costs and benefits. It is not clear if the present regulatory and energy market framework would provide sufficient incentives for an integrated energy system to be developed, even if this was efficient.

7.2. At present demand is not controllable (not responsive). Relatively low average plant utilisation opens a significant scope for widening demand side participation and inclusion of demand in system management although cost and benefits of this are yet to be determined.

7.3. In this context, it would be appropriate to support research and pilot demonstration of “Smart Metering”. There are two important issues: (i) to demonstrate and gain experience of the “Smart Metering” technology but also (ii) to determine the functions required of the “Smart Metering”. The latter remains unclear and greater clarity is required before national implementation of “Smart Metering” should be considered[45].

7.4. System costs and benefits of integrating various forms of new generation technologies in the operation and development of the electricity system need further investigations. Particularly interesting in this context are renewables, both large and small, but also micro-generation.

7.5. It is important to ensure that the system cost and benefits of various alternative generation technologies can be captured through pricing arrangements that are cost reflective. Significantly more work is required in this area.

*Transmission networks*

7.6. In the short to medium term it will be critical to ensure that adequate transmission capacity is made available to integrate on and off-shore shore

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[45] Recently, OFGEM carried out a consultation exploring issues souring Smart Metering and its implementation.

wind generation. Determining the transmission requirements to accommodate future wind generation and deliver cost effective transmission solutions will be a major challenge in this time horizon. Particularly important are the technical and commercial arrangements associated with offshore renewables.

7.7. Government should support the development of new standards for electricity transmission and distribution network design and changes in the present network access and pricing arrangements to reflect the effects of variable renewable generation.

7.8. When considering the long term, it is important to bear in mind that future form of the transmission network is heavily dependent on the forms, scale and location of generation to be used. Although there is much common transmission technology for any of the reasonable scenarios for electricity generation and use, there are huge challenges in keeping the system well prepared for the changes.

7.9. This preparedness is necessary because of the long asset life time and, in comparison, the rapid switching between favoured generation types in the electricity market. The key to preparedness is being watchful of developments and having the analytical skills and innovation to be able to respond to changed circumstances. The issue may be more one of skills for innovation than any particular innovation itself. Some academic work is in progress on the network implications of each electrical energy scenario but comprehensive analysis of cost and benefits yet to be carried out to understand policy implications.

7.10. Notwithstanding the need to be generally prepared for a wide range of possible outcomes, there are some particular areas where research and development should be pursued because these are important across a wide range of scenarios.

7.11. Real-time network analysis and control and more broadly a move to corrective control are widely indicated as key technologies for all scenarios. Further, in several scenarios, decentralised control of the network is required.

7.12. An important means to exercise control over the transmission network (in the face of reduced means to do this through conventional generators) is FACTS technology which itself rests on power electronics. Much research work has been undertaken in this area but two important blockers are the specific issues of conduction and switching losses and equipment costs. A target research programme to tackle these issues could offer great benefits. (There are some further issues with power electronics such as transient current rating, reliability and fault modes.)

7.13. Present cable technology limits both the range and ratings of AC subsurface connections which are key to grid expansion. Again target research to relieve these limits is indicated. Network expansion also indicates greater use of

HVDC with multi-node variants to be developed. Up-rating of overhead lines along existing way-leaves will require research and development for higher voltage lines and gas insulated lines.

7.14. In this context, it is appropriate to support transmission related RD&D and make a case an expansion of OFGEM's IFI initiative to include transmission networks (in addition to distribution).

*Distribution networks*

7.15. The role of a distribution system is to connect customers (either load or local generation) with the transmission and central generation systems. Hence its development is critically dependent on the functions required by the customers. In the longer term (out to 2050 and beyond) these requirements are not yet clear and the Government (through OFGEM) should develop policies that allows the distribution system to be able to respond flexibly to future needs. In particular it should:

7.16. Ensure the existing distribution system is maintained and replaced at the appropriate rate. Although this is obviously a key responsibility of OFGEM, determination of appropriate rates of replacement is not straightforward, as evidenced by the differing replacement policies adopted by the various Distribution Network Operators. Further work should be commissioned to determine the state of distribution network assets and if like-for-like replacement is the best option. Particular attention should be paid to the staff and skills required for replacement programmes.

7.17. Support RD&D on distribution systems including OFGEM's IFI initiative. This initiative needs stability over at least two Distribution Price Controls as the DNOs rebuild their RD&D capacity.

7.18. Support OFGEMs RPZ initiative to stimulate deployment of active distribution networks.

7.19. Support research into the integration of various forms of distributed generation including micro-generation with the distribution network. It is presently unclear at what volumes and density levels micro-generation will necessitate to changes in the distribution network. Also system benefits of micro-generation would need to be quantified more precisely.