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Transforming Europe's Electricity Supply – An Infrastructure Strategy for a Reliable, Renewable and Secure Power System

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building science into policy at EU level

EASAC

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Foreword

European energy policy seeks to achieve a substantially increased contribution from renewable sources of electricity, and the creation of a pan-European competitive electricity market. The existing infrastructure of the European electricity grid, and generally low levels of integration and co-ordination in the planning and operation of the grid, will not enable these goals to be achieved. The European Academies Science Advisory Council (EASAC) has therefore examined the developments that are required in grid planning, operation and infrastructure to accommodate more renewable sources of electricity and to support a European electricity market.

The study concludes that developments are required in planning a European grid to ensure that investments are made in the right places, in the way the grid is operated so that maximum benefit is extracted from a given infrastructure, and in transmission technologies so that effective options are available for environmental, operational, energy efficiency and investment considerations. Specific recommendations are made in each of these areas.

The report is addressed to policy-makers in the European Union institutions and at Member State level, to research funders, professional and regulatory bodies, and to all other interested parties. Our objective is to provide the scientific evidence to inform and stimulate further debate on the challenges, and to indicate some specific options for change while recognising, of course, that much is already being achieved in Europe.

On behalf of EASAC, I thank the members of the Working Group, and Professor Michael Sterling and Professor Harry Frank who chaired it. Their hard work and knowledge is much appreciated. Working Group members were drawn from ten European countries and a range of relevant disciplines, providing a breadth of experience and viewpoints that proved invaluable in developing the findings and recommendations set out in this report.

Professor Volker ter Meulen
Chairman, EASAC

Summary

European energy policy seeks to create a pan-European competitive electricity market and to increase substantially the generation of electricity from renewable resources. In the coming years these two factors will require significantly increased transfer of large amounts of electrical energy across long distances and national borders in Europe. Historically, each country designed and built its electricity supply grid primarily to meet its own needs, and there have generally been rather limited transfers of electrical energy between countries. If energy policy goals are to be achieved, a more integrated European grid needs to be developed which can enable a competitive electrical energy market and support the optimisation of Europe's use of electricity from renewable sources, while maintaining present high levels of reliability of electricity supply.

EASAC has therefore identified how the European electricity transmission grid needs to be developed if it is to enable the achievement of these policy goals. Developments are necessary in three main areas:

- the planning and development of a European grid to ensure that investments in capacity to transmit electrical energy are made in the right places;
- the physical and market aspects of the operation of a European grid to ensure that the maximum benefit is extracted from a given infrastructure; and
- the development of transmission technologies so that effective options are available for environmental, operational, energy efficiency and investment considerations.

For the planning and development of a European grid, EASAC considered that a much more co-ordinated and harmonised approach to planning is needed, based on common grid planning principles, practices and scenarios. Specific recommendations are:

- Common European models of the grid and the electricity market need to be developed which simulate power flows, power and energy exchanges, and the economics of electricity generation and transmission. Dynamic models of each of the four synchronous regions in Europe are also needed. These developments may appropriately be achieved through a collaborative initiative of the transmission system operators. European countries should also share grid data to enable more detailed simulations for different regions.
- A set of common, and mandatory, grid planning principles should be defined at a European level for short- and long-term planning. Issues they should address include defining the way future requirements are created and defining the credible faults and acceptable consequences of them. Plans need to be regularly updated.
- Given the scale of the European grid, there will inevitably need to be a combination of top-down and bottom-up planning processes that operate in a well-understood framework. Unco-ordinated local decisions will inevitably lead to difficulties.
- The approach taken to planning for operational security of supply requires further research. Decisions need to be taken about operational security of supply for Europe as a whole.
- Increased use should be made of revenues generated through congestion management to fund investment projects to strengthen transmission capacity.
- The successful realisation of an effective European transmission system will require human resources with the necessary skills to be put in place. This capacity must be planned for, and appropriate schemes for training and career development put in place.

The operation of the European grid will need to be through a more co-ordinated approach based on substantially enhanced levels of data sharing. Effective market mechanisms must be developed to produce correct pricing signals to ensure effective grid development and operation. The market must be compatible with the physical infrastructure and operation. Specific recommendations are:

- To the extent that incentives and subsidies are used, they need to be harmonised across Europe to get an optimal transmission system and to give the correct price signals.
- Congestion needs to be managed in a co-ordinated manner on a European Union system basis. As the system becomes more integrated, there will be an increasing need for European Union -wide control systems based on real-time information from advanced telemetry and the use of activating controls in real-time. This may require research and development.
- Issues of demand-side participation will need to be addressed, and a better understanding needs to be developed of the implications for electricity transmission of developments in load diversity, for example owing to the large-scale introduction of heat pumps or electric cars.

The transmission capacity of existing networks should be improved through the application of appropriate

control technologies; however, in all scenarios, extensions to the grid are required. Although the choice of transmission technology will depend on the particular circumstances, high voltage direct current (HVDC) transmission technology is developing rapidly and should be considered as an appropriate method of bulk power transmission from point to point. In addition, transmission cable technology, both alternating current (AC) and direct current (DC), is improving, allowing higher-voltage operation and greater power transmission capacities, and consequently reducing the cost differential compared with overhead lines. These developments are significant in relation to public objections to new overhead lines owing to their visual impact. However, it is not anticipated that it will be technically and economically feasible to replace all *existing* overhead line transmission circuits with buried cables.

Future European research and development on transmission technologies should ensure continuing progress in reducing investments costs, environmental impacts and energy losses, and may include, for example, development of gas-insulated and high-temperature superconducting transmission lines.

1 Introduction

Within Europe, there is an increasing need to transfer large quantities of electrical energy over longer distances. This is driven by European energy policy (European Commission 2007a) and specifically by the following developments:

- There is a desire within Europe to create a pan-European competitive electricity market which requires the ability to transfer large quantities of electrical energy across national borders (European Commission 2007b). Historically, each country designed and built its electricity supply system to serve its own needs with some limited interconnection to other countries. This limited interconnection allowed cross border trading at the margin, which assisted in the provision of reserves and enhanced security of supply, but did not typically support bulk transfers of energy (European Commission 2008a).
- Concerns about the environment and the scarcity of fossil energy reserves have driven the development of renewable energy in Europe, particularly the deployment of wind power in which it leads the world (European Commission 2007a). The European wind power resource is typically on the coast (particularly the western and northern coasts of Europe), or offshore. New coal-fired power stations are also being built on the coast as they are fuelled by imported coal rather than from local sources. Such coastal and offshore locations drive the need for the transfer of large quantities of electrical energy over relatively large distances from the sources to the demands, many of which are located inland and in southern Europe, remote from the main wind power resources.
- The variable nature of wind power and the need to maintain almost instantaneous supply-demand balance also necessitates the transfer of bulk electrical energy across long distances thereby utilising the geographical diversity of wind sources and of demands to their full potential (EWIS 2007; IEA Wind Task 25 2007).
- The European Council has set a target of a 20% share of renewable energy in the European Union (EU) by 2020 (European Commission 2008b). Consequently, additional requirements for the transfer of large quantities of electrical energy across Europe arise from the potential development of other large-scale renewable energy resources such as solar power from Southern Europe and North Africa, and the potential future exploitation of large-scale storage possibilities, for example hydro power schemes in Scandinavia. An effective European electricity transmission grid is a prerequisite for the large-scale introduction of renewable power sources.

Therefore, if Europe's energy policy goals are to be achieved, there is a need to develop the European grid not so much as a group of lightly interconnected national grids, but as one integrated grid that can facilitate a competitive electrical energy market and optimise Europe's use of renewable energy sources. Decisions on the necessary additions to electrical transmission capacity must address public concerns about the construction of new transmission lines (European Commission 2006).

There is clear evidence that the existing European grid infrastructure and its lack of integration are hindering the development of a competitive electricity market and the exploitation of renewable energy (EWIS 2007; IEA Wind Task 25 2007). Not only should the infrastructure of the grid be developed in a pan-European manner, but it also needs to be operated in a more co-ordinated way.

Recognising the significance of these issues to the achievement of European energy policy, EASAC established a group in September 2007 to study bulk electrical energy transport in Europe, and to make technically and economically feasible recommendations that should support the achievement of Europe's energy policy goals. This report presents the findings of this study, which has addressed the following specific areas, all of which are central to the development of an effective European transmission grid:

- the planning and development of a European grid;
- the physical and market aspects of the operation of a European grid; and
- current and future technology choices.

In line with European energy policy, the starting point for the study was taken to be that the future European grid should support the creation of a real European electricity market, accommodate large amounts of variable generation based on renewable resources, and maintain very high levels of reliability. It has been assumed that new generating capacity will be located where the economics are favourable. The study has not examined the overall economics of bulk transport of electrical energy across Europe in relation to other options. A previous EASAC report has reviewed price setting in the electricity markets within the EU single market (EASAC 2006). The study has taken a generally qualitative approach to evaluating and discussing the issues: more detailed follow-up studies would be required to make more quantified conclusions and recommendations, for example on the relative contributions of alternating and direct current transmission, or the locations of required grid reinforcement.

The Working Group comprised experts (from ten EU member states) in the various fields of knowledge relevant to the study. The members are listed in Annex 1. The Working Group met six times from September 2007 to November 2008, enabling discussion of the issues and the consequent development of the conclusions and recommendations presented in this report. Evidence was taken from manufacturers of transmission equipment and operators of transmission systems, as listed in Annex 2. Inputs to the study were also derived from published reports and the scientific literature (as listed in Annex 4).

The following section of the report briefly summarises how electricity grids work. It is followed by sections on each of the three areas listed above. The subsequent section then presents the Working Group's vision of how the European electricity grid needs to develop over the next 50 years. Finally, recommendations are made for the actions needed to realise these developments.

The report is aimed at policy-makers and other stakeholders in decisions on the future development of bulk electrical energy transmission in Europe. It is therefore written for the non-specialist, and technical terms have been avoided where possible. However, a few such terms have been needed and are explained in a Glossary, Annex 3.

2 How electricity grids work

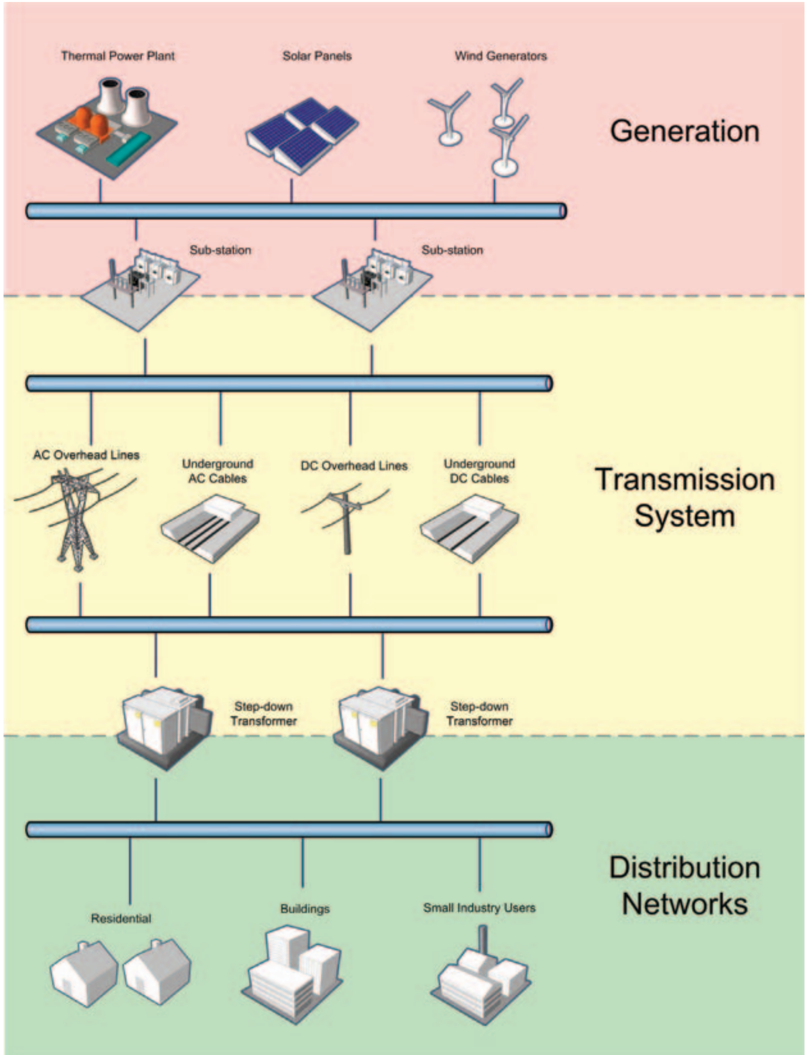
The transmission grids connect the generator plants with large demand centres and local distribution grids. They must meet the challenge of electricity transmission that electricity generation and demand need to be instantaneously in balance. Electrical power may be transmitted through overhead lines or underground cables, using alternating or direct current, as illustrated in Figure 1. In all cases, the voltages are high because, with present technologies, large amounts of power can only be transmitted efficiently with high voltages.

Lines and cables in transmission grids have limited capacities to transmit power (arising from thermal, contingency or stability considerations), and when these limits are reached the system is said to be congested. 'Congestion management' is a term that describes the techniques to operate the electricity grid so that these transmission limits are respected.

Overhead lines with alternating currents (AC lines) are the traditional way to transmit electrical energy. AC electrical energy takes the path with the lowest impedance, and it cannot be controlled without specific devices. This means that AC lines do not necessarily need any control devices, because the power flow is self-adjusting. In this respect, AC lines are more robust than direct current (DC) lines. The transmission capacity of an AC overhead line is determined by its thermal capacity, electrical stability or power system security. The advantages of overhead lines over underground cables are that, so far, the costs of building overhead lines have been significantly less than installing cables, and their capacity has been higher. The expected lifetime of overhead lines is high and can be up to 70 or 80 years. The main drawbacks of overhead lines are their use of land, and their visual impacts.

Alternating current cables (AC cables) are most often used in heavily populated areas such as large cities or under water. The cost of manufacturing and installing such cables is higher than the corresponding costs of overhead lines for a given length. The most serious limitation for the

Figure 1 Schematic diagram of generic power generation and transmission system.



use of AC cables is the fact that they cannot be used for long connections without extra devices, compensation reactors, which are needed at intervals along the cable to limit the reductions in transmission capacity arising from the reactive currents in AC cables. The transmission capacity of an AC cable is rather limited compared with overhead lines. It is constrained by heating of the cables and is strongly restricted by the length of the connection. The major disadvantages of AC cables are therefore their high costs and short length. Their main advantage compared with overhead AC lines is reduced visual impact.

Instead of using AC, energy may be transmitted by high voltage direct current (HVDC) using an overhead line, an underground or submarine cable, or a combination of these. Converter stations to switch between alternating and direct currents are needed at both ends of an HVDC connection. For a long sea connection where overhead lines and alternating current cables are neither technically or economically feasible, a submarine HVDC link is the only alternative. Also, HVDC is the only possibility when connecting two power systems that are not synchronous: so, in the case of Europe, connections between its four main synchronous regions (mainland Europe (the area covered by the Union for the Co-ordination of Transmission of Electricity (UCTE)), the Nordic countries (the Nordel area), the UK and Ireland). Furthermore, HVDC overhead lines are economic compared with AC lines when the transmission distance is very long (500–1000 kilometres).

HVDC interconnection is also a solution for weakly connected network parts. However, although HVDC links have been used as components of meshed AC grids (Pottonen *et al*. 1991, 1996; Bruer *et al*. 2004), there is no experience of the design and operation of meshed grids based primarily on HVDC, for which significant system issues would need to be addressed.

The transmission capacity of an HVDC link is limited by the rating of the power electronic devices in the AC/DC converters. The amount of power transmitted by an HVDC link can, and must, always be controlled. This can be an advantage in certain situations as it can be helpful to power system operation, for example by providing system protection through improved damping of electro-mechanical oscillations (see, for example, Nordel 2007). Generally, the lifetime of the components needed to control the power flows is shorter than those of primary components such as lines and cables, which brings additional costs. Comparing AC and DC underground cables, HVDC has the advantage of not requiring compensation reactors but the disadvantage of needing converter stations at each end of the DC link. HVDC cables are not limited by the same length restrictions as AC cables.

3 Planning and developing a European grid

3.1 National or multinational grid planning

Grid planning in Europe is generally done at a national level. Neighbouring countries share information and plan interconnections. However, approaches to defining transmission capacity, value of a grid investment, future scenarios and other issues that affect grid planning are not necessarily similar in different countries. Different national approaches cannot lead to one globally optimal grid in the sense of it being a robust grid that is optimal across a wide range of credible future scenarios.

Although the adoption of common approaches to grid planning would be a step in the right direction, it is not in itself sufficient. Harmonisation between countries is also needed on a range of issues, including:

- the rules governing the operation of electricity markets and congestion management;
- cross-border power transfers and compensation methods for the transfer of energy across intermediate countries between suppliers and users in other countries;
- sharing costs of international investments; and
- subsidies for different power generation methods.

Congestion management is a key issue and is discussed more thoroughly in Chapter 4 on 'Operation of a European Grid'. One example of congestion management that should be applied more often in cases of structural and long-lasting congestion is where the transmission system operators (TSOs) use the revenues arising from price differences between areas that can result from congestion to build new lines, rather than for tariff reductions. This should be possible even though the investment may be made some years after the TSO has recovered the income. Another example of how congestion is handled is provided by the European Union as a whole, where the taxpayer contributes to the funding of capacity investments to overcome transmission congestion (European Commission 2006).

Co-ordinated planning, including harmonisation of approaches to the issues listed above, would ensure that limited resources are used in the most efficient way and that all transmission capacity is fully used subject to system security constraints. It is recognised that this harmonisation is associated with significant political challenges given that there may be economic consequences for individual member states and organisations. However, the following example of the Nordic countries provides encouragement that such difficulties can be overcome.

One of the four synchronous regions in Europe, the Nordel area, already provides a good example of multinational grid planning. In 2002, the Nordic countries published the first Grid Master Plan, which was the result of a common grid planning process. The purpose of this process was to plan the grids of four interconnected countries (Norway, Sweden, Finland and the eastern part of Denmark) as if they were one grid rather than four grids connected together. The goal was to achieve a global optimum and to find those parts of the grid where investment in additional transmission capacity would provide most benefit for the whole system.

The result of this integrated planning approach was a plan in which Nordel defined five prioritised cross-sections, which needed to be reinforced (Jacobson & Krantz 2005). Three of the proposed transmission reinforcements are expected to be commissioned before January 2011 (Nordel 2008a). This integration of planning processes has continued, and in March 2008 Nordel published a new Grid Master Plan 2008 (Nordel 2008b), which describes the assumptions made and the planning process, as well as the conclusions on capacity development.

For the area of mainland Europe covered by the UCTE, the national TSOs that comprise UCTE's membership developed in 2008 the first 'UCTE Transmission Development Plan' (UCTE 2008). This takes a European overview of future investments in generation and transmission capacity based on plans developed in individual countries. This is a helpful step towards a more fully integrated planning process and will continue with an updating of the plan in 2010.

A further useful step for the co-ordination of the activities of the TSOs has been the creation, in December 2008, of the European Network of Transmission System Operators for Electricity (ENTSO-E) which brings together the 42 European TSOs. ENTSO-E will have a key role in planning the European transmission grid, analysing whether generation and network infrastructure is sufficient, developing common network operation tools, co-ordinating research activities in the field of transmission, and drafting network codes in collaboration with the Agency of Energy Regulators, the new regulators' organisation for Europe.

3.2 Common grid planning principles and practices

As further increases in transmission capacity will be needed, common grid planning is essential. Top-down and/or bottom-up planning approaches may be used. In a bottom-up approach, individual TSOs develop scenarios of generation and demand for their area, and accordingly plan their transmission grid investments. The individual plans are then amalgamated to develop a coherent plan for the European grid as a whole. In a top-down planning approach, a first step is the development of European scenarios of future generation and demand. This enables transmission capacity developments to be identified for the whole of Europe taking account of existing infrastructure, which are then translated into investment plans for individual TSOs.

A transparent planning process is needed for the European grid which has both top-down and bottom-up elements to enable the optimisation of grid developments for Europe as a whole. The bottom-up element would entail the gathering of information on anticipated levels and patterns of electricity production and consumption from the TSOs. Using this information, and taking a top-down approach, scenarios of future generation and demand would be developed for Europe as a whole, enabling the identification of where new transmission capacity is needed and hence the preparation of investment plans for the individual TSOs. After the grid development plans are made, they need to be updated regularly.

Again, taking the example of the Nordic countries, Nordel has a planning code, which is a part of the Nordic Grid Code (Nordel 2007) and is a recommendation for the TSOs. The Code defines the transmission capacity and describes the planning criteria. It also deals with some operational aspects. In a similar way, a set of common grid planning principles should be defined at a European level for short- and long-term planning. Issues that should be addressed include defining the way future scenarios are created and defining the credible faults and acceptable consequences of them.

Maintaining a high level of system security against the potential for operational failures in system components is a key consideration in grid planning in Europe, which must weigh the designed level of security against the increased costs associated with higher levels of security. An 'N-1' planning criterion is used in Europe as the way of expressing the design level of system security. This means that the power system always has to withstand the loss of an individual principal component such as a generation unit, line, cable or transformer (UCTE 2004; Nordel 2007). The additional use of probabilistic methods, which can complement the N-1 approach as part of grid security planning, potentially offers a more sophisticated and reliable approach. However, more research is required to obtain applicable, reliable and robust methods. Whatever method is used, the level of acceptable risk needs to be defined. A decision is also needed on whether the operational security of supply should be determined at the EU level or by each country.

Increasing the connectivity of electricity transmission across Europe will enable the realisation of the benefits from a more integrated market. Increasing the system size should result in fewer major disturbances to the system; however, when they occur, the consequences can spread to a larger area. These risks of 'cascade tripping' will need to be managed.

Common European models of the operation of the grid and the electricity market need to be developed which simulate power flows, power and energy exchanges and the economics of electricity generation and transmission. Dynamic models of each of the four synchronous areas in Europe are also needed. These developments may appropriately be achieved through a collaborative initiative of the TSOs. Countries should also share grid data to enable more detailed simulations for different regions.

Two important issues that need to be addressed are the development of fair methods of compensating TSOs for transmitting third-party power across their network, and creating incentives for relieving congestion through appropriate apportionment of costs and benefits. Harmonisation of definitions of transmission capacity and the optimisation of social welfare from grid investments are necessary precursors to these developments.

Because the European grid is large and composed of separate areas in which plant synchronisation and network are locally managed, the planning can be organised by regional working groups who co-operate with each other. In the longer term, given the availability of sophisticated, high-speed telemetry, it may be possible and appropriate to take a more centralised approach to management of the European grid.

3.3 Short- and long-term planning

The planning process should be divided into the short- (for example 5 years) and long-term (for example 25 years). Longer-term plans are developed in less detail than short-term plans and are concerned with identifying the paths where more transmission capacity is needed rather than how such capacity additions should be realised. Short-term planning should aim to identify ways of increasing the transmission capacity of the existing grid by modern devices, which are less costly and quicker to install than new lines and which the public does not resist. It should evaluate which devices in which locations can best increase transmission capacity. Candidate devices include power system stabilisers, wide area measurements with phasor measurement units, series compensation (for long lines), and a flexible alternating current transmission system (FACTS) (including static Var compensation, series capacitors, switchable compensation and phase shifting transformers).

Long-term planning requires that TSOs create a reasonable set of common scenarios for the future. These need to:

- cover demand, generation capacity, and the duration of power flows in lines;
- reflect national plans and incentives;
- use a common technical basis;
- extend sufficiently far into the future and in such a way that there are significant differences between them; and
- take into account the effects of the characteristics and costs of different methods of generation.

The predicted balance between generation and demand in each of the scenarios is key. Usually it is the high-load situation that is critical, and enough reserve generation and/or transmission capacity are needed for peak-load situations. If the peak load is not simultaneous in different countries, having enough transmission capacity helps to stabilise prices. The occurrence and duration of peak load hours should be estimated for each scenarios. The long-term plan enables the identification of critical areas of congestion and consequently the best locations for new lines.

The goal of long-term planning is to develop an optimal investment plan after identifying the remaining constraints for the European electricity market. The plan presents a global optimum based on common scenarios and planning principles instead of local optima.

3.4 Evaluating the grid plans and presentation of the results

There is an optimum level of investment in transmission capacity. If the investment is too high, it may outweigh the consequent benefits in the form of reduced market prices of electricity arising from the removal of congestion. If it is too low, then there will be too much congestion, resulting in an ineffective market and higher prices. The basis of cost calculations should be made clear. They should, as a minimum, include investments in lines and auxiliary equipment, and the costs of maintenance and predicted energy losses over the relevant period.

A report with assumptions, scenarios, tools, different plans and results should be prepared and published. Different optimal grid plans for different scenarios should be presented. The roles and benefits of grid investments in different scenarios should be described, and the sensitivity of the results to an appropriate range of assumptions should be presented.

3.5 Technical planning of new lines

After areas of congestion have been identified, the TSOs need to plan new connections. The technical solution for the grid investment can be AC or DC, cable or overhead line. The choice should be made in such a way that the technical properties, economics and environmental impacts are taken into account in each case. There cannot be any single technology best suited for all cases. When considering the economic aspects, a life-cycle cost analysis is key.

3.6 Planning for human resources

It is recognised that there is a shortage of people with the skills necessary to secure the improvements in the European transmission system discussed in this report. Appropriately trained people will be needed at all levels, and corresponding provision for training must be put in place (at technician, undergraduate, graduate, and PhD levels, and through schemes for continuing professional development). Increasingly, interdisciplinary training linking technical, economic and regulatory aspects will become a necessity. Given the timescales involved in developing the necessary skill base, planning must therefore also address these aspects.

Planning ensures that generation and transmission assets are in place to serve the demand: the political environment needs to provide stability for the TSOs' long-term planning. The operational issues of how resources are used to meet demand are the subject of the next chapter.

4 Operation of a European grid

Just as it is necessary to plan a robust grid, it is important that the grid is operated in an optimal way. Considering the targets and aspirations within Europe, construction of additional transmission is the only real solution to the development of competitive markets and the large-scale deployment of renewable energy. However, in the absence of additional transmission investments, some improvements can be made by operating the existing European grid in a better way.

The physical connectivity of the European grid dictates that for efficient use, co-ordination at all levels is paramount. This co-ordination is needed in the first instance at a policy level, leading next to the proper physical development of the infrastructure, and then in an operational period. Here the operational period covers issues such as maintenance planning, day-to-day physical scheduling of power flows all the way down to real-time secure operation. In parallel with the physical system, there is a need for transparent market mechanisms that will produce the correct price signals to ensure efficient grid development and operation. This complex co-ordination involves policy-makers, regulators, transmission system operators, grid owners, market operators and market participants. There needs to be clearly defined responsibilities, especially in emergencies.

4.1 Policy measures

Not only should policy-makers ensure regulatory co-ordination in the design of electricity markets and operational co-ordination between transmission system operators, but they also need to ensure that directives do not cause perverse behaviour. For example, priority dispatch (or firm access) for renewable energy sources (European Parliament 2001) can cause economic inefficiencies. Electricity has a market value at every location on the grid and at every instant in time. Sometimes the value is negative (Goggin 2008), indicating that the energy should not be accepted and should be spilled with no financial compensation (Schweppe *et al*. 1988). Also, distortions between renewable energy support mechanisms (including carbon prices) across Europe may result in an uneconomic deployment of renewable energy with consequential distortions in the development of the transmission system. For example, Germany has a very high wind penetration because of the generous German support for wind energy. This German wind resource induces unwanted power flows in other countries (for example, the Netherlands, Belgium, France and Poland).

Europe-wide co-ordination with exchange of all data is the best way to get co-ordination between European TSOs. Before that, however, European TSOs should continue to co-operate in grid operation and planning, define common acceptable consequences of grid disturbances and list credible events that are taken into account in grid operation planning (see, for example, UCTE 2004).

4.2 Market issues

Increasing interconnection between regions with compatible physical operations and market mechanisms increases the effective size of the market, which increases competition and is beneficial to the integration of large amounts of variable wind power (Meeus 2005). Within Europe, electricity markets for the time being have a regional characteristic, reflected in the physical operation of the electricity system. Although competition is the best driver for economic efficiency (Glachant *et al*. 2007), competitive markets must respect the physics of the underlying electricity system in order to harness the benefits. Therefore, enhancing competition in electricity across Europe will have limited beneficial impact unless the physical infrastructure (for example transmission) and physical operations (for example congestion management) are compatible with the market structure. Consequently, physical infrastructure developments need to be complimented by market developments and vice versa.

Increasing physical interconnection between regions will increase competition, improving economic efficiency and enabling the economic integration of renewable energy sources, so increasing social welfare. However, these links will have a physical limitation to the amount of power they can carry. Hence congestion management schemes are required, both between and within regions. These inter- and intra-regional schemes need to be compatible.

Some level of congestion is expected, as zero congestion indicates that there is probably over-investment in the transmission infrastructure. However, a situation without congestion may be justified in certain circumstances. For example, building transmission capacity between two regional systems may promote competition within one region but may not result in much energy flow. In the case of failures of competition authorities to prevent mergers or pursue stringent regulation, the costs of increasing inter-regional transmission capacity can be a second-best option to address structural problems such as market dominance within a region.

Transparent and non-discriminating market mechanisms, rules and procedures that facilitate trading across interconnectors between regions are necessary to ensure efficient use of the transmission infrastructure (Brunekreeft *et al*. 2005). Incompatibilities between markets can hinder this, and are referred to as seams issues or trading barriers that obstruct the smooth flow of electrical energy between electricity markets (Meeus *et al*. 2006). Even where similar market designs are pursued, this might not result in efficient use of transmission capacity if, for example, transmission and energy markets remain separated (Neuhoff *et al*. 2005). There is ample evidence that there is large-scale congestion across the European grid, and there is a need for increased interconnection capacity and more efficient congestion management mechanisms and operational and market co-ordination (Newbery 2005).

Internal regional issues of market structure may also impact adversely on the intra-regional trades; for example, unintentional loop flows within a region may result from poor co-ordination between intra- and inter-regional congestion management mechanisms (Ehrebmann & Smeers 2005). This raises the question of pan-European co-ordinated congestion management requiring the sharing of large volumes of real-time information, which has its own challenges but is particularly important for intermittent renewable power generation (Neuhoff *et al*. 2008).

Congestion management and the development of transmission infrastructure should be driven by undistorted locational market signals. However, justifying transmission investment is notoriously difficult. For example, investment in transmission infrastructure justified on the basis of price differences between regions (congestion rent), faces the challenge that once it is built price differences reduce destroying the congestion rent (Joskow and Tirole 2005). Transmission infrastructure built on a merchant basis (i.e. surviving on the rent alone) is rare (Meeus *et al*. 2007; Buijs *et al*. 2007).

Congestion and losses mean that the incremental costs of supplying electricity at different locations on the electricity grid are different, hence pricing needs to be locational (Schweppe *et al*. 1988). This locational marginal pricing model has been adopted widely in the USA as an efficient mechanism for management of congestion intra- and inter-regionally. It has not so far been adopted in Europe, and consideration should be given to its use in managing the inevitable congestion on the bulk electrical transmission system in Europe.

4.3 Physical operation of the system

As previously noted, the market operates in parallel to the physical operation of the system. The two are closely aligned, and any misalignment between them can limit competition and the integration of renewable energy. One of the most important technologies in achieving these goals is the advanced telecommunications networks and measurement systems that enable exchange of information in real time between TSOs on the grid state, which allows congestion management in real time. In addition, with real-time data, transmission limits can be updated in real time (that is, adaptive ratings) and it is no longer necessary to set lower limits with conservative off-line simulations based on a worst-case situation (CIGRE 2006b, 2007). Based on real-time measurements, it is possible to undertake contingency analysis and get more transmission capacity without reducing grid security.

It is crucial for secure grid operation that the operators get enough real-time data. Different tools are available that can help operators get a better view of the system state and hence enhance decision-making. For example, visualisation of voltage levels or energy flows in important cross-sections can be useful (Overbye & Wiegmann 2005). The use of phasor measurement units is a further example of the types of technology that can enhance grid operation (Phadke 2008).

Data exchange in general is important, both on a real-time basis to control and operate the system, but also in terms of developing tools and techniques that are used as operational study tools, market tools, and so on. In contrast to the USA, where there are databases covering large sections of the country that include transmission system, generator and load data, Europe does not have overall data sharing. Data exchange protocols and procedures need to be improved, and relevant databases to be developed that will allow pan-European market and operational studies to be conducted. These studies will assist in the smooth development of the European grid to allow more competition and deployment of renewable energy sources. Some analysis tools themselves may need to be enhanced and/or totally redeveloped in the light of developments of a European grid operated in a co-ordinated manner.

In some areas it is possible for the low-load situation to become critical. This can, for example, be a result of high wind penetration at times of low demand. These cases should be avoided by giving the TSO the ability to curtail supply during hours of low load if there are not enough flexible resources (generation or load), for example, as provided by recharging of battery-powered cars. The transmission capacity does not need to cover peaks of generation: the value of generated electricity may become zero or even negative in extreme cases when it may be appropriate to curtail generation.

4.4 New resources and technologies

The characteristics of the electricity system are changing. The changes involve more renewable resources, more distributed resources, smart meters and more flexible load. They bring substantial challenges to the reliable operation of the European grid and the associated issues of system control and computer simulation. If there were to be significant developments in storage devices for electrical energy, this would also have a major impact on how grids are operated, and on the levels of renewable resources that could be accommodated in the European electricity system.

Distributed resources, for example, will require more active control at the distribution level (but only up to a point that makes sense) and may need reinforcement of the distribution network. Smart meters and the possibility of more demand-side participation are particularly exciting. Flexible demand will allow for greater reduction of emissions, more integration of variable resources such as wind and the possibility of congestion management being performed using demand resources.

Not only will the demand-side be more flexible, but newer demands with particular characteristics will need to be accommodated; their characteristics should be used and leveraged operationally in the most optimal manner. For example, the potential proliferation of heat pumps and electric vehicles (Kempton & Tomic 2005; Denholm & Short 2006) is likely to bring significant changes to the operation and planning of the European grid. The European Technology Platform has drawn up an overall vision and has defined a research agenda leading to a user centred 'Smartgrids' concept (www.smartgrids.eu). Ultimately, these changes, which will all largely occur close to the consumer, may change our patterns of use, namely the load and the sources of generation. This may have significant implications for the patterns of power flows on the transmission system and hence the issues of bulk electrical energy transport being addressed here.

5 Current and future technologies

Mirroring the situation in the world more generally, the major part of the installed high-voltage electricity transmission capacity in Europe is overhead AC lines. For most situations, overhead lines have been preferred to underground cables because they have been significantly cheaper and they are easier to repair and maintain. Underground cables have generally just been used in heavily populated areas, under water, and in areas of high scenic value. AC has been used rather than DC because AC transmission is more readily accommodated in the synchronous AC power systems, which are the norm. Although such systems can accommodate, and indeed benefit from, some DC connections, the technical challenges of incorporating them increases as their relative contribution to the grid increases. As previously indicated, there is as yet no experience of the design and operation of meshed grids using HVDC.

However, there is increasing public opposition to the construction of high-voltage overhead transmission lines, which could be a considerable barrier to the development of a pan-European Grid. There have also been significant recent advances in HVDC and technologies for underground cables. Together, these changes may, in future, result in a shift in the balance of technologies chosen for new transmission capacity. Given their potentially increased role, technology developments in HVDC transmission and underground cables are discussed in the following paragraphs.

5.1 HVDC transmission technologies

There are two basic types of HVDC transmission link, depending on how the conversion between direct and alternating currents is made. Both types can be used for overhead lines and underground cables, but the technical properties of the two types differ.

In conventional HVDC line commutating converters (HVDC-LCC) (which may also be referred to as HVDC-Classic), the electrical switching that enables AC–DC conversion, depends on the line voltage. The switching process results in harmonic oscillations in the electrical current, and large harmonic filters are required which results in large space (or 'footprint') requirements for the converters. The converters have to be supplied from a relatively strong grid. HVDC-LCC technology has been extensively used across the world, operating at up to 6 gigawatts (GW) and 800 kilovolts (kV) (Szechtman *et al*. 2008): over 60 GW had been installed by the end of 2004.

The new type of HVDC voltage source convertor (HVDC-VSC) (which may also be referred to as HVDC-New), relies on current for switching and can be connected to both strong and weak grids. An advantage of HVDC-VSC is that it allows a more compact design: it is around half the size of HVDC-LCC. Unlike HVDC-LCC technology, it can be used for restarting after a system breakdown (a 'black start') if the other end of the line has a voltage or generators. A disadvantage is that it has higher losses than HVDC-LCC. The power and voltage ratings of HVDC-VSC have so far been lower than HVDC-LCC: the highest installed rating of HVDC-VSC is 350 megawatts(MW). However, it is a rapidly developing technology and significantly higher ratings are now being offered by manufacturers.

For both types, the ability to control the amount of power transmitted by an HVDC link can be an advantage over AC links. Fast control of power flow enables fast power transfer changes, which can be used to protect the system from a breakdown or to increase the security of the power system. Inclusion of an HVDC link of any type in an AC system can therefore improve system stability. HVDC-VSC has advantages over HVDC-LCC technology as, provided the rating is sufficiently high, it gives control of the reactive power at either end of the HVDC link independently of the power transfer over the DC connection itself.

For HVDC transmission technologies there are currently three potential European suppliers (ABB, Areva and Siemens) who have a major share of the world market.

5.2 Transmission cable technology: current status and future development

High-voltage cable insulation technology is well established and transmission cables can take one of two general forms, having either fluid-filled lapped paper insulation or an extruded polymeric dielectric. The earliest designs of high-voltage cables used paper insulation that was either mass impregnated or oil filled, and similar designs still represent most installed submarine and underground AC transmission systems. The first commercial use of polyethylene insulated AC high-voltage cable dates from the early 1950s, and over the past 20 years, there has been increasing application of extruded polymeric cable systems, initially for AC transmission voltages up to 270 kV and more recently at higher transmission voltages (up to 400 kV). Both in Germany and the UK there are installed and operational 400 kV AC polymeric cable circuits. The advent of HVDC has also seen increased application of polymeric cable systems at the expense of traditional fluid-filled systems.

Polymeric-based cable systems are becoming a mature technology, and current developments are mainly concerned with raising transmission voltages without significantly increasing cable diameter, increasing the lengths of cable between joints and improving the installation process. Higher voltages in cables result in lower losses, higher transmitted power and lower cost. A fundamental development that has accelerated the use of polymeric cables with HVDC technology has been the design and development of new polymeric materials for electrical insulation that have excellent DC and impulse breakdown strength. These materials have enabled HVDC cables to achieve ratings of 320 kV and 1.2 GW, and current developments should deliver ratings of 500–600 kV and more than 1.5 GW. Table 1 provides a comparison of the maximum voltage and power ratings (considering both AC and DC) currently installed for polymer- and fluid-based cables, and overhead lines.

Polymeric-based cables offer advantages over traditional fluid-based technologies as they are capable of operating at higher temperatures, have the potential to yield cable designs that are lighter and have smaller diameters, have simpler jointing requirements and remove the possibility of in-service environmental problems such as oil leaks. They are better to handle as they are more flexible and they make cable laying easier: the time required to joint sections of polymeric cables is one day compared with five days for fluid-based cables (presentation made to the Working Group by Lars Carlsson, Annex 2).

Further into the future, it is possible that high-voltage and extra-high-voltage transmission may involve the application of gas-insulated lines (that is, systems where the dielectric consists of a pressurised gas) and/or high-temperature superconducting (HTS) cables (systems using a very low loss HTS conductor, operating at cryogenic temperatures of around −200 °C (Takahashi *et al*. 2005; Institute of Physics 2008).

5.3 Comparison of technologies

Overhead lines and underground cables, AC and DC transmission, have strengths and weaknesses compared with each other, which are summarised in the following paragraphs for environmental impact, system operation, system flexibility and costs. The optimum choice of technology for a particular application will depend on the balance of these strengths and weaknesses in the specific context and parameters of the application.

For environmental impact, a key disadvantage of overhead lines is that they are more visually intrusive than underground cables. Public opposition to new transmission lines because of their visual impact is identified as a significant factor in delays to authorisation of new lines: typically, new connecting lines in Europe require around 10 years to build because of authorisation delays, whereas a new wind farm can be constructed in 2 to 3 years (European Commission 2006).

Table 1 Comparison of maximum installed ratings of cables and overhead lines

	Cables		
	Fluid based	**Polymer based**	**Overhead lines**
Gigawatts	2.2	1.7	6.0
Kilovolts	400	400	800

Overhead lines and underground cables will both have temporary environmental impacts due to their construction, and will require some permanent restrictions on the vegetation (particularly trees) that can be grown in their vicinity, and on associated land use more generally. Heavily loaded underground cables may cause soil drying, which can be an issue in particular circumstances. In certain weather conditions, overhead lines generate a certain level of audible noise due to the corona effect.

For system operation, an important issue is how often line outages occur and the time required to repair them. Overhead lines are more susceptible to outages due to the weather, but many such faults (for example lightning strikes) are transient and the lines can be re-opened after the trip in less than a second. Location of permanent faults in overhead lines may take some time. Location and repair of faults in underground cables can typically take rather longer than in overhead lines: historically, the ratio of out-of-service time between overhead lines and AC underground cables after a fault has been around 1:25 (Eurelectric 2004). Faults in cables tend to occur at joints, and hence HVDC cables provide higher levels of reliability than AC cables as they have fewer joints in a given length.

As indicated above, the inclusion of some HVDC links of any type in an AC system can improve system stability and security by controlling its active power flow. HVDC-VSC can also provide flexible and dynamic control of reactive power. In addition, HVDC connections can reduce system stability problems, which can arise when moving bulk power over long distances in AC systems. In contrast, the inclusion of AC cables may increase the risk of resonance oscillations in the system, which reduces system security.

Considerations of system flexibility also differentiate between AC and DC transmission. DC links are less flexible for future changes to the transmission system, as a connection into the link requires a converter station, which can be prohibitively expensive.

The relative costs of the different technologies depend on a range of factors including market conditions and the specific circumstances of the application (for example the terrain), making general comparisons difficult. However, looking at AC versus DC, the capital costs of the converter stations needed for HVDC are higher than those of the corresponding substations in

AC lines, but the costs of the lines themselves are lower for DC than AC. Operating costs arising from energy losses in transmission are significant in calculating overall life-cycle costs, and become relatively more important as energy prices increase. HVDC has significant energy losses in the converter stations (which are higher in HVDC-VSC than HVDC-LCC) but lower losses than AC per kilometre along the line. These relative characteristics of the capital and operating costs of AC and DC result in a 'breakeven distance', beyond which DC is economic over AC. Converters are becoming more powerful and cheaper, and energy losses in them are decreasing. As a result, the breakeven distance at which HVDC is favoured over AC is decreasing, but it is unlikely that it will ever reach zero.

Turning to the comparative costs of overhead lines and cables, cables are more expensive than overhead lines for high-voltage transmission. Historically, the cost differential has been high, around 20:1. However, cost differentials are reducing as developments in cable technology, particularly HVDC, have been more rapid in recent years than the relatively modest incremental improvements in overhead lines. Direct comparisons are hindered by the variation in transmission capacities and feasible lengths between different technologies, but the Working Group received evidence of current cost differentials in the range 5:1 to 10:1 for DC cables up to 200 km in length operating at 400 kV and 550 MW (see, for example, Energinet, DK 2008; Ecofys 2008).

Although AC cables become increasingly expensive for distances above around 40 km owing to the need to install compensation reactors, HVDC cables become relatively more economic at longer distances as a significant part of their costs are in the converter stations at each end. The transmission capacity of HVDC cables and converters is increasing rapidly, reflecting improvements in the ratio of power transmission to cable and converter costs, and hence further reductions in their cost differential compared with overhead lines may be anticipated. As an indication of possible future price differentials, a recent decision in Sweden to build a 400 km underground cable, operating at 300 kV with a capacity of 1 GW based on HVDC-VSC, reflected an estimated cost differential compared with an overhead line of just 2.2:1 (Larsson 2008).

Nonetheless, for high-voltage electricity transmission, AC overhead lines generally remain the preferred option unless there is a need to transmit large amounts of power over long distances (in which case HVDC overhead lines may offer cost and system stability advantages), or if environmental concerns are sufficient to merit the use of cables. Even if it could be afforded, the burying of all high-voltage transmission lines is not technically feasible given the length limitations of AC cables and that there is no experience of designing and operating meshed grids using HVDC. Choices between transmission technologies need to consider impacts on transmission system reliability, which is a significant factor in an overall economic appraisal.

The story is somewhat different for medium-voltage (up to 72.5 kV) electricity distribution. Here it is technically feasible to bury distribution circuits, and the cost differential between overhead lines and cables is lower than for high-voltage transmission (the technological challenges and costs of insulation for cables increases rapidly with voltage).

6 A future European grid

Consideration of the factors discussed in the previous sections enabled the Working Group to develop an outline of the key characteristics of a European electricity transmission system that we may expect to see in around 50 years' time. Development of that outline, which is presented in this section, has been guided by the Working Group's view on prospective technology developments, and assumes that the broad thrust of current EU policies, for example for integrated markets and reductions in greenhouse gas emissions, is maintained.

Recognising the continuing need to reduce the emissions of greenhouse gases and the consumption of fossil energy resources, we may expect a substantially increased use of renewable energy sources (wind power, photovoltaic, concentrated solar power, biomass, marine (wave and tidal) and geothermal), located according to the energy source, and based in both large and small distributed units. The drive for low-carbon energy sources may also promote the installation of new nuclear generating capacity.

The challenges of achieving supply–demand balance will increase owing to the much-increased role of variable energy sources. Demand-side participation may be expected to play a bigger role in achieving this balance, particularly as the potential large-scale introduction of, for example, heat pumps and electric cars, and the use of direct electrical heating in low-energy houses, will substantially increase the controllable loads and storage. There will potentially be more energy storage devices in the grid to help achieve supply-demand balancing. However, their level of penetration will depend on the economics of storage compared with other resources that can help with supply–demand balance such as flexible thermal plants. A key role will be played by the better physical and operational integration of the European grid to enable the matching of geographically and temporally diverse supplies and demands.

Operation of the European grid will be based on a far greater degree of dynamic load management than at present, based on a more comprehensive telemetry system and better predictions of the availability of energy from variable sources. Intelligent, electronic power-control devices will allow real-time control and self-healing of the system and its parts, managing loads, congestions and avoiding cascade decays and blackouts. There will be full on-line control and optimisation of the entire grid, with a more centralised approach to dispatching. Electricity markets will be pan-European and very sophisticated, with real-time pricing and an active demand-side participation in all aspects of the market.

There will be a greatly reinforced network structure to allow bulk transfers of power across Europe. HVDC links will be an important component of the network, but high-voltage AC grids (possibly operating at up to one million volts) will still provide the backbone of the system. The control of power flows will consequently be mixed: the self-organising flows in the AC grids will operate alongside more controlled AC and DC flows. Overhead lines will remain the main transmission mechanism, but more use will be made of cables where environmental concerns justify the required investment. The design and operation of the grid will put more emphasis on energy loss reduction.

7 Recommendations

The study has considered the developments of the European electricity transmission grid that will be needed if European energy policy is to be delivered, in particular what will be needed to support the creation of a real European electricity market, accommodate large amounts of variable generation based on renewable resources and maintain very high levels of system reliability. It must be recognised that this is a multifaceted and complex issue requiring many variables to be addressed on different timescales. However, there is a body of relevant research and practice from across the world on which development decisions can draw.

An overarching conclusion is that system planning and operations, and technology developments, all have an important role to play in meeting these needs. They must be considered on a Europe-wide basis if security of electricity supply is to be maintained. It is also important to recognise that in all scenarios the electricity transmission system will need to be substantially enhanced. Specific recommendations relating to planning, operations and technologies that need to be addressed in European policy-making and decisions are listed below.

Regarding planning and development:

- Common European models of the grid and the electricity market need to be developed which simulate power flows, power and energy exchanges and the economics of electricity generation and transmission. Dynamic models of each of the four synchronous regions in Europe are also needed. These developments may appropriately be achieved through a collaborative initiative of the TSOs. European countries should also share grid data to enable more detailed simulations for different regions.
- A set of common, and mandatory, grid planning principles should be defined at a European level for short- and long-term planning. Issues they should address include defining the way future situations are created and defining the credible faults and acceptable consequences of them. Plans need to be regularly updated.
- Given the scale of the European grid there will inevitably need to be a combination of top-down and bottom-up planning processes that operate in a well-understood framework. Unco-ordinated local decisions will inevitably lead to difficulties.
- The approach taken to planning for operational security of supply (for example N-1) requires further research. Decisions need to be taken about operational security of supply for Europe as a whole.
- Increased use should be made of revenues generated through congestion management to fund investment projects to strengthen transmission capacity.
- The successful realisation of an effective European transmission system will require human resources with the necessary skills to be in place. This capacity must be planned for and appropriate training and career development schemes put in place.

Regarding operations and markets:

- There will be a requirement for a high level of co-ordination and data sharing across Europe.
- To the extent that incentives and subsidies are used they need to be harmonised across Europe to get an optimal transmission system and to give the correct price signals.
- Congestion needs to be managed in a co-ordinated manner on an EU system basis. As the system becomes more integrated there will be an increasing need for EU-wide control systems based on real-time information from advanced telemetry and the use of activating controls in real-time. This may require research and development.
- Issues of demand-side participation will need to be addressed and a better understanding needs to be developed of the implications for electricity transmission of developments in load diversity, for example because of the large-scale introduction of heat pumps or electric cars.

Regarding technologies:

- The transmission capacity of existing networks should be improved through the application of control elements (for example FACTS), system control and wide area measurements.
- Extensions to the grid are required and while the choice of technology will depend on the particular circumstances, the following developments will be influential:
  - (i) HVDC transmission technology is developing rapidly and should be considered as an appropriate method of bulk power transmission from point to point.
  - (ii) Transmission cable technology, both AC and DC, is improving allowing higher-voltage operation and greater power transmission capacities, and consequently reducing the cost differential compared with overhead lines. These developments are significant in relation to public objections to new overhead lines owing to their visual impact. However, it is not anticipated that

it will be technically or economically feasible to replace all *existing* overhead line transmission circuits with buried cables.

- Future European research and development on transmission technologies should ensure continuing progress in reducing investments costs, environmental impacts and energy losses, and may include, for example, the development of gas insulated and high-temperature superconducting transmission lines.

At present, electricity customers in Europe generally enjoy high levels of security of supply based on transmission systems developed primarily on a national basis. To meet the challenges of the future, the focus for planning and operations must shift to a more Europe-wide system approach, and full advantage should be taken of the opportunities provided by rapid advances in transmission technologies.

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Annex 2 Presentations made to the Working Group

17–18 December 2007, Stockholm

- Gunnar Asplund, ABB: 'HVDC Classic-New, Electricity from the Sahara'
- Marc Jeroense, ABB: 'DC-cables'
- Lars Carlsson, ABB: 'Digging down, repairing DC-cables'
- Colin Oates, Areva: 'HVDC for underground cables'

29 February 2008, London

- Jussi Jyrinsalo, TSO Fingrid Oyj: 'The Nordel system – examples of grid development needs and strategies'
- Gunnar Evenset, Nexans Norway AS: 'Underground cables'
- Marco Marelli, Prysmian: 'High voltage underground and submarine cables for AC and DC transmission'

27 June 2008, London

- Olivier Herz, RTE: 'Transmission grid planning'

26 September 2008, London

- Karsten Neuhoff, Cambridge University: 'Congestion management in electricity transmission'
- Dale Osborn, MidWest ISO: 'Economic transmission planning for large systems'

Annex 3 Glossary

Black start: a black start is the process of restoring a power system to operation without relying on the power system itself to be energised.

Cable: an insulated conductor placed beneath the ground or sub-sea.

Compensation reactors: coils (air or oil insulated) that are used to counteract the increase in voltage caused by lightly loaded lines or other capacitative devices.

Congestion management: managing flow on lines in order to avoid overload.

Converter station: a substation where power is converted between AC and DC or vice versa.

Cross-section: a transmission cross-section is a cross-section on the transmission network between subsystems or areas within a subsystem.

Demand: power demand, required power or electric load.

Distribution grid: grid at a medium or lower voltage for bringing the power to the final customer.

Dynamic simulation: a means of simulating, via a computer model, what will happen to a system after a sudden change, such as a short circuit or a trip of a generator.

FACTS: a flexible alternating current transmission system (FACTS) is a system comprised of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally a power electronics-based device.

GW/MW/kW: units of power. The basic unit is the watt = 1 joule (unit of energy) flowing per second. kW is the symbol for a thousand watts, MW the symbol for a million watts, and GW the symbol for a billion watts.

HVDC-LCC: conventional HVDC is called HVDC-LCC or, alternatively, HVDC-Classic. The acronym derives from the use of line commutating converters (LCC) in which commutation – the electrical switching that enables AC-DC conversion and vice versa – depends on the line voltages of the AC grid and is made by using thyristor bridges.

HVDC-VSC: new type of HVDC (also called HVDC-New) for which the VSC acronym derives from the concept of 'voltage source converter', which uses forced commutating converters controlled by an algorithm defining the voltage shape to achieve the electrical switching that enables AC-DC conversion and vice versa.

Impedance: the electrical property of a network that measures its ability to conduct electrical AC current for a given AC voltage. Impedance is defined as the ratio of the AC voltage divided by the AC current at a given point in the network. In general, impedance has two parts: a real (resistive) part and an 'imaginary' (inductive or capacitive 'reactive') part.

Interconnection: a line that connects two power systems together.

kWh: a measure of energy: the amount of energy resulting from the flow of a kilowatt of power for an hour.

Line: a power-carrying conductor or group of conductors which can be AC or DC cables or overhead lines.

Locational marginal pricing: grid pricing depending on the actual incremental energy cost at a certain location.

Meshed grid: a grid where there are multiple pathways between the nodes (substations).

N-1 criterion: the power system always needs to cope with an unplanned outage of any of the N components, such as a line or a generator. This is called the 'N-1' principle. Therefore, the maximum power of a line cannot be more than an amount that can be added temporarily to other lines after a line trip.

Phase shifting transformer: a device that changes the difference in the phase of the voltage between two sections of a power system and can therefore be used to a limited extent to control energy flows.

Phasor measurement unit: measuring unit for assessing the phase angle of a voltage with respect to a reference voltage in a meshed, synchronised system.

Reactive power/current: in alternating current circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power flow that, averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as real power. On the other hand, the portion of power flow due to short-term (less than a quarter of the period of the fundamental frequency) stored energy, is known as reactive power. The associated currents are called reactive currents.

Spilled: refers to the situation where the power from a generator cannot be accepted by the transmission grid and most be turned off or disposed of at source.

Series compensation: where the compensation device is connected in series in a line.

Static simulation: static or steady state simulation is usually a calculation of the power flows in the lines and of the voltages (both amplitudes and angles) in particular grid locations.

Static Var compensation: a Static VAR Compensator (SVC) is an electrical device for providing fast-acting reactive power compensation on high-voltage electricity transmission networks. SVCs are part of the Flexible AC transmission system (FACTS) family of devices.

Strong grid: a grid in which there is additional capacity to accept more demand and/or generation without unduly impacting on the quality of supply. If the system is strong, the voltage variations during load changes are small compared with a weak system.

Synchronous power system: one in which all AC generation units are connected to the same AC grid and act at the same frequency.

System protection: system protection concerns the actions that may need to be taken to protect the integrity of the electricity supply system as a whole as distinct from protective actions for individual items of equipment.

Thyristor: a controllable power semiconducting device. It can only be on or off, with no intermediate operating states like transistors.

Transmission grid: electricity grid at high voltage for transporting large amounts of power over long distances, connecting major generating units and large demand centres or feeding into distribution grids.

TSO: transmission system operator.

Voltage – Medium and High: medium voltage is the term commonly used by the electrical utility and power distribution industry to denote voltages in the range 600 V to 72.5 kV typically used for electricity distribution. In the context of this report, high voltage is defined as voltages used for bulk transmission of electrical energy that are in excess of the medium voltages used in distribution networks.

Weak grid: one in which there is very little additional capacity to accept more demand and/or generation. In a weak grid, the voltage variations are large during faults and load changes compared with a strong grid.

Weak interconnection: a connection between two power systems which has a limited capacity.

Wide area measurements: measurements taken at different parts of the grid. Typically they are time synchronised by global positioning system (GPS) down to very small time resolutions typically of the order of less than 1/1000 of a second.

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