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Integrating wind power in EU electricity systems

Economic and technical issues

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Five case studies about balancing mechanisms in different countries are available via the GreenNet website, and are written by:
- Austria: Lukas Weißensteiner and Hans Auer, Vienna University of Technology, Energy Economics group (EEG),
- Denmark: Lars Henrik Nielsen, Peter Fristrup and Poul Erik Morthorst, Risoe, Energy Systems Analysis (ESA),
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Greennet project scope
Objectives and problems to be solved
The core objective of the project GreenNet is to enhance the proportion of electricity from renewable energy sources (RES-E) in the EU by applying a least-cost approach. Moreover, the costs - and interactions - of all-important supply-side and demand-side options will be considered.

These options are:
- The technical constraints and the necessity of an update and/or extension of the grid for RES-E grid access and integration,
- The technical constraints and the opportunities of advanced storage technology integration,
- The technical constraints and the opportunities of load reduction and energy conservation by means of demand side management.

These analyses will be conducted in a dynamic framework. Considering all these options it will be ensured that a certain quota of RES-E will be met with lowest costs for society.

The major product
The major product of this project will be the simulation software GreenNet containing the following major features:
- A comprehensive database describing potentials and costs of:
  - (i) different RES-E technologies in different EU countries,
  - (ii) the grid to accept RES-E integration (as well as potential and costs of an upgrade/ extension of the grid),
  - (iii) storage technology integration to support intermittent RES-E generation,

(iv) DSM (demand side management) measures for load reduction and energy conservation.

- Definition of different policy instruments for supply and demand for the EU as whole as well as for single countries for all or single technologies.
- Simulation of any kind of scenarios for supply-side and demand-side options in a dynamic approach, i.e. allowing also changes of strategies and scenarios over time.
- Depending on the features and policy instruments chosen derivation of a least-cost priority list for the deployment of RES-E by technology and country to meet the certain quota.

Finally, based on the results of the simulation software GreenNet, comprehensive models for financial burden sharing of cost caused between different players in the electricity market will be derived.

Expected results and exploitation plans
The major expected result is a least-cost time path for a continuous and significant increase of RES-E to meet certain quotas. This includes a year-by-year recommendation for different measures (development of RES-E technologies, grid upgrade/extension, storage technology integration, and different DSM measures) for the EU as a whole as well as for single countries.

Abstract

In view of the ongoing process of liberalisation of the electricity market and the expected increase of wind power pursuant the RES-E Directive and the need to minimise the costs of the RES-E targets, this study discusses the technical and economic impacts of integrating wind power into the electricity system. Furthermore, two options for reducing costs of intermittency are researched: forecasting of wind power output and electricity storage.

An increasing penetration of wind power into the electricity system causes additional costs, partly due to the fact that the energy source of wind power is uncontrollable, variable (on the short term as well as on the longer term), and unpredictable (especially on the longer term). Consequently, balancing generation and demand becomes more complicated, creating a need for additional secondary and tertiary control. Although the sources of increasing costs are becoming more clearly understood, as are means to mitigate them, the quantification of costs of operating an electricity system with high wind penetration is very hard. Two possible options to reduce costs of intermittency are discussed in this report: forecasting of wind power output and electricity storage.

The need for and benefit of wind energy forecasting have been increasingly recognised in recent years. Forecasting of wind power directs on increasing the predictability of the resource and improved forecasting can help to enhance the balancing of supply and demand. DG operators can provide better information about their expected power output, energy suppliers can submit better estimates of electricity production to the TSO, and system operators can improve network management through better information about expected power flows.

Electricity storage systems can, at the same time, offer different services to a number of actors. Next to benefits that result from price arbitrage, energy suppliers can better comply with their submitted demand and production estimates and will be able to reduce balancing costs, and DG operators can optimise the output of their generation facilities. DSOs and TSOs will be able to limit extreme situations due to low demand in combination with high peaks in power supply (or vice versa) and will be able to stabilise conditions in the grid (i.e. maintain power quality and provide balance in energy and/or reactive power).

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SUMMARY AND CONCLUSIONS

In view of the ongoing process of liberalisation of the electricity market and the expected increase of wind energy capacity pursuant the EU RES-E Directive and the need to minimise the costs of the RES-E targets, the aim of this report is to research:

1. the technical and economic impacts of integrating wind power into the electricity system,
2. technical options for reducing costs of intermittency by means of:
    a. forecasting wind power output
    b. electricity storage.

Impacts and costs of an increasing penetration of wind power

Characteristics of wind power substantially differ from conventional generation and wind power affects many aspects of power systems. Therefore, a number of issues must be resolved before large-scale application of wind power is feasible. An increasing penetration of wind power into the electricity system causes additional costs, which are partly caused by the fact that the energy source of wind power is uncontrollable. Furthermore, wind power output is variable (on the short term as well as on the longer term) and unpredictable (especially on the longer term). Consequently, balancing generation and demand becomes more complicated, creating a need for additional regulating and reserve power.

The aggregated very short-term (<1 min) output power fluctuations of a large number of wind turbines are very much smoothed and are generally not considered problematic. These fluctuations are induced by turbulence, which is a stochastic quantity that evens out when many turbines are considered. However, although a large number of wind turbines are not considered problematic, wind power hardly ever contributes to primary frequency control. Furthermore, storm-induced outages that occur when the wind speed exceeds the cut-out value do form a problem. These are not induced by stochastic turbulence but by storm fronts and can therefore affect a large number of turbines simultaneously.

The variability of the wind on the short term (15 minutes to hours) tends to complicate the load following with the conventional units that remain in the system, as it makes the demand curve to be matched by these units (which equals the system load minus the wind power generation) far less smooth than would be the case without wind power. There is a need for additional secondary control (spinning reserves, regulating power) to overcome these short-term fluctuations in power output and to be able to follow loads properly.

Furthermore, there is, because of the possible non-availability of wind power, an additional need for tertiary reserves (back-up capacity; longer term) to be able to integrate increasing shares of wind power without affecting the reliability of the electricity system. These reserves are not used for setting off short-term deviations in wind power output (which is done by the secondary control), but to be able to meet loads when there is little or too much wind. The non-availability of wind power causes the capacity credit to be relatively low. The capacity credit is the fraction of installed (wind) capacity by which the conventional power generation capacity can be reduced without affecting the reliability of the system (loss of load probability).

The impact of wind power on balancing the system becomes more severe the higher the wind power penetration level is. Thus, the requirements on secondary and tertiary control must be stricter in order to match the demand curve and to keep the fluctuations of the system's frequency, caused by unbalances between generation and load, within acceptable limits. It is, however, impossible to quantify the wind power penetration level at which the effects start to occur. Many factors influence the magnitude of the system-wide effects of integrating wind power, like, for example, the (load-following capability of the) conventional generation portfolio, the

wind speed regime, the geographical spread of the turbines, the demand curve, and the network topology between various power systems (including interconnection).

Another consequence of integrating large amounts of wind power into the electricity system concerns the grid. Wind power changes the power flows through the network and grids must be technically able to deal with this. Apart from the fact that grids must be able to handle the variability of wind power, wind resources may be located in remote areas far from population concentrations. Sometimes transmission network extensions are needed to integrate the wind power in the generation mix. Especially for offshore wind power, the distance that must be covered for connecting to the grid can be long (increasing energy losses), and the required reinforcements in the grid can be expensive.

Summarising, the main system costs (excluding the capital and operating costs of wind generation and excluding connection costs) comprise:

- Balancing energy generation and demand, including:
  - short-term response and reserve, and
  - long-term system security
- Reinforcing and managing the transmission system
- The impact on transmission losses and
- Reinforcing and managing the distribution networks.

Although the sources of increasing costs are becoming more clearly understood, as are means to mitigate them, the quantification of costs of operating an electricity system with high wind penetration is very hard. Two possible options to reduce costs of intermittency are qualitatively discussed in this report: forecasting of wind power output and electricity storage.

Forecasting wind power output

As wind energy penetration increases, the need for forecasting is essential in accommodating this intermittent energy source into the electricity network. Improved forecasting of wind power can help to enhance the balancing of supply and demand. This may give a higher value to the produced wind energy and reduce balancing costs. Forecasting of wind power directs on increasing the *predictability* of the resource. It has no effect on the variability and actual output of wind power, but it gives better insight in the (near) future output. It offers different benefits to different actors in the electricity system (provided that they have access to the forecast data, allowing them to better predict wind production):

- Energy suppliers are responsible for the supply and demand of electricity according to a beforehand made program (prediction of supply and demand). With improved forecasting data, these “energy programs” become more adequate. The energy supplier can submit better estimates of electricity production to the transmission system operator (TSO), thereby reducing its balancing charges to be paid to the TSO.
- The wind energy producer can provide better information about its expected power output to the energy supplier that may provide the wind energy producer with higher electricity prices in return, due to benefits in the field of balancing (described in the previous point).
- The distribution system operator (DSO) can improve its network management through better information about expected power flows, thereby lowering network operational costs and reducing or possibly postponing grid investments.
- The TSO can improve its network management through better information about power flows, thereby lowering network operational costs and reducing or postponing grid investments. If the TSO makes the forecast information public to the market, balancing the system will be easier and balancing costs for the total system will decrease.

The benefits and the application of a technology as the wind power prediction tool (WPPT) highly depend on national regulatory-, technology- and site-specific issues. National circumstances strongly determine which party invests in a wind power prediction tool:

- In the UK, power producers are obliged under the New Electricity Trading Arrangements (NETA) to remain within the agreed power output. In case an owner of a wind park cannot stay within this band, relatively high penalties are charged. Therefore, it is in the interest of the wind energy producer to invest in a Wind Power Prediction Tool.
- In Germany the case is different. Here the TSO/DSOs are solely responsible for the system balance and are obliged to connect any wind producer and purchase all RES electricity offered to them. Therefore, in Germany a TSO or DSO could be the party to invest in a WPPT.
- In the Netherlands, the electricity supplier is usually the party bearing the responsibility for a sound energy program on behalf of small-scale wind power producers. The energy supplier will have to cover any imbalance costs and could therefore be motivated to invest in the WPPT.

Storage

Storage facilities can have the following benefits for different actors:

- The energy supplier buying power from uncontrollable generators or intermittent energy resources (wind, solar) can better comply with its submitted energy program and thus will be able to reduce balancing costs. Furthermore, the energy supplier is able to use the storage facility for price arbitrage (via the wholesale and/or balancing market).
- A wind energy producer can optimise the output of its generation facilities, enabling the energy supplier to better fulfil its energy program and enabling the DSO to better manage its network tasks. Furthermore, the wind energy producer as well is potentially able to use the storage facility for price arbitrage (via the wholesale and/or balancing market).
- Assuming that DSOs are allowed to operate storage devices or to make use of storage services provided by a third party, a DSO will be able to limit extreme situations due to low demand in combination with high peaks in power supply (or vice versa) and therefore will be able to stabilise conditions in the grid (i.e. maintain power quality and provide balance in energy and/or reactive power). Consequently, DSOs will save on operational costs and reduce investments in or reinforcements of the grid.
- Assuming that the TSO is allowed to operate a storage device or to make use of storage services provided by a third party, it may improve network stability and it may be able to postpone grid investments.

As shown in the above enumeration, an electricity storage system can, at the same time, offer different services to a number of actors. For the economically most profitable exploitation of storage, it is helpful to exploit as much benefits of storage as possible and thus actually provide the different services to more actors. The potential total, social benefits of storage will partly disappear when allocated to individual market players. To exploit the potential benefits of storage as much as possible, it can be imagined that the storage device is operated by a separate entity. This entity can then optimise the supply of the different services to the different interested market parties. Furthermore, it provides a solution for the regulatory difficulties that exist when system operators want to invest in storage devices. The separate entity can provide the DSOs and TSO with grid related services, without violating the issue of unbundling.

1. INTRODUCTION

In 2001 the European parliament and the Council adopted the directive on the promotion of electricity produced from renewable energy sources in the internal electricity market: the RES-E Directive (EC, 2001). The RES-E Directive (article 3) stipulates a EU-wide target to increase the share of RES-E to 22 percent in 2010 from 14 percent in 1997. In addition to this EU target indicative targets have been set at the Member State level. The RES-E Directive has provided a major impuls to the development of national RES-E support policies.

A key contribution to meeting the RES-E targets is expected from onshore and offshore wind energy. The total current installed onshore and offshore wind generating capacity in the EU-15 amounts to 28.4 GW[1], with a forecasted growth to 120.2 GW by 2030[2].

Because of its intermittent nature, the integration of an increasing share of wind generating capacity into the European electricity system may impose additional costs to the system. The allocation of these costs and the incentives to minimise these costs are determined by the rules set up to govern the functioning of the electricity market. To date, however, the costs of intermittency remain largely unkown and intransparent.

The expansion of wind power poses a number of issues for electricity systems and their development (EWEA, 2004):
- Wind energy output fluctuates. To an extent, this can be controlled and/or predicted, but sometimes it cannot, or only with short notice. This is an added complication for grid operators. Intermittency issues require an understanding of variability and predictability.
- The technical characteristics of wind generation do not match the technical characteristics of conventional forms of generation, around which the existing electricity systems have evolved.
- Wind energy can be in locations remote from demand and/or remote from existing conventional generators. This means that there need to be changes in the grid infrastructure.

In view of the ongoing process of liberalisation of the electricity market and the expected increase of wind energy capacity pursuant the EU RES-E Directive and the need to minimise the costs of reaching the RES-E targets, the aim of this report is to research:
1. the technical and economic impacts of integrating wind power into the electricity system,
2. technical supply options for reducing costs of intermittency by means of[3]:
   a. forecasting wind power output, and
   b. electricity storage.

Reading guide

In Chapter 2, Electricity market structure, a theoretical model of the electricity market is introduced, describing the different relevant actors and relations that exist between them. Furthermore, it discusses a general balancing mechanism and the different (technical) ways of keeping supply equal to demand on the very short and longer term. Chapter 3, Impacts of wind power on the electricity system, comprises technical and economical impacts of an increasing penetration of wind power into the electricity system. In Chapter 4, Forecasting of wind power output, forecasting techniques are discussed, including benefits that relevant actors derive from forecasting. The theoretical model that is introduced in Chapter 2 is used to provide insight into

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[1] This is the total wind capacity for EU-15 at the end of 2003 (EU-25: 28.5 GW, total EU: 28.7 GW; source: http://www.bwea.com/energy/Europe.html).

[2] The forecasted growth is 69.9 GW for 2010 and 94.8 GW for 2020; source: EC (2003).

[3] Demand options to reduce costs of intermittency (demand response; shifting electricity demand during scarcity) do not fall under the scope of this project.

this subject. The final Chapter, Storage, offers an analysis of the costs and benefits of storage facilities. Here as well, the model of Chapter 2 is used to illustrate one thing and another. Conclusions and a summary are included in the beginning of this report.

2. ELECTRICITY MARKET STRUCTURE

2.1 Liberalisation and the need for regulation

Before the introduction of competition, the electricity market's greatest bottleneck was the lack of incentive for efficiency. Because all integral costs of infrastructure and all operating costs (profitable or not) could easily be passed on to the consumers (the 'cost-plus principle'), the electricity sector, which was unhampered by any form of competition, was hardly cost-efficient. In 1992 the European Commission proposed an electricity directive that had the objective to liberalise the electricity sector in Europe.[4] Liberalisation was thought to lead to lower electricity prices, which should help to strengthen the competitiveness of Europe. Liberalisation is a way to introduce (more) market competition, which eventually results in more cost efficient and more customer oriented companies that better cater to the needs and wishes of consumers: better quality and service at relatively lower prices. Four general motives for introducing competition can be distinguished (Van Hulst, 1996):

1. Remove welfare losses which originate from monopoloid price-making,
2. Promote allocative efficiency (prices are determined by marginal costs), dynamic efficiency (innovation), and cost efficiency (production at the lowest possible cost level),
3. Strengthen the international competitiveness, and
4. Improve the working of public regulation.

Liberalising the electricity market has a lot of potential advantages, but in the situation that free competition cannot protect the interests of consumers, introduction of economic regulation is necessary to monitor and control the activities of companies. If introduction of competition is not desirable or possible in certain elements of the electricity sector, economic regulation is required, especially to prevent abuse by dominant or monopolistic enterprises. Transport of electricity (via the transmission and distribution networks) is a natural monopoly. Other activities, like production, trade, sales, and metering, are competitive activities. Because transport is a natural monopoly, regulation of the grid is necessary to protect consumers and to guarantee free access to the grid (network access). To allow competition in the other segments of the market, the (natural) monopoly activities must be unbundled from other activities. If grid owners also have interests in other segments of the market besides transport, e.g. in production and/or supply activities, they might abuse their monopolistic power to favour these interests and to raise entry barriers on the grid. Insufficient vertical unbundling between transport and production or supply creates possibilities for cross-subsidisation. Revenues obtained from the grid are then used to strengthen the competitiveness of the production or supply activities. Trade interests and the working of the electricity grids must therefore be completely unbundled to make it possible to create a level playing field, to guarantee free access to the grid, and to avoid distortion of competition, discrimination and cross-subsidisation.

Next to the protection of the interests of consumers there where free competition fails to do so, another reason for the introduction of regulation is the promotion of sustainable energy supply. Liberalisation should, in theory, create the right conditions for any generator to sell electricity on the free market, including electricity generated from renewable energy sources (RES). But energy from these sources is more costly, and therefore, following different EU Directives[5], Member States (MS) have implemented support mechanisms to stimulate production and consumption of renewable electricity, including wind power. The European RES-E Directive (Directive 2001/77/EC, particularly article 7) states that MS must guarantee the transmission and

[4] Directive 96/92/EC.
[5] The first and new Electricity Directive: Directive 96/92/EC and Directive 2003/54/EC respectively; and the RES-E Directive: Directive 2001/77/EC.

distribution of renewable electricity. Furthermore it states that: "*When dispatching generating installations, transmission system operators shall give priority to generating installations using renewable energy sources insofar as the operation of the national electricity system permits*." Article 11 of the Electricity Directive is of the same tenor.

2.2 Model of the electricity market structure

This section will discuss the architecture of the electricity market, but before diving into this description of the electricity market structure, it is useful to discuss a few typical characteristics of electricity, which makes the electricity market in some respects differ from markets in other sectors.

2.2.1 Key characteristics of electricity

If demand and supply are not in balance, due to a shortage (or excess) of supplied electricity, the integrity of the entire system is at danger. This creates a chance of wide spread service interruptions (black outs). However, a typical characteristic of electricity is that large-scale storage is not viable in conventional electricity markets from a commercial perspective, except for pumped-hydro facilities.[6] Because the network does not store electricity neither, there is no possibility to create a buffer to absorb short-term deviations between supply and demand. Therefore, supply and demand must be kept in balance continuously. To withstand disruptions in the electricity system, available generating capacity must always exceed demand by a certain margin, so unplanned deviations in electricity production or demand can immediately be met by this so-called reserve capacity (operational reserve). Because of its intermittent character and its variable electricity output, wind power creates the need of extra reserve capacity, as will be discussed further on in this report.[7]

A second typical characteristic of the conventional electricity sector is the extremely low price-elasticity of demand, which means that variation in electricity prices hardly influences demand. An instantaneously responding demand to changes in the availability of electricity (reflected by the price) would be helpful in fulfilling the need to balance supply and demand continuously. On the one hand, this low price-elasticity of demand may be caused by the fact that there is no readily available alternative for most applications of electricity. On the other hand, and at least as important, only few consumers receive the required price information in time to adjust their behaviour. Consumers usually receive bills that cover a number of weeks or months and which state only the average price for that period. This means that whatever price-elasticity exists cannot manifest itself. As a result, the observed price-elasticity may be significantly lower than the real price-elasticity of demand. (De Vries, 2004) However, the intrinsic price-elasticity of demand may still be very low, because the willingness to pay high prices for electricity is high.

Because the price mechanism appears not to work properly in balancing supply and demand on the short term, there is a need for an additional balancing mechanism. Therefore, in most countries a separate balancing market has been set up. In section 2.2.2, first the electricity market structure will be described by means of a model, including the wholesale market where the price mechanism balances supply and demand as far as it goes. Then, in section 2.2.3, the balancing market will be added to the model, describing the balancing mechanism that matches demand and supply on the short term, until the actual moment of delivery.

[6] Electricity storage is the topic of Chapter 5.
[7] Especially Chapter 3 will focus on this subject.

2.2.2 The electricity system

Figure 2.1 presents a model of the electricity system and gives an overview of the physical and financial flows. In this report, the financial flows that result from the electricity trade is referred to as the 'commodity', to distinguish it from the physical electricity flows. The figure shows a theoretical view of the most important actors when they are completely unbundled. This means that all activities in the electricity market (production, transmission, distribution, and supply) are undertaken by different parties. Not only the grid is unbundled from production and supply, but production and supply are mutually separated as well. In this way the different costs and revenues of every separate activity can more easily be made transparent. In integrated companies, revenue and expenditure streams between the different activity-based departments are not always explicitly known.

Market actors

In the liberalised electricity market, several relevant parties can be distinguished:[8]

- The *producer* is responsible for generating electricity (large power producers, including offshore wind power, as well as DG-operators that produce electricity with small scale distributed generation (DG), including onshore wind power).
- The *transmission system operator* (TSO) is responsible for operating, ensuring the maintenance of and, if necessary, developing the transmission system in a given area and, where applicable, its interconnections with other systems, and for ensuring the long term ability of the system to meet reasonable demands for the transmission of electricity. In this context *transmission* stands for the transport of electricity on the extra high-voltage and high-voltage interconnected system with a view to its delivery to final customers or to distributors, but not including supply[9].
- The *distribution system operator* (DSO) is responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long term ability of the system to meet reasonable demands for the distribution of electricity. In this context *distribution* means the transport of electricity on high-voltage, medium voltage and low voltage distribution systems with a view to its delivery to customers, but not including supply.
- The *supplier* is responsible for the sale of electricity to customers (retail). Producer and supplier can be the same entity but this is not always the case. A supplier can also be a *wholesale customer* or *independent trader* who purchases electricity with the purpose to resell this in- or outside the system.
- The *final customer* purchases electricity for its own use and is free to purchase electricity from the supplier of its choice.

Figure 2.1[10] includes all above-mentioned stakeholders: the large power producer connected to the transmission network, the DG operator connected to the distribution network, the TSO, the DSO, a separate energy supplier, and the final consumer.

In the figure, the physical power flows have been separated from the commodity trade. Following De Vries (2004), the term *electricity system* is used to indicate the combination of the systems that produce, transport and deliver power and provide related services. It includes the actors that trade the commodity or provide trade-related services such as electricity exchanges and brokerage services. In the figure, the electricity system is divided into a technical subsystem, centred around production, transmission, and distribution of electricity, and an economic subsystem, in which the commodity and transmission services are traded. The two subsystems are related but they are not linked one on one. A generator with a constant output may have fluctu-

[8] These parties and their definitions are based on Article 2 of Directive 2003/54/EC.
[9] Extra high-voltage is defined as a voltage level equal to or larger than 220 kV. High voltage is defined as a voltage level smaller than 220 kV but bigger than or equal to 35 kV. (Website IPA Energy Consulting).
[10] The figure is partly based on Ten Donkelaar & Scheepers (2004).

ating revenues as a result of variations in market price. Both subsystems are constrained by regulations, such as safety limits; construction permits, operating licenses and emission permits for the technical subsystem, and competition law and EU directives for the economic subsystem. It is important to note that in the figure, for simplicity, different actors of the same type (like different DSOs) are aggregated into one presented actor. Furthermore, import and export of electricity are not shown as separate rectangles, as the model gives a simplified idea of the electricity market structure. However, imports have the same impact as the large power producers, and exports can be seen as additional buyers on the wholesale market (like the energy suppliers).

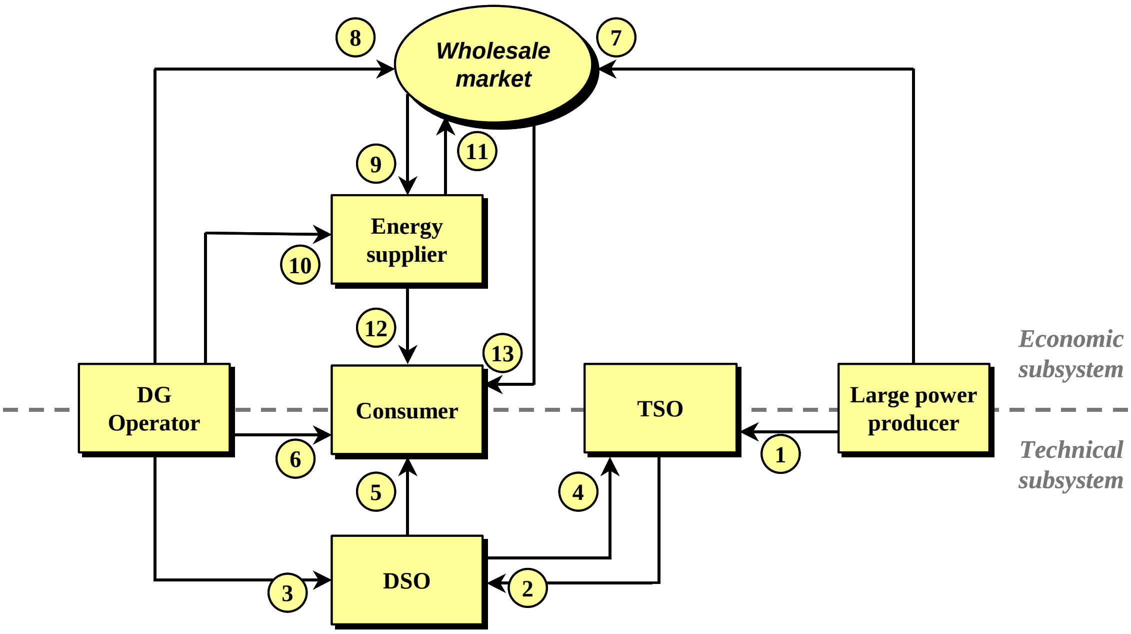

Figure 2.1 *Overview of economic and technical interactions in the electricity market*

Technical subsystem

The technical subsystem consists of the hardware that physically produces and transports electricity to customers, as well as the equipment that uses the electricity. Its goal is to ensure a secure and reliable delivery of physical electricity. The structure of the technical subsystem is determined by the nature of the components that make up the electricity supply system: the generators (large power producers and DG operators), the transmission network (TSO), the distribution networks (DSOs) and the loads (consumers). (De Vries, 2004) The technical subsystem is depicted in the lower part of Figure 2.1. The large power producers generate electricity that is fed into the transmission grid (TSO, relation 1). The TSO transports this electricity to the DSOs (2), which distribute it to the final consumer (5). DG operators generate electricity as well (onshore wind power included), but they feed the produced electricity directly into the distribution network (DSO, relation 3). Most of this electricity is then distributed to the consumer by the DSOs (5), although in some cases a local situation can occur in which supply is larger than demand. In that case the surplus of electricity is fed upwards into the transmission grid (4), after which the TSO transports it to other distribution networks (2). The increasing amount of DG capacity in electricity systems creates different kinds of network problems, because the network is not configured to transport electricity bi-directionally (4 and 2). A last relevant physical flow concerns the auto-production of DG electricity (6). This is the direct consumption of electricity produced on-site by a consumer.

At least one of the parties involved in each series of transactions from power producer to consumer must pay a transmission tariff to the system operator. Generally producers pay connection charges (in proportion of their capacity; kW) and consumers also pay for transport and system services (in proportion of their use; kWh). For clarity reasons, these use of system (UoS) and connection charges are kept out of the figures.

Economic subsystem

The physical power streams are paid for through the commodity flow.[11] This commodity flow (merely administrative) is depicted in the upper part of Figure: the economic subsystem. Its goal is an efficient allocation of costs and benefits, within the constraints imposed by the technical system. The economic subsystem is defined as the actors that are involved in the production, trade or consumption of electricity, in supporting activities or their regulation and their mutual relations. (De Vries, 2004) The economic subsystem controls the technical subsystem, but is constrained by it at as well. Large power producers (7) and some very large DG operators (8) offer the commodity to the wholesale market. There the commodity is traded between different actors. Very large electricity consumers can buy the commodity directly on the wholesale market (13). Next to those consumers, energy suppliers buy commodity in the wholesale market (9) on the basis of wholesale contracts to serve smaller consumers (12). The trade on the wholesale market actually provides a payment for the produced, physical electricity (1 and 3). Besides the wholesale market, the energy supplier extracts the commodity directly via (small) DG operators (10). The energy supplier subsequently delivers the commodity from the wholesale market and the DG operators to the consumers (12) who pay for it[12], while the corresponding physical electricity actually is supplied by the DSO (5). Because energy suppliers are often 'long' (which means they have contracted more commodity than they plan to offer to consumers) there is a commodity flow backwards to the wholesale market (11).[13] Therefore, the energy supplier is a third party that offers commodity to the wholesale market.

In the situation that the energy supplier has accurately forecasted the actual amount of electricity that his consumers use, the received payment for the commodity (12) perfectly corresponds to the amount of delivered electricity (5). But deviations from forecasted use or planned generation are often occurring, and, due to the failing of the price mechanism to balance supply and demand on the short-term, they create the need for an additional short-term balancing mechanism.

2.2.3 The balancing market

System operators and contractors have to estimate demand in order to make sure that sufficient supply is available on short (seconds and minutes), medium (hours), and long timescales (days). Because the electricity system is liberalised, the market itself is responsible for matching supply and demand on the long term.[14] As stated before, the electricity supply (output from all generators including import) has to be controlled to be very close to demand. This has to be maintained on the timescale of seconds. Maintaining the short and medium term balance is the responsibility of the system operator, which for this purpose uses forecasts of electricity production and demand that are submitted by market players (in so-called energy programs[15]).

[11] Except for the auto-production of DG electricity (6), which does not make use of the networks (DSO and TSO) and skips the commodity purchase and sale process through the energy supplier. This flow has no counterpart in the economic subsystem.

[12] Relation 12 coincides with the retail market.

[13] To be sure to have enough commodity available for consumers, energy suppliers often contract more commodity beforehand than they think they will need at actual delivery. As from a day before actual delivery (when energy suppliers have a sound insight in the commodity demand for the next day), they offer their surplus commodity to the wholesale market.

[14] Maintenance planning of generating capacity is an example of this long-term responsibility. The very long-term investment in generating capacity is another element of this responsibility which is left to the market. However, it is to be seen if these investments will be sufficient to be able to meet the growing demand on the long term. Currently, generating margins are decreasing. However, although important, the question of security or adequacy of supply is not a part of this report.

[15] Each party connected to the electricity grid, generators as well as consumers, is responsible for the supply and demand of electricity according to a beforehand made program. In this report, an energy program is referred to as the

Deviations between electricity demand and production on the actual moment of execution of the energy programs become visible to the TSO as an exchange of electrical power with neighbouring control areas, different from the agreed international exchange programs (involuntary or unintentional exchange[16]). In this way the TSO has insight in the actual balance of the total system. The TSO monitors and adjusts the collective actions of the full complement of market players at any moment, automatically compensating the imbalance, if any, of the full complement of deviations from forecasts by adjusting generating capacity up and down. If actual demand and supply deviate from the amounts that were contracted by market players, the TSO uses a balancing mechanism to balance the system by producing additional electricity (upward adjustment of production units), making use of demand response (both in case of a shortage) or by adjusting production units downwards (in case of a surplus). For this balancing purpose, TSOs can bilaterally contract balancing power from large power producers (e.g. by annual or monthly contracts). The costs for this balancing can be socialised by means of the system tariffs of the TSO. In that case, all market players pay for the balancing costs. But it is also possible that the TSO uses the forecasts (energy programs) to determine which players are not complying with their forecasts at actual delivery and, consequently, who has to pay for restoring the balance. In that case, the balancing costs are allocated specifically to the players that cause the imbalance. To stimulate market players to make their forecasts of electricity production and demand as accurate as possible and to act in accordance with these energy programs, the price for this balancing power must be above the market price for electricity. This incentive can be artificially introduced by imposing a balancing fine. However, a major drawback of the described balancing mechanism is that the exact balancing price is not univocal. Furthermore, because balancing power is only contracted once a year or once a month the system is not very efficient, as the TSO has contracted balancing power beforehand while during actual deployment there may be cheaper options available.

A more elegant and efficient way of balancing the electricity system is the establishment of a separate balancing market, apart from the wholesale and retail market. In many European control areas[17] the ongoing liberalisation of the energy market has led to the establishment of these separate balancing markets. This market is controlled by the TSO, who is the single buyer on this market. Access to the supply side of the balancing market is mainly limited to the large power producers, but DG operators (CHP-units) and energy suppliers also have access.[18] Figure 2.2 shows the impact of the balancing market. The transactions that are less common in existing electricity markets are shown with dotted lines. As soon as a situation of shortage arises, the TSO corrects this by buying the lowest priced commodity offer in the balancing market (16). Most offers come from the large power producers (14), but sometimes DG operators offer electricity as well (15, CHP units), just as energy suppliers (18). The TSO then delivers the commodity to the energy supplier (17) and receives the (relatively high) price that it has paid on the balancing market to pay the generator who produces the electricity. In case of a surplus of produced electricity, the TSO accepts and receives the highest bid in the balancing market for adjusting generating units downwards.[19] These payments between the energy supplier and the TSO

deliveries of electrical energy agreed between market players, as reported to the TSO. The responsibility for this program can be transferred between parties (small consumers pass their responsibility on to energy suppliers).

[16] An unintentional deviation is the difference between the sum of scheduled electricity exchanges in a given control area and the electricity which has actually been exchanged within a given time interval. Unintentional deviations will be corrected by means of a compensation programme for the supply of electricity to (or the importing of electricity from) the remainder of the system during the following week, in accordance with fixed rules.

[17] A control area is a concept that usually coincides with the territory of a country and is operated by a single TSO. In this report, control areas are sometimes referred to as ‘countries’. This may in fact be incorrect: e.g. Denmark and Germany exist of two and four control areas respectively, and consequently have as many TSOs.

[18] The offers of energy suppliers in the balancing market commonly consist of electricity produced within the ‘utility’ (the supplier is vertically integrated with a power producer). However, in the figures these actors are strictly separated. Demand response by their consumers (curtailment or shift of electricity use) is another option for energy suppliers for offering on the balancing market, but this is not commonly done yet.

[19] Normally, producers have to pay the TSO (a relatively low price) for adjusting generating units downwards during a surplus in the total system. But it is possible that a negative price for electricity develops, in which case the producer receives money for producing less electricity (adjusting generating units downwards).

are called imbalance charges. Handling these imbalance charges is arranged in the energy contracts between market players, but mostly energy suppliers are responsible for the demand of its contracted consumers and contracted DG-operators. Therefore, the energy supplier has to pay the balancing costs in case there is a deviation of the forecasted use of its consumers or forecasted generation of its contracted DG operators.[20] In case a large power producer does not comply with its contracts, e.g. there is a malfunctioning of a generating facility; it has to pay for the balancing costs itself, as large power producers are responsible for their own energy program. As stated before, to stimulate market players to make their forecasts of electricity production and demand as accurate as possible and to act in accordance with these energy programs, the price for balancing power (imbalance charges) must be above the market price for electricity. Because balancing power is typically provided by units with high marginal costs, this is practically always the case.

In conventional electricity systems, (contracted) imports and exports are not used in balancing supply and demand on the short term. Imports are traded on daily, monthly and yearly basis. However, if the imbalance deviates outside the specified standards and the balancing market cannot restore the balance between demand and supply, more drastic measures are required. Most TSOs have an agreement with neighbouring control areas that they will supply electricity in the event of an imminent overload or underload. This situation cannot last for more than 15 minutes. Section 2.3 will discuss this subject in more detail.

The physical electricity that is generated for the balancing market (1 or 3, depending on the contracted party) follows the physical electricity path as described for Figure 2.1.

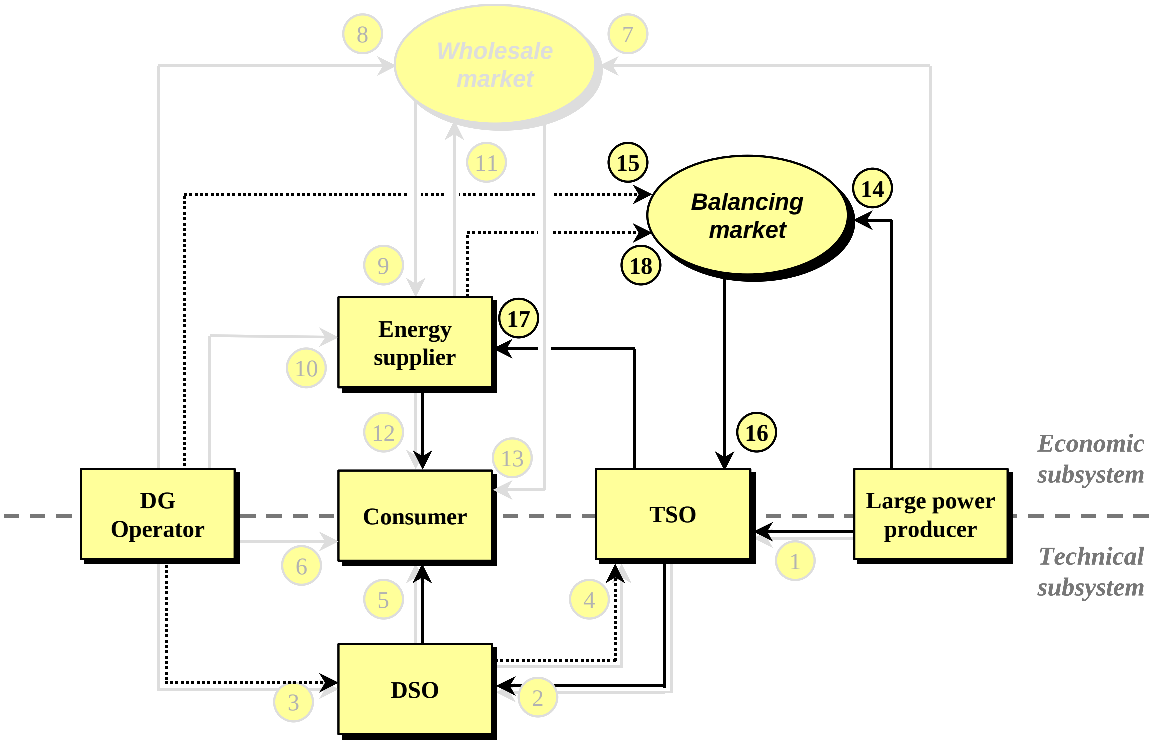

Figure 2.2 *Overview of transactions within the electricity market, including the balancing market*

[20] An energy supplier takes over the 'energy program responsibility' of consumers. This means the responsibility of customers (who are not protected customers or licence holders) to draw up, or have drawn up, energy programs relating to the production, transmission and consumption of electricity, to announce them to the grid administrators and to act in accordance with these energy programs.

Because of the intermittent nature of wind power (power output is variable and unpredictable), the imbalance costs are relatively high for this way of electricity generation, and consequently, its value to the (wholesale) market is lower.

2.3 Technical dispatch of balancing power and its international context

The main objective of a power system is to satisfy the demand for electricity power effectively, efficiently, and reliably within certain technical, environmental, and economic constraints. This requires day-to-day operation of installed generation capacity in a way that follows the fluctuating demand at the lowest overall costs, provided that environmental constraints are met. The efficiency rule states that power plants are operated in order of variable costs: the merit order strategy. Capital-intensive plants with low operational costs, such as nuclear, coal and wind power, will therefore in principle be operated as many hours as possible, i.e. in the base-load. They may be run the whole year except when taken out for repair and maintenance or due to failure (forced outage): they are filling the bottom part of the Load Duration Curve (LDC) of a power system. Intermediate plants are designed to serve the shoulder load, which is not constant during the day. These intermediate plants are typical partly loaded conventional plants that use a variety of energy sources, such as coal, natural gas, or hydro. Often the demand for power exceeds this base-load and shoulder-load and the market has to run plants with excellent load-following capabilities (fast start-up). During short periods of the year demand may be extremely high. Such (super) peak-loads are fulfilled by units with low specific capital costs, quick-start capability and high variable costs due to their low conversion efficiency and/or expensive fuel (and fuel contracts), e.g. gas turbines or diesel engines, but also hydro power or pumped storage plants can be used during these periods. (Hoogwijk, 2004)

Supply and demand has to be balanced at different time scales, varying from seconds to minutes to days and longer. As already described in the previous section, the market itself is responsible for balancing demand and supply on the longer term. The TSO is responsible for maintenance of the actual, short-term balance between supply and demand in the electricity system. Because the price mechanism does not wok properly in the short term, the TSO uses an additional balancing mechanism to control demand and supply (within seconds to minutes). For this purpose, there are different kinds of generation capacity available, roughly dividable into three categories: primary, secondary, and tertiary control. When an electricity system of a certain control area is not in balance, electricity is automatically imported or exported from interconnected adjoining control areas, according to the laws of physics.[21] For this reason, balancing is an international affair, and therefore, an association has been formed that, amongst other things, coordinates the international balancing: the UCTE. This 'Union for the Co-ordination of Transmission of Electricity' is the association of transmission system operators in continental Europe, providing a reliable market base by efficient and secure electric 'power highways'.[22] The UCTE has formulated specific rules and standards concerning the different categories of reserve power.[23] (UCTE, 2000)

Primary control

If a sudden deviation between demand and supply in the interconnected European electricity grid occurs, the balance between supplied and demanded power has to be directly restored as

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[21] Involuntary exchange: the exchange of electrical power with other countries different from the agreed international exchange programmes. This situation cannot last for more than 15 minutes, according to UCTE rules. See also Footnote 16.

[22] There are four regional coordinating organisations in Europe: ATSOI in the Irish Republic, UKTSOA in the United Kingdom, NORDEL in the Scandinavian countries, and UCTE for the countries in the western part of mainland Europe and in central Europe. In 1999 these organisations recognised that there was a need to harmonise access to the grid and the conditions for use throughout the EU, particularly with regard to cross-border trade in electricity, and they set up ETSO (European Transmission System Operator) as a coordinating association.

[23] Beneath, these UCTE rules and standards are discussed, but it must be noted that they apply only to the UCTE countries and that other European countries may have different rules and standards.

much as possible by means of the primary control on production units. If there is an outage of generation in a control area, the nominal frequency of 50 Hz drops. The frequency is the measure that indicates if generation and load are in balance on a certain moment. Disturbances of this balance are neutralised by the rotating mass of the generators in power plants. If a surplus of energy is fed into the electricity system, the rotation speed of the turbines increases. In case of a shortage, rotation energy is extracted from the turbines, and the rotation speed decreases. Technical devices detect the frequency changes and intervene to restore the power balance and to bring back the frequency to its nominal value (of 50 Hz). The frequency is the signal for previously determined generation units throughout the whole UCTE system to raise or diminish their output within seconds, limiting automatically the frequency deviation occurring in the system. This control function, the primary regulation, is shared by all UCTE countries, which act simultaneously. The bigger the system, the smaller the risk that disturbances cannot be overcome, provided that no congestion problems occur on the net. A large system can overcome extensive disturbances within seconds by direct regulation of the rotation speed of generating units.

Some characteristics of the primary control:
- The maximum instantaneous deviation between generation and demand to be corrected by primary control is 3.000 MW for all UCTE partners together.
- Each country contributes to primary control in accordance with its respective contribution coefficient C_i, where C_i is the share of annual electricity generation in country i in total UCTE production. This share is determined annually.
- Primary reserves should be activated within 15-30 seconds.
- After activation, the altered output must be able to be maintained for at least 15 minutes.
- There is no payment for the primary control that generators supply.

Secondary control
After the automatic activation of the primary control, the TSO activates to restore frequency to the pre-set value of 50 Hz, within minutes, the secondary regulation reserve generating capacities to secure the import/export balance with neighbouring control areas. When this is achieved, the units acting in primary regulation in the whole synchronous system return to their normal operational conditions, prepared to balance a new impair. This secondary control (or spinning reserve, or rotating reserve) is provided chiefly by storage stations, pumped-storage stations, gas turbines, and by thermal power stations operating at less than full output. The costs that TSOs make with contracting the secondary reserves are remunerated by the Use of System (UoS) charges (network charges), paid by the end users.

The function of secondary control in a given control area is the maintenance of the scheduled power exchange programme between the control area concerned and all adjoining interconnected control areas. Its goal is the restoration of the synchronous system frequency to its set point value (50 Hz). Secondary control takes over from the primary control reserve deployed by all UCTE members to offset an imbalance between generation and demand. Ideally, only the TSO of the control area where the imbalance appeared will respond and initiate the deployment of the requisite secondary control capacity. These actions on generated power and frequency will take place either in response to minor deviations which will inevitably occur in the course of normal operation, or in response to a major discrepancy between generation and demand associated e.g. with the tripping of a generating unit. Secondary control must begin within 30 seconds of the disturbance concerned, i.e. when the action of primary control is completed, and must be fully deployed within 15 minutes (the minimum duration that primary control must be able to maintain the altered output after activation). The size of the secondary reserve within a country depends on the peak load in that country and can be derived from Figure 2.3.

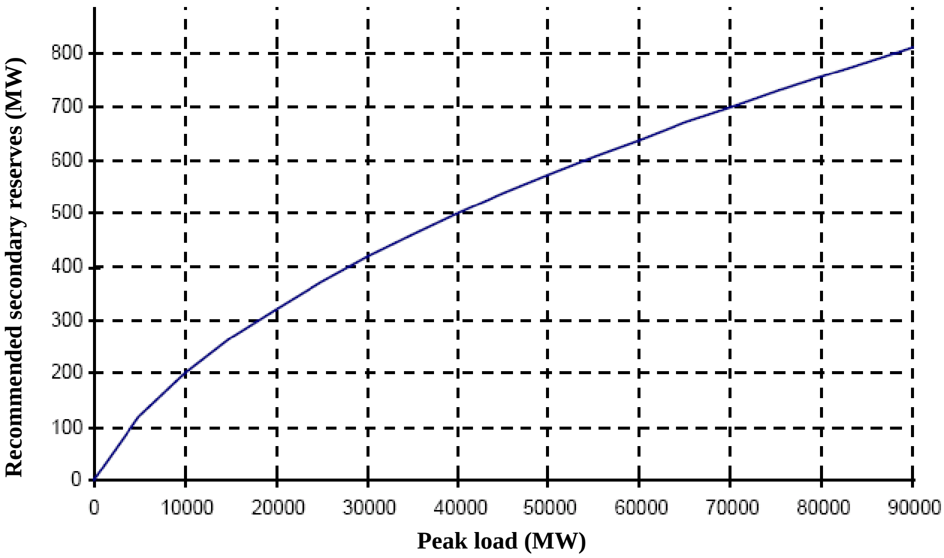


Figure 2.3 *Recommended size of secondary reserve within a country (UCTE, 2000)*

Primary and secondary reserve is provided in the framework of the 'frequency control' system service by those power plant operators that have implemented, in co-operation with the TSOs, the necessary technical measures and have been bound by the TSO by contract to provide this reserve, and are called upon to make it available. Hence, this reserve is well known to the TSO.

Tertiary control

If the imbalance deviates outside the specified standards, more drastic measures are required. If secondary reserves are lengthy used, offers of tertiary reserves are called upon. Tertiary control (or reserve power or stand-by reserve) is generating capacity or interruptible load that must be available in the market to maintain the balance in the electricity system during exceptional deviations in demand or supply. These reserves are offered on the balancing market. Tertiary reserves are provided by the power plant operators that have to start thermal power stations for this purpose. Reserves are activated as a function of the contractual arrangements concluded between customers and power plant operators, independently to a large extent of TSOs. In some countries (e.g. in the Netherlands), the TSO has contracted additional, permanent options on 'emergency power' to be dispatched if the balancing market cannot be appealed to. These options also fall under tertiary control and cause a discrete leap of the balancing price when called upon.

2.4 The efficiency of the balancing system

This section briefly discusses some points of interest regarding the efficiency of the balancing system. Thereby, the focus is on the balancing mechanism concerning secondary, but mainly tertiary control[24], and henceforth, imbalances refer to the demand and deployment of secondary and tertiary reserves (primary control is left out of consideration).

The most efficient balancing system neutralises actual imbalances by deploying the generating balancing unit that has the lowest (marginal) costs at that time. If the TSO makes long-term contracts for balancing power with power producers, there is a loss of efficiency because the TSO contracts balancing power beforehand while during actual deployment there may be options available with lower costs. In that respect, the establishment of a balancing market is an improvement, because the deployment of balancing units has become a continuous, real-time process (at least for part of the balancing power). At each moment of imbalance, the balancing

[24] Secondary control is at least partially contracted by the TSO beforehand and primary control is deployed automatically.

unit with lowest costs can be called upon. However, the efficiency of the balancing market is bound by the offers of the market players. Only balancing units that are offered to the balancing market are available for deployment. Therefore, it is of major importance that available generating capacity (that is suitable for balancing purposes) is actually offered to the balancing market. That determines the efficiency of the balancing mechanism. In current electricity markets, access to the supply side of the balancing markets is mainly limited to large power producers *within* the concerning control area.[25] This means that the efficiency of the balancing system is restricted by the physical borders of the control area. Low-cost balancing power from adjoining control areas that is available during a situation of imbalance, is not allowed to be offered on the concerned balancing market. This implies a less than optimal efficiency. A possible solution for this problem is to enlarge the control area, by e.g. consolidating adjoining control areas.[26] A requirement is that the interconnection capacity between the former control areas is sufficient to prevent congestion resulting from extra balancing flows. That can imply that current networks have to be reinforced or new lines have to be constructed. Costs and benefits have to be weighed to determine which is the most efficient.

In addition to this, there are alternatives for above-mentioned short-term balancing options that may increase the efficiency of the balancing mechanism. The use of storage may (in the future) be more efficient than the deployment of (other) balancing power. Furthermore, using demand response can be an efficient way of neutralising deviations between demand and supply.[27]

[25] As stated in section 2.2.3, energy suppliers (demand response) and DG operators sometimes have access to the balancing market as well.
[26] In Germany, the option is researched to consolidate the current four control areas into one new one.
[27] Point of attention is that demand response may be of less value in the short-term balancing of the electricity system (secondary control).

3. IMPACTS OF WIND POWER ON THE ELECTRICITY SYSTEM

In some regions in Europe, generation from wind power already plays a significant role in meeting electricity demand. In Denmark, for example, the share of wind electricity in the electricity supply on annual basis is about 17 percent (Danish Wind Industry Association, 2002), and in Schleswig-Holstein, a region in Germany, about 25 percent (Bundesverband Wind Energie, 2003). In the concerned control areas, these figures can be much higher from time to time, in case there is a lot of wind during off-peak hours. Figure 3.1[28] gives an overview of the development of wind power in the EU and Figure 3.2[29] gives the current status for separate EU-15 Member States (in capacities, not in energy).

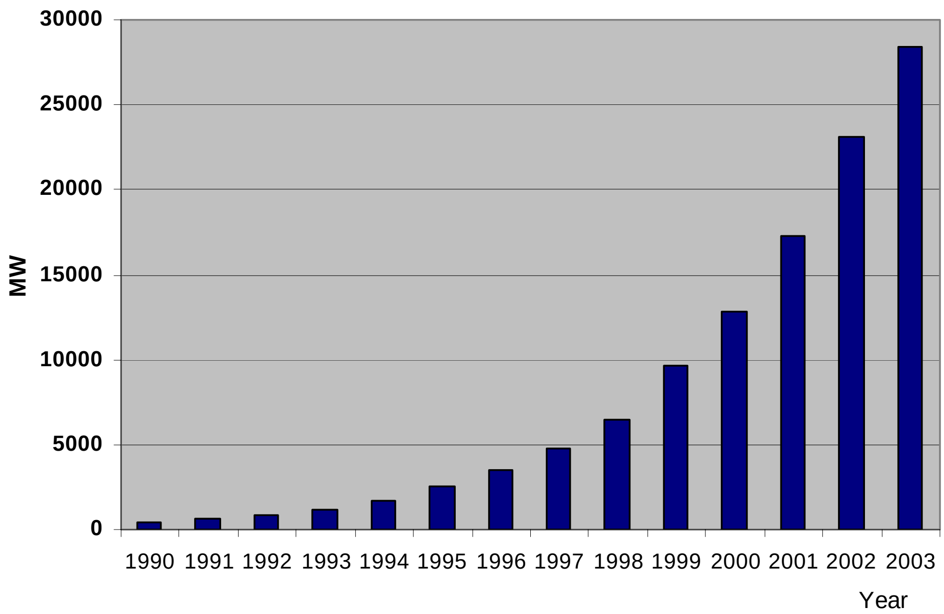


Figure 3.1 *Wind Power Cumulative Capacity EU 15*

Great challenges of wind power production are created by the limited predictability and the high fluctuations in production levels as the energy source of wind turbines, i.e. the wind, is not controllable and fluctuates randomly. Location of resources, whether onshore or offshore, poses additional logistic problems as they are in general located in remote areas far from population centres and transmission network facilities. In case of offshore plants, the additional costs of constructing offshore and the longer distance to be covered for connecting to the grid must be considered. Using intermittent sources such as wind to produce electricity differs from generating electricity by conventional power plants, because availability and quality are largely outside control of the system operator (TSO). This has technical consequences as well as economical consequences for the power system at different time scales, varying from seconds to minutes to days and longer. Sections 3.1[30] and 3.2 discuss technical and economical impacts of an increasing penetration of wind energy in the electricity system.

[28] Source: http://www.bwea.com/media/news/ewea2003.html.

[29] The data for the installed wind power by the end of 2003 are derived from the website of the British Wind Energy Association (www.bwea.com/energy/Europe.html). The given percentages represent the wind generating capacity in 2002 as a fraction of total generating capacity in 2002 per country and are derived from IEA statistics (Electricity Information 2004).

[30] Section 3.1 has been prepared by J.T.G. Pierik of ECN Wind Energy.

Figure 3.2 *Wind power installed in Europe by the end of 2003 (in MW and as a fraction of total generating capacity per country)*

In Work Package 4 of the GreenNet project, five case studies are made, which separately describe the electricity systems of Austria, Denmark, Germany, the Netherlands, and the United Kingdom. They are available on the GreenNet website.

3.1 Technical impacts of wind power on the electricity system

3.1.1 Electrical power system control

The two main variables in the electrical power system are frequency and voltage. The main function of the electrical power system is to deliver at any moment the required amount of electrical power to the consumers while maintaining the system frequency and the node voltages within the required margins.

The frequency is the number of oscillations of currents and voltages per second (typically 50 or 60 Hz). The frequency is a system wide variable and is the same at any location in the power system. There is a direct relation between the frequency and the rotational speed of all generators in the power system. A mismatch between power production and power consumption (imbalance) leads to a change in frequency. Since there is practically no storage in the system[31] this mismatch must be corrected immediately. In each control area the grid operator is responsible for maintaining the frequency close to the required value. Frequency problems can be solved anywhere in the system by increasing or decreasing the electric power production at least as long as sufficient transport capacity is available to get the power to the demand centres. From an economic point of view it is often better to generate power as near to the demand location as possible to reduce the transport losses.

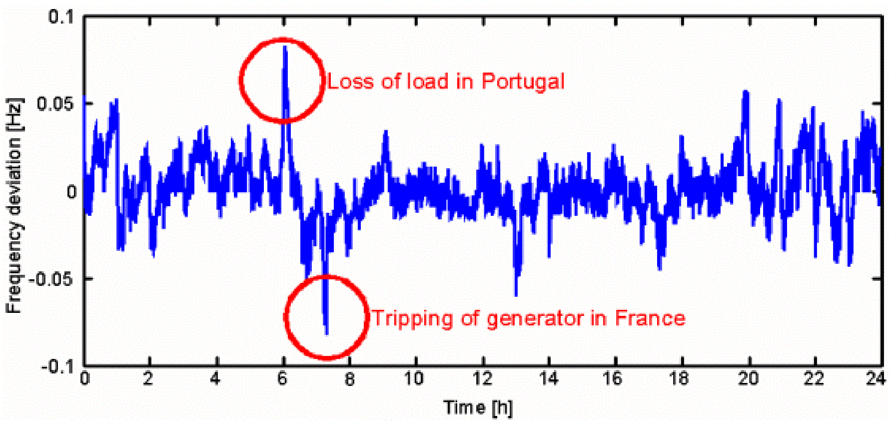


Figure 3.3 *Two events in the European Electrical Power System on January 10, 2001 leading to frequency excursions (Slootweg)*

The second main control parameter in the electrical power system is the grid voltage. The goal of the voltage control is to keep node voltages close to their nominal values in order to assure correct operation of customer equipment and to prevent equipment, both of the grid company and the customer, from being damaged. The voltage is a local parameter: its value depends on the location in the grid. Therefore, voltage control is mainly a local matter. The primary sources of voltage control are the controllers on the electrical generators in the power stations. In the transmission and distribution systems the voltages are controlled by the transformers (active or passive) and by reactive power compensation.[32] Voltage problems must be solved in the vicinity of the location where the problem exists.

[31] Only the rotating masses of the generators and motors connected to the grid form a small buffer.

[32] Reactive power is the quantity associated with an alternating voltage and the out-of-phase component of the alternating current. It is independent of the amount of power associated with the voltage and the in-phase component of the current, but it strongly affects local voltage levels.

Types of wind turbines

Electrical systems in wind turbines differ from the synchronous generator used in conventional power plants. The two main types of wind turbines in production nowadays are the (horizontal axis) constant speed and the variable speed turbine. A recent development is a variable speed turbine equipped with a Doubly Fed Induction Generator (DFIG). Three different types of turbines are discussed in this textbox:

- Constant speed turbine
- Variable speed turbine with synchronous or induction generator
- Variable speed turbine with doubly fed (wound rotor) induction generator.

Constant speed turbine

In a constant speed turbine, an induction generator is directly connected to the grid by means of a transformer. This implies that the generator speed is practically proportional to the grid frequency, which is practically constant. In this concept, wind speed variations do not result in turbine speed variations but immediately result in electric power variations. The power converted from the wind is limited by designing the turbine rotor in such a way that its efficiency decreases in high wind speed. The induction generator always consumes reactive power; hence capacitors are necessary close to generators to avoid a voltage decrease. Induction generators cannot control the voltage. In general, constant speed turbines are relatively small (less than one MW).

Variable speed turbine with synchronous or induction generator

In these variable speed turbine types, the generator stator is connected to the grid via an AC-DC-AC converter. The frequency in the stator is variable; it is not linked to the grid frequency. In this concept, the speed of the turbine will follow the wind speed, and wind power variations are not directly transferred to the grid.

Variable speed turbine with doubly fed induction generator

A recent development is a variable speed turbine equipped with a Doubly Fed Induction Generator (DFIG): an induction generator with a wound rotor is connected via an AC-DC-AC converter to the grid. By changing the frequency in the rotor, the turbine speed can be controlled.

The variable speed turbines are generally larger and are better suitable for large wind farms than constant speed turbines. They are well controllable and can flexibly handle grid disruptions.

The characteristics of wind power are reflected in a different interaction with the electricity system. Impacts can be divided into a local and a system-wide component. Local impacts of wind power are impacts that occur in the (electrical) vicinity of a wind turbine or wind farm and can be attributed to a specific turbine or farm. Local impacts occur at each turbine or farm and are largely independent of the overall wind power penetration level in the system as a whole. System-wide impacts, on the other hand, are impacts that affect the behaviour of the system as a whole. They are an inherent consequence of the application of wind power, but cannot be attributed to individual turbines or farms. These system-wide impacts have consequences for balancing the electricity system and become stronger if the penetration level increases. Both forms of impacts are discussed in this section.

3.1.2 Local impacts of wind power

Local impacts of wind power mainly concern the effect of wind power on the (local) voltage. The local items to be considered are:

- Steady state voltage deviations
- Power quality
- Voltage control.

Steady state voltage deviations

Steady state voltage deviations are not specific for wind power. If currents flow in lines or cables this inevitably leads to a voltage difference over the line or cable. A voltage difference is required for a flow of power. This need not always be a difference in voltage amplitude, in an AC systems a difference in phase is also a perfectly suitable driver. In most cases there is an amplitude difference however, and the deviation from the desired amplitude needs to be limited. If turbines are connected to the grid at a low voltage level, voltage deviations can be reduced by:

- Increasing the rating of the connection (expensive),
- Reactive current compensation (constant speed turbine) or reactive power control (variable speed turbine),
- Changing the tap settings of the grid transformer one-voltage level upstream (not the turbine transformer).

Power quality

Power quality examines the electric power produced by a turbine or wind farm with respect to:

- Reactive power production
- Flicker (dynamic voltage fluctuations)
- Harmonic distortion.

Reactive power is the result of a phase difference between alternating current and alternating voltage and causes additional losses in the grid. Constant speed turbines (see the above textbox) consume reactive power and this is often compensated by capacitor banks installed in the turbine. Variable speed turbines with self-commutating switches[33] can control the amount of reactive power.

Flicker is caused by wind power variations, which result in voltage amplitude variations. Voltage variations in the range of 0.2-1600 oscillations per minute can lead to visible fluctuations in the intensity of the light produced by light bulbs. The visibility of the fluctuations depends on the amplitude of the voltage variations. Constant speed systems tend to produce more flicker than variable speed systems since wind speed variations are immediately transmitted as electric power variations and the oscillations of the mechanical-electrical system of the turbine (for instance drive train oscillations) are also transferred to electric power variations. The electric power output of variable speed systems is less sensitive to wind speed variations and the flicker caused by these systems is generally low.

Harmonic distortion occurs if currents and voltages are not sinusoidal. Nonsinusoidal currents and voltages result in extra losses, which may cause problems in consumer appliances and may cause overloading of grid components. Harmonic distortion is mainly caused by power electronic devices (AC-DC converters), which contain switches. Therefore, constant speed turbines are not considered to be a significant source of harmonics, while variable speed systems are. The best way to solve this problem is to apply filters at the source, i.e. at the grid connection of the variable speed turbine.

[33] Self-commutating means that the moment of interruption of the current in a switch can be controlled.

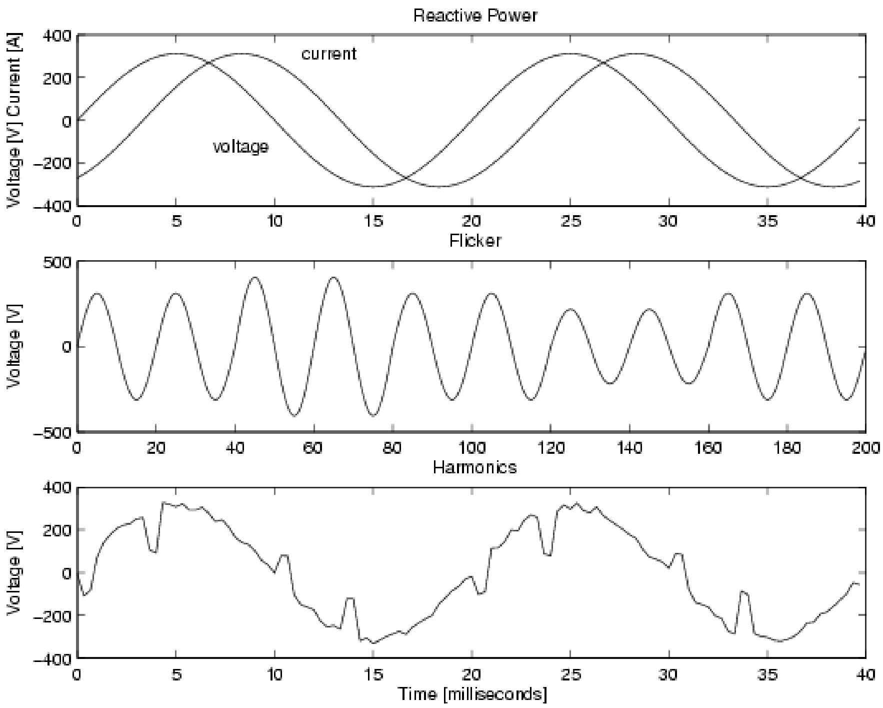


Figure 3.4 *Illustration of the different aspects of power quality*

Local voltage control

Local voltage control depends on the local grid properties, whether the connection is predominantly resistive or inductive in nature and secondly the controllability of the reactive power. Figure 3.5 illustrates the effect of an increasing amount of reactive current on the voltage at the turbine in case of an inductive connection between the turbine voltage U_1 and the grid voltage U_2. The grid voltage is constant (dictated by the grid transformer upstream) and the turbine voltage can be changed by changing the amount of reactive power. In the figure, the sinusoidal currents and voltages are represented by vectors. The length represents the amplitude of the sine wave and the direction represents the phase shift. In this example, an increase in reactive power (the current component perpendicular to the voltage increases) gives a decrease of the turbine voltage. Thus, turbines with reactive power control capability are able to control the voltage at the turbine or at the point of connection of the turbine to the grid. Variable speed turbines are able to support local voltage control.

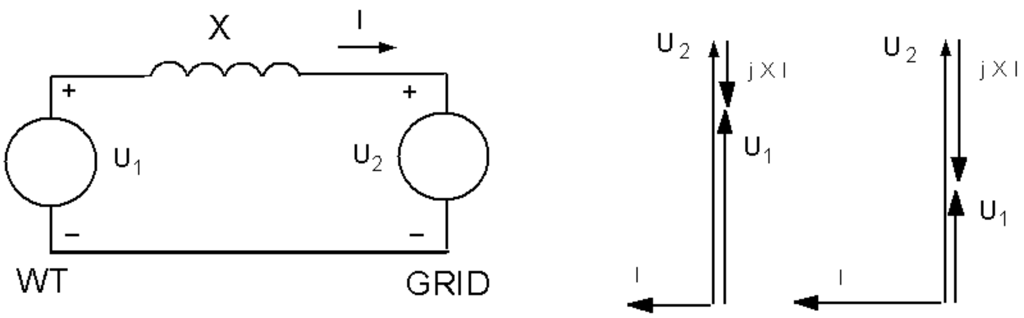


Figure 3.5 *Effect of the reactive power on voltage U_1*

3.1.1 System-wide impacts

System-wide impacts of wind power are:

- Output power variability, predictability and secondary reserve.
- Contribution of wind power to a fault current.
- Transport capability and grid reinforcement, required extra grid control equipment.
- Undesirable power flows.
- Power system dynamics and stability.
- Power system reliability:
    - Fault ride through,
    - Wind farm outages and extreme wind speed changes.
- Power limitation and contribution to frequency control.

Output power variability, predictability and secondary reserve

Wind power is by nature a variable source of power. Without special control measures, wind power hardly ever contributes to primary frequency regulation.[34] Further, the variability of the wind on the longer term (15 minutes to hours) tends to complicate the load following with the conventional units that remain in the system. This is a problem for the grid operator if a substantial amount of the consumer demand is generated by wind power. The frequency control capability has to be secured to provide stable operation of the grid and this may require more rotating reserve (instantaneously available backup power; secondary control) than in the case of a mix of conventional production. Variability, predictability and controllability of wind power will affect the need for the rotating reserve. The impact of wind power on frequency control and load following becomes more severe the higher the wind power penetration level is. The (economic) impacts of variability, predictability and controllability of wind power will be discussed in more detail in section 3.2.

Contribution of wind power to a fault current

Wind turbines and wind farms will contribute to the fault current of a nearby fault; the contribution will depend on the type of turbine and its control.[35] Protection devices in the grid have to take this contribution into account and additional switchgear may be required since otherwise cables and lines may overheat or be damaged. Constant speed turbines with induction generators will typically contribute more to the fault current than variable speed turbines with controlled converters. Converters are capable of limiting currents during voltage dips.

Transport capability and grid reinforcement, required extra grid control equipment

Transport capability and grid reinforcement is another issue to be considered in case of large-scale introduction of wind power. In a recent study on the introduction of 6 GW offshore wind power in the Netherlands it was shown that this requires the extension and reinforcement of the high voltage grid of the Netherlands. (Jansen & De Groot, 2003) The location and the type of measures depend on the location at which the wind power is fed into the grid. Substations have to be upgraded, additional transport capacity for overhead lines has to be realised and capacitor banks have to be built to keep voltages at some grid locations within acceptable limits. A similar study has been done to the situation in the UK. (ILEX, 2002)

Undesirable power flows

The effect of large amounts of wind power on the flow in the European grid can be illustrated by the recent changes in power flow in the border region of Netherlands and Germany. The North of Germany is a substantial wind power producer and part of this power is transported to the South of Germany. Due to local voltage levels, part of this power passes the border to the Netherlands in the North and returns to Germany via the South of the Netherlands. This power

[34] Variable speed wind turbines with pitch control can contribute to frequency control by sacrificing energy yield. See *Power limitation and contribution to frequency control* at the end of this sub section.

[35] Variable speed turbines are better able to resist fault currents than constant speed turbines.

flow cannot be influenced easily, since the direction of power flows in a standard transformer cannot be controlled. The Dutch grid operator TenneT recently installed special transformers with additional sets of windings, which not only maintain an amplitude difference between the two sides but also can control the phase difference between the voltages on both sides. In this way the amount and direction of power flow over the transformer can be controlled.

Power system dynamics and stability

Power system dynamics and stability is a complicated issue. Power system stability is the property that a power system is able to stay within the required operation range, also when subject to disturbances and preferably with a minimum of oscillation. From the point of view of an average consumer, the electrical power system looks very stable (no flickering lights, conditions seem to be constant) but this is not really the case. (Local) voltages are changing all the time. So looking more closely, there is a lot of transient behaviour (dynamics) in the system, which is caused by on the one hand the consumer load changes (disturbances for the system) and on the other hand by the response of all power plants and other controlling devices to these demand changes. One of the important phenomena in dynamic studies in power systems is the rotor angle oscillation of the large synchronous machines, which control the grid voltage and frequency. These oscillations are badly damped and thus potentially unstable. The angles of the machines depend on the power produced by the machines, so the stability also depends on the operating condition of the grid. A second stability problem is voltage stability and voltage collapse. In many cases a blackout is not caused by insufficient power production capability but by insufficient (local) reactive power production in combination with insufficient transport capacity. If, for instance, a large power plant shuts down unexpectedly due to a fault, then the power has to come from other plants in the vicinity and has to be transported to the load centres. However, the support of the local voltage by the faulted power plant has also vanished. Supporting local voltage requires reactive power and if the lines are already fully used, this cannot be supplied, resulting in voltage collapse.

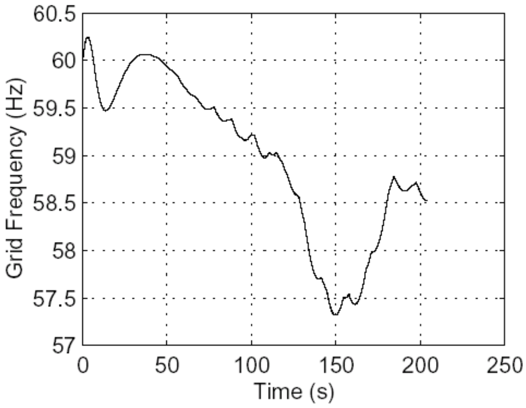
Wind power has an effect on power system dynamics and stability in two ways:

- Since wind turbines do not use synchronous machines (the standard machine in large power plants) they will not display rotor angle oscillations and have a different effect on system dynamics than conventional plants. The concrete effect depends on the type of turbine, the electrical system of the turbine and its control.
- Wind turbines and farms that can assist in voltage control, can be useful in preventing local voltage control problems. This is not only relevant during normal operation of the power system, but even more so during faults and the clearance of faults.

Power system reliability

The reliability of the European power system is high. Almost everywhere in Europe we take for granted that a blackout is very rare and even severe voltage dips are scarce. This is mainly the result of the design philosophy of the grid, which tries to separate problems with malfunctioning equipment by automatically operating selective protection devices. Only the section of the grid with the fault is taken out of operation, and switched back on again after the problem is solved. Secondly, the power system design takes into account that each component can fail or is taken out of operation (especially the shut down of a large production unit). The system then still has to be able to continue operation and supply the demanded power. If the mix of production units is changing, in this case conventional production is replaced by wind power, this will have an effect on the system reliability. On the one hand, the failure rate of components in large wind farms and its effect on the production of the farm has to be considered. On the other hand, power system operation with wind farms shutting down has to be checked. See also the below textbox.

Extreme wind conditions in Costa Rica
Power system reliability can be affected by extreme wind conditions since these may result in loss of a large amount of wind power within minutes. A specific example, possibly the most severe imaginable, is discussed in a recent study for the high voltage grid of Costa Rica, which currently includes about 6% (66 MW) wind power, while plans exist for more. The study shows that disconnection can have a large effect on the grid frequency; see the below figure that illustrates a simulation of ICE, the TSO of Costa Rica. A frequency dip of this size cannot be sustained by the grid and will lead to load shedding. The almost instantaneous disconnection of several wind farms at the same moment is, however, very unlikely.



Frequency dip of the Costa Rica grid in isolated operation resulting from a shutdown of 198 MW wind power in three minutes (Pierik and Montero)

With an increasing amount of wind power in their grid control area, grid operators impose additional requirements on wind farms. The most severe one is the so-called *fault ride-through capability*. Grid operators require that large wind farms stay in operation during a severe voltage dip. Wind power should not disconnect immediately due to a fault and the subsequent voltage dip, because this would lead to the loss of a large amount of generation, and thus make a recovery process more difficult. Turbines without pitch control cannot satisfy this requirement. Variable speed turbines with controllable converters have the additional advantage of limiting the fault current during the dip. The DFIG system needs additional control equipment in order to survive the voltage dip without damage.

Power system reliability can also be affected by extreme wind conditions since these may result in loss of a large amount of wind power within minutes.

Power limitation and contribution to frequency control
Power limitation can be useful in cases where the wind power cannot be used locally and cannot be transported to distant demand centres. This condition sometimes occurs in the North of Denmark. Variable speed wind turbines can easily be modified to limit or reduce production depending on the grid conditions.

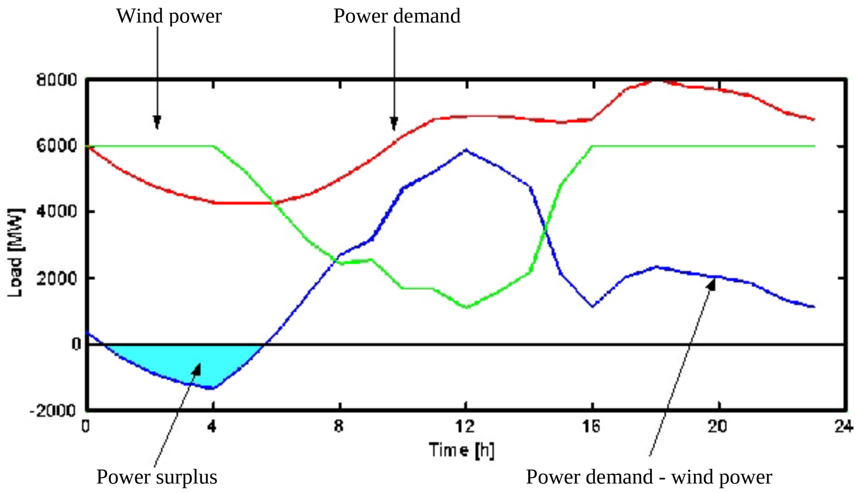


Figure 3.6 *Example of a power surplus in a grid control area (Slootweg)*

Generally, wind turbines are programmed to produce the maximum amount of power given the variations in wind speed. Thus the power is dictated by the wind and wind power does not contribute to frequency control. In order to support the grid frequency by wind power, the turbine power should react to changes in frequency. Variable speed wind turbines with pitch control can contribute to frequency control by sacrificing energy yield. A margin is kept between the actual production and the production based on the actual wind speed. During a frequency dip, the wind farm increases its power to the maximum available value at that moment. Since power control in wind turbines is relatively fast, this helps the frequency recovery. However, this control option has a price, since a certain amount of wind power is sacrificed. Frequency control with constant speed turbines is only possible if the turbines are equipped with pitch control.

3.2 Economic impacts of wind power on the electricity system

3.2.1 Additional cost factors with increasing penetration of wind power

Based on Hoogwijk (2004)[36], there can be distinguished four mutually related factors, which tend to cause additional costs as wind power penetrates deeper into the local or regional system:

1. Declining quality of the resource in terms of power density and location (onshore).
2. The need for large investments in back-up capacity due to a low and decreasing capacity credit[37] of wind power.
3. Additional operational requirements, such as an increase of secondary reserves due to the fluctuating nature of wind power.
4. The necessity to discard part of the available wind electricity at higher penetrations unless this energy can be stored.

Declining quality of resource

As is discussed in the previous section, with increasing installed wind capacity, power generation costs will tend to increase as less favourable sites come into operation. Wind speeds may be lower, as well as load factors. And additional (transmission and distribution) network costs may be necessary to integrate the wind power into the system, as new locations can be less favourable from the perspective of grid (voltage) control.

[36] The whole section 3.2 is mainly based on Hoogwijk (2004).
[37] The capacity credit assigned to a regenerative conversion plant is the fraction of installed (regenerative) capacity by which the conventional power generation capacity can be reduced without affecting the reliability of the system (loss of load probability).

Need for back-up capacity

Another cost impact with rising shares of wind power is the need for additional back-up capacity (reserve power or tertiary control).[38] Because wind power is not always available during parts of the day or the week and possibly during hours of maximal demand, and this non-availability is practically unpredictable for the long term, wind power has a negative impact on the system reliability. For each additional MW of wind capacity that is installed, only a small part can be considered to be available capacity from a system operating point of view. The fraction of installed wind capacity by which the conventional power generation capacity of the electricity system can be reduced without affecting the reliability of the total system is called *capacity credit*. The capacity credit depends on, amongst other things, the penetration level of wind power, on the characteristics of the generation mix in the total system, and on the grid characteristics. A low or zero capacity credit means that the reserve margin (tertiary control) has to be increased by the installation of back-up capacity with good load-following capabilities. Model experiments on the capacity credit of wind turbines show that at low penetrations of wind power, the capacity credit equals the load factor.[39] (Hoogwijk, 2004) Wind energy does have a capacity credit and can therefore be relied upon, although the wind is not always available. However, as the level of wind penetration rises, the capacity credit begins to tail off.[40] Part of the cost-increasing back-up power that consequently has to be installed to keep the system reliable should be allocated to wind electricity production.

Additional operational requirements

In the previous passage, the need for tertiary reserves (back-up capacity) resulting from the possible non-availability of wind power is indicated. But next to the possible non-availability of wind power, wind power generation has a fluctuating nature on the short term as well (within 15 minutes of actual delivery), which has a negative impact on the load-following characteristics of the electricity system. Due to storms, short-term fluctuations can become extreme, as sudden drops of significant amounts of wind power are possible if the wind speed exceeds the cutout wind speed of the turbine. The fluctuating nature of wind power on the short term causes a need for additional secondary reserves (regulation power). Additional secondary reserves must be deployed to overcome short-term fluctuations in power output. Besides, a change in operational strategy (dispatch or contracting of more load-following capacity) may be necessary. The variability in power output requires quick-start capacity, which is obtained by the secondary reserve and is mostly provided by conventional thermal power stations operating at less than full output (spinning reserves: see section 2.3). However, high spinning reserve requirements lead to higher fuel use and therefore cause efficiency losses and higher emissions. Besides power plants are operating more often on part load, some of the operated conventional power plants will make more repeated plant starts - causing additional fuel costs, maintenance costs, and emissions. According to Grubb (1988), such operational losses might be in the range of maximum 5 to 8 percent of the fuel use in parts of the operated park. The level of spinning reserve at system level normally varies from 1 to 3 percent of the peak load, depending amongst others on the size of the largest plant.[41] But if wind power penetration becomes significantly high, estimates of the required spinning reserve given in the literature increase to about 10 to 85 percent of the installed wind capacity. (Milligan, 2002) (Grubb, 1988) Especially if the existing park relies on significant amounts of slow-start capacity, e.g. large nuclear or coal-fired plants, and/or if no good forecasting instruments are available, high values for secondary control are to be expected.

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[38] As discussed in Section 2.4, there are alternatives for back-up capacity, like storage (Chapter 5) and demand response.

[39] The load factor, also known as capacity factor, is the percentage of power production as a fraction of the nameplate capacity of the wind energy conversion system.

[40] Geographical dispersion of wind power can increase the capacity credit. Section 3.2.2 discusses different aspects that influence the cost factors.

[41] See Figure 2.3.

Discarded electricity
Another reason for additional costs with increasing penetration of wind power is that part of the power may be generated at times when the system cannot use it due to demand profile, the strategy of power supply used in the system, or limited transmission capabilities. Without storage options this electricity is to be discarded.

However, in most electricity markets in Europe, priority is given to production units, including wind power, that generate renewable electricity.[42] The system operator must accept all wind generation that wishes to generate at any time, in preference to generation from conventional sources. Deviations in wind power output are neutralised by the balancing market and no wind power is discarded. It does, however, lead to balancing costs, because secondary and tertiary reserves have to be deployed or adjusted downwards. In some countries, the costs of secondary and tertiary control are socialised via the TSO and paid by the end-users. In the Netherlands, only part of the secondary reserves and tertiary reserves (in the form of emergency power) is contracted by the TSO; most is traded via the balancing market.

3.2.2 Four aspects influencing the cost factors of wind power

Different aspects determine the impact of the factors that are discussed in the previous sub section. At least four of them, by affecting the penetration level and the costs of wind power, are of relevance:
1. The geographical dispersion of wind power
2. The interconnection with other grids
3. The load-following capabilities of the generation mix
4. The ability of power forecasting.

Geographical dispersion of wind power
As the geographical spread of an electricity system increases, the wind speeds across it become less correlated. Some areas will be windy, some will not. Some areas will have rising power output; others will have falling power output, etc. If wind power supply is geographically uncorrelated, supply is smoothened and fluctuations in supply are reduced. E.g. for the Northern European countries, wind power supplies from sites of more than 1500 kilometres apart are nearly uncorrelated and it was found that on a time scale of 12 hours, variation can be up to only 30 percent once a year and production is never completely down. (Giebel, 2000) If data only of Denmark are used, where wind power is less dispersed, production can come down to zero in about a few hours. Similar results for wind supply are found for Germany: fluctuations for a single turbine on a time scale of 12 hours were reported over the total power range (100 percent), whereas the output of 1496 widely spread turbines showed maximum variations of 60 percent in the 4-hour gradient. (FGW & ISET, 2000) This effect of geographical dispersion reduces the need for secondary reserves (back-up and spinning reserve capacity) due to a smoothening of output fluctuations. The need for tertiary reserves (back-up capacity, reserve power) is reduced as well, provided that there are no congestion problems in the network. This effect is powerful and the level of needed backup decreases, depending on the geographical disparity of the wind farms, the size of the weather systems and the size of the interconnected system.

Interconnection with other grids
Interconnection of electricity systems with wind energy brings benefits, and these can be characterised as being due to the ability to reduce the effect of the variability of wind. (EWEA, 2004) Interconnection between adjoining electric power systems increases the capability to match supply and demand efficiently. However, the way that interconnection capacity is placed at the disposal of the market (e.g. by an auction) can be of major influence. The importance of interconnection of national systems in Europe can be illustrated by to extreme cases: Denmark

[42] See also Section 3.3.

and Spain. The interconnection of the Danish system with the Nordic and the German system is more than 30 percent, in contrast with about 3 percent interconnection of Spain with France. The main reason for the relatively smooth penetration of large quantities of wind in the Danish system is the well-established interconnection with the large conventional fossil fuel-based power systems of central Europe (especially Germany) and with the Nordic countries having large quantities of hydropower, which is well capable of following loads. The fact that the Red Eléctrica Española (REE, the Spanish TSO) can import very little power to cover drops in voltage is mentioned as one of the main reasons for the grid instabilities due to wind power in Spain, next to low geographical dispersion of the wind resources and the difficulties with wind forecasting in mountainous areas. The degree of interconnection affects the capacity credit. (Hoogwijk, 2004)

Forecasting of power output

The planning of slow-start and quick-start capacity operation is typically done one day ahead. If the expected output from wind power can be forecasted within this period, it improves the utilisation of this source and lowers operational costs. (Brand & Kok, 2003) In the USA and Europe commercial wind forecasting instruments are available and applied. Typical accuracy reached for forecasting wind power 48 hours ahead are in the order of 10 percent, but also less accurate forecasts are mentioned. (Brand & Kok, 2003) The shorter the prediction horizon, the more reliable the forecasting is. Chapter 4 will discuss forecasting in more detail.

The load-following capability of the generation mix

The load-following capability of the generation mix is an important factor for the costs of wind power. Large numbers of quick-start plants, like gas turbines, hydropower or storage plants with high load-following capability, can compensate larger amounts of intermittent supply than typical baseload units such as large nuclear and coal-fired plants. If large fluctuations occur, this cannot be neutralised by baseload plants. If the load-following capacity is limited, it engenders high balancing costs if wind power penetration increases.

3.3 Support mechanisms

To stimulate the development of renewable technologies, at least until external costs are fully integrated into conventional energy economics, some form of market incentive is required for electricity generated from renewable energy sources. Together with good planning procedures and fair conditions for accessing the electricity grid, support mechanisms for wind power are an important ingredient of successful market development. Support for such incentives is provided by the RES-E Directive, which sets indicative targets for the level of electricity to be achieved from renewables in each member state by 2010. The overall Community target is to increase renewables' share of electricity from 14 percent in 1997 to 22 percent in 2010. Several support mechanisms are used by EU Member States to achieve these targets. The most important support mechanisms that will be discussed in this chapter are:

1. priority dispatch
2. feed-in tariff
3. tender
4. obligation
5. price support of demand side.

Priority Dispatch

Dispatch in the context of the electricity market literally means the turning on and off of production units. Priority dispatch in the electricity market means that priority is given to certain production units, for example the production units that generate renewable electricity.

Conform article 11 of the Electricity Directive, the transmission system operator is responsible for dispatching the generating installations in its area. In this directive each Member State gets the freedom to "*require the system operator to give priority to generating installations using* *renewable energy sources or waste or producing combined heat and power*" (Article 11.3). This is elaborated more in Directive 2001/77/EC on the promotion of renewable electricity in the internal electricity market. In Article 7.1 guidelines are given to member states to ensure that transmission and distribution system operators in their territory guarantee the transmission and distribution of electricity produced from renewable energy sources. When dispatching generating installations, transmission system operators shall give priority to generating installations using renewable energy sources insofar as the operation of the national electricity system permits so.

The goal of priority dispatch for renewable electricity is to maximise the contribution of renewable electricity to the electricity market. This striving for maximisation comes forth from environmental reasoning. But the output of renewable electricity can be uncertain and uncontrollable, and that may stand in the way of integrating renewable electricity into the market. Through priority dispatch it gets a protected position in the electricity market. A system of priority dispatch secures the input of renewable electricity on the grid. Wind power, however, has low marginal costs and therefore is generally deployed at all times anyhow (if there is wind). Therefore, priority dispatch for wind power especially means that it cannot be interrupted by system operators if the electricity system (particularly the network) is faced with difficulties.

Feed-in tariff

In a system of feed-in tariffs, the producer of renewable electricity receives a guaranteed price for his production when he offers his product to the market. The price has been pre-determined and is guaranteed for several years. This implies that these producers do not react on price signals from the spot market -wind power producers under priority dispatch are paid the feed- in tariff for everything they produce.

Tender

A tender is a competitive bidding system in which a certain amount of subsidy is being divided under a selected group of projects. The financing of the tender is often realised by a generic levy on electricity consumption and is being remunerated by a feed-in tariff to the selected projects. In every round of tendering the government decides how much capacity is planned to tender per renewable energy source.

Obligation

In case of an obligation, a minimum quota is being imposed on the producer, supplier or consumer of electricity towards the part of renewable electricity in his production, supply or consumption respectively. A penalty will be given if the obliged quota is not met. In most of the cases a system of tradable green-certificates is in force besides the system of obligation. Green-certificates represent the so-called green value of the production of renewable electricity. These certificates are tradable independent of the produced electricity itself. Goals of this system of tradable certificates are stimulation of competition between producers of renewable electricity, which leads to a decrease of costs of production in the long term, and another way for the parties to meet their quota, namely by buying these certificates.

Price support of the demand side

Price support of the demand side can be expressed by an ecotax-exemption. The ecotax itself tries to internalise the external costs of energy-use. Goal is to diminish energy-use. Ecotax-exemption, for example when renewable electricity is chosen above non-renewable produced electricity, functions as a subsidy on the demand side.

4. FORECASTING OF WIND POWER OUTPUT

4.1 Forecasting and intermittent sources of electricity

The need for and benefit of wind energy forecasting have been increasingly recognised in recent years. As wind energy penetration increases, the need for forecasting is recognised by system operators as essential in accommodating this intermittent energy source into the electricity network. Improved forecasting of wind power can help the party responsible for the energy program[43] to improve its internal balancing of supply and demand. This may give a higher value to the wind energy installed and possibly also reduce balancing costs.

Of all intermittent electricity generating options, the conversion of wind energy is the most widely used technology. This chapter will focus on forecasting of wind power. For integrating wind turbines into a power system it is important to distinguish two fields of concern: *predictability* and *variability* of supply from wind energy.

The limited predictability of the wind power to be supplied in short-term future complicates integration into the electricity system. This limited knowledge on wind power supply needs to be compensated by the use of balancing power (primary and secondary control) from predictable technologies, such as fossil fuelled power plants, with their total capacity available as backup, or plants running on part-load, that can increase or decrease supply on a short term (see section 2.3). One of the possibilities on improving predictability is to develop forecasting tools. This is the subject of the current chapter.

Note, that the variability is hardly decreased by using forecasting technologies. In reaction to the difficulty of integrating this variable power source into the electricity system, different strategies can be considered, including demand response and storage of electricity.[44] The issue of storage will be discussed in Chapter 5.

In the current chapter two aspects of forecasting issues are discussed. Firstly, methodological aspects of forecasting and prediction of power output from wind power are discussed. Secondly, focus will be on regulatory aspects and the role that prediction tools can play.

4.2 Introduction to wind power prediction methodology

In Europe as well as in the United States, several methods have been developed for producing prognoses with respect to expected wind energy production. Most of these methods involve the derivation of expectations regarding wind energy production from prognoses of wind speed and direction as provided by meteorological institutes. These wind prognoses are without exceptions all provided by atmospheric models. Historic and current production observations can be used to improve the expectations.

In general, such a method is divided in four steps. These (1) translate the wind prognosis on the grid points of the atmospheric model into a local wind expectation valid for the location of the wind turbine site, account for (2) turbine and (3) park characteristics and (4) correct systematic errors.

[43] In this report, an energy program is referred to as the deliveries of electrical energy agreed between market players, as reported to the TSO.

[44] Geographical dispersion of wind power and interconnection with other grids can reduce the variability as well (see Section 3.2.2).

Some of the developed systems were demonstrated only in test cases; others are fully operational. The methods that were demonstrated or operational before the year 2000 include the Prediktor and WPPT from Denmark, the methods from ISET and Oldenburg/Magdeburg from Germany and eWind from the United States of America. Today, the most important developments are carried out in the EU R&D project ANEMOS (Kariniotakis et al, 2003; Barquero, 2003). This project aims to develop accurate models that considerably outperform actual state-of-the-art, for onshore and offshore wind resource forecasting (statistical and physical). Emphasis is put on integrating high-resolution meteorological forecasts.

4.3 Method versus prediction horizon

Wind power forecasting methods can be divided in three families of models, depending on the prediction horizon on which the methods perform well: [45]

- *Persistence model:* also known as naive predictor. This is one of the most simple prediction methods in which the predictions for the future (for example tomorrow) are set equal to the most recent realised output values (for example today's measurements).
- *Meteorologically based model:* the wind power predictor uses the output of an atmospheric model as input (and additional local measurements if available).
- *Climatological model:* the wind power predictor uses climatological data as input.

The three model families each perform best in a specific prediction horizon (see Table 4.1). Persistence models are typically used for the very short term (a few minutes up to a few hours in advance). The techniques for prediction in the very short term have been fully developed and are easy to apply (Nielsen, 1998). In a time-span of approximately four hours the persistence model loses its accuracy, because the autocorrelation of the wind speed decreases strongly (Giebel, 2001).

In a time-span of a couple of hours to a week in advance, the best accuracy can be obtained through the use of meteorological forecasts. This model family typically uses the output of an atmospheric model as input and can be considered a post-processor of the meteorological model: the meteorological prediction is transferred into a power prediction.

In the long term the predictability of the weather decreases and only the climatological data remain for statements on the expected efficiency of a certain wind turbine in a certain place. This type of prognosis is typically used for long-term efficiency prognoses, e.g. the planning of new wind parks.

Table 4.1 *Three model families and their prediction time-span*

	Quarter ahead	Hour ahead	Day ahead	Week ahead	Year ahead	Decade ahead
Persistence	×	×				
Meteorological			×	×		
Climatological					×	×

4.4 Overview of wind power prognosis methods

Wind power prognosis methods can be divided into two types: the physical methods and the statistical methods. This section describes these two types and provides an explanation of the role of atmospheric models. Also, the advantages and disadvantages of the physical and statistical methods are discussed.

[45] Sections 4.3 and 4.4 are based on Kok et al. (2003).

4.4.1 Description of the physical and statistical method

A wind prognosis is the expected wind speed and direction in a future point in time. Based on such a wind prognosis the wind energy prognosis must be determined, i.e. the expected electricity production of a wind turbine or park. There are two essential methods for producing a wind energy prognosis: the physical and the statistical method.

The physical method consists of a number of sub models that together produce a translation of wind expectation at the atmospheric model's grid points into a wind energy expectation for a wind turbine or park. Each sub model contains a mathematical description of a physical process that is relevant for this translation. Examples of sub models are models that account for the effect of roughness and stability on wind speed and the effect of wakes on wind turbines in park configuration. Therefore, knowledge of all relevant processes is a prerequisite for a pure physical method.

The statistical method also consists of sub models for the translation of grid point wind expectation into local energy expectations, but in this case it is based on mathematical descriptions. The mathematical descriptions are estimators for the relevant variables. As the parameters in the estimators do not have a universal value, the parameter values must be derived from (historical) observations. This can be derived using recursive smallest squares estimates or a neural network. For a pure statistical method it is therefore necessary to consist of continuous observations in order to keep the parameter values up to date.

The main characteristic of the (weather) forecasting tools is that they try to predict the amount of wind and the intensity thereof. It depends on the type of tool that is used which data are used. In the statistical forecasting tools, meteorological data are used while in the physical forecasting tools more environmental factors are necessary to make good predictions of the amount of electricity that will be generated.

In practise, both the physical and the statistical method do not occur in a pure form. Generally, a physical method also has a statistical sub method to be able to apply systematic corrections. And a statistical method generally also relies on information from an atmospherical model.

4.4.2 The role of atmospherical models

Meteorological institutes use atmospherical models when drawing up weather forecasts in the short and medium term. These are numerical approaches of the physical description of a future situation of the atmosphere above a part of the earth's surface that are regularly calculated by supercomputers. Each calculation starts with an up to date starting point on the basis of observations. The calculation result constitutes the value of several variables per grid point and for a number of steps ahead in time.

For a number of reasons, the models provide an approximation of reality. First of all, not all atmospherical processes are represented in a model. Moreover, the starting point of a calculation can be impure and the calculation results are only available for discrete points in space (both horizontal and vertical) and in time. Finally, the starting values become outdated after a period of time. As a result of these limitations, the atmospherical models are merely tools in the determination of weather forecasts; they are not the only tools, as also other prognosis methods exist for weather forecasting.

There are many atmospherical models, varying from academic research objects to fully operational instruments. The models therefore differ both in nature of modelling (e.g. physical processes or numerical schemes) and in a number of externally recognisable aspects. These are the time horizon (from several hours up unto several days ahead), the domain (from an area of several ten thousands of square kilometres to broadly half of the earth's surface), the horizontal resolution (from one to broadly one hundred kilometres) and a time step (from one to several hours).

One of the many atmospherical models is the High Resolution Limited Area Model (Hirlam), which is used in Europe. It is better to speak of ‘a’ Hirlam model instead of ‘the’ Hirlam model because this model occurs in many different versions. These versions are maintained by various national institutes as a result of which, for example, Danish (DMI) and Finish (FMI) versions co-exist next to the Dutch one (KNMI). Beside operational versions, each institute also has versions that are pre-operational or semi-operational, as well as versions that are used for research. In order to arrive at weather forecasts up to 48 hours ahead, for example the KNMI has a Hirlam operational with a horizontal resolution of 22 kilometres. Further, a Hirlam is operational for the expectations until 24 hours ahead on a more detailed grid of 11 kilometres. Higher resolution versions are available for research purposes. In all cases hourly or three-hourly prognosis values are involved.

4.4.3 Advantaged and disadvantages of the two types of methods

The physical and statistical methods have specific advantages and disadvantages. These have been summarised in Table 4.2.

The physical methods have the advantage that they are adaptable and transferable. Various factors of influence, such as the terrain roughness around the wind turbine (park) and the power characteristics of the turbine (park), are input for the method. These parameters can be altered if necessary or desired and this means that the method can be transferred to another location by adapting the input elements. The disadvantages of the physical method are the long processing time and the fixed interval at which expectations become available. These characteristics are the direct result of using the output of an atmospherical model as input for the methods. Several hours pass between the moment of initialisation and the moment that the output is delivered to the user. Moreover, the atmospherical model runs only several times a day, i.e. two, four or eight times, depending on the model.

The advantages of the statistical methods are the large degree of detail and the self-learning capacity. These characteristics are the direct result of the use of estimators for the relevant processes. As a result, influences such as direction dependency or prognosis age are well represented in the power forecast. Moreover, the parameters in the estimators adapt to the changing situations such as a change in turbine characteristics or environmental influences. The statistical methods have the disadvantage that they need these measuring data and are location-bound, which is a consequence of the use of estimators for the description of the relevant processes. The estimators adapt their parameters through a correlation between realisations and expectations. Another disadvantage is the fact that a considerable period of time passes before the estimators are optimised. The consequence of this dependency on measured data is that estimators that are optimal for a certain location generally are not suitable for another location.

Table 4.2 *Advantages and disadvantages of the physical and statistical methods*

	Physical	Statistical
Disadvantages	Processing time	Measuring data
	Regularity	Location-bound
Advantages	Adaptable	Degree of details
	Transferable	Self-cleaning capacity

For a full overview of the current state of the art in short-term prediction of wind power, we refer to (Giebel, 2003).

4.5 Impacts of a wind power prediction tool

In this section, the impact of forecasting on the electricity system is analysed. First a reference case is described by ways of the model presented in Section 2.2, including wind power production (DG operator). Then the impact of a Wind Power Prediction Tool (WPPT)[46] is analysed from the perspective of the investing party. Depending on the situation, the DG operator, the energy supplier, the DSO or the TSO can invest in a WPPT and gain certain benefits for their own business, but also influencing the economics of others. The possible direct effects (costs and benefits related to the party investing) and indirect effects (costs and benefits related to third parties) are described. In Figure 4.2 and further, the bold lines present the direct impacts for the party investing in the technology. The normal black lines present the indirect effects of the technology to third parties. The grey lines present the transactions/information exchanges that are not affected by the technology (compared to the reference case). With implementing the forecasting technology by one of the actors in the model of the electricity system, all other circumstances remain the same. The analysis remains qualitative in nature.

The reference situation, before implementation of the WPPT, is based on Figure 2.2 and shown in Figure 4.1. Relation (15) does not apply for wind producers, because wind power output does not take part in the balancing market. However, other DG operators (e.g. CHP operators) are still able to offer balancing services to the balancing market. Further, in this section and in Section 5.4 it is assumed that wind operators do not offer their electricity to the wholesale market (8), but directly to the energy supplier (10).

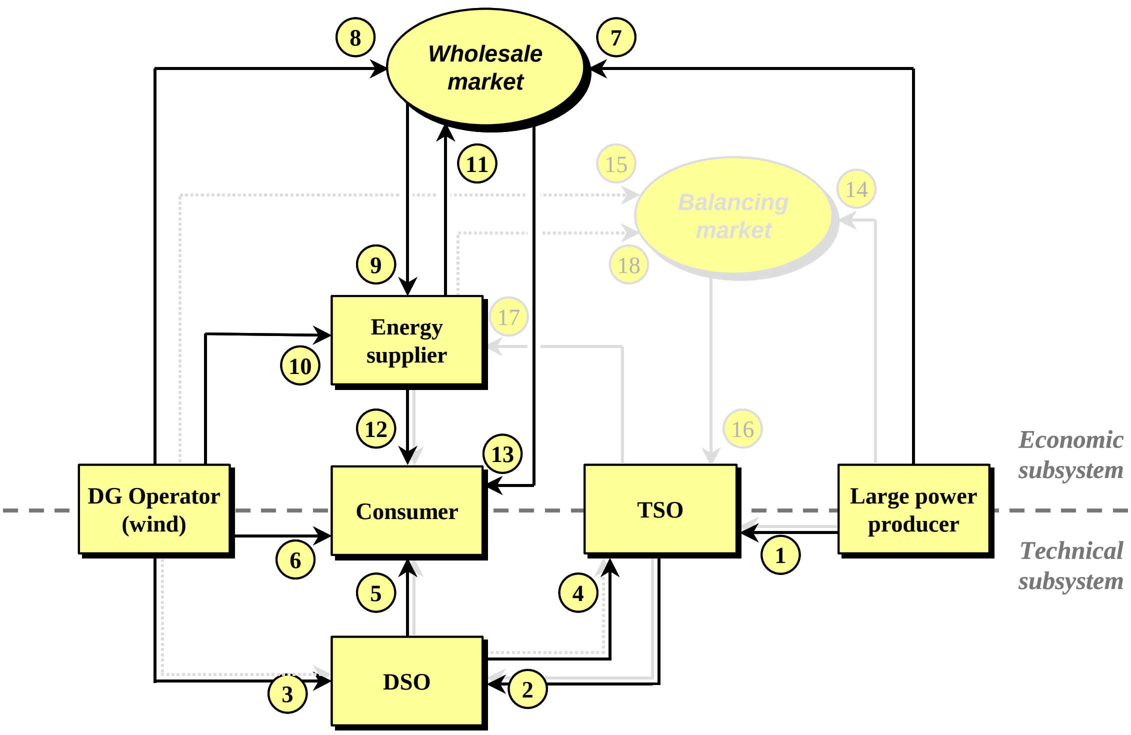

Figure 4.1 *Model of the electricity system, including DG (wind) operator*

In the reference case, an energy supplier purchases its electricity via the wholesale market (9) from large power producers (7) and from DG operators (8). Most of the electricity produced by DG operators, including wind, is directly bought from DG (wind) operators (10). The energy supplier buying power from a wind farm or turbine is unsure about the exact power output. This output can change within hours, i.e. after the energy program is submitted to the TSO. A devia-

[46] Actually, a WPPT is a specific forecasting system, developed by the Institute for Mathematical Modelling of the Danish Technological University (DTU). However, in this report, WPPT is referred to as a non-specific forecasting method.

tion of the actual power flows (registered by the DSO) from the energy program is compensated by the TSO via the balancing market.

4.5.1 Use of the wind power prediction tool by the energy supplier

Figure 4.2 shows the implications in case the energy supplier invests and utilises a WPPT as described before. All other conditions and activities of other actors remain equal to the reference situation.

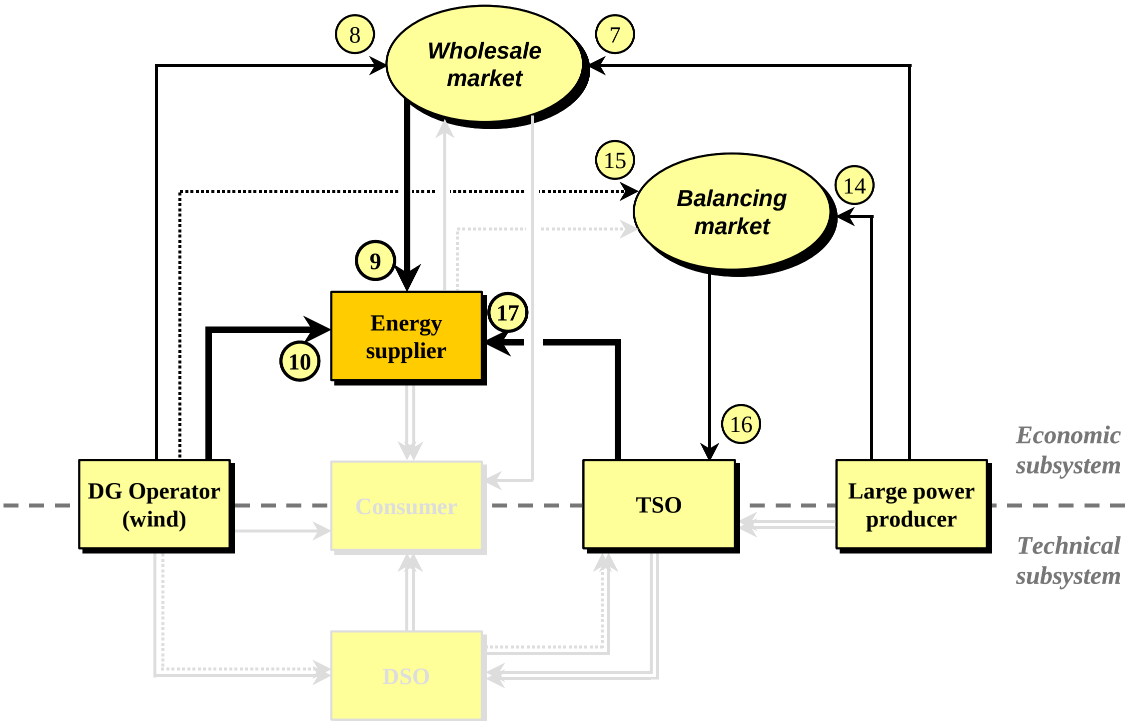

Figure 4.2 *Wind power prediction tool implemented by the energy supplier*

The wind power prediction tool enables the energy supplier to better-forecast changes in the power output from wind operators (10). Instead of paying relatively high balancing costs in the reference case (17), the energy supplier can now, in advance, buy more (lower priced) peaking power in case of lesser wind and less peaking power in case of more wind (9). This is a cost saving for the energy supplier. The TSO has to compensate lesser deviations, resulting in lower purchases on the balancing market (16). The revenues from the large power producers and the (controllable) DG producers from the balancing market may therefore decrease (14 and 15), but the substitution for this balancing power is now traded on the wholesale market in advance (7 and 8).[47]

The most important incentive for the energy supplier to invest in a wind power prediction tool is the reduced balancing costs.

[47] Forecasting makes wind power more predictable, but variability remains equal. This means that the energy supplier has to contract the same amount of electricity to neutralise the variability. But with better forecasts of wind power output, the energy supplier can contract this electricity in advance via the wholesale market, instead of buying it (via the TSO) on the higher-priced balancing market.

4.5.2 Use of the wind power prediction tool by the DG wind operator

Figure 4.3 shows the implications in case the DG operator invests and utilises the wind power prediction tool.

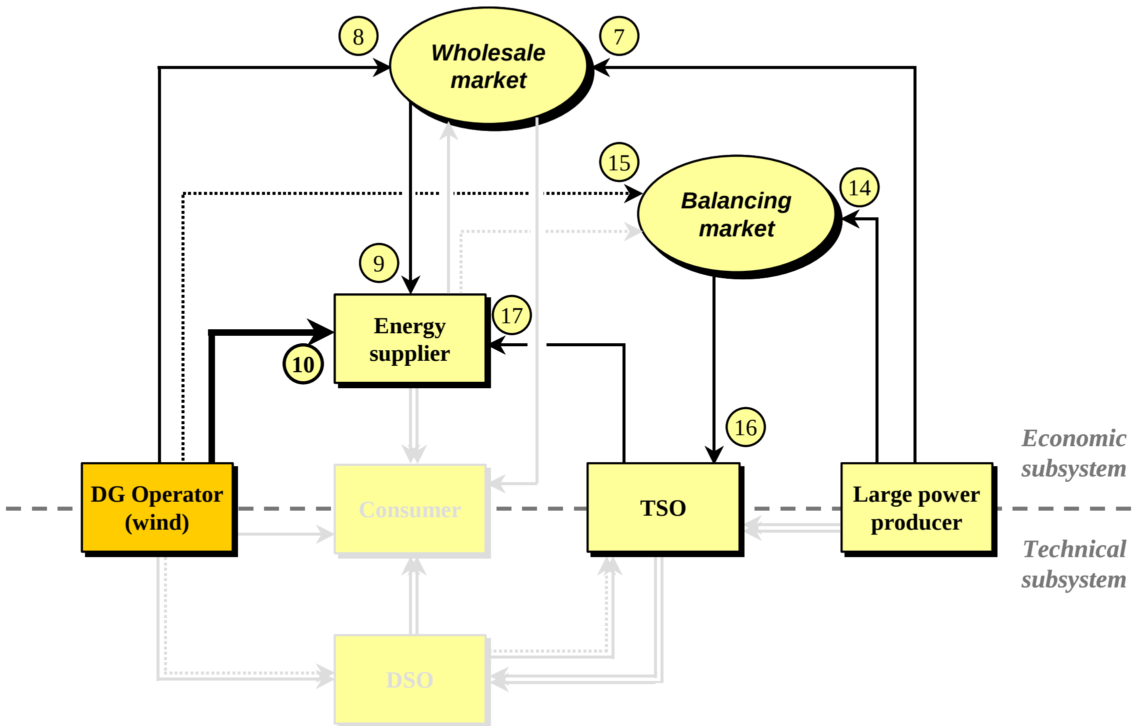

Figure 4.3 *Wind power prediction tool implemented by the DG operator*

A wind power operator that invests in a wind power prediction tool can better forecast changes in its own power output and can provide the energy supplier with more reliable information about it. The energy supplier may offer a higher electricity price to the wind power operator in return (10) because it will have an easier job in meeting its energy program, resulting in reduced balancing costs (17). Further, the effects of better forecasts are the same as discussed in Section 4.5.1.

The most important incentive for the DG wind operator to invest in a wind power prediction tool is the higher price it is able to get from the energy supplier.

4.5.3 Use by the DSO

Figure 4.4 shows the impacts in case the DSO invests and utilises the wind power prediction tool.

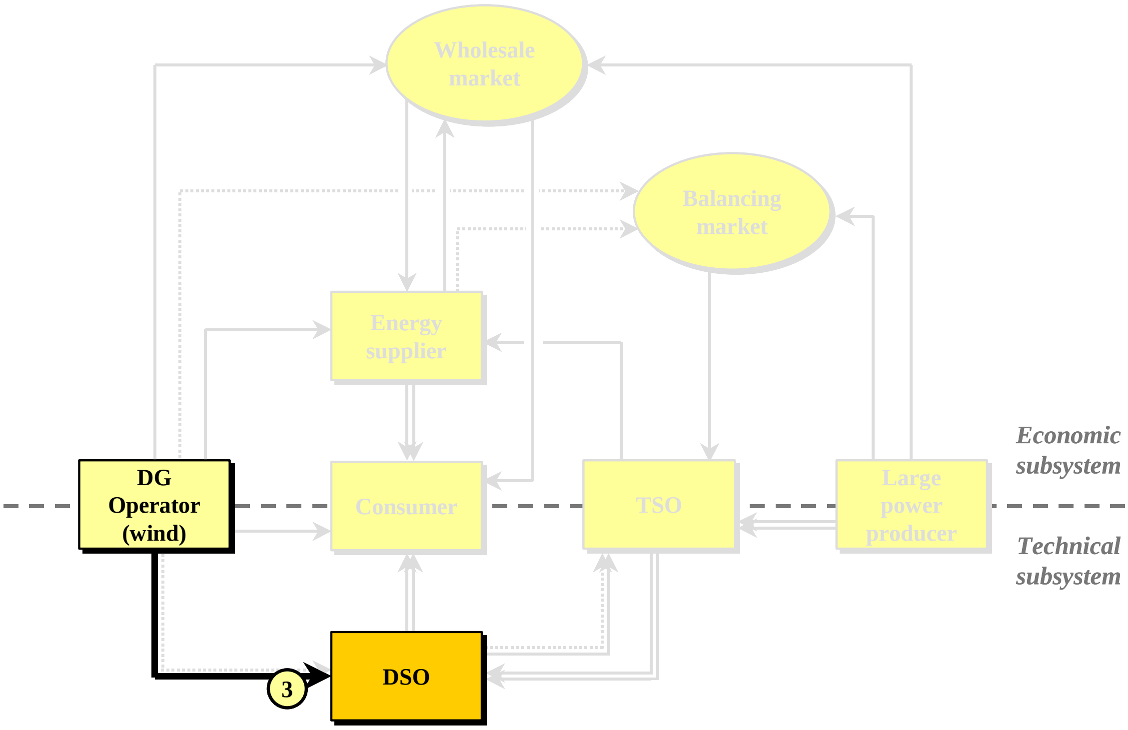

Figure 4.4 *Wind power prediction tool implemented by the DSO*

In case the DSO invests and utilises the wind power prediction tool it will improve the ability to predict and control the power flows in the distribution network, thereby decreasing network operational costs (3). The main benefit for the DSO in this respect is to be able to better control the peak load in the network system and to control power quality, i.e. voltage control and reactive power management. Precondition is that the DSO has insight in the technical characteristics of the wind farms that are connected to its grid. The utilisation of the WPPT by the DSO may increase the allowable capacity of wind power connected to the network, meaning higher revenues for the DG wind operator (10).

The most important incentive for the DSO to invest in a wind power prediction tool is the enhanced possibilities for network optimisation and management.

4.5.4 Use by the TSO

Figure 4.5 shows the impacts in case the TSO invests and utilises the wind power prediction tool.

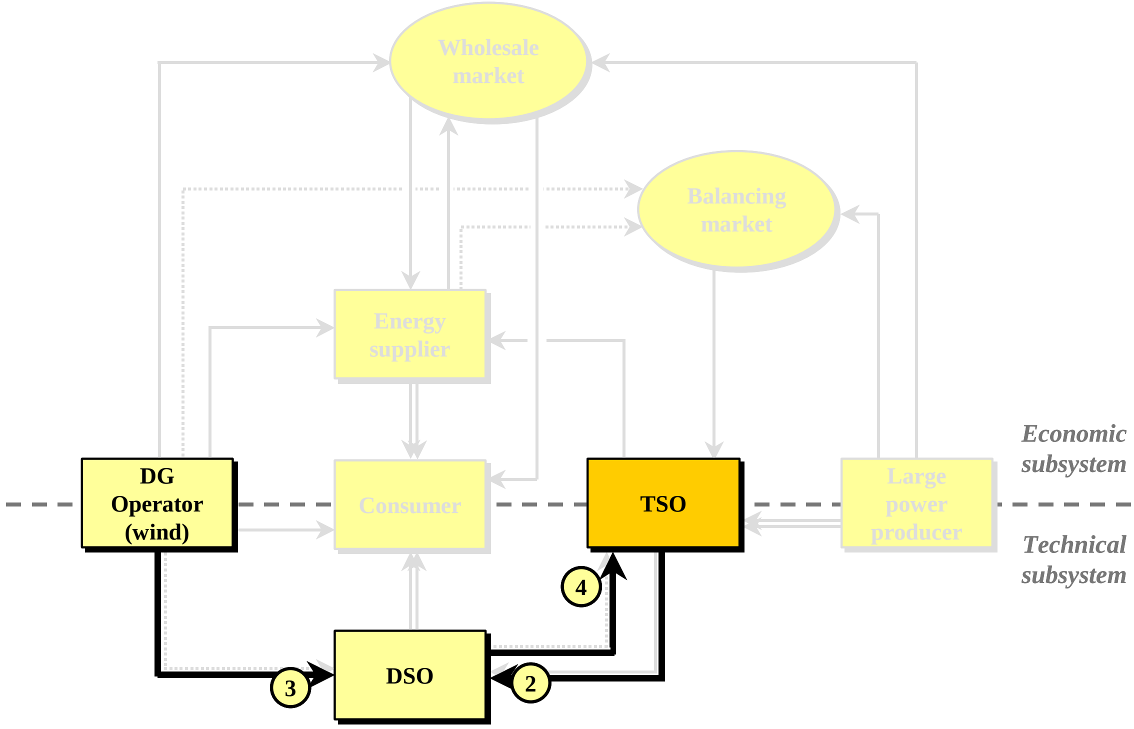

Figure 4.5 *Wind power prediction tool implemented by the TSO*

In case the TSO invests and utilises the wind power prediction tool it will be able to better predict and control the power flows in the network (2-4) and obtain better insight in possible congestion problems. Precondition is that the TSO has insight in the technical characteristics of the wind farms that are connected to the grid. The main benefit for the TSO is to be able to better control the peak loads in the network and to control power quality, i.e. improving voltage control and reactive power management. Network costs may decrease. These possible benefits could be transferred to the market via e.g. reduced use of system charges (which are not shown in the figure).

Concerning the balancing of the total system, it is the market that, via offerings to the balancing market, has to neutralise possible imbalances. The TSO only has a co-ordinating role. Therefore, the TSO has no direct benefits of investing in the wind power prediction tool concerning the balancing of the system.[48] Only if the TSO makes the predictions public, it will observe that system balancing will be easier. The utilisation of the WPPT by the TSO should then be regarded as a service to the market players, which obtain an additional service, but in return will have to contribute financially to the operation of the WPPT. It can be efficient if only one party (the TSO) is engaged in the forecasting of wind. The impact of this situation is an addition of all impacts of the different actors investing in the forecasting tool.

4.5.5 Cost and revenue overview of the wind power prediction tool

The previous four figures showed a number of changes occurring in the distribution power system when the energy supplier, wind power operator, DSO or TSO invests in a wind power prediction tool. The following impacts on cost/revenue streams can be identified:

[48] If the TSO balances the system by the use of annual contracts (instead of the settlement of a balancing market), the WPPT does have benefits for the TSO.

- The energy supplier will improve the forecasts of power output of the DG (wind power) operator when investing in the WPPT. This enables the energy supplier to improve supply and demand matching (through more/less purchase of peak generation capacity), to submit better estimates of electricity production to the system operator, and to reduce balancing charges to be paid to the TSO.
- The DG operator can provide better information about its expected power output to the energy supplier that may provide the DG operator with higher electricity prices in return, due to benefits in the field of balancing (described in the previous point).
- The DSO can improve its network management through better information about expected power flows, thereby lowering network operational costs and reducing or possibly postponing grid investments.
- The TSO can improve its network management through better information about power loads, thereby lowering network operational costs and reducing or postponing network investments. If the TSO makes the forecast information public to the market, balancing the system will be easier and balancing costs for the total system will decrease.

The benefits and the application of a technology as the wind power prediction tool as was shown above, highly depend on national regulatory-, technology- and site-specific issues. The analysis showed the possible impact of investment of one of the energy market actors and the effects of costs and revenues. National circumstances, however, strongly determine which party invests in a wind power prediction tool:

- In the UK, power producers are obliged under the New Electricity Trading Arrangements (NETA) to remain within the agreed power output. In case an owner of a wind park cannot stay within this band, relatively high penalties are charged. Therefore, it is in the interest of the DG operator to invest in a Wind Power Prediction Tool.
- In Germany the case is different. Here the TSO/DSOs are solely responsible for the system balance and are obliged to connect any wind producer and purchase all RES electricity offered to them. Therefore, in Germany a TSO or DSO could be the party to invest in a WPPT.
- In the Netherlands, the electricity supplier is usually the party bearing the responsibility for a sound energy program on behalf of small-scale wind power producers. The energy supplier will have to cover any imbalance costs and could therefore be motivated to invest in the WPPT.

5. STORAGE

5.1 Storage and intermittent sources of electricity

For integrating wind power into a power system it is important to distinguish two fields of concern: *predictability* and *variability* of supply from wind energy.

The limited predictability of the wind power to be supplied in short-term future complicates integration into the electricity system. This limited knowledge on wind power supply needs to be compensated by the use of balancing power from predictable technologies, such as fossil fired power plants, with their total capacity available as backup, or plants running on part-load, that can increase or decrease supply on a short term. One of the possibilities on tackling the predictability issue is to use storage facilities. This is the subject of the current chapter.

Secondly, the issue of wind power variability is important. Variability in supply is something that cannot be anticipated on. Wind power will always fluctuate over time; improved knowledge on wind speeds cannot decrease this aspect. In reaction to the difficulty of integrating this variable power source into the electricity system, storage of electricity is a strategy that can be considered.[49] The strategy to store electricity is discussed in the current chapter.

5.2 Storage of energy

Energy storage systems can play a major role in the development and exploitation of medium and low voltage networks. They can be decisive in the following cases/circumstances:

- For supporting the introduction of intermittent energy production (RES-E management),
- For obtaining a sufficient power quality degree (customer power applications),
- In controlling power flow for better matching generation with the demand profile (generation and reserve capacity),
- For avoiding network investments (i.e. load management) increasing reliability (transport and delivery applications).

Energy storage systems can be profitable both in grid-connected applications and in stand-alone applications for improving reliability and quality of supply. This latter configuration will not be further assessed in this report.

The management of intermittent sources is not the only function that can be performed by energy storage systems. In the GreenNet WP3 report (Mariyappan, 2004) an extensive overview is given of storage technologies, and their performances, as well as its possible behaviour in power systems. Within the four categories mentioned above, a number of fifteen specific areas are distinguished (see Table 5.1) that are all discussed in the abovementioned report, where more details can be found on the technical parameters of these storage options.

[49] Next to storage, also demand response, geographical dispersion of wind power and interconnection with other grids can reduce the variability (see Section 3.2.2).

Table 5.1 *Overview of application areas for storage technology in electricity networks*

Application type	Specific application
Management of renewable electricity sources	Control, integration and output smoothing
	Matching and ride-trough for hybrid generators
	Firming up and backup capacity
Customer power applications	Power quality
	Reliability and bridging
	Reducing peak demand
Generation and reserve capacity	Area control and frequency response
	Black start
	Rapid deployment of spinning reserve
	Standing or energy imbalance reserve
	Load levelling or commodity storage
Transmission and distribution applications	Stabilisation
	Voltage control
	Transmission investment deferral
	Distribution investment deferral

Mariyappan, 2004.

In (Mariyappan, 2004) a methodology has been derived, in which the value of electricity storage is estimated using a dispatch routine based on a modelled power system. This allows calculating, based on the technology parameters specified and the constraints set to the system, a number of parameters for electricity production.

As the goal is to estimate the *value* of storage (and not the *costs*), no costs are attributed to the storage option, only an efficiency at which electricity can be released after having been stored.

Based on an imaginary power model with only three technologies (i.e. gas combined cycle, wind power and storage technology), several runs are performed, in which different costs of power supply can be found for several sizes of the storage capacity. The idea is that by adding a storage technology, the total system costs decrease. The value of storage is then found by comparing system costs at a certain amount of storage capacity to the base case, in which no storage is available. Then, the results are presented, where a difference is made between the allocation of the value of storage and the amount of energy that is attributed (i.e. relative to the amount of wind power, or relative to the total power supplied). Most useful figure is the value relative to the amount of wind power, of which results are presented below.

In qualitative ways, it can be concluded that, compared to the base case, the large-scale integration of wind power (i.e. 20% to 30% of the power mix) into an electricity system increases the balancing costs. Thereby it can be stated that in each case, adding storage capacity reduces these balancing costs. This reduction can be quantified as a range from 27% to 80% reduction in balancing costs, depending on several model parameters: a) the share of wind power in the modelled electricity system, b) the amount of storage capacity and c) the flexibility of the power system at stake. Table 5.2 presents and overview of the outcome of WP3 modelling activities.

Table 5.2 *Outcome of WP3 model runs to assess storage impacts*

Share of wind power in total system [%]	Average reduction in balancing costs (financial implications by adding storage to the power system) [%]	Range in reduction[1] [%]
20	61	(40 - 80)
25	53	(37 - 74)
30	47	(27 - 69)

Mariyappan, 2004

[1] The range in reduction follows from storage capacity and sensitivity study on flexibility of the reference power system.

5.3 Economics of storage technology devices

The costs of an electricity storage system comprise capital and operational expenditures. The height and type of operational costs are dependent on the situation. The following costs can in general be named (KEMA, 2005):

- A once-only investment in the storage system, to be paid to the manufacturer of the storage system.
- A once-only investment for connecting to the grid, to be paid to the system operator.
- Recurrent costs for connection, transport, and system services, to be paid to the system operator.
- Operational and maintenance costs, like:
  - Personal costs
  - Maintenance of the storage system
  - Energy losses of the storage system during the process of charging and discharging
  - Transaction costs: expenditures for making purchase and sale contracts.

The additional costs of discharged electricity (apart from the purchase price of electricity) can be found in a range of 10 EUR/MWh to 1000 EUR/MWh, based on currently available technology (excluding hydropower pumped storage) and assumptions on typical cycling (much cycles result in lower costs per kWh). Note, that these numbers only refer to the electricity actually stored (the peaks only): this amount can be allocated to the total electricity produced from an intermittent source, which reduces the amount considerably. Still, storage of electricity (except hydropower) remains very costly. Storage efficiencies typically can be found in a range of 50 to 90 percent. (Beurskens, 2003)

The costs have to be recovered by the revenues (including avoided costs) that the storage system generates. The most important services and revenue sources are:

- Arbitrage of prices: trade to use price differences on the market in the course of time.
- Network services: enhancement of power quality and the postponement or avoidance of network investments.
- System services: the offering of regulation, reserve, or emergency power.
- Peak load reduction (for wind: high supply in combination with low demand) and load management: reduction of balancing costs.

5.4 Parties involved for integration of storage devices into a power system

An electricity storage system can, at the same time, offer different services to a number of actors. For an economically profitable exploitation, it is necessary to provide services to more actors. The expected total, social benefits are difficult to translate (or even disappear) when allocated to individual market players. (KEMA, 2005) Nonetheless, for clarity reasons, in the next sub sections the benefits of investing in a storage facility are (qualitatively) discussed for separate actors. The electricity storage technology can be linked to four different actors, the DG operator, the energy supplier, the DSO and the TSO. The analysis in this section focuses on these four different parties investing in the technology.

In the next sub section, not all the potential revenues are always explicitly mentioned. Only the revenues that obviously seem to belong to the core business of the concerned party are discussed. For example, DG operators can use a storage facility to enhance (smoothen) their power output, but earning money through price arbitrage is not mentioned. However, this is of course possible.

5.4.1 Use of storage technology by the energy supplier

An energy supplier may be interested in investing in a storage device to better match its energy program, especially when it has contracted a number of (intermittent) DG operators. The impacts are shown in Figure 5.1.

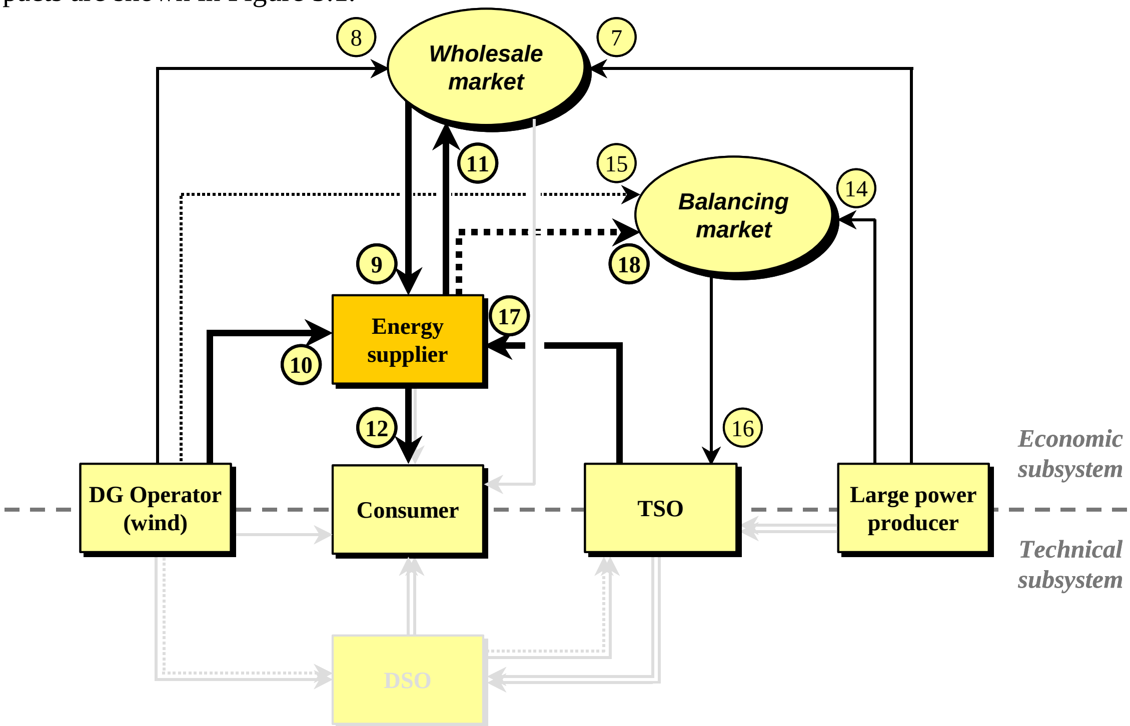

Figure 5.1 *Energy storage device implemented by the energy supplier*

The energy supplier is unsure about the power output from wind generation (DG operator wind, 10). This uncertainty/intermittency can influence the possibility to meet the composed energy program. Short-term deviations from the energy program will lead to balancing costs paid to the TSO (17) and deviations that are foreseeable on a longer term lead to purchase costs of controllable DG or large power producers via the wholesale market (7-9). With a storage device, the energy supplier is able to level out any demand peaks and valleys (12) and to control the power output from uncontrollable DG units (10). This limits the purchase of peaking power (7-9) and the balancing costs the energy supplier has to pay to the TSO (17). This again influences the transactions on the balancing market (14-15). Besides this, the energy supplier is able to offer the electricity from the storage device to the wholesale or balancing market (11,18).

5.4.2 Use of storage technology by the DG operator

The impacts of investment in a power storage device by the DG operator (wind) are illustrated in Figure 5.2.

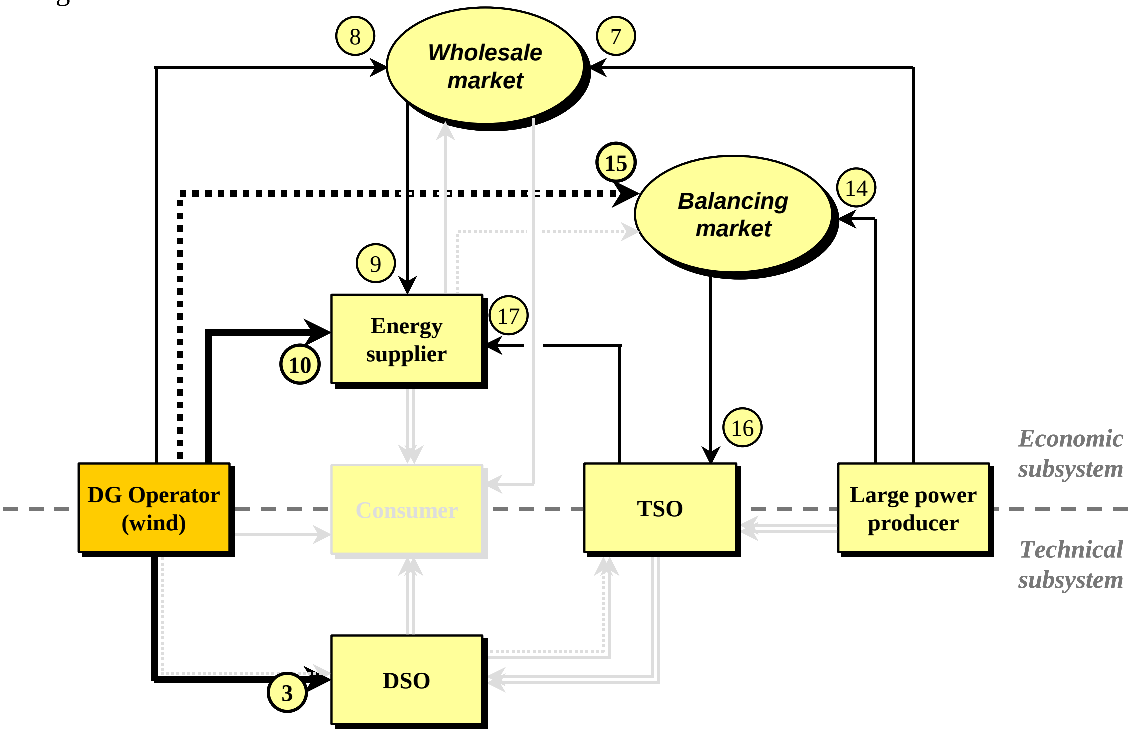

Figure 5.2 *Power storage device implemented by the DG operator*

The most direct impact for the DG operator when investing in a storage facility is the optimisation of the power output (10). The energy supplier may offer a higher electricity price to the wind power operator in return because it will have an easier job in meeting its energy program and can lower its balancing costs (17; see section 5.4.1). Another benefit is related to the influence on the distribution network (3). The DG facility will have a lower burden on the distribution network (levelling of peaks), decreasing the network costs for the DSO. The DSO may reward this in the form of lower connection or use of system charges (not depicted in the figure). Participation in the balancing market now also belongs to the possibilities for the DG operator with intermittent energy resources, creating an additional source of revenue (15).[50]

5.4.3 Use of storage technology by the DSO and TSO

An important issue of the use of storage by system operators is that they are not allowed to perform commercial activities, like trading. Due to unbundling regulation, it is forbidden for system operators to own production. That may imply that it is impossible to invest in storage. However, in this report it is assumed that they may invest the storage facilities, but only to solve network problems and they are not allowed to make use of price arbitrage. Therefore, they are only able to receive limited profits from investments in electricity storage.

The most direct benefit for the DSO is the decreasing need for network investments and reducing operation costs. The storage device can optimise the power output of (distributed) generators, preventing situations of high production at minimum load, a situation that is the most demanding to distribution networks. Storage is an alternative for grid reinforcements that are

[50] Earlier (section 4.5) it was assumed that wind power producers offer their electricity directly to the energy supplier (10) and not to the wholesale market (8).

needed to transport supply peaks. An advantage for the DSO when investing in storage is that it is able to choose the location in the grid: there where the largest bottlenecks appear.

For the TSO the same applies: by investing in storage it can reduce grid investments or reinforcements as storage devices can be integrated on weaker locations in the grid. The storage device can optimise the power throughput, preventing situations like local overload of the grid. The balancing task of the TSO, however, is another matter. Trading of electricity is unbundled from the operation of the network system. Maintaining the balance is a matter of minimising total transmission costs while guaranteeing grid stability, based on demand and supply of other players. The TSO does not experience any incentive to manipulate this market, and is thus perceived as very objective. If the TSO is participating in the balancing market by operating a storage device, it might become a strategic player. For this reason, if such a configuration is realised, regulatory issues will play an important role.

5.5 Conclusion

As stated earlier, and showed in the below enumeration, an electricity storage system can, at the same time, offer different services to a number of actors. For the economically most profitable exploitation of storage, it is helpful to exploit as much benefits of storage as possible and thus actually provide the different services to more actors. The potential total, social benefits of storage will partly disappear when allocated to individual market players. (KEMA, 2005) To exploit the potential benefits of storage as much as possible, it can be imagined that the storage device is operated by a separate entity. This entity can then optimise the supply of the different services to the different interested market parties. Furthermore, it provides a solution for the mentioned regulatory difficulties that exist when system operators want to invest in storage devices. The separate entity can provide the DSOs and TSO with grid related services, without violating the issue of unbundling.

Attempting to allocate the benefits of storage to individual actors, storage facilities can have the following impacts:

- The energy supplier buying power from uncontrollable generators or intermittent energy resources (wind, solar) can better comply with its submitted energy program and thus will be able to reduce balancing costs. Furthermore, the energy supplier is able to use the storage facility for price arbitrage (via the wholesale and/or balancing market).
- A DG operator can optimise the output of its generation facilities, enabling the energy supplier to better fulfil its energy program and enabling the DSO to better manage its network tasks. Furthermore, the DG operator as well is potentially able to use the storage facility for price arbitrage (via the wholesale and/or balancing market).
- Assuming that DSOs are allowed to operate storage devices or to make use of services provided by a separate storage entity, a DSO will be able to limit extreme situations due to low demand in combination with high peaks in power supply (or vice versa) and therefore will be able to stabilise conditions in the grid (i.e. maintain power quality and provide balance in energy and/or reactive power). Consequently, DSOs will save on operational costs and reduce investments in or reinforcements of the grid.
- Assuming that the TSO is allowed to operate a storage device or to make use of services provided by a separate storage entity, it may improve network stability and it may be able to postpone grid investments.

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