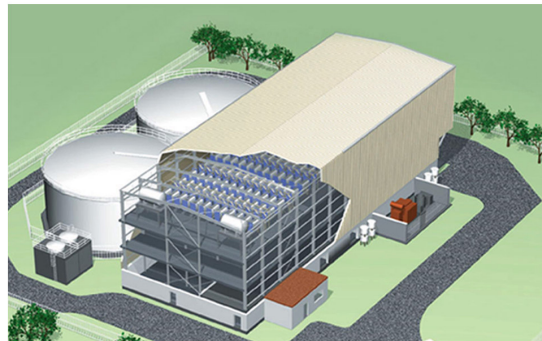


ELECTRICITY STORAGE: A SOLUTION FOR WIND POWER INTEGRATION?

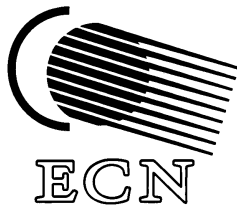


Study on the economic and institutional aspects of the implementation
of electricity storage for the integration of wind power

Master Thesis
Ruud Hendriks
June 2004

ELECTRICITY STORAGE: A SOLUTION FOR WIND POWER INTEGRATION?

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Master Thesis of R.H. Hendriks

June 2004

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PREFACE

This research marks the end of my study period that has begun about six years ago when I entered the first year of System Engineering, Policy Analysis and Management at the Delft University of Technology. Predominantly in the last two years I have developed a special interest for the energy sector, which has resulted in this master thesis regarding the economic and institutional aspects of the implementation of electricity storage systems for the integration of wind power. One of the reasons the energy sector interests me is the fact that energy security of supply is a matter of major importance in today's society. On a micro level this is illustrated by the fact that regular life is disrupted completely in case of a power cut. On a macro level international politics is heavily influenced by countries striving to secure their energy resources. The fact that energy supply will have to develop towards the use of more renewable energy sources under the influence of the threat of climate changes and the depletion of conventional resources contributes even more to my interest for the sector.

Therefore I am glad to have been offered the possibility to carry out this investigation at the unit Policy Studies at the Energy Research of The Netherlands (ECN). The last months have been very interesting, educational and productive. I hope this research will not only mark the end of my studies but also the beginning of a professional career in the energy sector.

Finally I would like to thank my supervisors who have helped me in the process of doing this research: from the TU Delft, Rolf Kunneke chairman of the graduation committee; Theo Fens first supervisor; Warren Walker second supervisor and the external supervisor from ECN, Gerard Martinus. Without their professional advice this result couldn't have been achieved.

Ruud Hendriks

Amsterdam, June 2004

ABSTRACT

Introduction

In today's society a power outage can lead to major financial damage. It is therefore of high importance that the electricity system is reliable and that customers can rely on high security of supply. To prevent power outages, the electricity system has to be in balance continuously: supply and load have to be equal (see paragraph 4.1). Currently the majority of the electricity generation is done by conventional power plants which' operation schedule is fully controllable. This means that these plants can be operated in such way that electricity demand, which vary during the day, can be met continuously. The integration of a large share of wind power in the electricity supply system however, can lead to problems with respect to the balancing of the electricity system. This is caused by the fact that wind power has an intermittent character. Its production fluctuates and is uncertain: it therefore cannot be used to follow the varying load.

Electricity storage could contribute to the integration of wind power in the electricity supply system. Storage systems can decouple the timing of generation and consumption of electricity and can therefore compensate for the fluctuations in wind power production. This investigation aims at identifying what problems the integration of a large share wind power will cause and how electricity storage can resolve these problems. Subsequently the implementation costs of storage systems for the identified applications will be investigated. Finally the current regulatory environment will be discussed to evaluate whether it is geared to the implementation of electricity storage. Therefore, the following research question is formulated:

Research question

Under which technological and institutional preconditions will it be advantageous to implement electricity storage systems, in combination with wind farms, in the next 20 years?

To answer the research question the following sub questions have been formulated:

1. What are the implications of the market design on the implementation of electricity storage and what important developments are taking place in the context of electricity storage?
2. Which electricity storage systems are currently available and what are the characteristics of these systems relevant for market introduction?
3. In what way can electricity storage contribute to the integration of wind power in the electricity supply system?
4. Is the implementation of electricity storage systems economically profitable?
5. What are the advantages and disadvantages of ownership of storage systems by grid managers compared to ownership by market parties?
6. Does the current regulation provide possibilities for grid managers to stimulate private parties to invest in storage systems?

*Sub question 1:
implications of the market
design and important
developments*

The liberalisation of the electricity sector has led to several changes that affect the possibilities for the implementation of electricity storage. The introduction of the free electricity market has led to the creation of incentives for producers and suppliers to respond to the fluctuating costs of electricity production. As storage systems can be used to charge electricity in times of low prices, and supply electricity in times when prices are high this is seen as major driver for the implementation of electricity storage.

A second implication is that in order to liberalise the electricity sector the electricity value chain is unbundled. In the current unbundled market design, in which production and transmission and distribution are strictly separated, the design can pose barriers for the introduction of technologies or changes of processes that require coordination between the links in view of the implementation of electricity storage. Regulation can anticipate on these reduced possibilities for coordination. This sets requirements for the regulation that is evaluated in chapter 6: the regulation should reduce these barriers to the implementation of electricity storage systems.

The third implication of the market design is the fact that in a liberalised market parties receive several negative incentives for risky investments in innovation like electricity storage systems. Conversely it is argued that the introduction of competition in the electricity sector stimulates innovations and therefore could promote investments in electricity storage.

The policy objective of the government entails to implement a large share wind power in The Netherlands and yet ensure the reliability of the electricity supply system. This could lead to the situation that electricity storage will be an important factor in the electricity supply system in the coming years.

*Sub question 2: inventory
of storage systems*

From an inventory of electricity storage systems it appeared that there are many different storage systems varying from pumped hydro storage to electro chemical systems like stationary batteries and flow batteries. Large-scale storage systems can have power capacities from about 1 MW to 2000 MW and storage capacities ranging from 1 MWh up to 50 GWh. Some storage systems like for example super capacitors, have very limited applications. Other systems like (flow) batteries are suitable for a wide range of applications. A promising storage system that has many applications is the Polysulfide Bromide (PSB) flow battery system. The PSB system can achieve high efficiencies and is quite flexible with respect to discharge times and storage capacity. The fact that the PSB system doesn't have specific requirements regarding its location, in contrast to pumped hydro storage and CAES (Compressed Air Energy Storage) favours possible implementation of the system in The Netherlands. Small-scale versions of the PSB system have operated well, the development of this system for larger scale application is however still to be undertaken.

*Sub question 3: the
contribution of electricity
storage to the integration
of wind power*

This research identifies four electricity storage systems that can contribute to the integration of a large share of wind power into the electricity system. Firstly storage systems can provide balancing services that are required to compensate for unexpected fluctuations of wind power production. The uncertainty regarding the forecasts of wind speeds causes errors in predictions of the production of wind power. This could lead to an increase of the required adjustment and reserve capacity. Besides a shortage on reserve and adjustment capacity, the uncertainty of wind power production can lead to deviations from the E-programs. This can

cause high imbalance costs for wind farm exploiters. Large-scale storage systems like the PSB and large conventional batteries can be implemented to compensate for the unpredicted fluctuations of the wind power production.

Secondly storage systems can also be used for energy management. The longer-term fluctuations of wind power demands irregular production behaviour of conventional power. Storage systems can be used to smooth wind power fluctuations to prevent considerable more control actions to be required, which would lead to a decrease of the efficiency and life cycle of the conventional generation plants. Furthermore storage systems can be used for peak shaving to reduce required generation capacity and increase the utilisation rates of the installed capacity. Finally electricity generated during the night at base load prices can be stored and sold at daytime for high prices during peak hours. These applications require large-scale storage systems like the PSB system.

Thirdly storage systems can be used for the supply of power quality services. The implementation of storage systems can reduce output fluctuations generated by wind farms and therefore also reduce flicker. Furthermore, storage systems like batteries and flow batteries can supply reactive power in order to control the voltage level. Finally storage systems, often equipped with electronic filters, can reduce the harmonics in the grid.

The fourth identified application of storage systems is the reduction of the required grid capacity. If a storage system, located close to a wind farm, limits the maximal amount of power that is fed in by the wind farm, the grid doesn't have to be dimensioned on the maximal amount of installed wind power capacity. This application requires large-scale storage systems like the PSB flow battery.

Sub question 4: cost-benefit analysis of the PSB system

In order to analyse the profitability of the applications that are identified a cost-benefit-analysis of the PSB storage system is carried out. The investment costs of the Polysulfide Bromide system (PSB) are currently estimated at about 1200 €/kW which makes its supply costs significantly higher than the production costs of a gas-fired plant and a STEG unit: 67 €/MWh for the PSB system compared to 45 €/MWh and 39 €/MWh respectively for the gas-fired plant and the STEG unit. A case study shows that trading on the APX with a PSB storage system, at 2002 APX prices, wouldn't have been profitable at current, nor at in the near future, expected investment costs levels. At 2003 APX prices however, the trading would have been profitable at investment cost of about 900 €/kW.

The unpredictability of wind speeds causes errors in the production forecasts of wind farms. These prediction errors in turn cause deviations from the E-programs for which the wind farm exploiters have to pay imbalance fines. A cost-benefits analysis of the implementation of a PSB system for the prevention of imbalance costs shows that at current imbalance prices and PSB investment cost level this isn't profitable. Only at an investment costs level of 500 €/kW preventing shortage with the PSB would be profitable; a cost level that is not expected to be achieved within the coming years based on current price developments in the market.

A plant for peak capacity only supplies electricity at limited number of hours per year. A PSB system can be used for peak supply and carry out a balancing function during the off peak hours. This way, although used for peak supply, a high utilisation rate can be accomplished. This combination of applications leads

to a decrease of the PSB supply costs so that at 2003 prices the PSB system would supply electricity at lower costs than a gas-fired plant at a production rate of less than 1600 hours of peak supply per year; in this case the implementation of the PSB system would be cost beneficial.

*Sub question 5:
comparison of ownership
by grid managers and by
private parties*

It could be beneficial for both private parties and grid managers to implement storage systems. However, it is not likely that under the current E-law grid managers are allowed to implement storage systems for adjustment and reserve capacity, deferral of grid investment or peak power supply. Although an amendment of the E-law could make it possible for grid managers to carry out these applications, these activities could lead to substantial market distortion. Grid managers could face conflicting interest, which endangers a non-discriminatory grid management. In addition information advantages could lead to unfair competitive advantages for the grid managers when entering the electricity market. An advantage of ownership of storage systems by grid managers is the fact that this could contribute to higher technical efficiency to the electricity system by enabling integrated grid and capacity planning. Ownership of storage systems by private parties does not offer opportunities for the integration of capacity and grid planning and therefore does not generate synergy benefits.

*Sub question 6: evaluation
of current incentive
regulation*

From the answer to sub question 5 it appears that grid managers are not likely to be allowed to carry out several applications of electricity storage systems. This means that when they want to benefit from the services the implementation of storage systems can offer, parties in other links of the electricity value chain will have to supply them with these services. While the conventional possibilities for coordination are restricted by the current unbundled market design, incentive regulation should enable to stimulate private parties to provide these services.

When we analyse current regulation regarding connections charges, system charges and the balancing market, we find that it not always offer possibilities for grid managers to give incentives to private parties to do so. The connection tariffs system, for connections smaller than 10 MVA, does not offer possibilities for grid managers to give out incentives to private parties for selecting an efficient location with respect to the grid nor to stimulate the implementation of storage systems. For connections larger than 10 MW the grid managers do have possibilities to give out incentives to the parties although other regulatory measures could extent these possibilities. The current regulation regarding ancillary services foresees in the possibility for TenneT to stimulate investments in storage systems. However, since the regulation that allocates the system charges does not provide producers incentives to minimize the ancillary service costs; parties are not stimulated to consider whether implementing storage systems could reduce the system costs. Finally we found that although producers can gain revenues by offering their available adjustment capacity on the imbalance market, the incentives to do so might not be strong enough. It can therefore be questioned whether producers offer all their available adjustment capacity on the imbalance market in order to create a healthy market. In general the current regulation leaves room for improvement of the possibilities for grid managers to provide incentives regarding the implementation of storage systems.

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1 INTRODUCTION

1.1 Background

Liberalisation of the electricity sector

The electricity sector has been subjected to many changes in the past years. This was mainly caused by the liberalisation of the sector that had its official starting point in The Netherlands in 1998, when the Dutch government passed a new Electricity Act. In order to introduce competition in the electricity sector, the different activities in the energy value chain, that up till then were vertically integrated in a few large organisations, were unbundled. Production, trade, transmission, distribution, metering and supply became separated activities. This process is still ongoing and recently it was decided by the government that in 2007 the distribution will be fully separated from the remainder of the energy value chain. The main change caused by liberalisation is the fact that utilities enter a competitive market environment, which necessitates increasing efficiency. This could stimulate the parties in the electricity sector to adopt new technologies and operational processes that can lead to cost reductions and thus a competitive advantage.

Implementation of new technologies: storage systems

In their search for competitive advantages the parties investigate new technologies that can lead to cost reductions. A technology that could play an important role in the future is the storage of electricity. At this moment the electricity production and consumption have to be precisely equal at all times, hence a continuous balance has to be maintained. Storage systems provide the possibility to decouple production and consumption with respect to this balance.

Security of supply

One of the main reasons to carry out research on the implementation of electricity storage systems is the current concern that the liberalised market may not ensure security of supply at an acceptable level. In today's society a power outage can lead to major financial damage (SEO, 2003). It is therefore of high importance that the electricity system is reliable and that customers can rely on high security of supply. A major risk regarding security of supply is the availability of sufficient production capacity. In the liberalised electricity sector the government is no longer prime responsible for the availability of sufficient production capacity: this is left to market parties. It is currently doubted whether investments in production capacity by market parties will be sufficient to secure an acceptable level of security of supply (Min.EZ, 2003). As the implementation of electricity storage systems can reduce the required amount of production capacity it could in future play an important role in securing the supply of electricity.

Large scale wind power

An additional threat for security of supply is the large-scale implementation of wind power. The Dutch government stimulates large-scale use of renewable generation for electricity. Its aim is to realise an installed capacity of 7500 MW wind power in The Netherlands by 2020 (Min.EZ, 2002). Wind power however has an intermittent character. Its production fluctuates and is uncertain. The implementation of wind power on a large scale could therefore cause problems with respect to security of supply. First of all it is not clear whether the electricity grid is prepared to cope with these shares of wind power that result in large

variations of power production (KEMA, 02). Secondly the fluctuations in wind power supply require the availability of sufficient conventional production power to compensate for the lack of wind power in times of low wind. Thirdly the unpredictability of wind power could cause economic problems for wind farm exploiters. The Dutch transmission system operator TenneT fines unpredicted variations of electricity production of wind turbines. This can lead to undesirably high costs for wind farm owners. Electricity storage systems could help to resolve the technical as well as the economical problems by ‘absorbing’ the variation in production of wind based production.

Promising storage technologies

Recent technological developments have resulted in a new type of electricity storage systems: the flow battery. This storage technology has several advantages compared to already existing systems. Although it can store electricity on a large-scale of the orders of hundreds of MW's, the system doesn't require as specific location conditions as for example a hydro pumped storage system does. Moreover, the flow battery is very flexible regarding the ratio of the energy storage capacity and the supply capacity. Unlike with conventional batteries these two can be chosen independently providing the possibility to design the storage system optimally for its application. In addition, ongoing development of the flow battery technology could lead to a considerable reduction of costs, which makes it more applicable than the currently known existing storage systems.

Given the extensive plans the Dutch government has regarding wind power, the implementation of electricity storage systems in combination with wind power may have a large potential. This master thesis will therefore investigate the economic and institutional aspects of this specific application of electricity storage systems.

1.2 Framework

ECN, PREGO

The current master thesis is carried out at the Energy research Centre of The Netherlands (ECN). The business unit Policy Studies offers public authorities, companies and civil society independent advice with respect to energy and environmental issues. Policy studies focuses on the enhancement of the synergy between market forces and goals of sustainability. The multidisciplinary project teams provide consultancy services at the national, European and global level. ECN is involved with the PREGO-program (Programma Elektriciteitsnetwerk Gebruikers Onderzoek), a research financed by the ministry of Economic Affairs. PREGO aims at preserving and extending economically important knowledge concerning the electricity sector. One of the projects within this program is PREGO 19, Technical, economic, social and governmental implications of the preferred energy storage methodology. The Netherlands, like other European countries, strive to achieve a growing share of renewable energy in future energy supply. A large share of wind and solar energy however, can lead to complications in the energy supply because of the intermittent and supply following character of these two renewable energy sources. Within PREGO 19 it has been investigated at a macro level whether a need will arise for energy storage systems to integrate a large share (20% or more) of supply following power in the (Western) European grid (Martinus, 04). Besides this quantitative technical concern, the economic and institutional aspects of the implementation of storage systems have been analysed for the PREGO 19 project (Wals, 04). As an

extension to this research, this master thesis investigates the economical and institutional aspects of the implementation of storage systems for the purpose of the integration of wind power in the electricity grid.

1.3 Problem statement and research question

Problem statement

In today's society a power outage can lead to major financial damage. It is therefore of high importance that the electricity system is reliable and that customers can rely on high security of supply. To prevent power outages, the electricity system has to be in balance continuously: supply and load have to be equal (see paragraph 4.1). Currently the majority of the electricity generation is done by conventional power plants which' operation schedule is fully controllable. This means that the plants can be operated in such way that electricity demand, which vary during the day, can be met continuously. The integration of a large share wind power in the electricity supply system however, can lead to problems with respect to the balancing of the electricity system. This is caused by the fact that wind power has an intermittent character. Its production fluctuates and is uncertain: it therefore cannot be used to precisely follow the varying load.

Electricity storage could contribute to the integration of wind power in the electricity supply system. Storage systems can decouple the timing of generation and consumption of electricity and can therefore compensate for the fluctuations in wind power production. However, to find out whether the implementation of storage systems is advantageous, firstly it will have to be investigated profoundly what problems the integration of a large share wind power can cause and how electricity storage can resolve these problems. Subsequently it will have to become clear what costs are associated with the implementation of storage systems and if current regulation is geared towards the implementation of storage systems. Therefore, the following research question is formulated:

Research question

Under which technological and institutional preconditions will it be advantageous to implement electricity storage systems, in combination with wind farms, in the next 20 years?

To answer the research question the following sub questions have been formulated:

1. What are the implications of the market design on the implementation of electricity storage and what important developments are taking place in the context of electricity storage?
2. Which electricity storage systems are currently available and what are the characteristics of these systems relevant for market introduction?
3. In what way can electricity storage contribute to the integration of wind power in the electricity supply system?
4. Is the implementation of electricity storage systems economically profitable?
5. What are the advantages and disadvantages of ownership of storage systems by grid managers compared to ownership by market parties?

6. Does the current regulation provide possibilities for grid managers to stimulate private parties to invest in storage systems?

1.4 Scope of the project and perspective

Considering the research question we define the following scope:

<i>Applications</i>	In order to accomplish the policy objective of the Dutch government to install 7500 MW of wind power in 2020, many problems regarding the integration of wind power in the electricity system will have to be assessed and solved. For this reason we focus on the implementation of storage systems for the purpose of the integration of wind power.
<i>Geography</i>	This research is aimed at the implementation of storage systems in The Netherlands. Despite the fact that energy markets in Europe unite quickly, energy policy and systems regarding grid control are still mainly national activities.
<i>Time scale</i>	A time scale of twenty years has been chosen for this research. It is expected that within 20 years wind power will contribute substantially to the energy supply system. Therefore the research investigates the contribution of storage systems within this particular time frame in relation to the integration of wind power in the electricity supply system.
<i>Storage systems</i>	The (regulatory) complexity of the implementation of storage systems concerns in particular large-scale storage systems. This research therefore focuses on the implementation of large-scale storage systems. Because of the restricted time available for this research, the cost-benefit calculations have been carried out for one storage system only: the Polysulphide Bromide battery.
<i>Perspective</i>	This master thesis has been devised from the perspective of both the transmission operator TenneT and the distribution network operators. If in future large shares of wind power will have to be integrated in the electricity system, the grid managers may have to adjust the power grid configuration and operation in order to secure the reliability and continuity of the electricity supply in The Netherlands. Large offshore wind farms will probably be connected directly to the high voltage grid and therefore will be TenneT's responsibility. Onshore turbines will predominately be connected to the mid voltage grid and therefore will be the responsibility of the distribution network managers.

1.5 Structure of the report

The report has a structure that is analogue to the six formulated sub questions. Figure 1.1 presents the structure: the boxes state the contents of the chapter, the arrows illustrate where results of the chapter are used.

<i>Chapter 2</i>	Chapter 2 answers the first sub question. Firstly it investigates the implications of the market design on the implementation of electricity storage. If the current market design poses barriers for the implementation of electricity storage, regulation could be used to deal with these barriers. The barriers that are identified in chapter 2 form the starting point for chapter 6 that evaluates whether
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regulation provides the correct incentives regarding electricity storage to reduce the barriers. Furthermore chapter 2 describes the actors and markets in electricity sector as they outline the context for the applications of electricity storage that are identified in chapter 4.

- Chapter 3* Next, chapter 3 contains an inventory of different storage systems, their applications and other import characteristics. The technical characteristics are required in chapter 4 to investigate which storage systems are suitable for the integration of wind power in the electricity system. The economic characteristics are used in chapter 5 to carry out the cost-benefit analysis. Chapter 3 answers the second sub question.
- Chapter 4* In chapter 4 we analyse how electricity storage can contribute to the integration of wind power in the electricity system. Furthermore the advantages and disadvantages of several storage systems for each of the identified applications are analysed. This gives an answer to sub question 4.
- Chapter 5* The profitability of some of the applications identified in chapter 4 is considered in chapter 5, which gives an answer to sub question 4. A cost benefit analysis of several applications of the Polysulfide Bromide storage system will reflect on the economic part of the research question.
- Chapter 6* Finally the institutional aspects regarding the implementation of electricity storage are evaluated in chapter 6. This chapter first evaluates the implications of both ownership of storage systems by market parties and ownership by grid managers on the application possibilities, market distortion and the (technical) efficiency of the total electricity system. Subsequently it will be evaluated whether current regulation is geared optimally in relation to the problems regarding the ownership of storage systems by private parties and the main market barriers identified in chapter 2.

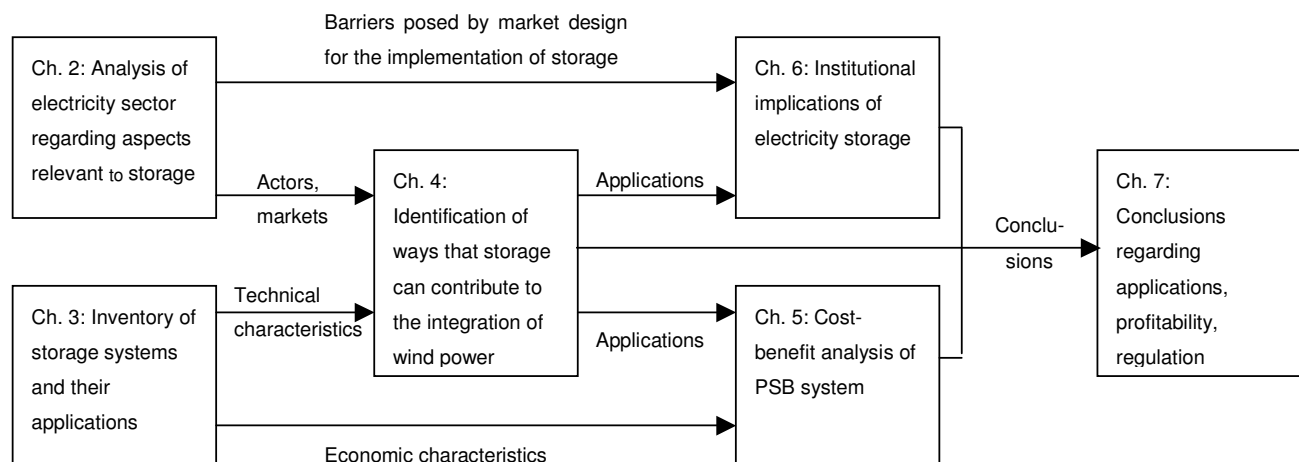


Figure 1.1: Structure of the report

1.6 Approach, methods and theory

General approach

There are several different perspectives that can be assessed to investigate the implementation of electricity storage systems. Technology, economics and policy are all three aspects that are individually of major importance regarding electricity storage. In the context of the aims of this investigation however, an integrated approach of these three aspects is required. Given the interdependency of the three aspects only an integrated approach would result in a complete analysis of the problem. The choice for one specific point of view could lead to the neglect of the interactions of the different aspects. Choosing a technical point of view for example could, given the current liberalised market, lead to an underexposure of the economic aspects of the implementation of storage systems, whereas from a purely economic perspective technical restrictions of the electricity system could be ignored. Figure 1.2 shows the position of the electricity storage within the three perspectives.

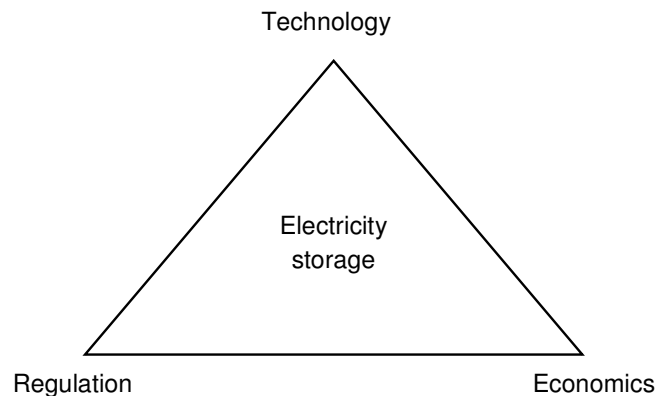


Figure 1.2: Integrated perspective on electricity storage

Methods and theory

Besides the above-mentioned general approach, we use different methods and theory in the various chapters. In chapter 2 the implications of the unbundled market design on the implementation of storage systems are evaluated using the framework of the electricity value chain. This concept contributes to the identification of the implications of the separation of interrelated activities.

The inventory in chapter 3 is made based on a literature survey of both technical studies and Internet sites.

In chapter 4 a system technical approach is used to analyse the influence of a large share wind power on the electricity supply system and the role electricity storage can play to integrate wind power. This is predominantly carried out by means of a literature survey. Furthermore scorecard methodologies are used to evaluate the advantages and disadvantages of the various storage systems. Theory regarding the functioning of the electricity supply system, the uncertainty of wind power electricity production and the impact of this on the total supply system forms the technical theoretical framework for this part of the investigation. Besides literature research, several experts have been consulted on the subject of storage systems, both within as outside of ECN (Continuon, TuDelft). Furthermore a workshop within the framework of the PREGO project, at KEMA was attended.

In chapter 5 a cost-benefit analysis is used to calculate the profitability of the implementation of storage systems for several applications.

In chapter 6 a policy analytic framework is used to analyse the institutional aspects of the implementation of storage systems. The two sub questions posed in the chapter are answered by means of a literature surveys. The literature survey consists of policy documents, the Electricity law and various technical codes of the DTe, the Dutch regulator.

2 THE DUTCH ELECTRICITY SECTOR

Sub question 1

This chapter discusses several aspects of the Dutch electricity sector that are relevant in the context of electricity storage. It answers the first sub question posed in this research: What are the implications of the market design on the implementation of electricity storage and what important developments are taking place in the context of electricity storage?

The barriers posed by the market design that are identified in this chapter set requirements to regulation: regulation should reduce these barriers. This chapter therefore forms a starting point for chapter 6 that evaluates whether the current regulation, given the market barriers put up by the market design that are found in this chapter, is geared optimally to benefit from the advantages electricity storage can offer. Furthermore the discussion of the actors, electricity markets and important developments in this chapter outline the context for the applications of electricity storage that are identified in chapter 4.

Paragraph 2.1 introduces the concept of the electricity value chain and shortly describes the Dutch electricity sector under the Electricity Act 1989. In paragraph 2.2 the electricity market design is discussed followed by its implications for the implementation of electricity storage. Next, paragraph 2.4 and 2.5 describe the actors in the electricity sector and the Dutch electricity markets. Paragraph 2.6 identifies two important developments with respect to electricity storage: the increasing concerns regarding the security of supply and the increasing share of wind power in the electricity supply system. Finally paragraph 2.7 draws conclusions on the issues considered in chapter 2.

2.1 The electricity value chain

The electricity value chain

In this chapter the market design of the electricity sector will be discussed using the concept of the value chain (Porter, 85). With this approach the different interrelated activities in the electricity sector are identified and modelled as series of activities that all contribute to the end-value of the product. This concept contributes to the identification of the implications of the separation of interrelated activities. Figure 2.1 shows the electricity value chain of the electricity sector under the E-Act 1989 both as an example and to refer to when discussing the structure of the current liberalised market design in the next paragraph.

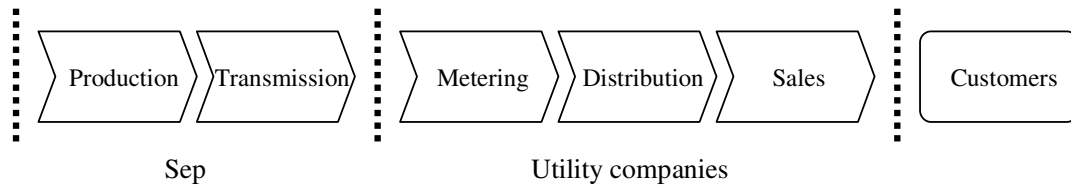


Figure 2.1: Electricity value chain up to 1998

Integration of production and transmission

Under the E-Act 1989 the electricity value chain consisted of five different links, integrated in two organisations as illustrated in Figure 2.1. Characteristic for the sector in that period was the integration of production and transmission in one organisation: Sep (Cooperating Electricity Producers) (Huygen, 95). Sep was a cooperation of the four large Dutch production companies, each of which having the monopoly for the production of electricity in their own region. The electricity sector was purely supply driven. It was centrally decided by Sep how much electricity had to be produced and at which location. The price wasn't determined by means of a market mechanism but was based on the integral costs of the electricity supply. Sep had to take care of the matching of the demand of distribution companies and the production of the power plants. It was responsible for the availability of sufficient electricity production capacity as well as for the continuous balancing of production and demand. Sep also owned the high-voltage grid and had to ensure the availability of sufficient transmission facilities via the grid (Kling, 00).

Integration of distribution and supply

Also within the regional distribution companies multiple activities were integrated (Huygen, 95). The distribution companies owned and operated the regional grids. In addition they were responsible for the supply of the electricity to the end consumers. Every region had its own distribution company that enjoyed the monopoly to supply electricity in their area.

2.2 The design of the Dutch electricity market

In 1992 the European Parliament proposed a new electricity directive (EP, 92). The aim of this directive was to liberalise the internal European electricity sectors and vest a European level playing field for the electricity market. This was the immediate cause for the introduction of liberalisation in the Dutch electricity sector. In order to adopt the directive, the market structure and design would have to be changed completely and therefore the Electricity Act 1989 had to be renewed. In 1995 the Dutch government issued the *Derde Energienota* (Min.EZ, 95). This policy document contained the outlines of the new market structure announcing a transition to a fully liberalised energy market. Finally three years later the Electricity Act 1998 was introduced into the Parliament and accepted, and passed as a bill.

Restructuring the electricity sector: unbundling

As explained in paragraph 2.1 the Dutch electricity value chain was highly integrated up to 1998. All different links in the value chain were either heavily regulated and/or owned by the government. To be able to introduce competition in the electricity sector the electricity value chain is restructured. The five links in the value chain have different economic characteristics. The nature of some links

allows the introduction of competition while others do not. In order to be able to design each link and its role optimally with respect to these characteristics, the different links are separated (figure 2.2). This process is called unbundling. Following the different links of the current electricity value chain are discussed, paragraph 2.3 elaborates on the actors in the electricity sector.

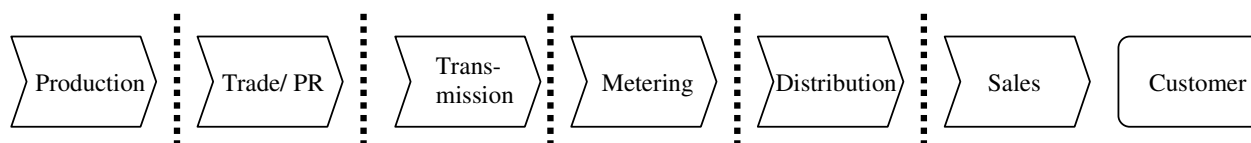


Figure 2.2: Electricity value chain from 1998

Production

The first step in the value chain is production. Figure 2.2 shows that production has been separated from transmission: these two activities are no longer coordinated by one organisation. The producers individually decide their operation schedules. In the production sector competition has been introduced. The producers do not have a regional monopoly anymore but have to sell their power on the electricity market.

Trade/Program Responsibility

The liberalisation of the electricity sector has introduced a new link in the electricity value chain: trade and program responsibility. Since power producers can sell their electricity to different supply companies and consumers, there are possibilities for the trade of electricity. Traders can do business by buying and selling electricity. Furthermore the Program Responsibility system has been introduced (PR-system). This system stimulates market players to supply and consume in accordance with a previously determined program. The Program Responsibility system will be discussed in paragraph 4.1. Paragraph 2.4 gives an overview of the Dutch electricity market that facilitates both conventional trading and trading with respect to the PR-system.

Transmission and distribution

Also metering, distribution and sales of electricity, formerly carried out by one regional utility company, are unbundled. In contrast with the situation before 1998, transmission and distribution are strictly separated from production and supply in the new market design. Because of the natural monopoly characteristics of the electricity grid, both in the transmission and distribution links of the electricity value chain full competition is not introduced. Even though the electricity grid remains a natural monopoly as in the period under the Electricity Act 1989, it plays a new role in the liberalised energy sector. The grid now has to offer access to every supplier on non-discriminatory grounds. The existence of a level playing field is essential in order to create a good functioning electricity market. Because the regional grids are still in the hands of the utility companies, the government decided that grid management has to be facilitated by a grid manager, which is legally separated from the utility companies. The grid manager is responsible for the operation, maintenance and reliability of the grid (Electricity Act 1998, 98). As the grid managers are monopolists, in the new liberalised market, a regulator has been vested to supervise them.

Metering

The unbundling of supply and metering offers the possibility for the introduction of a free market for the installation and maintenance of the electricity meters. The

metering companies can also read the meter data and pass this data to the grid manager and the suppliers.

Sales Also in sales, the last link of the electricity value chain, competition has been introduced. The suppliers are the face of the electricity supply towards the customers: they buy electricity from the production companies and sell it the consumers.

2.3 Implications of the electricity market design on the implementation of electricity storage

This paragraph discusses three aspects of the current market design that affect the implementation of electricity storage: the market based pricing of electricity, the unbundling of the value chain and impact of competition on the willingness of parties to implement innovating technologies.

Market based pricing of electricity

The introduction of a free electricity market in the current market design is a major driver for the implementation of electricity storage. The liberalisation of the electricity market has introduced market-based pricing of electricity. The cost of producing electricity fluctuates widely by hour or even block of 15 minutes. Before the liberalisation of the electricity market, these fluctuations in production costs were present as well, however producers, suppliers and consumers were given few incentives to respond to these fluctuations. Producers and suppliers enjoyed a monopoly in a certain area and captive consumers paid a flat rate that reflected the average cost over months or years. In the current liberalised electricity sector prices are determined by means of a market mechanism. Producers and suppliers compete on the market to sell their electricity. As they can increase their benefits by reducing their costs, the parties now receive incentives to respond to the fluctuations of the electricity prices.

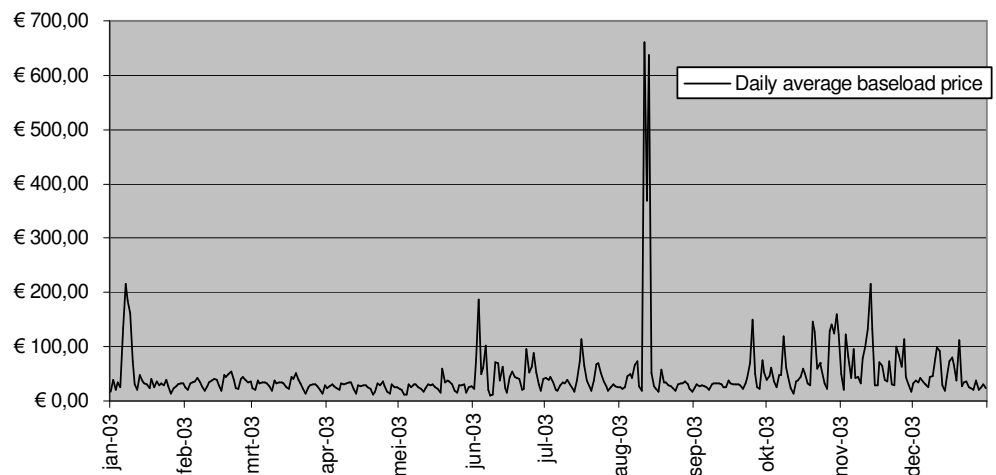


Figure 2.3: Average 2003 APX prices

The fluctuating value of electricity is reflected in the electricity prices at the APX spot market: a scarcity of electricity causes prices to rise, a surplus causes prices to decrease. Figure 2.3 shows the average 2003 price level of the APX. During

the summer months the electricity consumption is high because of air conditioning systems whereas during the cold winter months heating systems cause consumption to rise considerably. The extreme large price peak in August 2003 was caused by the limited availability of generation capacity because of the high temperatures of the cooling water (see paragraph 2.5). These fluctuations of the electricity price offers possibilities to use storage systems to charge electricity in times of low prices, and supply electricity in times when prices are high.

Besides the fact that liberalisation has lead to the pricing of electricity which is a major driver for the implementation of electricity storage, we identify two other characteristics of the current market design that also affect the implementation of storage, although to a lesser extent: the reduced possibilities for coordination in the electricity sector caused by the unbundling of the electricity value chain and the impact of the introduction of competition on the willingness to invest in innovative technologies.

The unbundling of the electricity market

The electricity sector is considered to be a network industry (Barale, 03). Network industries are characterised by the presence of strong complementary relationships between the different activities in the industry. The introduction of a new technology or a change of a process in one link of the electricity value chain therefore often requires coordination between several links. This also means that changes in one link of the value chain will often affect cost and benefits changes in a number of links. Before the restructuring of the electricity sector a single organisation would coordinate the operations in the different links. After the unbundling in contrast, the strict separation of production, transmission and distribution does not effectively facilitate integrated planning of production activities and grid management and design. This can cause problems regarding the implementation of technologies or new operational processes that affect activities in different links of the electricity value chain. Since the organisations are detached, coordination now has to be arranged largely through contractual arrangements or incentive regulation facilitated by extensive message exchange. As we will discuss in chapter 4, where several applications of storage systems are identified, the implementation of electricity storage often affects activities in more than one link of the value chain. The current unbundled market design can therefore form a barrier for the implementation of storage systems.

Implications of competition on the implementation of innovations

The introduction of innovating techniques often first enhances (high) investments in research and development. Moreover these innovations often have a high-risk profile and have long payback times. (Drillisch, 98) argues that the introduction of competition has lead to the creation of market barriers that discourage investments in innovating projects. In a free market environment there is much uncertainty about the future. Furthermore parties have less information to base their investment decisions on compared to the time that the electricity sector was vertically integrated and activities were centrally coordinated. This makes that parties carry more risks not to recover the investment costs of innovations. Since the private parties are in a competitive environment this discourages them to make the investments.

These negative incentives for innovations not only influence private producers and suppliers that are in a free market environment, but also grid managers. As previously discussed the grid managers are supervised by a regulator, DTe (Dienst uitvoering en toezicht energie). Currently DTe uses a price-cap system to regulate the Dutch distribution network sector. The price cap system stimulates

competitive forces that promote efficiency via tariff reductions. The tariff reductions per year depend on the x-factor. This x-factor is the discount to promote an efficient operation by network firms and is based on the benchmarking of the operational and capital expenditures between the different grid managers. In other words, consistent with the developments in the production and supply sectors, incentive regulation aims at stimulating competitive forces in the distribution sector (Jamasb, 00). A disadvantage of this type of price cap regulation is it emphasises on the short-term economic performance of grid managers (Scheepers, 2004). This could lead to the fact that not just the market parties, but also the grid managers receive incentives to reduce their investments in research and development.

The uncertainty, imperfect information and incentives for short-term economic performance for as well private parties in the market as governmental owned grid managers in the electricity sector, can form a barrier for the implementation of innovating technologies like electricity storage systems.

On the other side however, liberalisation is also argued to be a major driver for innovations. Companies in a competitive environment have more incentives to innovate than monopolists (Tirole, 88). Market liberalisation can therefore lead to strong competition that stimulates continuous efficiency improvements and product innovations. In conclusion we find several arguments to suggest that the introduction of competition discourages innovations that have a high-risk profile and have long payback times like the implementation of electricity storage. Conversely it is also argued that the introduction of competition in the electricity sector stimulates innovations and therefore could promote investments in electricity storage.

2.4 The actors in the electricity sector

This paragraph discusses the main actors that can be concerned with the implementation of electricity storage systems in the electricity sector.

Electricity producers

There are four large electricity producers in The Netherlands. Two of them, Electrabel (Belgium) and E.on (Germany), are in foreign hands. The two others large producers, Nuon and Essent, are Dutch and both own a regional grid. At this moment there is some 900 MW wind power capacity in Holland (Wind Service Holland, 03). Many of the 1580 wind turbines that make up for this capacity are privately owned. Sometimes private owners form co-operations in order to reduce costs and create a good negotiation position to sell their electricity to the utility companies. Utility companies like Nuon or Essent usually own the larger wind farms, sometimes in combination with private owners. The two offshore wind farms that are currently planned in the North Sea will be realised by joint ventures. The Nordzeewind consortium that will construct the Near Shore Wind Farm consists of Shell Wind Energy and Nuon Renewables. The Q 7 farm will be realised by a joint venture of E-connection, Vestas and several technical contractors.

Figure 2.4 on the next page shows that conventional thermal power plants produce the largest share (53%) of the Dutch electricity production. These are fossil fuel burning plants. Furthermore there are five high voltage connections with Belgium and Germany. The Netherlands is a net importer of electricity. On

yearly base 16 TWh is imported which consists of 15% of the annual total usage. Distributed production such as CHP and wind energy makes up for 29% of the production. The one nuclear power plant in The Netherlands contributes some 3% of the total usage.

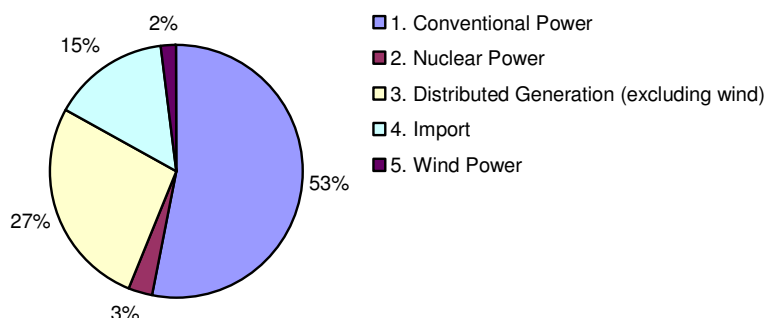


Figure 2.4: Sources of the Dutch electricity consumption (Energie, 03)

DTe The responsibility for the implementation of the Electricity Act of 1998 and the Gas Act, as well as supervising compliance with these Acts, has been assigned to the Office for Energy Regulation (DTe). The DTe ensures the conditions for the free market, such as completely free access to the electricity grids on equal terms. In addition, the DTe advises the Minister of Economic Affairs on the appointment of grid administrators, licences for suppliers of those consumers who are not yet free, on tariffs and on the tariff structure for transmission and system services. Furthermore, once every two years the DTe assesses whether the grid administrators can adequately and efficiently provide for all requirements in terms of transport capacity.

Transmission System Operator

TenneT is the Dutch Transmission System Operator (TSO) (Appendix A discusses the Dutch electricity grid). TenneT manages the infrastructure of the 380 kV and 220 kV grids and also has to protect and restore the balance in the electricity grid. In October 2001 the Dutch government bought the TSO of Sep obtaining full authority over the high voltage grid. TenneT also controls the cross border connections and daughter company TSO Auction is responsible for the allocation of cross border capacity. Another daughter company of TenneT is CertiQ, the organisation that manages the certificate system for producers of renewable energy. Finally TenneT owns the Amsterdam Power Exchange (APX), the Dutch electricity spot market.

Distribution network managers

There are 22 distribution network managers in The Netherlands. In some cases these are daughters of utility companies like Essent Networks and Continuon, which are administratively and legally separated from their holding company. Finally, there are also managers that don't have ties with utility companies like TZh and Noord West Net.

As is already stated in the paragraph 1.4, this Master Thesis has been devised from the perspective of both the transmission operator TenneT and the distribution network operators. The network operators are responsible to ensure the reliability and continuity of the electricity supply in The Netherlands. They

will therefore be responsible for the possible future integration of a large share wind power in the electricity grid.

Suppliers The position of the electricity suppliers has changed considerably in the liberalised market. Whereas in the past they had the exclusive rights to supply electricity in their region, they now will have to compete to acquire a certain market share. In order to face competition, supply companies have started different strategies with important positions for differentiation, identity and marketing (ECN, 01). As the retail market still wasn't liberalised at the time of writing of this report, this market is still served by the traditional utility companies like Nuon, Essent and Eneco. On the large-scale and mid consumer markets a considerable amount of customers already has switched suppliers. The same goes for the liberalised "green power" market, the only part of the retail market already liberalised. In addition, several new dot-com suppliers have accessed this market. The large suppliers such as Nuon, Essent, Eneco and Delta are still owned by provincial and municipal authorities.

Traders Within the new market design possibilities have been created for the trade of electricity. Traders try to make a profit by buying electricity from the APX or directly from producers and sell it to suppliers or large consumers or even retrade it via the APX.

Consumers As discussed, the consumer market is liberalised in three different stages. Whereas the large-scale and mid segment consumers already have the possibilities to choose their supplier, at the time of writing this report the retail market still consists of captive users.

2.5 The Dutch electricity markets

This paragraph identifies which of the Dutch electricity markets are most suited for storage operators to participate on.

In The Netherlands electricity is traded in three separate, time-based markets. Two of the markets are centralised, formal markets: the Balancing market operated by TenneT and the Day-ahead or spot market operated by the APX. The third is a bilateral market for trades among suppliers, traders and consumers for example for day ahead contracts of derivatives. Figure 2.5 shows that transactions made less than one day prior to the moment of operation are settled at the Balancing market. Trading electricity in the period between one day and two days prior to the day of operation is carried out at the day-ahead spot market as well as the bilateral market. The bilateral market facilitates trading of electricity prior to any moment of supply.

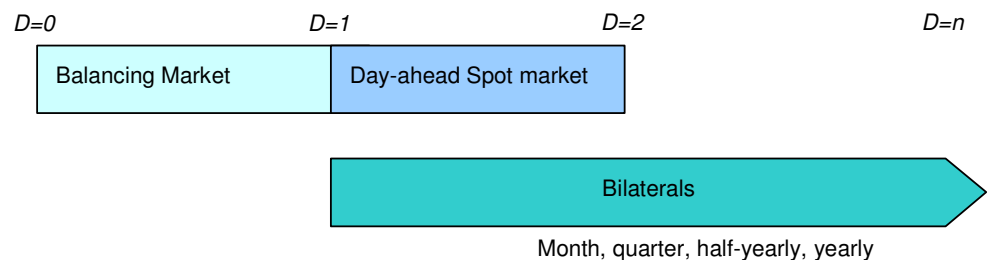


Figure 2.5: Time frame of the Dutch electricity markets

<i>Balancing Market</i>	Under the Dutch Electricity Law TenneT is responsible for the balancing of the electricity grid. When the imbalance in the electricity grid becomes too large, TenneT interferes by dispatching adjustment and reserve power in order to restore the system balance (see paragraph 4.1 for a detailed explanation of the balancing system). All market participants with a production capacity larger than 60 MW must offer their capacity suitable for adjustment power on the balancing market. The bids are aggregated in ascending order by TenneT. When the load is lower than production (a power shortage), TenneT corrects by buying power on the balancing market. When there is more production than load, (a power surplus), TenneT absorbs by selling power to market parties who made bids to buy on the balancing market. The final adjustment and reserve power prices are equal to price of the most expensive adjustment power used by TenneT. The total volume of settled imbalances is approximately 3% of Dutch electricity consumption.
<i>The APX spot market</i>	The APX spot market, operational since May 1999, facilitates day-ahead electricity trading. In 2003 about 15% of the Dutch electricity consumption was traded on the spot market (APX, 04). This relatively small amount demonstrates that market participants prefer to sign long-term bilateral contracts rather than rely on the short-term market. Participation in the APX Day-ahead market is voluntary and anonymous for all participants. Any market participant can act as a buyer or seller, by making bids, in € per MWh in blocks of one hour, one-day in advance prior to market closure at 10:30. After the market closure, the supply bids are aggregated in ascending order while demand bids are ranked in descending order. The market clearing price and volume for every hour are set by the intersection of supply and demand curve in that specific hour, given the generators' operating restrictions. At 16:00h on the day prior to the day of operation, the APX publishes a final price index on its website. Once supply and demand are matched, the APX submits its hourly balance or energy program (E-program) to TenneT.
<i>Bilateral Market</i>	The bilateral market operates independently from the APX and allows buyers and sellers to make transactions among themselves. The bilateral market is the most important in terms of volume, representing about 80% of total power in The Netherlands. Because bilateral trades occur independently from the spot market and are confidential for strategic reasons, only very little data is available on the prices of bilateral trades.
<i>Suitable markets for storage systems</i>	The flexibility of the storage systems makes them especially valuable for the balancing market. Several types of electro-chemical storage systems like batteries have a short response time and are easy dispatch able; they can be regulated up and down extremely fast regardless of their output level. Furthermore storage systems can be used to trade at the APX market: the systems can store electricity at night when prices are low, and supply this electricity during peak hours when prices are high. Storage systems are less applicable for the supply of electricity for longer-term contracts as often traded on the bilateral market while the dispatch of conventional power plant to execute these contracts can be more economical.

2.6 Security of supply and wind power

This paragraph discusses two developments in the electricity sector that could lead to opportunities for the implementation of electricity storage: the growing

concern regarding the security of supply and the increase share of wind power supply.

Security of supply

In the last years concerns have risen whether an adequate level of security of supply is ensured in a fully liberalised market. This concern has been strengthened by the recent occurrence of several blackouts in the US, the UK and Italy. The vulnerability of the electricity supply in The Netherlands was demonstrated in August 2003, when TenneT declared a 'code red' status: less than 100 MW of reserve capacity was available. This was caused by the fact that many Dutch producers use water from rivers for the cooling of their power plants. The hot summer of 2003 had lead to a significant rise of the temperature of river water. Since the temperature at which the cooling water is allowed to be drained into the rivers is regulated, producers had to adjust down their electricity production in order to limit the amount of cooling water. The decrease of available production capacity didn't result in outages in The Netherlands but the scarcity of electricity did lead to enormous prices peaks on the APX market (Figure 2.3).

Reserve capacity

These incidents have raised worries about security of supply. Two different components of security of supply can be identified. Firstly sufficient production capacity has to be available. This means there has to be a certain amount of reserve capacity that is only operated in times of peak loads. Since the production capacity for peak load often stands idle, it is uncertain whether investment costs will be recovered. By liberalising the electricity sector the government has given away control over the investments in production capacity. The high financial risks concerned with the investments in peak capacity makes it questionable whether private companies will realise sufficiently production capacity to always be able to meet demand. Figure 2.6 shows a possible development of the reserve capacity in The Netherlands based on the expected future investments in new production capacity. It shows that domestic reserve capacity might decrease to almost zero, meaning that The Netherlands will depend fully on foreign reserve capacity. Currently the government investigates the necessity of instruments to retain the level of investments at a sufficient level.

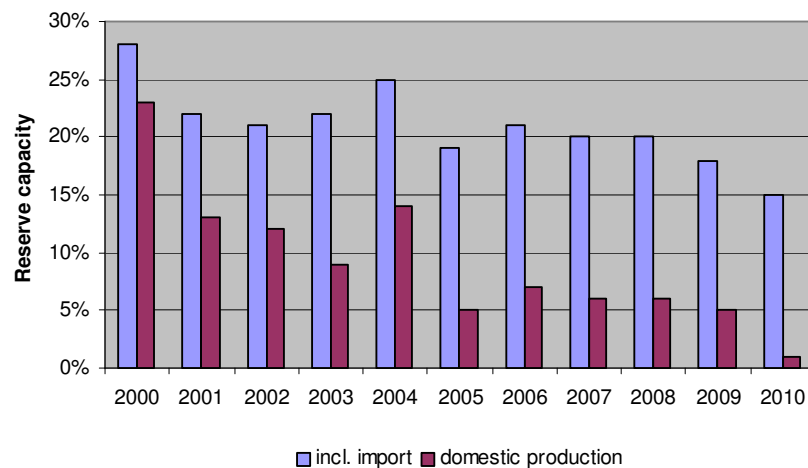


Figure 2.6: Possible development of reserve capacity in the Dutch market (ECN, 02a)

<i>Transportation capacity</i>	The second aspect of security of supply consists of the availability of sufficient transportation capacity. While electricity consumption increases every year, not only generation capacity but also transport capacity has to be increased continuously. Unlike regarding production capacity however, the government can influence the level of investments in transportation capacity. TenneT, which is responsible for the high voltage grid, is a public organisation. When the recently presented plans regarding the distributed grids will be realised also the lower voltage grid will be in public ownership. Therefore the main concern regarding security of supply is with respect to the availability of sufficient production capacity.
<i>Wind power</i>	The Dutch government aims at a contribution from renewable energy of at least 10% of the overall demand for energy in 2020. Wind energy is one of the most important options. The government has formulated a target for 2020 to have at least 7500 MW installed wind power capacity, of which 1500 MW on land and 6000 MW offshore (Min. EZ, 02). When realised the wind power capacity will make up for approximately 20% of the total installed generation capacity by 2020. The electricity supply in The Netherlands is generally reliable and very stable. The uncertainty caused by the implementation of a large share of intermittent wind power supply is identified to be a risk factor. Wind power can have a large effect on the security of supply, power quality and the costs of the electricity supply system. Besides the earlier mentioned doubts about the willingness of private parties to invest in production capacity, the integration of a large share wind power is an extra threat to the security of supply.

2.7 Conclusions

This chapter has answered the following sub question:

What are the implications of the unbundled market design on the implementation of electricity storage and what important developments are taking place in the context of electricity storage?

<i>Conclusions</i>	The introduction of the free electricity market has lead to the creation of incentives for producers and suppliers to respond to the fluctuating costs of electricity production. As storage systems can be used to charge electricity in times of low prices, and supply electricity in times when prices are high, this is a major driver for the implementation of electricity storage. One of the prime implications of the current market design of the electricity sector, in which production and transmission and distribution are strictly separated, is that the design can pose barriers for the introduction of technologies or changes of processes that require coordination between the links like the implementation of electricity storage. There are several arguments that suggest that parties carry more risk not to recover investment costs of innovative projects since the introduction of competition in the electricity sector. This discourages risky investment in innovations like electricity storage systems. Conversely it is argued that the introduction of competition in the electricity sector stimulates innovations and therefore could promote investments in electricity storage.
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The policy objective of the government to implement a large share of wind power in The Netherlands and yet ensure the reliability of the electricity supply system, could lead electricity storage to be an important factor in the electricity supply system within the coming years.

*Main consequences for the
following chapters*

This chapter forms a base for the following chapters as it outlines the context for the implementation of electricity storage systems.

The main barrier that the electricity market design poses for the implementation of storage systems is the fact that the links in the electricity value chain are strictly separated. This sets a requirement for the regulation that will be evaluated in chapter 6: the regulation should reduce this barrier.

3 ELECTRICITY STORAGE

Sub question 2 This chapter contains an inventory of different storage systems and their applications. It answers the second sub question: Which electricity storage systems are currently available and what are the characteristics of these systems relevant for market introduction?

The technical characteristics presented in this inventory are required in chapter 4 to investigate which systems are suitable for the integration of wind power in the electricity system. The economic characteristics are assessed in chapter 5 for the cost-benefits analysis.

This chapter starts with an introduction that discusses the difference between large and small-scale storage systems. In paragraph 3.2 several applications of electricity storage are identified. Paragraph 3.3 contains an inventory of the storage systems that are considered of importance for this study. Finally in paragraph 3.4 we draw conclusions and an overview of various storage systems and their possible application is presented.

3.1 Introduction

Small-scale systems One way of categorising storage systems is the distinction between large-scale and small-scale systems. Storage technologies that are often used for small-scale electricity storage systems are super-conducting magnetic energy storage (SMES), super-capacitors and ultra-capacitors, flywheel energy storage units and small-scale batteries. These systems have power capacities of at maximum several MW's and energy capacities up to 1 MWh.

Large-scale storage systems Storage technologies that are often used for large-scale electricity storage are pumped storage hydropower, compressed air energy storage (CAES) and large-scale (flow) batteries. The energy capacity of these systems can reach up to 50000 MWh with power capacities up to 2000 MW (pumped hydro storage).

3.2 Applications of electricity storage

Peak shaving The required electricity production capacity depends on the maximum share of power that is consumed (peak load). It is therefore desirable to keep the maximum demand of electricity as low as possible. Large-scale electricity storage systems can supply peak power using electricity that is stored at off peak hours. This way less power production capacity is required; this process is known as peak shaving.

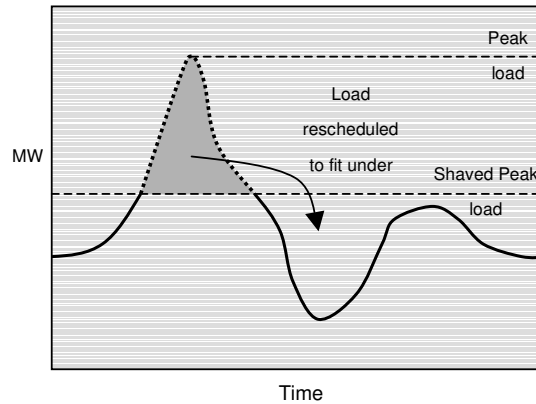


Figure 3.1: Peak shaving

Adjustment and reserve power

In order to keep production and load in balance, adjustment and reserve power is used (see paragraph 4.1 for a detailed explanation of balancing and adjustment and reserve power). This is production capacity that can be put into or out of operation within seconds. Since large-scale electro-chemical storage systems like batteries have short response times and fast regulation rates, they can be used to supply adjustment and reserve power. Storage systems like pumped hydrogen storage have a long reaction time and are therefore by nature unsuited for adjustment. These systems can only be used for reserve power supply.

Black start supply

In case of a power outage, power plants need to be brought back on-line. Normally, this is done with the help of power from the rest of the grid to which the synchronisation can take place. In the absence of grid power, black start supply is necessary to bring the power supply of a power plant, after which the production of electricity can be resumed.

Integration of renewables

Electricity storage systems can contribute to the integration of renewable energy sources into the network. Renewable power like wind energy or photovoltaic (PV) are characterised by intermittent availability. In combination with renewable resources, energy storage can increase the value of PV and wind-generated electricity, making supply coincident with periods of peak consumer demand.

Defer upgrade investments/ asset utilisation

An electricity grid that is dimensioned on the peak-level of electricity consumption has a low utilisation rate for many hours a day. By installing a storage system close to a load centre and use it to supply power during peak hours, the grid can be used more efficiently. This way a lower grid capacity may be required.

UPS

Another application of electricity storage systems is Uninterrupted Power Supply (UPS). Organisations like hospitals and computer related businesses that suffer substantial damage in case of power outages can invest in their own private emergency power system.

Power quality

Energy storage can provide "ride-through" for momentary outages, and extended protection from longer outages. Coupled with advanced power electronics, storage systems can reduce harmonic distortions and flicker, and eliminate voltage fluctuations. Power quality services can only be supplied locally.

Voltage control

The voltage level in the grid can vary within certain limits. A too high voltage level however can lead to the overload of certain grid parts, while a low voltage

level can lead to black out of equipment. Grid voltage is mainly controlled by reactive power. This is the part of electricity that is necessary in an alternating current system to build up electric and magnetic fields to maintain the network on voltage level and to operate transformers and motors. Reactive power supply is not a primary application of a storage system.

3.3 Electricity storage systems

Pumped storage hydropower

The most widespread large-scale electricity storage technology is pumped storage hydropower. With a world wide installed capacity of 90 GW, pumped storage is considered to be a proven technology. A pumped storage plant uses two reservoirs: an upper storage basin providing the head to drive the hydropower turbines, and another to collect water back into the upper basin using surplus base-load electricity during off-peak hours. A hydro storage plant can store large amounts of electricity (1-50 GWh) for long periods of time. It therefore is suitable for peak-load management, emergency power and black start supply. Pumped storage, reaching efficiencies up to 75%, is one of the most efficient ways to store and retrieve electricity. Costs of hydro pumped plants highly depend on their location. The lack of suitable sites in the future will limit the growth of pumped storage capacity. The pumped storage technology has already been developed to a large extent; a significant decrease in costs is therefore not expected. Because of a lack of suitable sites there are no hydro power stations with reservoirs in The Netherlands. In the 1980s studies have been made to build water reservoirs in the IJsselmeer (Min.EZ, 88). These would be formed by large basins surrounded by ring dikes with heights of 80 to 100 meters. The large environmental impact, high costs and safety risks make the implementation of these types of plants highly unlikely.

CAES

In compressed air energy storage (CAES), air is compressed and stored under pressure. Release of the pressurised air is subsequently used to generate electricity, most efficiently in conjunction with a gas turbine. In a CAES plant compressed air is used to drive the compressor of the gas turbine, which makes up 50-60% of the total energy consumed by the gas turbine system. The most important part of the CAES plant is the storage facility for compressed air. Usually a man-made rock cavern, salt cavern, or porous rock, either created by water-bearing aquifers or a natural depleted oil and gas reservoir, can be used. Aquifers in particular can be very attractive as storage media because the compressed air will displace water, setting up a constant pressure storage system. The pressure in the alternative systems will vary when adding or releasing air. The largest CAES plant, built at Huntorf in Germany, is 290 MW. The Alabama Electric Co-operative built a 110 MW commercial project. Several other projects are in process at the moment. CAES plants can be used for peak load management, emergency power and black start supply and can achieve efficiencies of about 70%.

As with pumped storage capacity, the development of large-scale CAES is limited by the scarce availability of suitable sites. Costs of CAES plants highly depend on their location. Because of the maturity of technology, costs are not expected to decrease substantially. The safety risks regarding CAES are comparable with those of activities of the production of natural gas. Suitable sites for the implementation of CAES in The Netherlands could be found in empty gas

fields (in the North East of Holland) or salt caverns (in the South East). Costs are expected to be high however.

Flywheels

Today's flywheel energy storage systems can provide highly reliable, high quality, uninterruptible electric power for different applications. Very heavy flywheel systems have been used for many years in electricity plants, but now development is focused on smaller systems. The charging of a flywheel is based on putting heavy symmetrical circumferential masses, originally made of steel, into rotation. The masses can rotate at about 50,000 revolutions per minute almost without friction around a titanium axle using magnetic bearings. The rotating masses are used in conjunction with a dynamo to generate electricity on demand. The latest modern flywheel energy storage systems make use of advanced composite materials and state-of-the-art active bearing technologies.

The storage time of flywheels is limited to periods in the order of 24 hours. They can store up to 1 MWh with a power capacity of 1 MW. Flywheels therefore can be used to improve power quality, integrate renewable power, voltage control and UPS. Flywheels, currently not being produced in large amounts, are still relatively expensive. When flywheels will be taken in mass-production a significant cost reduction is expected. Flywheels don't demand specific conditions regarding location and aren't accompanied by safety risks.

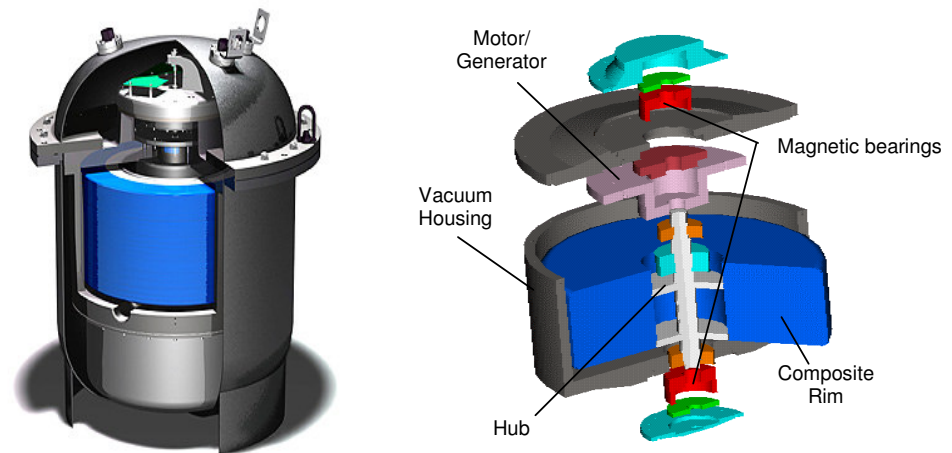


Figure 3.2: Flywheel storage system

Batteries

The oldest and best-established way of storing electricity is in the form of chemical energy in batteries. As with the energy stored in fossil fuels in form of chemical bonds formed originally via photosynthesis, batteries also use the principle of chemical bond formation to store energy. Electrochemical storage is characterised as the ability to convert chemical binding energy directly to electricity. The process can be reversed for rechargeable batteries or accumulators in order to recharge the storage media. Batteries cover an enormous range with many types in different stage of development and with different costs.

<i>Lead-acid battery</i>	The lead-acid battery is the most used battery system. Its power ranges varies from small scale up to 20 MW. It is therefore applicable to a broad range: peak load management, black start supply, regulating and reserve power, power quality and UPS. At this moment the lead-acid battery is one of the cheapest ways to store electricity. Because of the mature state of the technology a large decrease in cost isn't expected. The lead-acid battery can achieve efficiencies up to 75%.
<i>Nickel-cadmium battery</i>	Another battery that is already used on a large scale is the nickel-cadmium battery. As well as the lead-acid battery the nickel cadmium system has a large power range (100kW-40 MW) and is suitable for many different applications like peak load management, black start supply, adjustment and reserve power, power quality and UPS. The efficiency of the nickel-cadmium system (60-65%) is relatively low compared to other types of batteries. The low investments cost in combination with the robustness and high reliability of the battery make it a popular type. A negative aspect of the nickel-cadmium battery is the limited availability of cadmium reserves and the problems regarding the disposal of used batteries, as heavy metals are considered environmentally hazardous.
<i>Lithium-battery</i>	The lithium-battery is a relative new battery with a very high efficiency (over 90%). Within a few years it has conquered about 50 % of the small mobile battery market. It is expected that within a short period of time also stationary systems will be available and gain a significant market share. It will be fit for small-scale applications like, power quality and UPS.
<i>Sodium-sulphur battery</i>	A system that is already in an advanced stage of development is the sodium-sulphur battery. In Japan already 30 batteries have been installed with a total capacity of 20 MW, the largest system is 6 MW power, with 12 MWh energy supply. The system can store electricity for several days with high efficiency (90%) and can be used for power quality applications and UPS. Costs are still relatively high but are expected to decrease as further development evolves.
<i>Flow batteries</i>	A way to escape storage constraints in battery design is to store all the energy in the electrolyte and not some in the electrolyte and some in the electrodes as with a standard battery design. Achieving this means that storage capacity is limited only by the volume of electrolyte the battery can contain. If, then, the electrolyte could be located away from the active cell itself, even the containment constraint would be avoided. The electrolyte could be stored in tanks as large as required, a flow being created through the cell by pumping. This is the basic idea of the flow battery, which is a promising system for large-scale applications including integrating renewables into distributed or centralized electricity grids. Flow batteries, generally operating at an efficiency rate of 75-80%, are flexible in operation, especially with respect to discharge times that can range from minutes to many hours. Nor do they have obvious scale limits and are not location restricted.
<i>PSB flow battery</i>	The poly-sulphide bromide battery (PSB) is a flow battery also known as the Regenesys system. The PSB system recently was commercially available and besides a 120 MWh plant at Little Barford, UK, the American utility Tennessee Valley Authority was building a 12 MW/120 MWh system. At the end of 2003 however, both projects were cancelled and the Regenesys company was shut down. It is not unlikely that the development of the PSB technology will be continued in future given the developments take up to increase the security of

supply and the diminishing space production capacity as a result of the liberalisation of electricity markets.

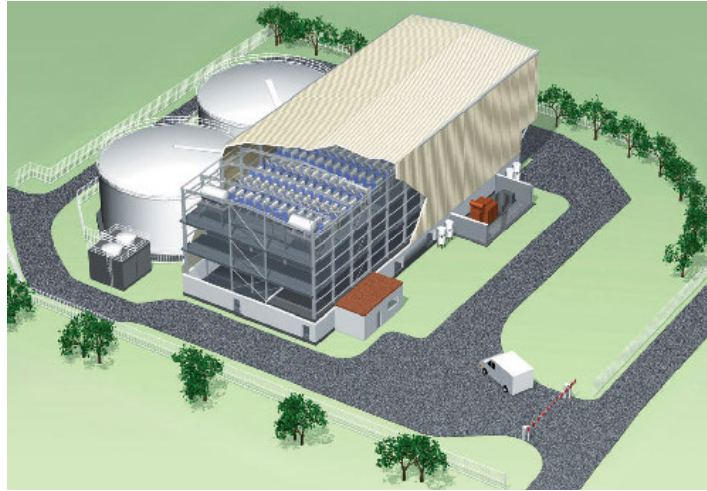


Figure 3.3: PSB storage system

It is expected that PSB systems varying from 5 MW until 500 MW will become available. At the moment of writing this report, the PSB technology was still expensive in comparison with normal batteries but prices are expected to decrease significantly. Compared to other flow batteries the PSB system has the largest energy storage and power capacity and can be used for peak load management, black start supply, adjustment and reserve power, power quality and UPS. The efficiency of the system currently is about 65% but technology is expected to improve resulting in efficiencies up to 75%.

ZnBr flow battery

The zinc-bromide flow battery (ZnBr) has smaller power capacity and energy capacity than the PSB system, at maximum 1 MW/ 4 MWh. Through the years many prototypes have been build and tested. The ZnBr technology, unlike the PSB, is not expected to develop much further in future, therefore cost reductions have to be obtained by introducing serial production. The ZnBr battery can be used for power quality applications, UPS, Renewable support and has an efficiency of approximately 75%.

Vanadium flow battery

The vanadium flow battery can reach power and energy capacities up to 10 MW/100 MWh. Like all above discussed flow battery systems it can store electricity for a long period, currently with an efficiency rate of 80%. Improvement of technology however is expected to increase efficiency up to 85% and decrease costs. The power and energy capacity characteristics make the vanadium battery suitable for power quality applications, UPS and voltage control.

Super capacitors

Super capacitors offer extremely fast charge and discharge capability, although with a lower energy density than conventional batteries, and can be cycled tens of thousands of times. Super capacitors, also known as electrochemical capacitors, store energy in an electric double layer formed between each of two electrodes and the ions in the electrolyte.

3.4 Conclusions

This chapter answers the following sub question:

Which electricity system storage systems are currently available and what are the characteristics of these systems relevant for market introduction?

Conclusions Table 3.1 presents the storage systems discussed in this chapter with three important characteristics.

	Typical power rating	Typical energy rating	Status of development
Pumped hydro storage	100 - 2000 MW	1 - 50 GWh	90 GW installed, mature
CAES	100 - 300 MW	1 - 10 GWh	400 MW installed, 2 commercial installations
Flywheels	5 kW - 1.5 MW	< 1 MWh	Commercial available
Lead acid battery	< 20 MW	< 60 MWh	Commercial available
Nickel cadmium battery	< 40 MW	< 10 MWh	Commercial available
Lithium battery	< 5 kW	< 5 kWh	Small units commercial available, larger scale expected within few years
Sodium-sulphur battery	< 10 MW	< 20 MWh	20 MW installed demo's, small units commercial available
PSB flow battery	5 MW - 500 MW	50 - 5000 MWh	Two 15 MW demo's recently stopped
ZnBr flow battery	< 1 MW	< 4 MWh	250 kWh units commercial available
Vanadium flow battery	< 10 MW	< 100 MWh	250 kWh unit commercial available
Super capacitors	< 100 kW	20 kWh	Small units commercial available

Table 3.1: Overview of storage systems

Table 3.2 on the next pages gives an overview of the various storage systems and their applications. In the column “Defer of upgrade” a “T” stands for the fact that the storage system is applicable for the defer of upgrade in the transmission network, a “D” means the storage system is applicable for the defer of upgrade in the distributed network.

Storage systems	Applications						
	Peak shaving	R&R power	Black start	Integr. of renew.	Defer of upgrade	UPS	Power quality
	Pumped hydro storage	+	-	+	+	T	-
	CAES	+	-	+	+	T	-
	Flywheels	-	-	-	0	-	+
	Lead acid battery	-	+	0	0	-	+
	Nickel cadmium battery	-	+	0	0	-	+
	Lithium battery	-	-	-	-	0	+
	Sodium-sulphur battery	-	+	-	-	+	+
	PSB flow battery	0	+	0	+	T/D	+
	ZnBr flow battery	-	-	-	+	-	+
	Vanadium flow battery	-	0	0	+	-	+
	Super capacitors	-	-	-	-	-	+

Table 3.2: Overview of storage systems applications

There are many different applications of electricity storage varying from small scale applications for the supply of power quality services up to large scale applications like peak shaving (Table 3.1). Some storage systems like for example super capacitors have very limited applications, other systems like (flow) batteries are suitable for a wide range of applications. In contrast with some mature storage technologies that are already implemented on a large scale, several storage technologies are still in the phase of development. A promising storage system that has many applications is the Polysulfide Bromide system. The PSB system can achieve high efficiencies and is flexible with respect to discharge times and storage capacity. The fact that the PSB system does not have specific requirements regarding its location, in contrast to pumped storage and CAES, it enables the implementation of the system in The Netherlands. Though on the moment of writing this report the costs of the PSB system are still high, further development of the PSB technology is expected to result in a significant decrease of investment and operational costs.

Main consequences for the following chapters

This chapter has identified characteristics of storage systems that will be used to investigate which systems are most appropriate for the applications that are discussed in following chapter. The economic characteristics of the PSB storage system will be used in chapter 5 to carry out a cost-benefit analysis.

4 HOW CAN ELECTRICITY STORAGE CONTRIBUTE TO THE INTEGRATION OF WIND POWER IN THE ELECTRICITY SECTOR?

Sub question 3

This chapter identifies four problems regarding the integration of wind power in the electricity supply system for which the implementation of storage systems could provide a solution. It answers the third sub question: In what way can electricity storage contribute to the integration of wind power in the electricity supply system?

Currently the use of wind power does not jeopardise this reliability of the Dutch electricity supply system. In the long term however, an increasing share of wind power in the electricity system could form a threat for the security of supply. The inventory in chapter 3 showed that there are several storage systems available with different characteristics. This chapter discusses how these storage systems can be useful for the integration of wind power and which storage systems are most appropriate to do within the Dutch electricity sector.

This chapter starts with an analysis of the problems a large share wind power can cause concerning the short-term balance of the electricity system and the role electricity storage can play to resolve them (Brand, 03) (KEMA, 02) (Pedersen, 99). Wind power also influences the long-term balance of the electricity system. In paragraph 4.2 the advantages of the implementation of storage systems regarding the long-term balance are discussed. Paragraph 4.3 considers how storage systems can secure to power quality when a large share of wind power is integrated in the electricity system. Finally paragraph 4.4 discusses how the implementation of an electricity storage system can defer grid investments. At the end of paragraph 4.1 and 4.2 a scorecard approach presents the advantages and disadvantages of the use of various types of storage systems for the discussed application. The final conclusions are presented in paragraph 4.5.

4.1 Compensating unpredicted fluctuations in wind power supply

This paragraph first discusses the concept of balancing the electricity system and the fact that this requires adjustment and reserve power (an introduction of the main characteristics of the electricity grid can be found in Appendix A). Then, the influence on short-term balance of a large share of wind power in the electricity supply system is analysed. This is followed by a description of the imbalance pricing system. Next it will become clear that the unpredictability of wind power supply can lead to high imbalance costs for wind farm operators. Finally the benefits that electricity storage can have with respect to short-term balancing are discussed and the storage systems that are suitable for this application are evaluated in a scorecard.

Balance

An important feature of the electricity grid is the fact that it has to be continuously in balance. Every second of the day electricity supply and consumption have to be equal in order to maintain the set voltage and frequency level. The matching of supply and demand is called balancing. When the

electricity grid is not in balance the frequency of the electricity deviates from the European standard, 50 Hz. When this deviation becomes too large, equipment connected to the grid can be harmed. Maintaining the energy balance between generation and load occurs on two time-scales. On the short-term, a few seconds up to approximately one minute, the power transfer between generation and load is relative small, compared to the total system. In 2001, the maximum load of the combined European system was 341,4 GW. A large power step of 3000 MW corresponds to a power imbalance in the combined European system, of less than 1%. TenneT, the Dutch TSO, has to protect and restore the balance in the grid (vested by the E-law). In order to keep the grid in balance TenneT has to know how much electricity the producers plan to feed into the grid. Electricity producers are urged to produce exactly what they have planned so the grid can be kept stable with respect to voltage and frequency. On the other hand TenneT has to know precisely how much electricity will be consumed. The amount of electricity that will be consumed has to be estimated as this is by nature varying. In reality the level of production and consumption is hardly ever equal, caused by sudden loss of generation, off-system purchases, unexpected load fluctuations, and/or unexpected transmission line outages. When the imbalance becomes too large, TenneT interferes by dispatching adjustment and reserve power in order to restore the system balance.

*Adjustment and reserve
power*

In case of significant imbalance TenneT tries to estimate the degree to which and the timeslots the market players themselves will be able to deal with the consequences of the imbalance. Until such time the consequences from the imbalance will, where possible, be neutralized by using adjustment power. Adjustment power is power that TenneT dispatches via load frequency control (LFC). The LFC is the automatic regulation system that enables TenneT to control generation units to provide power for upward or downward adjustment depending on the imbalance nature. When a drop of frequency is observed, the generated power is increased automatically, in order to restore the balance between load and generation. When a frequency increase is observed, the generated power is reduced. Besides being LFC controllable, adjustment power has to have a response time of less than 30 seconds and a regulation speed of 7% (TenneT, 02). This means that the production of the generation unit has to be able to increase with 7% of its capacity per minute. Currently adjustment power is provided by spinning, i.e. online reserves. To enable adequate response to a power imbalance, and to minimise the frequency deviations, all operational generating units are not fully utilised, thus not all production units are running their full capacity. The units assigned for adjustment are running below nominal capacity, thus fast power increase is possible. These units are called spinning reserve. If imbalances are so large that adjustment power has been exhausted, or is expected to drop below a particular threshold (set at 100 MW) and this situation is expected to hold on for a longer period of time, reserve power will be called in until adjustment power has been released.

*Implications of wind power
on regulating and reserve
power requirements*

The amount of operating reserve that is retained in any period of time is based on the probable, but unpredictable, variations in load or generation that can be expected to occur in that period. An increase in share of wind power in the electrical power system complicates this planning: the short-term wind power fluctuations, caused by wind speed variations, will increase. This occurs when more wind turbines are in operation and all are influenced by wind speed variations. In recent literature however, it is generally assumed, that with a large

share of wind power, due to the geographical distribution, the short-term fluctuations are reduced to such an extent that specific measures are not required to compensate for the 'normal' fluctuations in the generated power (KEMA, 03). Normal fluctuations are fluctuations caused by changing wind speeds. The common opinion is that the current balancing approach will still be applicable when the required power reserve has to be determined. The short-term power fluctuations are most likely smaller than the power that is lost by the failure of a large power plant. The analysis of the power loss risk, the size of the units and the capacity of the cables, as currently used to determine the required regulation and reserve power, are sufficient also when wind power share increases. It is expected that this is also the case for the Dutch electricity grid, although this still has to be confirmed with measurements and further investigated by modelling (KEMA, 03).

The influence of wind power on the required adjustment power is not only determined by the possibility of short-term power fluctuations caused by variable wind speeds, but also by large-scale power loss caused by for instance a storm. If wind speed suddenly exceeds the cut-out speed, wind turbines have to be shutdown to prevent damage (Appendix B). This effect will increase as the wind power is geographically more concentrated. With a larger geographical area, local wind speed variations will be smoothed. If it is possible to predict storm behaviour, the controlled shutdown of the wind turbines can take place over a longer period of time, in parallel with the start-up of other conventional production units. The prediction of wind does not reduce the measures to be taken to compensate for the power loss of larger quantities of wind power, but it reduces the time in which these measures should be effective. In contrast with the 'normal' fluctuations of wind power supply, the fluctuations caused by exceeding the cut out wind speed could lead to an increase of the required amount of adjustment and reserve power.

*Implications of wind power
on the allocation of
adjustment power*

Besides the fact that wind power could enlarge the required the adjustment and reserve power requirements, the integration of large-scale wind could cause problems regarding the allocation of reserve and adjustment power. The operating units designated for reserve and adjustment power should take care of the short-term disturbance of the power balance. When a large share of wind power is installed in the Dutch electricity system, conventional generation power will relatively decrease. The largest reduction will occur at a high wind speed and at the same time low load, say at base load times in summer nights. In such a situation only a few conventional units will be operating. This will lead to difficulties with allocation of the adjustment power over the available conventional units. First, the minimum total capacity of the operational units, necessary to allocate the adjustment power, may be larger than the load minus the generated wind power. This will result in a power surplus. Secondly, the adjustment power should be distributed over several units in the grid to be reliable. This means that keeping on line only the minimum of conventional units that can supply sufficient adjustment power may be not enough to realise the desired level of security of supply. Keeping online more units would cause an electricity surplus. To conclude the decrease of the number of units that functions partly as adjustment power units, has consequences for their adjustment speed. To compensate a power unbalance, a certain amount of generated power is required. With only a few units online, each unit will have to be able generate more power

to meet the requirements. With more units, less generated power is required of each unit.

As mentioned before, the current system used for determining the amount of adjustment power makes that the electricity system is prepared for unexpected changes in load and production. Only if intermittent power capacity increases considerably this could impose extra demands on the system. The Dutch government aims at having 7500 MW installed wind capacity by 2020. The maximal electricity demand for 2020 is estimated on 23 GW, based on a yearly load growth of 2.5 % per annum (KEMA, 03). This means wind share could rise up to 30% of total maximal demand. 6000 MW of the planned capacity consists of offshore wind farms. The area in the North Sea that is designated for wind power is relatively small. As a consequence the 6000 MW installed wind power will be geographically concentrated. Thus, should wind share indeed grow significantly in the coming decades TenneT could face a shortage on adjustment power. Similar problems already have occurred in Denmark where about 2500 MW wind power is installed at a relatively small area. Eltra, the Western Danish TSO, therefore uses German reserve power located in the area where E.on is the responsible TSO (Eltra, 03).

The imbalance pricing system

Besides the fact that the uncertain production behaviour of wind power may cause problems regarding the availability of sufficient adjustment power for TenneT, it could also cause wind farm operators to incur substantial imbalance costs. In its capacity as the administrator of the national high-voltage grid, TenneT has the obligation to monitor and preserve the balance in the Dutch grid. In order to achieve this TenneT uses a system aimed at ensuring a balance intended energy supply involving market players. Every day market players (producers, supply companies, traders etc) have to set out their proposed supply or consumption in a program (E-program) (TenneT, 02). The parties that have to submit a program are called Programme Responsible Parties (PRP's). These E-programs have to contain supply and load data for every 15 minutes period (= 1 PTU, Program Time Unit). If a PRP deviates from the E-program and this results in an imbalance of the system TenneT automatically compensates the imbalance. This is achieved by dispatching adjustment power aimed at supporting the balance preservation. When load is lower than production (a power shortage), TenneT corrects by buying power from the suppliers of positive power. When there is more production than load, (a power surplus), TenneT absorbs by selling power to the suppliers of negative power. On a daily basis suppliers can tender their bids on the adjustment and reserve power market, also known as the adjustment market.

Implications of wind power on imbalance costs

The market players, whose actual supply or load deviates from their E-program handed in to TenneT, are charged with the costs made by TenneT to compensate for their deviations. The unpredictability of wind power supply causes wind energy to deviate largely from the E-programmes and thus incurs imbalance costs. Data of one of the Danish TSO's, Eltra, illustrate this. In 2000 there was an installed capacity of 1630 MW wind power in the Eltra area. One third of the total year production of these wind turbines was produced in imbalance (Brand, 03). This caused imbalance costs of 8.8 million Euros. Unbalance costs per kWh in that period were about 3 times lower in Denmark than the average imbalance cost in The Netherlands. The same amount of imbalance in The Netherlands would therefore have incurred costs to about 25 million Euros. TenneT charges the

imbalance costs to PRP's. A PRP that feeds in a lot of wind energy, like a supply company that buys wind energy from a wind farm exploiter or wind cooperation, can therefore incur high imbalance costs. This is a substantial economic risk and should be included in the business model of the exploiter of a wind farm.

Usefulness of electricity storage

Storage systems can be used to absorb unpredicted fluctuations in the production of wind energy. In times of surplus production by wind power the storage systems can be charged while during shortage production of the wind power the storage systems can supply electricity. The storage capacity can be offered as adjustment and reserve power at the balancing market, or can be used by PRP's to settle their imbalances internally and in this way prevent imbalance costs.

Suitable storage technologies

As concluded from the inventory of storage systems, not all storage systems are suitable for absorbing fluctuations on a time scale of seconds. An additional constraint is the power capacity of the storage systems. Research by the National Renewable Energy Laboratory (NREL, USA) shows that power fluctuation by wind farms, within one second, can reach up to 3 % of the installed wind power capacity. The variation within one minute is limited at about 10% of the installed capacity. However, the measurements in this research are based on the average production of two wind farms, less geographically concentrated compared to the Dutch situation. Wind speed changes in the Dutch generation area will therefore be more correlated and will probably induce larger power variations. When the output of the 7500 MW planned wind power capacity changes with 3%, this will lead to a 375 MW fluctuation. Only large-scale storage systems can significantly contribute to the absorption of fluctuations on this scale. The only large-scale systems that can change their output with such short response time are (flow) batteries. Table 4.1 shows the four most appropriate storage systems compared with respect to three important characteristics. The first criterion pertains to the expected costs. Taking into account the expected development of the share of wind power in the Dutch electricity system, and the expected development of the large scale storage system, it will take at least another ten to fifteen years before storage systems will possibly be implemented on a large scale for balancing applications. That is why we choose to compare the expected costs of storage systems in 2020. The second criterion is the storage capacity of the storage systems. Third criterion is the stage of development of the storage systems. This criterion expresses the uncertainty regarding the development of the technology and the costs of the storage system. Three different scores are used to value the storage systems, a '+' for a positive score, a '0' for a neutral score and a '-' for a negative score.

	PSB flow battery	Zinc-bromide flow battery	Lead-acid battery	Sodium-sulphur battery
Expected costs	+	0	0	+
Storage capacity	+	0	-	-
Stage of development	-	0	+	0

Table 4.1: Scorecard balancing

On a longer term the PSB system and the Sodium-sulphur battery (NaS) seem the most appropriate systems for balancing. The large storage capacity of the PSB system can make it preferable over the NaS.

4.2 Energy management

This paragraph first explains the difference between short and long-term balancing. Long-term balance is maintained by load following as is discussed subsequently. Next it will become clear that the integration of a large share of wind power requires that conventional generation no longer only has to respond to fluctuations in load but also to fluctuations in (wind power) production. This paragraph concludes with the possibilities the implementation of storage systems offers for energy management and an evaluation of the different types of storage systems.

Long-term balance

Besides unexpected load changes and outages that require short-term balancing, in the long-term (minutes up to days), structural load changes cause a disturbance of energy balance between generation and load. These load changes are very large, even related to the total electricity system. This is caused by the fact that load depends on the time of day, the day of the week and time of year. In figure 4.1 the load curve of the day when the highest load of 2003 was reached is shown.

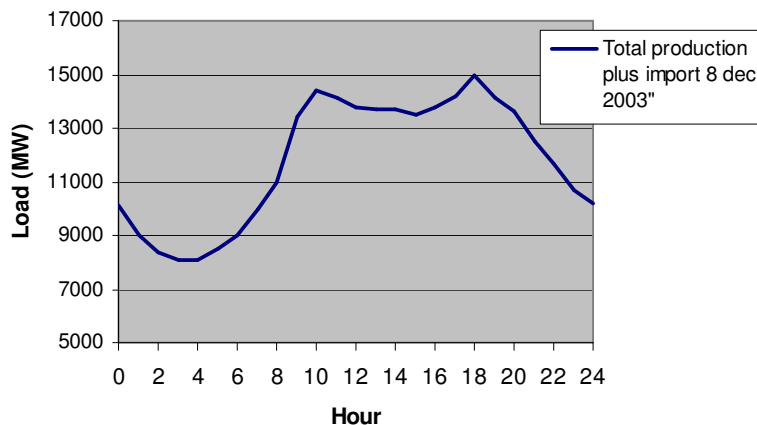


Figure 4.1 Load curve of the day with the highest peak load 2003 (TenneT, 04)

Load following

The large load fluctuations that occur during day, week and year, are not handled in the same way as small disturbances of the energy balance on the seconds time scale. Whereas short-term disturbances are balanced by adjusting up or down power units, long-term balance is kept by taking out of operation specific power units. When load increases, the units start to operate again. This is called load following. The planning of the unit commitment, the operating point where power-generation units generate enough power to meet demand at minimal costs, can be quite complicated since the time needed to take the different units in and out of operation can in case of large thermal and nuclear plants be more than 12 hours.

Peak supply

The fact that during an average night the load can decrease to 6 GW means that less than 1/3 of the total installed generation capacity of 22 GW is used. The larger part of the production capacity is only used during daytime. Some plants are even operated not more than several hundred hours per year. These so-called

peak plants are only in operation during a few peak hours a day, at days when total load is high (predominantly at cold winter days around 17.00 PM and hot summer days at midday). Because of their low utilisation rate, these peak plants exhibit high production costs. When a gas fired plant operates hundred hours a year, its production costs can be over 500 €/MWh.

*Implications of wind power
on long-term balance*

The implementation of wind power will influence the long-term balance in two ways. First of all wind power production varies considerably on the long-term (figure 4.2). Therefore large-scale implementation of wind power would introduce, besides the already existing fluctuations in load, fluctuations in production output. This complicates unit operational planning. The fluctuation in wind power demands irregular production behaviour of conventional power. This means that the operation schedules of the existing plants are influenced more frequently, as the relative contribution of wind power increases in the coming decades in The Netherlands. This indicates that considerable more control actions will be required, which will result in an increase of costs and a decrease of the efficiency and life cycles of the conventional generation plants.

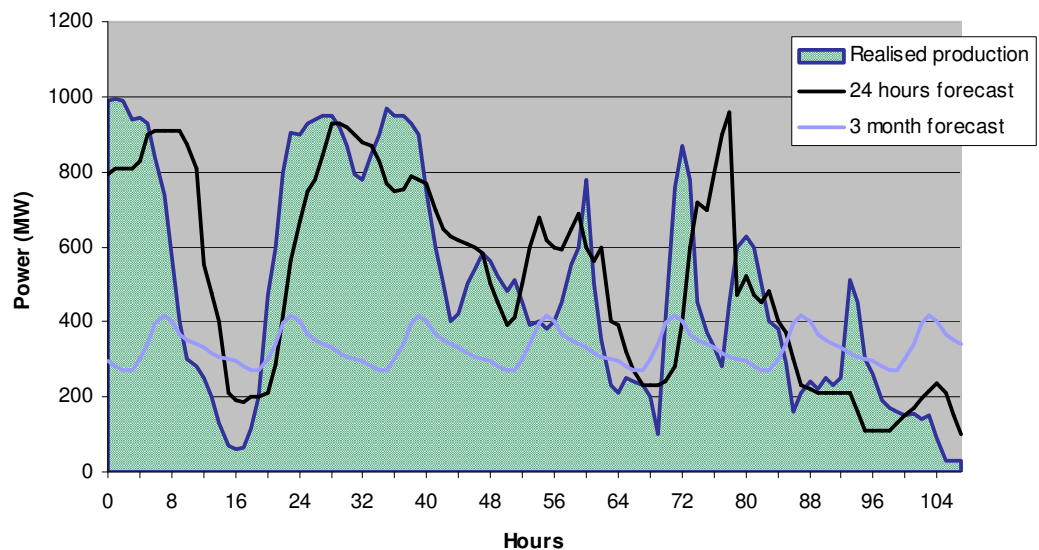


Figure 4.2: Realised wind power production and forecasts (Eltra, 02)

In addition, the conventional plants on average will have less hours of operation and therefore lower utilisation rates. This is caused by the fact that very little conventional generation capacity is substituted by the installation of wind power, as sufficient back up capacity still has to be maintained. In the absence of wind, the installed conventional capacity still has to be able to meet the maximal electricity demand hence the peak load. For example, suppose during daytime the load is 14 GW and wind power production is 5 GW. If wind power is available, the conventional capacity will have to produce less power, resulting in lower utilisation rates and thus incur higher production costs.

*Usefulness of electricity
storage*

Storage systems can decouple the timing of generation and consumption of electricity. One example of energy management is peak shaving. Peak shaving reduces the required generation capacity and 'increases' the utilisation rates of the installed capacity. As wind power production is independent of the load, energy

management applications can be very valuable for wind power. Electricity generated during the night at base load prices can be stored and sold at daytime for high prices during peak hours. Furthermore most storage systems are easy to dispatch; they can be regulated up and down extremely fast by power electronics regardless of their output level. This can simplify unit operational planning and reduce its costs.

Suitable storage technologies

Storage systems that are suitable for energy management applications are large-scale systems like pumped storage hydro, CAES, the PSB system and large-scale 'conventional' batteries. Since the location requirements of the pumped hydro storage and CAES makes their implementation in The Netherlands highly unlikely, these systems are not considered in the following scorecard.

	PSB flow battery	Lead-acid battery	Sodium-sulphur battery
Costs	+	0	+
Storage capacity	+	-	-
Stage of development	-	+	0

Table 4.2: Scorecard Energy management

On a longer term the PSB system and the Sodium-sulphur battery (NaS) seem the most appropriate systems for energy management applications. Even more as for balancing applications the relatively small storage capacity of the NaS can make the implementation of the PSB system preferable.

4.3 Power quality

Power quality is an important issue in today's power supply. As the share of computer equipment in the load increases power quality becomes a concern of more and more customers. What is power quality? Alternating voltage can be presented as a sinusoidal wave in time. Any distortion of the shape of the wave can be considered a power quality deviation. The distortions can be induced both by generation units and load. The three main power quality problems are harmonics, voltage variations and flicker. These effects can harm the end-users' equipment or cause malfunctioning. Also for generators or other grid components, for example transformers, a low power quality can have undesirable effects.

Harmonics

Harmonics are the distortions of sinusoidal voltage or current waveforms characterised by either voltage or current components at multiples of the fundamental frequency. Many types of electrical equipment, for example with build in converters, produce harmonic disturbances that may cause different types of damage to electrical equipment connected to the grid. In figure 4.3 the upper waveform is the superposition of the lower two of which the lowest is the original 50 Hz waveform. The middle one is the second harmonic and

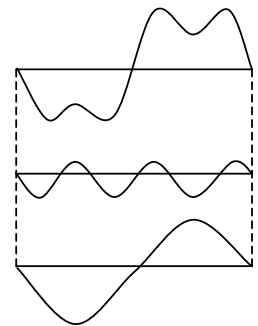


Figure 4.3: Harmonics

the superposition results in a very distorted waveform that by far not resembles the sine wave.

Voltage level

The voltage level is not the same at different points in the grid. However, the level may not deviate too much from the nominal value. A too low voltage level will result in the incorrect functioning of the electrical equipment while a too high voltage level can result in damage of the equipment and grid components. Variations in the long-term voltage level are caused by fluctuations in load and generation. Moreover, voltage variations at different places in the grid will result in undesired current loops causing losses.

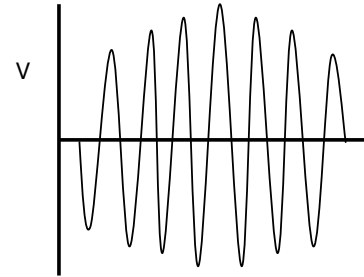


Figure 4.4: Voltage variations

Flicker

Voltage fluctuations that occur on a smaller time scale are referred to as flicker. In general the fluctuations at these high frequencies do not cause equipment failures but result in light flickering.

Implications of wind power on power quality

The integration of wind turbines can have a negative influence on power quality. The turbines can cause flicker, voltage variations and can inject currents with non-sinusoidal waveform, harmonics. The type of wind turbine and the characteristics of the grid are the main factors that determine power quality impacts of wind power (Appendix B contains an detailed discussion of the impacts on power quality of different wind turbine types). Flicker can be caused by tower shadow, the effect on a turbine with a down-wind rotor of the tower itself obstructing the wind entering its plane of rotation. The distortion of harmonics by wind turbines is mainly caused by the power converters used in variable speed wind turbines. Finally the integration of wind power can have a large impact on the voltage levels in the electricity grid. Reactive power supply, which has a large influence on the voltage level, of fixed speed turbines is not controllable.

Weak grids

The integration of wind power will cause problems regarding power quality in so-called weak grids that are usually found in more remote places (Appendix B). Offshore wind farms will most likely be connected to the high voltage transmission grid where flicker and harmonics have limited impacts (Offshore wind power, 2004). Therefore power quality will predominantly be a problem for onshore wind farms. This means that the effects of wind power on power quality will be a concern of the distribution grid managers. Although all actors who want to be connected to the grid have to live up to the power quality demands imposed by the grid managers, the grid managers may have to take specific, and perhaps costly, measures to retain power quality at an acceptable level.

Usefulness of electricity storage

Electricity storage systems offer possibilities for the improvement of power quality. In case of offshore wind power, storage systems like batteries and flow batteries can supply reactive power with the help of advanced power electronics in order to control the voltage level. It must be taken in account however that a voltage is a local variable and a large-scale 'central' storage system can therefore only support the voltage level in a limited area. Pumped hydro systems and CAES therefore have little benefits for power quality. Smaller scale storage

systems, connected to the distribution grids can have more value for power quality. In these grids, sensitive for fluctuations of wind turbines, storage systems can be used to keep the output power more constant. This will reduce voltage fluctuations generated by wind farms and therefore also reduce flicker. Moreover the implementation of storage systems provides the possibility to supply reactive power in weak grids. Finally storage systems, often equipped with electronic filters, can reduce the harmonics in the grid.

Suitable storage technologies

While for larger scale systems like flow batteries power quality services are side functions, it is difficult to compare the costs of the power quality services they supply with the costs of small-scale systems that are dedicated to supplying power quality services. Therefore we choose not to use a scorecard to compare the different storage systems. The most important conclusions with respect to the comparison of different storage systems for the supply of power quality services is that small scale storage systems like flywheels, super capacitors and small scale batteries are more useful for the supply of power quality services than large-scale (flow) batteries. This is caused by the fact that small-scale systems can be distributed more evenly over the grid to prevent power quality problems that occur very local.

4.4 Deferral of grid investments

Implications of wind power on grid investments

Electricity consumption in The Netherlands increases every year with about 2.5% (KEMA, 02). This not only has consequences for the required generation capacity but also for the grid capacity. Every other year TenneT carries out a transmission and system exploration to determine the capacity requirement for the electricity grid. To integrate the large share of wind power certain reinforcements to the grid have to be carried out. Large scale wind farms that will be realised in the future in the North Sea area will probably be connected to the high voltage transmission grid at two or three different points (KEMA, 02). This will require sufficient transmission capacity from the new large generation centres to the load centres. The investments for these extensions are estimated at 400 to 600 million Euros (KEMA, 02). The share of onshore wind power that has to be integrated in the electricity grid is much smaller than the planned share of offshore capacity. The integration can lead to problems however, since this new onshore capacity will mainly be situated in remote areas. The grids in these areas are usually designed for low loads. Therefore, even though onshore wind power capacity is not that large, it can lead to capacity problems in the distribution grids. The integration of onshore wind power will be a concern of the distribution grid managers. When the electricity grid will be dimensioned on the maximal output of the installed wind power, this can result in a low utilisation rate of the grid capacity. This is caused by the fact that the wind farm only produces the full output.

Usefulness of electricity storage

The connection of storage systems to the grid, situated at a location close to the point of generation could reduce the required grid capacity extension. In times of wind high speeds, the generated electricity can be stored. This way only a limited amount of power has to be transported from the point where the wind power is fed into the grid to the different load centres. The grid does not have to be dimensioned on the maximal amount of installed wind power capacity. In times of low wind speeds the stored electricity can be supplied and despite of low wind power generation the transportation capacity of grid from the wind production

centre to the load centre is utilised. The further the storage systems are situated from the wind production centre, the more grid capacity has to be dimensioned on the entire amount of possible wind power output and therefore the less grid investment costs can be prevented.

Suitable systems

Large-scale storage systems like CAES, pumped hydro storage and large-scale flow batteries are suitable for the deferral of grid investments caused by large scale of shore wind farms. Because of their specific requirements regarding location, CAES and pumped hydro storage are less easy to implement, which only leaves the flow battery as a real candidate for this application in The Netherlands. Energy and power capacities of the storage systems for the deferral of investments in the distribution grid caused by onshore wind farms are not required to be as high as the systems used in combination with offshore wind farms. However, still only a large-scale PSB system seems sufficiently suitable for this application.

4.5 Conclusions

This chapter has answered the third sub question:

How can electricity storage contribute to the integration of wind power in the electricity supply system?

Conclusions

There are four main applications for electricity storage systems to contribute to the integration of a large share of wind power into the electricity system. First of all storage systems can provide balancing services. A large share of wind power can cause problems regarding the allocation of adjustment and reserve power that has to be carried to be able to compensate for unexpected fluctuations in load or production. The uncertainty regarding the forecasts of wind speeds causes errors in predictions of the production of wind power. This could lead to an increase of the required adjustment and reserve capacity. Besides a shortage on reserve and adjustment capacity, the uncertainty of wind power production can lead to deviations from the E-programs. This can cause high imbalance costs for wind farm exploiters. Large-scale storage systems like the PSB and large conventional batteries can be implemented to compensate for the unpredicted fluctuations of the wind power production.

Secondly storage systems can be used for energy management. The longer-term fluctuations of wind power demands irregular production behaviour of conventional power. This indicates that considerable more control actions will be required, which will result in an increase of costs and a decrease of the efficiency and life cycles of the conventional generation plants. Storage systems can be used for peak shaving in order to required generation capacity and ‘increases’ the utilisation rates of the installed capacity. As wind power production is independent of the load, energy management applications can be very valuable for wind power. Electricity generated during the night at base load prices can be stored and sold at daytime for high prices during peak hours. Furthermore most storage systems are easy dispatch able: this can simplify unit operational planning and reduce its costs. These applications require large-scale storage systems like the PSB system.

Thirdly storage systems can be used for the supply of power quality services. The integration of wind turbines can have a negative influence on power quality. The turbines can cause flicker, voltage variations and can inject currents with non-sinusoidal waveform, harmonics. The implementation of storage systems will reduce output fluctuations generated by wind farms and therefore also reduce flicker. Furthermore storage systems like batteries and flow batteries can supply reactive power in order to control the voltage level. Finally storage systems, often equipped with electronic filters, can reduce the harmonics in the grid.

The connection of storage systems to the grid, situated at a location close to the point of generation could reduce the required grid capacity extension. The grid doesn't have to be dimensioned on the maximal amount of installed wind power capacity. The PSB system seems the only storage system that can develop to have a storage capacity that is sufficiently large for this application.

*Consequences for the next
chapters*

This chapter has identified four applications of storage systems that can contribute to the integration of wind power in the electricity supply system. These applications will be used in chapters 5 for the cost-benefit analysis and in chapter 6 for the evaluation institutional aspects of electricity storage.

5 COST-BENEFIT ANALYSIS OF THE PSB FLOW BATTERY

Sub question 4 In the previous chapter four applications of storage systems have been identified that can contribute to the integration of wind power in the electricity supply system: balancing, energy management, power quality services and the deferral of grid investments. This chapter contains a cost-benefit analysis of two of these applications: balancing and peak supply, an energy management application. Furthermore, a case study is carried out that investigates the profitability of the use of electricity storage to trade on the APX. This will answer the fourth sub question: Is the implementation of electricity storage systems economically profitable?

Selection of applications The two other identified applications, the supply of power services and the implementation of storage systems for the deferral of grid investments are not considered in this chapter. As stated in paragraph 1.4, Scope of the project, this research focuses on the implementation of large-scale storage systems. The supply of power quality services is a side function of large-scale storage systems. The benefits that can be gained with this side function will in general be relatively small in relation to the principal application that can be carried out with large-scale storage systems. It is therefore chosen not to consider the supply of power quality services in the financial analysis in this chapter. The deferral of grid investments can be a principal application of a large-scale storage system. However, neither this application is considered in this chapter. It is very complex to calculate the grid investment costs that a storage system can prevent. Firstly the system, especially when implemented in combination with large-scale offshore wind power, prevents costs at various voltage levels in the grid. Secondly the storage system will often only postpone the investment in extra grid capacity. This means only a certain share of the prevented costs can be really considered benefits. Because of the complexity of the analysis and the restricted time available, it is chosen not to consider the deferral of grid investments in this research.

Selection of storage technology From the analysis in the previous chapter it appeared that the Polysulfide Bromide flow battery (PSB) is a promising large-scale storage system that is suitable for both the balancing as energy management applications. An advantage of the system is that its power capacity, determined by the amount of conversion cells, can be chosen independently from the energy capacity that is determined by the amount of electrolyte that is located away from the active cells. The flexibility regarding power and energy capacity makes the system employable for various applications and especially suitable for the integration of renewable energy sources. Moreover the implementation of the PSB system does not require specific sites, which makes it applicable in The Netherlands. The cost-benefits analysis in this chapter is therefore carried out based on this storage system.

In this chapter the main formulas and parameters that are used to carry out the cost and benefits calculations will be presented and discussed, for a more detailed overview of the calculations we refer to the appendixes. Paragraph 5.1 calculates the supply costs of the PSB system. In paragraph 5.2 a cost-benefit analysis of the implementation of the PSB system for trade of electricity on the APX spot market

is carried out. Next the profitability of the use of a PSB system for a balancing application is calculated. In paragraph 5.4 we compare the costs of peak supply by a gas-fired plant, a STEG unit and the PSB system. Finally the conclusions or the cost-benefit analyses are discussed.

5.1 PSB supply costs

To calculate the supply cost of the PSB, first the total annual costs, C_{tot} , of the system will be calculated:

$$C_{tot} = C_f + C_v \quad (1)$$

$$C_f = C_{capex}(P, C_c) + C_m \& c \quad (2)$$

$$C_v = p_e \cdot E \quad (3)$$

In which C_f are the fixed costs, and C_v the variable costs of the storage system. The C_{capex} is the capital expenditure that mainly depends on the total investment costs that are calculated by multiplying the power capacity P by the power capacity costs, C_c . Other variables, which have an influence on the C_{capex} , like the interest rate and the discount term, can be found in appendix A. $C_m \& c$ are the annual maintenance and control costs of the PSB system, p_e is the purchase price of the stored electricity (or if the stored electricity is not bought on the market p_e is the market value of the electricity at the moment of storage). E is the electricity stored by the PSB. E is calculated by,

$$E = \frac{E_s}{e} \quad (4)$$

Where E_s is the supplied electricity and e the efficiency of the charge and discharge cycle of the PSB. Based on equations (1), (2), (3) and (4) the cost of the supply of electricity per MWh, C_{MWh} , can be calculated by:

$$C_{MWh} = \frac{C_{capex}(P, C_c) + C_m \& c + p_e \cdot (E_s / e)}{E} \quad (5)$$

This paragraph continues with the cost analyses of a PSB system with a power capacity of 100 MW, a charge capacity of 80 MW and a storage capacity of 800 MWh. This means that one cycle of charging and discharging takes $800/100 + 800/80 = 18$ hours. Consequently, on a yearly base the maximum power that can be supplied is: $(8760h / 18h) \cdot 800MWh \approx 400GWh$.

Economic characteristics of the PSB system

An important economic characteristic of a PSB system is its high investment costs. The investment costs of the two existing testing projects of the PSB system were planned to be 1400 €/kW, compared to 375 €/kW for a regular gas plant. Since these PSB plants were testing projects however and thereby experimental, they would be equipped with a large amount of instruments to analyse the condition and output of the flow battery. Technical development and large-scale production of the PSB are likely to result in significant cost reduction. Figures of KEMA indicate an expected reduction of investment cost to respectively 800

€/kW in 2020 and 400 €/kW in 2050 (KEMA, 03). The variable costs of a PSB system on the contrary, can be substantially lower than conventional gas and STEG plants. To produce one MWh, a gas fired plant combusts about € 40 of natural gas. The variable costs of a storage system depend on the purchase price of the stored electricity. The price of electricity during off peak hours on the APX was on average 18 €/MWh in 2003. The high investment costs on the one hand and the low variable costs on the other hand, imply for the PSB system that at a low production rate the supply costs are high, but costs decrease significantly as the amount of supplied electricity increases.

Using the above-derived relations result in supply costs curves as showed in figure 5.1. Figure 5.1 presents the supply costs for different production rates with the corresponding amount of production hours. The curves stop at the theoretically maximal amount of production hours: 4000h. However, it is more likely that maximal production rates of about 3000h are achieved. This is the case when the PSB system carries out one charge and discharge cycle a day. Figure 5.1 illustrates the rapid decrease of the supply costs when the production rate increases. The efficiency rate of the PSB in the calculations is, as in every of the following calculations, set at 70%. The electricity purchase price is set at 18 €/MWh. A list with all used parameters with their set values can be found in Appendix C.

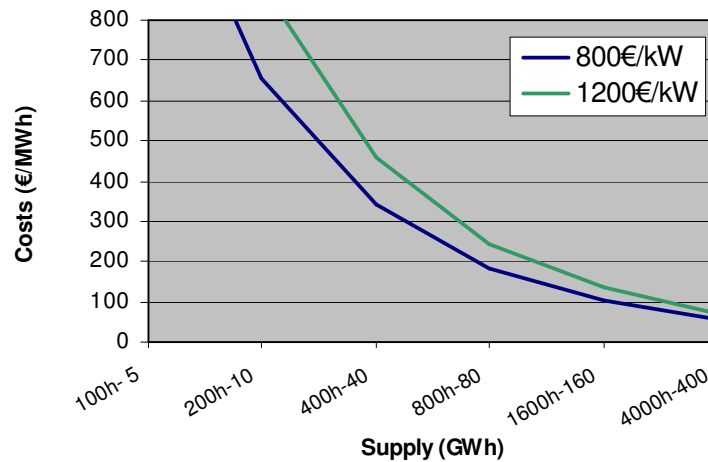


Figure 5.1: PSB supply costs

The main part of the current Dutch electricity production capacity consists of gas-fired plants. New investments in production capacity, are also mainly in gas-fired plants. Moreover, possible applications of storage systems, like balancing and peak supply, are currently predominately carried out by gas plants. Therefore the costs of the PSB will be compared with a gas turbine (GT) and a STEG-unit.

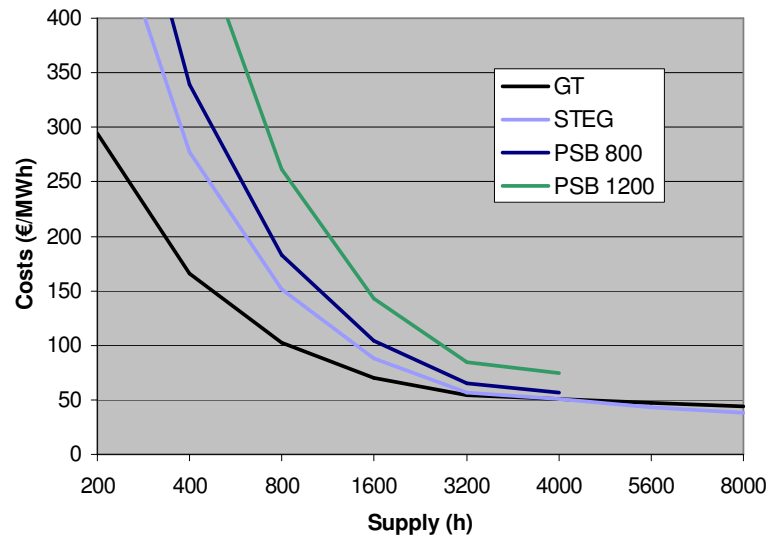


Figure 5.2: Cost comparison PSB, GT, STEG

Figure 5.2 shows that both the PSB system at investment costs of 800 €/kW and 1200 €/kW are more expensive when compared to a gas turbine and a STEG plant. A decrease of investment costs to 400 €/kW would bring the PSB on the same supply cost level as a gas turbine.

5.2 Trading on the APX

A storage system can be used for trade of electricity on the spot market. It can be charged with low priced electricity during off peak hours and discharged during peak hours when electricity prices are high. In this paragraph it will be investigated whether it is profitable to use the PSB flow battery to trade at the spot market based on 2002 and 2003 APX prices. In this case study the PSB will be operated in the price domain as follows:

- It will be charged during the 10 hours a day when electricity prices on average are the lowest: from 22h to 08h. The average APX price during these hours was € 14.60 in 2002 and € 20.40 in 2003.
- It will be discharge during the 8 hours with highest market prices: from 09h to 15h and from 17h to 19h. The average APX price in these periods was € 48.15 in 2002 and € 80.14 in 2003.
- It is assumed that the extra amount of electricity offered by the storage system doesn't influence the market prices, hence the spot market is of sufficient liquidity.

Figure 5.3 shows the results of these calculations. The supply costs of the PSB are given for different power capacity costs (€/kW). The benefits of trade on the APX, of course, don't depend on this. Appendix D contains an overview of all used parameters and their set values.

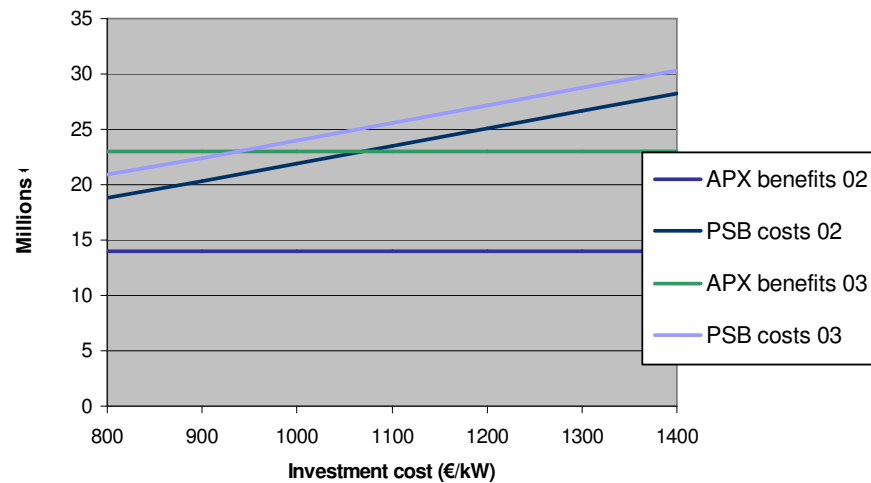


Figure 5.3: APX trading cost-benefit analysis

The figure shows that trading with the PSB based on 2002 APX prices is not profitable. Even at a low level of investment cost, 800 €/kW, a loss of 5 million Euros would be incurred. The electricity prices in 2003 were significantly higher than in 2002. This causes an increase of the PSB's variable costs since the purchase price of the stored electricity is higher. The benefits of the trade on the APX however, increase even more. As a result the implementation of the PSB at 2003 prices is profitable at an investment costs level of about 900 €/kW.

5.3 Prevention of imbalance costs

As discussed in paragraph 4.1 a wind farm exploiter has to pay for the amount of imbalance a wind farm causes. Producers can use wind power prediction methods in order to reduce the uncertainty of the production of wind farms. The output of the prediction tools depends on the forecasted wind speeds in the area. Although these forecast methods become more and more accurate, considerable differences between the predicted production and the actual production still occur.

Wind power prediction errors

A PSB system can be used to control the output of a wind farm to reduce imbalance costs. To estimate the imbalance cost that the implementation of a PSB system can prevent we first consider how much imbalance is caused by a wind farm. In the western part of Denmark about 2000 MW wind power capacity was installed in 2001. Eltra, the TSO in Western Danish area, has carried out research to analyse how much the actual output of the wind power system differs from the predicted output. The estimation errors of wind power predictions depend on the period of time the predictions are carried out prior to the moment of supply. For the Eltra area every day a 24-hours prediction (at 0.00 am, 24 hours prior to the day of supply) and a 12-hours prediction are carried out (12.00 pm, 12 hours prior to the day of supply). Since the spot market closes in the morning and also the E-programs have to be submitted before 12 pm, trading and setting up the E-program is done based on the 24-hours prediction. The 12-hours prediction can be

used to make adjustments in the E-program, which can be submitted in the late afternoon, albeit only with extra payment. This case study therefore will use the 24-hours prediction. The results of the 24-hours prediction error analysis are presented in figure 5.4. It shows that the prediction error of 1000 MW wind power in 29% of time is between 0 and +50 MW. In 16% of time the error is between 0 and -50MW, etc.

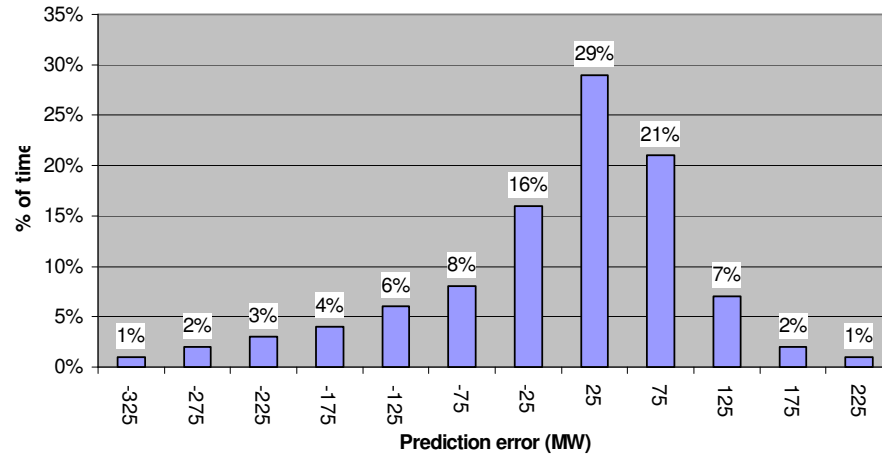


Figure 5.4: Prediction errors of 1000MW wind power (Eltra, 02)

Data from E.on on the wind power production in the Northwestern part of Germany provides similar figures on prediction errors (Eon, 02).

In the following we will evaluate whether it is profitable to implement a PSB system to reduce imbalance cost created by a wind farm. Every day before 12 pm the PRP of the wind farm has to submit his E-program to TenneT. This E-program contains, specified for every quarter of an hour (PTU, Program Time Unit), the amount of electricity the wind farm will produce the next day. The PRP will devise this E-program that is based on the 24h forecast of the production of his wind farm. The submitted E-program will contain errors with a distribution as shown in Figure 5.4 caused by the errors in the wind speed forecasts. The implementation of a PSB system will make it possible to supply stored electricity when the wind farm produces less than predicted so the producer still will supply according to the E-program. When the wind farm produces more than predicted the day before, the storage system can be charged as such still meeting the E-program. The operations of the PSB system prevent that TenneT has to use adjustment power to keep the electricity system in balance and thereby reduce the imbalance costs of the PRP wind farm operator. In the following we will evaluate how much imbalance a PSB system can prevent with a supply capacity of 100 MW in combination with a 1000 MW wind farm.

Imbalances prices

For every PTU TenneT determines the amount of electricity that a PRP has supplied or produced. When the PRP produces more than expected, a surplus occurs, when less is produced than expected, a shortage is the result. The PRP's imbalance has a different effect on the grid when it's a surplus regarding to when it's a shortage. In some cases, the imbalance of the PRP counterbalances the grid's

imbalance and in other cases it makes the grid's imbalance worse. Therefore, for every PTU, two imbalance prices are known: the imbalance price for shortage production and the imbalance price for surplus production. These imbalance prices depend on the costs of the adjustment power TenneT has to dispatch to keep the electricity system in balance. The prices of adjustment power are the result of two effects: the amount of adjustment power offered on the imbalance market, and the amount of imbalance produced in a certain PTU. The imbalance prices, and thus the costs of supplying one MWh, in surplus or in shortage can vary substantially. Figure 5.5 illustrates possible differences in imbalance prices during the day. In case a large shortage occurs in PTU 69, we assume TenneT has to dispatch 600 MW of upward regulation power, every PRP that is short has to pay 600 €/MWh for the compensation of this shortage. When the wind farm in this situation produces more than predicted, the PRP receives 600 €/MWh surplus as the surplus counterbalances the total systems imbalance. If however, the wind farm produces less than predicted, the PRP has to pay 600 €/MWh shortage. In case there is a surplus in PTU 69 and TenneT has to adjust down lets say 100 MW, the figure shows that every PRP that has a shortage incurs about 10 €/MWh shortage costs.

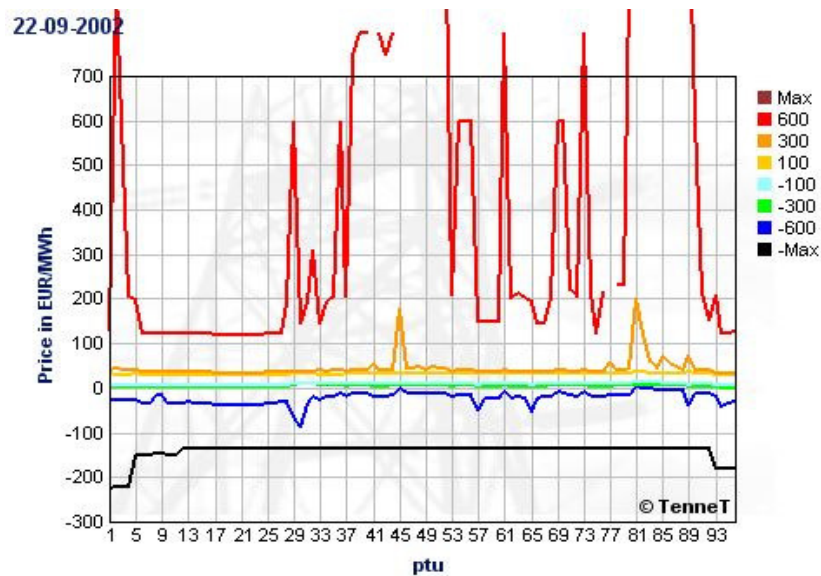


Figure 5.5: Imbalance price ladder

From an analysis of the daily imbalance prices it appears that certain patterns are observed in the imbalance prices (ECN, 03). Figure 5.6 shows this behaviour based on 2001 imbalance prices.

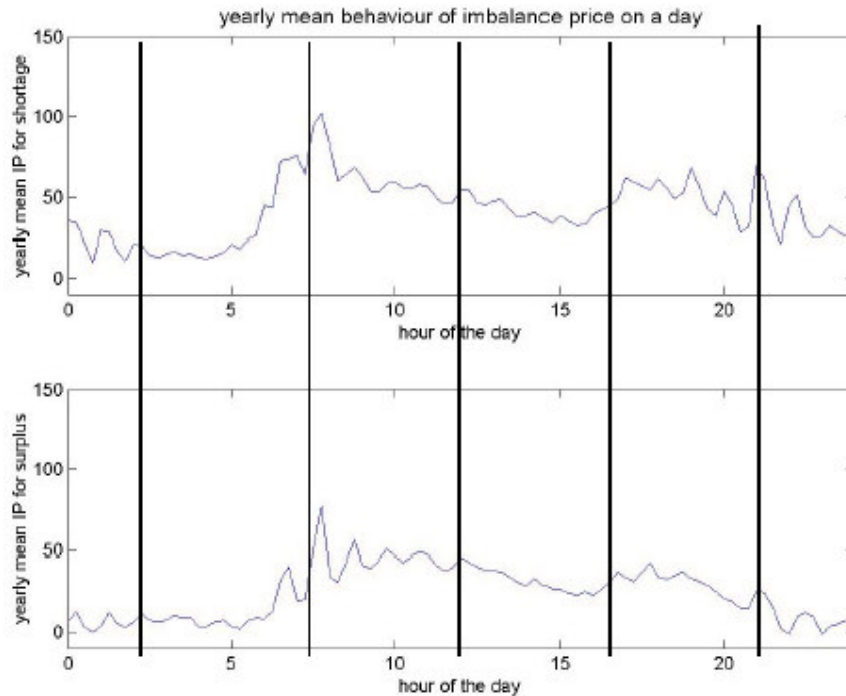


Figure 5.6: Yearly mean 2001 imbalance prices (ECN, 02b)

The following observations can be made:

- From about 21h to 06h imbalance prices are relatively steady and low. This can be explained from the fact that during the night the load is low and stable. This results in a large volume of offered adjustment power and thus low adjustment power prices. Furthermore loads can be predicted very well during these hours. This means there is little imbalance and therefore TenneT only dispatches the low priced adjustment power if so required.
- From 06h to 09h imbalance prices fluctuate and are relatively high. This is caused mainly by the uncertainty of the load during these hours and results in substantial imbalance and thereby high imbalance prices.
- From 09h to 21h the imbalance prices drop but still remain relatively high compared to the imbalance prices during the night.
- Surplus prices are on average positive during the whole day.

These patterns in the daily imbalance price can be valuable in the process of designing an operation schedule for the PSB system. How does the PSB system has to be operated in order to reduce the imbalance costs of the wind farm as much as possible? Which hours does it have to be charged to prevent surplus and which hours does it have to supply to prevent shortage production by the wind farm?

Designing an operation schedule

The patterns in the daily imbalance prices make clear that it's best to charge the PSB at night with surplus production of the wind farm and use this stored electricity during daytime to prevent shortage. This way the low valued surplus that is produced during the night is supplied during daytime to compensate for the shortage which otherwise would have to be bought on the imbalance market while the prices on that market are high. The prevention of surplus during daytime does not lead to much extra revenue. The average prices of surplus from 06h to 21h are always positive and not very low compared to the APX prices. In 2001 average surplus price was 35 €/MWh. This means that when the wind farm produces more than predicted, although it's an imbalance production, the PRP still receives on averaged 35 €/MWh from 'selling' it on the imbalance market. Given this behaviour of the imbalance prices, how can the PSB be operated in order to achieve a maximal reduction of the imbalance costs? To illustrate this we will carry out an evaluation in which we will use the following schedule:

- From 21h to 06h the PSB system will be charged when the wind farm produces a surplus to the E-program.
- From 06h to 21h the PSB system will supply stored electricity in case of shortage and store electricity in case of a surplus.

At which shortage costs the PSB system will be operated according to this schedule? We will first assess how much shortage the 1000 MW wind farm on average per hour will produce. Figure 5.4 shows certain intervals of prediction errors and the percentage of time the prediction error is between the intervals. The average error of a shortage in interval i , $R_{s,i}$, with maximal error $R_{\max}$ and minimal error $R_{\min}$ is assumed to be:

$$R_{s,i} = \frac{R_{\max,i} - R_{\min,i}}{2} \quad (6)$$

The PSB system can prevent a shortage by supply of stored electricity. For the shortage SH_i that can be prevented by the PSB system when the error is in interval i it follows that:

$$SH_i = a \cdot R_{s,i} \quad , \text{if } R_{\min} > -P_{\text{sup}} \quad (7)$$

$$SH_i = a \cdot P_{\text{st},i} \quad , \text{if } R_{\min} < -P_{\text{sup}} \quad (8)$$

Where 'a' is the percentage of time the error is in interval $R_{\max}$ and $R_{\min}$, P_{st} is the storage capacity of the PSB and P_{sup} the supply capacity. The total prevented shortage SH_h in an hour can now be calculated,

$$SH_h = \sum_i SH_i \quad (9)$$

The prevented shortage costs, which in fact are the benefits of the storage system, B_h in hour j , with a price of upward regulation power $p_{u,j}$ are,

$$B_{h,j} = SH_h \cdot p_{u,j} \quad (10)$$

The yearly-prevented amount of shortage costs B_{tot} is,

$$B_{tot} = \sum_j B_{h,j} \quad (11)$$

The yearly amount of prevented surplus can be calculated using a similar method. Using equation 11 to calculate the yearly preventable shortage cost is found that at 2002 imbalance prices 6.1 million Euros shortage costs could be prevented using the PSB system. Due to a significant increase of imbalance prices in 2003 the amount of prevented shortage costs are 10.8 million Euros at 2003 prices. Using equation 5 the supply costs of the PSB with the supply rate that follows from this case study can be calculated. The power capacity costs have been set at 800 €/kW. Appendix E contains an overview of all used parameters and their set values.

	2002	2003
Benefits (mil. €)	6	11
Costs (mil. €)	15	15
Result (mil. €)	-10	-4

Table 5.1: Imbalance price ladder

It turns out that the implementation of the PSB battery in this case study is not profitable. Even at a quite low level of investment costs, 800€/kW, the prevented shortage cost are much lower than investment costs of the PSB. This is mainly caused by the low utilisation rate of the PSB system. Not until the level of the investment costs of the PSB system decrease to 500 €/kW, balancing with the PSB system will be profitable. Such a low cost level is not expected to be achieved within the near future.

5.4 Combined applications: Peak supply and balancing

In the previous section the PSB system was only used to prevent shortages produced by the wind farm from 6h until 21h. As discussed in paragraph 4.2 however, a storage system can also be implemented for peak power supply. From the calculations in paragraph 5.1 it is concluded that because of the high investment costs of the PSB system, the supply costs when the system only supplies during peak hours are high compared to the production costs of a gas fired plant. Figure 5.2 shows that when put into operation for 400 h the PSB system supplies at a cost level of 350 €/MWh whereas one MWh produced by the gas turbines only requires 150 euro. Although peak supply costs of the gas turbine are lower than those of the PSB system, costs are still relatively high because peak plants stand idle most of the time a year. An advantage of the PSB system could be that when it's not used for peak supply it can be used for balancing. What is the influence on the production costs of the PSB system when it is used for balancing as well as peak power supply? To calculate this the cost model used in paragraph 5.2 is extended.

The variable costs, C_v , given in relation 3 now become,

$$Cv = p_{e1} \cdot E1 + p_{e2} \cdot E2 \quad (12)$$

Where p_{e1} is the purchase price of the electricity used for balancing, E_1 the amount of stored electricity, p_{e2} the purchase price of the electricity used for peak supply and E_2 the electricity used for the peak supply. Note that p_{e1} and p_{e2} can have different values because the electricity used for balancing can be stored at night using the low value surplus produced by the wind farm. When the PSB system is used for peak supply, the surplus produced by the wind farm might not be sufficient any more to meet all required supply. This means the PSB has to be charged with additional, likely higher valued, electricity. The annual volume of electricity bought for peak supply E_2 is calculated by,

$$E_2 = \frac{P_s \cdot H_p}{e} \quad (13)$$

H_p is the yearly amount of supply hours, P_s the supply capacity of the PSB, 'e' the efficiency. The total yearly supply of system is,

$$E_{tot} = E1 + E2 \quad (14)$$

This results in the following equation for the cost per supplied MWh by the PSB system,

$$C_{MWh} = \frac{C_{capex}(P_s, C_i) + C_M \& C + p_{e1} \cdot (E_s / e) + p_{e2} (P_s \cdot H_p / e)}{E_{tot}} \quad (15)$$

In this case the operation schedule of the PSB system is set active on days when it is not used for peak supply similar to the previous paragraph: it is charged with the surplus produced by the wind farm during the night, supplies when the wind farm produces shortage from 6h until 21h and stores the produced surplus during these hours. Lets now assume however, that on a certain day the next day's load during peak hours is expected to be high which will probably result in high APX prices. The operator of the PSB system can now decide to offer his supply capacity, 100 MW, at the APX for example from 16h to 18h. In order to be sure that the PSB system will be sufficiently charged to supply the 200 MWh the next day, the operator can dispatch his own conventional generation capacity to charge the PSB system. If the operator does not have generation capacity to dispatch, the required power can be acquired on the APX.

Since the PSB system now has to supply at full capacity from 16h to 18h, it is not possible to adjust the PSB system to the intermittent behaviour of the wind farm when this produces shortage. Therefore, the more hours per year the storage system is used for peak hour supply, the less it can be used for balancing and the less shortage costs it will prevent. The supply costs of the PSB system at different levels of peak power supply and balancing are shown in table 5-2. The calculations are based on an investment costs level of the PSB system at 800€/kW. For the value of the shortage reduction the shortage prices of 2003 have been used. All parameters and settings used in the calculation can be found in Appendix F.

Hours of peak sup.	Annual supply (GWh)			Costs (€/MWh)		
	Peak supply	Shortage prevention	Total supply	Fixed costs	Variable costs	Total costs
100h	10	121	131	96	15	111
200h	20	119	139	90	15	106
400h	40	115	155	81	16	97
800h	80	103	183	69	17	86
1600h	160	72	232	54	19	73
3200h	320	22	342	37	21	58

Table 5.2: PSB supply costs: combined peak supply and balancing

Firstly the results show that the more the PSB system is used for peak power production and thus less for balancing, total production rate increases and thereby the average supply cost decrease. Secondly the results show that using the PSB system for balancing in combination with peak power supply, the peak supply costs at low peak power production rates are relatively low. This is caused by the fact that the investment costs can be distributed over both the peak production supply and the electricity supplied for the balancing. At a peak supply production rate of 400h the production costs now are 97 €/MWh while in case the PSB systems is used for peak power supply only, the costs, as calculated in paragraph 5.2, are 350 €/MWh.

Comparing the PSB, GT and STEG

To investigate whether the PSB system is the lowest cost option for peak power supply, the supply costs should be compared with the production costs of a gas-fired plant. However, the production costs as shown in table 5.2 can't be directly compared to the production costs of a gas-fired plant. The reason is that in this calculation only the costs were considered, and not the benefits. The balancing activities are, as showed in the previous section, not always profitable. In table 5.2 it can be observed that when the PSB system is operated 100h per year for peak supply, the total supply costs of the PSB system are 111 €/MWh. Given the fact that the average shortage costs in 2003 were 88 €/MWh, the balancing activity will not be profitable. Only when the peak supply production rate increases to about 800h, average supply costs drop to less than 88 €/MWh and it is at this point that using the PSB for shortage prevention will be profitable. This means that although balancing leads to a decrease of the average supply costs of the PSB system at low peak supply rates, it also creates extra costs caused by the fact that implementing the PSB system for balancing costs are higher than having the imbalance 'traded away' on the imbalance market. In order to make a fair comparison of the production costs between a gas-fired plant and the PSB system, these extra costs will be distributed over the total supplied electricity by the PSB system. However, in case shortage prevention is profitable, thus when the supply costs of the PSB system are lower than 88 €/MWh, the PSB system gains extra benefits compared to a gas turbine that would be used for peak supply only. These

benefits are therefore subtracted from the supply costs. Cost relation (15), which describes the average supply costs of the PSB, CMWh, is extended,

$$C_{MWh} = \frac{C_{capex}(P_s, C_i) + C_M \& C + p_{e1} \cdot (E_s / e) + p_{e2} (P_s H_p / e)}{E_{tot}} + \frac{B_{res}}{E_{tot}} \quad (16)$$

Where B_{res} are the balancing results, which represent the loss incurred by using the PSB system for balancing, or the benefits gained by balancing. Using equation 16, the supply costs, based on 2002 imbalance prices, as presented in figure 5.7 are found.

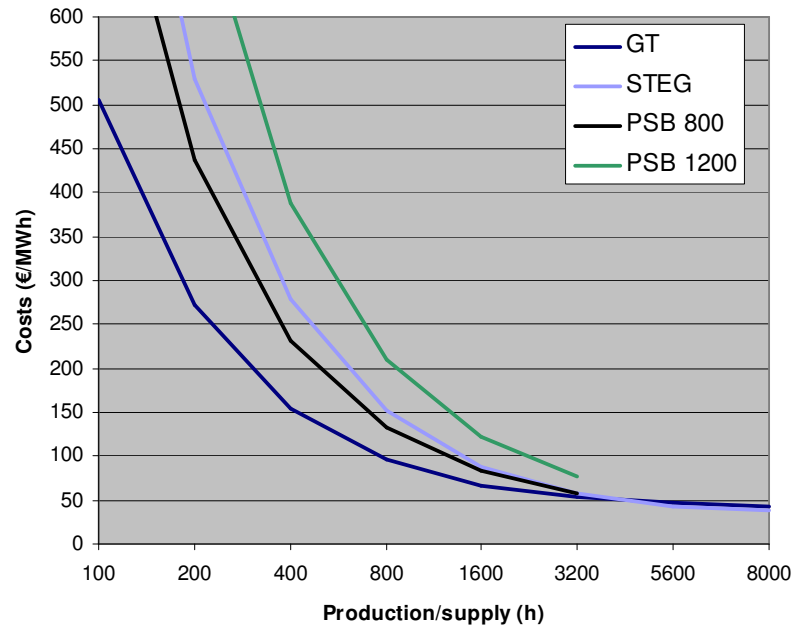


Figure 5.7: PSB, GT, STEG supply costs, 2002 imbalance prices

Figure 5.7 shows that at less than 3200 hours of operation per year the PSB system at investment costs of 800€/kW supplies electricity at lower costs than the STEG unit but higher costs than the gas-fired plant. When operation hours increase further the supply costs of the STEG unit are lower than the PSB's. At investment costs of 1200€/kW the PSB supplies electricity at higher costs than both the gas turbine as the STEG unit. In Figure 5.8 the supply costs at 2003 imbalance prices are shown.

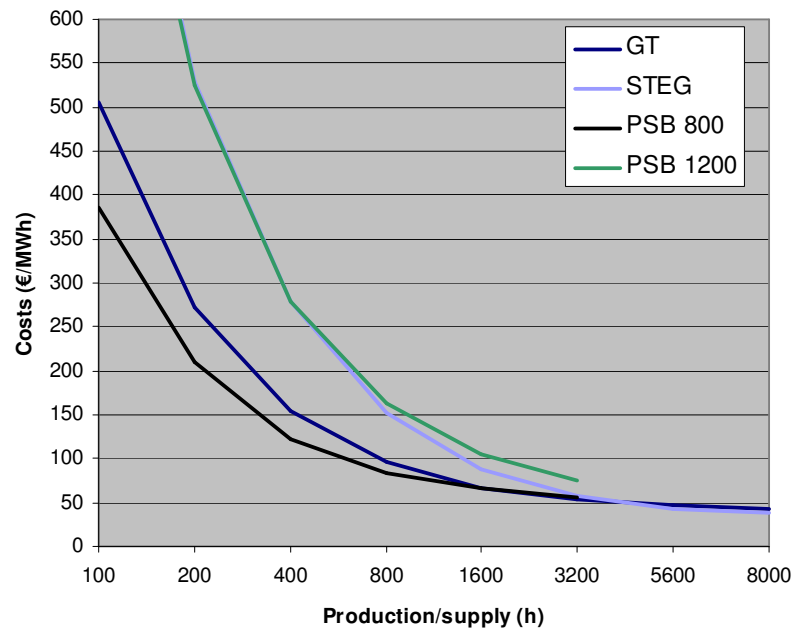


Figure 5.8: PSB, GT, STEG supply costs, 2003 imbalance prices

Figure 5.8 shows that at less than 1600 operation hours a year the PSB system, at investment costs of 800€/kW, supplies electricity at lower costs than both a gas fired plant and the STEG. At more than 1600 hours of operation per year a gas-fired plant supplies at lower costs.

Sensitivity analysis

Several assumptions have been made in this cost-benefit analysis. We did also test whether the outcomes of the analysis are sensitive to some of the assumptions used. In case the PSB system supplies peak power for 800 hours a year its supply costs in the base case are 83 €/MWh (Table 5.2). Table 5.3 shows the influence that changes of the four different parameters have on the supply costs of the PSB at a peak power supply level of 800h. The sensitivity analysis is carried out with four parameters: the efficiency of the PSB system, the shortage prices, the investment costs and the discount factor. The discount factor is the interest rate used to compute the annual capital expenditure of the PSB system. If the efficiency of the PSB system is decreased with 25% with respect to the value used in the calculation of the base case (from 70% to 52.5%), the supply costs increase from 83 €/MWh in the base case to 97 €/MWh; an increase 17%. If the efficiency is increased with 25% compared to value used in the base case, the supply costs decrease to 75 €/MWh; a decrease of 9%. This calculation has been performed for all four parameters.

	Efficiency	Discount factor	Shortage prices	Investment costs
75%	+16	-17	+34	-47
125%	-9	+18	-34	+47

Table 5.3: Sensitivity analysis

The numbers in table 5.3 show that the outcomes are much more sensitive to changes of the shortage prices and the investment costs compared to changes of efficiency and the discount factor. At an equal change of the parameters in terms of percentage, an increase of the shortage price causes an decrease of supply costs that is almost four times as large as the decrease caused by a higher efficiency of the PSB (34% to 9%). The influence of a change in investment costs is even larger (47%). The sensitivity analysis shows that the results are quite robust regarding changes in efficiency and the discount factor, but is rather sensitive for changes of the shortage price and the investment costs. Therefore it has been chosen to present the results of the cost-benefits analysis, in figure 5.4 and 5.5, for both two different levels of investment costs and two different shortage price levels.

5.5 Conclusions

This chapter has answered the following sub question:

Is the implementation of electricity storage systems economically profitable?

The investment costs of the Polysulfide Bromide system (PSB) are estimated at about 1200 €/kW at the moment of writing this report. Because of the high investment costs the electricity supply costs of a PSB system are significantly higher than the production costs of a gas-fired plant and a STEG unit. The supply costs of a PSB system, when charged at night, are at minimum about 67 €/MWh, whereas the production costs of a base load gas-fired plant and STEG unit are about 45 €/MWh and 39 €/MWh respectively.

A PSB system can be used for the trade of electricity: it can be charged at night when electricity prices are low, and supply during daytime when electricity prices are high. A case study has shown that trading on the APX with a PSB storage system, at 2002 APX prices, wouldn't have been profitable a current nor at in near future expected investment costs levels. At 2003 APX prices however, the trading would have been profitable at investment cost of about 900 €/kW.

The uncertainty of wind speeds causes errors in the production forecast of wind farms. These prediction errors in turn cause deviations from the E-programs that are fined by TenneT. When a 100 MW PSB system is implemented to prevent shortage productions of a 1000 MW wind farm, this can save up to 5 million Euros at 2002 imbalance prices, and 10 million at 2003 prices. However, the yearly costs of a 100 MW PSB system are about 15 million Euros and thus the project would not be profitable. Only at an investment costs level of 500 €/kW preventing shortage with the PSB would be profitable; a cost level that isn't expected to be achieve in the coming future.

A peak supply generator only supplies electricity at limited number of hours per year. A PSB system can be used for peak supply and carry out a balancing function during the off peak hours. This way, although used for peak supply, a high occupation rate can be accomplished. The combination of peak supply and balancing results in a significant decrease of the peak supply costs of the PSB system. At 2002 imbalance prices however, a gas-fired plant would still produce the peak supply at lower costs; the implementation of the PSB system would not be cost beneficial. At 2003 prices the PSB system would supply electricity at

lower costs than a gas-fired plant at a production rate of less than 1600 hours of peak supply per year; in this case the implementation of the PSB system would be cost beneficial.

The sensitivity analysis shows that the results of the cost-benefits analysis are quite insensitive to changes of the efficiency of the PSB system and the discount value used in the calculations, but sensitive for changes in the investment costs and imbalance prices.

6 INSTITUTIONAL ASPECTS OF ELECTRICITY STORAGE

Sub question 5 This chapter evaluates the implications of both ownership of storage systems by grid managers and ownership by private parties on three aspects: application possibilities, market distortion and (technical) efficiency of the total electricity system. It answers the fifth sub question: What are the advantages and disadvantages of ownership of storage systems by grid managers compared to ownership by market parties?

In chapter 4 several applications of storage systems that can contribute to the efficient and effective integration of wind turbines in the Dutch power grid have been identified. Some of these applications are specifically useful for (wind power) producers, other applications pertain to grid managers, and others can be valuable for both actors. Producers as well as grid managers could therefore be interested to implement a storage system. This chapter compares the two ownership structures regarding three criteria to find the advantageous and disadvantages of both structures.

Sub question 6 Subsequently it is evaluated whether the current regulation is geared optimally in relation with the disadvantage regarding the ownership of storage systems by private parties and the main market barrier identified in chapter 2: the reduction of coordination possibilities between activities in different links of the electricity value chain. This answers the sixth sub question: Does the current regulation provide possibilities for grid managers to stimulate private parties to invest in storage systems?

In chapter 2 we found that one of the implications of the unbundled market design is that the design can pose barriers for the introduction of technologies or changes of processes that require coordination between the links of the electricity value chain. From the answer to sub question 5 appears that grid managers are not likely to be allowed to carry out several application of electricity storage systems. This means that if they want to benefit from the services the implementation of storage systems can offer, parties in other links of the electricity value chain will have to supply these services. This requires certain coordination between the activities of the different links that is, as discussed, hindered by the current market design. In the second part of this chapter it is argued that incentive regulation can substitute for this coordination. Next, it is evaluated whether current regulation provides the grid managers enough possibilities to give incentives to private parties regarding the implementation of electricity storage systems.

This chapter starts with the analysis of the advantages and disadvantages of a private ownership of storage systems compared to an ownership by the grid managers. This will be considered from the grid manager's point of view, the actor that is considered to be the problem owner in this research. First it will be evaluated to which extent the two ownership structures are compatible with the current Electricity Law. In paragraph 6.2 and 6.3 the two ownership structures will be valued with respect to their consequences regarding market distortion and the (technical) efficiency of the total electricity system. These are both criteria that a grid manager has to take into account according to the E-Act and the

Network code that applies at the moment of writing of this report. Three different scores will be used to value the ownership structure, a '+' when an ownership structure scores positive on a criterion, '0' when it scores neutral and '-' when it scores negatively. Paragraph 6.4 presents an overview of the scores in a scorecard. Next, paragraph 6.5 discusses possible amendments to the regulation that can be carried out to deal with problems of ownership of storage system by private parties. In addition, four financial relations between storage operators and grid managers are identified which are discussed individually in the following paragraphs. Finally paragraph 6.9 draws conclusions on the topics that are considered in this chapter.

6.1 Legal compatibility

In chapter 4 several applications of storage systems have been identified that can be valuable for grid managers. As discussed in paragraph 2.2 however, the activities of the Dutch grid companies (both for the transmission network and for the distribution network) are strictly regulated. The commercial activities in the energy value chain (production, trade, metering and sales) are separated from the distribution function in order to establish a level playing field, which is one of the preconditions for a well functioning liberalised electricity market. This paragraph evaluates which of the four identified applications of storage systems is allowed to be carried out by grid managers. We will evaluate this from the perspective of the Electricity Act.

Section 17 of the Electricity Act is established to prevent distortion of the free market competition by grid companies. Section 17 of the Act of 2 July 1998 states:

The grid manager, or a legal entity in which the grid manager has a participating interest, as referred to in section 24(c) of Book 2 of the Netherlands Civil Code, may not supply goods or services resulting in competition between them and third parties, unless this relates to carrying out activities in respect of:

(a) the performance of the duties referred to in sections 16(1) and 16(2), either for himself or for other grid managers, or on behalf of third parties entitled to use a grid;

The section contains the restriction that grid managers are not allowed to supply any goods or services, other than referred to in Section 16, resulting in competition between them and third parties. Whether the relevant sub articles of section 16(1) and 16(2) restrict the possibilities for grid managers to use storage systems for the applications identified in chapter 4 will be considered below.

Section 16:

1) Within the framework of the management of the grids in the area assigned to him, in accordance with section 36, the grid manager shall have the duty:

(a) to ensure the operation and maintenance of the grids managed by him;

(b) to ensure, in the most effective manner, the safety and reliability of the grids and of the transmission of electricity across the grids;

(2) In addition to the duties referred to in subsection (1), the manager of the national high-voltage grid shall also have the duty:

(a) to make such technical provisions and carry out such system services as are necessary to guarantee the transmission of electricity over all grids in a safe and efficient manner;

(d) to take measures to ensure the security of supply of electricity;

From these sections it can be concluded that implementing electricity storage systems for commercial goals is not allowed for grid managers. But does this imply that also the applications identified in chapter 4 are prohibited?

Power quality

In paragraph 4.3 the possibilities for the use of storage systems for power quality functions are discussed. The grid managers are responsible for the power quality. Controlling the reactive power supply is one of these duties that are appointed to the grid managers (section 3.2.1.c Tariffs Code). Grid managers use capacitors for reactive power supply and give instructions to producers to control the level of reactive power supply. This is a service that producers have to offer as is laid down in section 2.5.4.1 of the Network Code. The use of storage systems for reactive power supply is not an activity that competes with activities of third parties and grid managers therefore are allowed to the implementation of storage systems for the purpose of power quality functions, albeit that the use should then be restricted to the provision of reactive power.

Three other useful applications of storage systems for grid managers were identified in chapter 4: balancing power, energy management and deferral of grid investments. The implementation of storage systems for these applications however, implies that the grid manager undertakes a commercial activity: it has to offer the stored power on the electricity market. This commercial activity competes with activities of market parties. However, when these activities relate to carrying out activities for the performance of the duties referred to in sections 16(1) and 16(2), the grid managers are allowed to use storage systems for these functions provided that the market is not influenced by the information at the disposal to the grid manager.

Balancing power

Section 16(2) states that the manager of the national high-voltage grid has to “make such technical provisions and carry out such system services as are necessary to guarantee the transmission of electricity over all grids in a safe and efficient manner”. Dispatching regulation power via the imbalance system is one of these services. However, balancing power is either bought by TenneT on the imbalance market or contracted from a private producer. TenneT does not dispatch balancing power from systems they own. The price ladder system ensures TenneT dispatches the power in a market conform method. When TenneT would own storage capacity and offer this as balancing power on the imbalance market, they would, having important strategic information at their disposal, have unfair competitive advantages over other power producers. TenneT therefore is

not likely to be allowed to dispatch balancing power supplied by storage systems that it has in its possession.

Energy management

The responsibilities that the Electricity Act imposes on the grid managers, are confined to the secure and reliable operation of the transmission grids, with TenneT in its capacity as TSO being additionally charged with preserving the Dutch energy balance (Section 16(2)). The responsibility for the availability of sufficient generation capacity on the long term however, is not appointed to TenneT (TenneT, 02). This is left to market forces as was established in the liberalisation starting in 1998. The implementation of storage systems for energy management applications like peak power supply would result in competition between TenneT and third parties and is not one of the activities referred to in Section 16 of the Electricity Act. Therefore the use of storage systems for peak power supply will not be allowed for TenneT.

Deferral of grid investments

In their responsibility "to ensure, in the most effective manner, the transmission of electricity across the grids" as is stated in Section 16(1b), grid managers could consider the use of storage systems to avoid investments in grid capacity. The connection of a storage system to the grid at a strategic position enables the grid manager to store electricity at off peak hours and supply this at peak hours in order to prevent expensive grid expansions. However, this would mean that the grid managers would have to sell the stored power at the electricity market. Just like in case of the implementation of storage systems as balancing power, this would create unfair competitive advantages for the grid managers. It therefore is not likely that grid managers will be allowed to implement storage systems for the deferral of grid investments.

The exploitation of storage systems by private actors complies with the current E-Act for all four applications. Ownership by private parties therefore scores 'good' (+) on the criterion legal compatibility, ownership by grid managers 'bad' (-).

6.2 Market distortion

An important criterion when comparing the two ownership structures is market distortion. Although it is most likely that grid managers are not allowed to implement certain applications of storage systems under the current law, if desirable, the law could be adjusted in order to allow this. The question that now arises is whether this would be desirable considering the risks regarding the distortion of competition these implementations might cause, hence does it then comply with competition law? For example, in its function as TSO, TenneT is responsible for the allocation, on non-discriminatory grounds, of the capacity of the grid lines. The situation can occur that the capacity of a certain grid line is too small for all the transmission requests of the PRP's. When TenneT would own a storage system it could suspend access by other parties because it also requires transportation capacity on the grid line. If supplying electricity from their storage system at that moment is financially attractive for the TSO, they could give their own activities a preferential treatment. Another example of possible conflicts of interests occurs when a new producer wants to be connected to the grid. The new to be connected capacity competes with the already installed capacity. If the grid manager operates a storage system, connecting the new producer to the grid could reduce the grid manager's benefits. However, if the producer needs a connection larger than 10MVA, the producer has to negotiate with the grid manager about

the connection charges. This means the grid manager could impose extra financial barriers for the new producer in order to protect their own revenues. Finally, in order to check whether the transportation capacity of the grid is sufficient, TenneT receives all data of transactions between producers and suppliers on a daily basis. This highly confidential information could be used by TenneT to determine the amount of electricity they will offer on the market and for which price.

The fact that grid managers can enter a situation of conflicting interests endangers a non-discriminatory grid control, and is therefore a risk for appropriate functioning free electricity market. Having the TSO implementing storage systems therefore scores 'bad' (-) on the criterion market distortion. The implementation of electricity storage systems by private actors does not cause market distortion as it is comparable to production capacity and thus scores good (+).

6.3 Optimising system-wide efficiency

The interaction between production and transmission is very important for the electricity network. To a certain extent the two can substitute each other: local production reduces transmission capacity needs whereas central production enlarges transmissions capacity needs. The technical optimisation of the electricity system can be obtained by an optimal configuration production capacity and transmission lines. The same goes for storage capacity and transmission capacity. When for example a large amount of wind power has to be integrated into the electricity grid, the grid should be dimensioned on the maximum production of the wind farm. However, since the wind farm only produces a part of the time the full output, the utilisation rate of the grid capacity will not be very high. A storage system could be used to reduce the maximal output of the wind farm and therefore reduce the required grid capacity. When the costs of implementing a storage system to integrate the wind farm into the electricity grid are less than the extra investments in grid capacity that would be needed to integrate the wind farm, a situation as illustrated in figure 6.1 occurs.

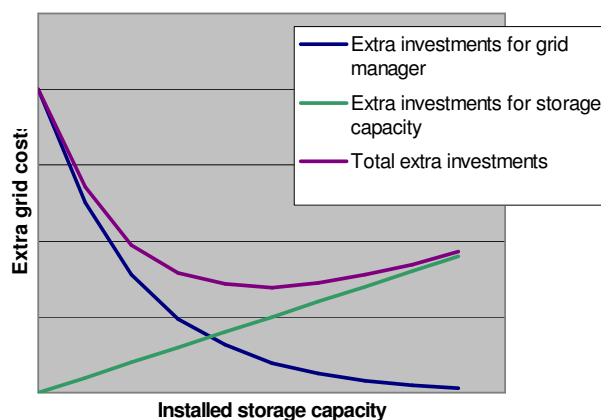


Figure 6.1: Storage capacity/grid investment trade-off

Figure 6.1 shows that a trade-off between the installation of storage capacity and upgrading the grid capacity will lead to the minimization of the system-wide costs. If grid managers are allowed to implement storage systems they can make this trade-off. Integrated planning of storage and transmission could then lead to a technically optimised electricity system. Private actors make their decisions regarding the size, location and operation of the storage capacity responding to the economic incentives given by the free market environment. Only considering their own interest this will result in a technically sub optimal configuration of the electricity system which will not lead to a minimization of system wide costs.

When the grid managers can decide where to install storage capacity, this will extend their possibilities to integrate the generation and transmission plans in order to achieve the optimal configuration of the electricity system. Ownership by grid managers scores 'good' on the criterion system wide efficiency. Ownership of storage systems by private actors doesn't offer possibilities for the integration of generation and grid planning and therefore doesn't generate synergy benefits: it scores neutral (0).

6.4 Comparison of ownership structures

Table 6.1 presents an overview of the scores of the ownership structures on the three criteria.

	Legal compatibility	Market distortion	System-wide efficiency
Grid managers	-	-	+
Private actors	+	+	0

Table 6.1: Scorecard ownership structures

These results show that an ownership by grid managers of storage systems for regulation and reserve power supply, deferral of grid investment or energy management, scores bad on the criterion legal compatibility compared to a private ownership. Although legislation could be adjusted to allow ownership by grid managers, it is very questionable whether this would be a desirable option because this could lead to serious market distortions. A private ownership of storage systems fully complies with the current liberalised electricity market. An advantage of an ownership of storage systems by grid managers can be found in the benefits that this can have for the technical efficiency of the electricity grid. When private actors exploit storage systems these benefits are less easy to obtain, as this will require agreement between producers and grid managers.

The analysis shows that when the choice will be made to leave it to private actors to facilitate storage systems, extra attention has to be paid to the contribution of the storage systems to the technical efficiency of the electricity grid, albeit that this can be vested in the conditions under which connection to the grid is allowed. Regulation systems can provide incentives for private actors to guide them to take decisions that lead to the lowest cost electricity system. The next paragraph will discuss the development of regulation that creates the proper incentives for the actors in the electricity sector as pertaining to storage systems.

6.5 Amendments to regulation

The analysis in chapter 2 has pointed out that the unbundled market design has reduced the possibilities for coordination between the different links of the electricity value chain. This paragraph argues that incentive regulation may substitute for this reduced coordination.

In the previous sections it has become clear that although the implementation of electricity storage systems by grid managers could contribute to the minimization of the electricity system costs, the implementation of storage systems is not likely to be allowed for grid managers. Since in this case the grid manager is not able to make the trade-off as presented in figure 6.1, this can lead to an inefficient operation of the electricity grid. The following example will illustrate this.

*Inappropriate incentives
lead to an inefficient
electricity system*

A wind farm operator wants to connect a new wind farm to the electricity grid. Since the local grid doesn't have sufficient capacity to deal with the full wind farm's production certain modifications to the grid have to be carried out to enable this. This can be accomplished by upgrading the grid capacity, which would have to be carried out by the grid manager. Let's assume however that the lowest cost option would be to implement a storage system that stores the electricity produced by the wind farm at times when local consumption is low but wind power production is high. At times when the local consumption is high the storage system can supply the stored electricity. Since the grid manager is not allowed to implement a storage system for this application the wind farm operator would have to carry the extra investments in the storage system. However, the grid manager will gain the benefits of this investment: a reduction of the investments in grid extension. The wind farm operator will select his lowest cost option and will not invest in the storage system. This means the grid manager will have to invest in the extra grid capacity with the result that the most cost beneficial option will not be realized.

This example shows that a lack of coordination can lead to an inefficient electricity supply system. This puts us for the question how the wind farm operator can be guided in such way that he invests in the storage system without the direct coordination of activities? In the ideal situation the individual producer would bear the full costs of their behaviour regarding the extra investments in the grid they cause. In this case when a producer is facing the decision whether to invest in storage or not, he would choose the option that is optimal for the efficiency of the total electricity system. However, since many costs are socialized by being passed on through general transmission tariffs, the producers are not confronted with all costs their decisions impose on the network.

*What does regulation have
to do?*

Incentive regulation can stimulate private actors to invest in storage systems by providing them incentives that internalise the upgrading costs of the grid that they cause. This leads producers to investment decisions that contribute as much as possible to the total efficiency of the grid. If the correct incentives are provided the private parties are guided to the implementation of an efficient option without the need for the coordination of activities.

To evaluate whether the current regulation provides possibilities for grid managers to give incentives to private parties, the financial relations between these two parties will be identified. In chapter 4, four different applications of storage systems have been identified that can contribute to the integration of a

large share wind power in the electricity system: energy management, power quality services, deferral of grid investments and balancing. Especially the latter three applications can be interesting for grid managers. In the following it will be evaluated whether in the current regulatory situation there are possibilities for the grid managers to reward the private actors for the services they can supply with storage systems. Figure 6.2 gives an overview of the financial relations of the storage operator.

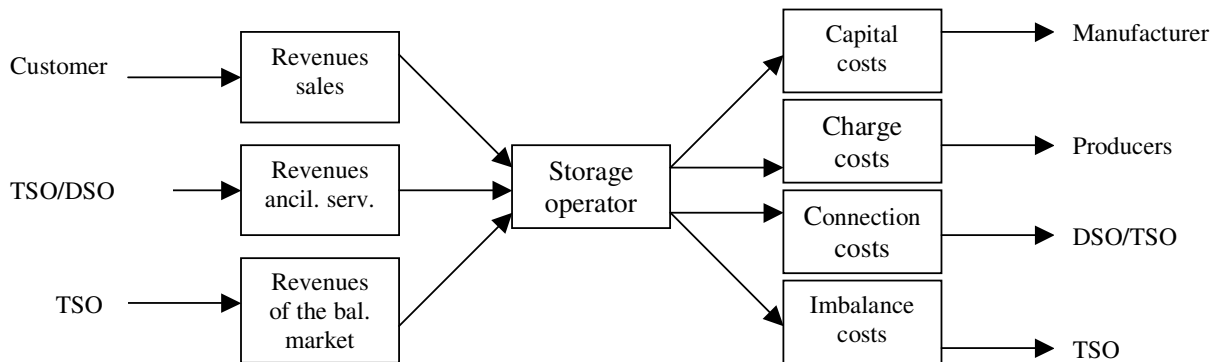


Figure 6.2: Financial relations of a storage operator

Figure 6.2 shows that besides the relations the storage operator has with his regular customers, the manufacturer and the electricity producer, there are four direct financial relations between the grid managers (both Transmission and Distribution Systems Operator) and the storage operator: contracts for the supply of ancillary services, balance market revenues, imbalance fines, and connection charges. In the next paragraphs these four financial relations will be evaluated to investigate whether they can be used by grid managers to reward storage operators for the services they can provide to the grid managers with their storage system.

6.6 Connection charges

The Electricity Act and the Network Code impose large responsibilities on the grid managers regarding the connection of customers. The grid manager is 'required to provide any person who requests such with a connection to the grid' (E-Act). This obligation is in accordance with the idea that electricity is a basic good that must be easily available for every person. On the other hand grid managers want to ensure that their investments in grid extensions will be paid back for by means of the connection and transportation tariffs. Unprofitable grid extensions will, in the long-term, lead to an increase of the connection and transportation tariffs or, if investments aren't covered by tariffs, an unhealthy financial situation of the grid managers (DTe, 03b). The connection of wind power to the electricity grid often requires large investments in the grid that because of the intermittent character of wind power are only utilised partly. It therefore is important to carefully analyse how wind power can be integrated in the grid most efficiently. This paragraph investigates whether the connection

charges system provides possibilities for grid managers to provide incentives to private parties to implement storage systems when this is cost beneficial. Finally some alternative regulation systems that could extend the possibilities for grid managers to give incentives will be discussed.

*Connection tariffs
<10MVA*

When a new wind farm is connected to the electricity grid, the owner of the farm is charged for the connection costs. The connections tariffs are determined by the DTe and depend on the size of the connection. Connections tariffs for connections until 10MVA are shallow, regulated and averaged. Shallow means that the customer is only charged for the capital and maintenance costs of the connection but not directly for other costs like upgrades beyond the point of connection. The capital costs consist among others of the cable costs from customer to the grid. The length of the cable is defined as the distance between the customer and the nearest already laid out grid cable, regardless of the fact that whether the capacity of this cable is sufficient for the new connection. Consequently, the indirect costs to upgrade the grid are not charged through the connection tariff. These costs are passed on to the consumers through the use of the transportation tariffs. Since the connections costs are not individually calculated but are set to cover a wide range of profiles they are referred to as regulated.

This means that for connections smaller than 10 MVA, grid managers don't have possibilities to give incentives to the wind producers to choose an efficient location as regards the grid nor to stimulate the implementation of storage systems. Even though using a storage system would be the most cost efficient option to integrate the new wind power into the grid, grid managers aren't allowed to implement this option and the operator of the wind farm doesn't receive incentives to do so. Moreover, producers don't pay transportation tariffs. As a result they will not be confronted with a possible future increase of the transportation tariffs caused by the grid investments. The grid manager is thus forced to choose an inefficient option and he, and finally the consumers, will pay for the costs made for upgrading the grid.

*Connection tariffs
>10MVA*

Connections that are larger than 10 MVA are charged according to tariffs that are negotiated and deep. Deep refers to the fact that all direct and indirect costs caused by the new connection are charged to the customer. These charges are determined through a negotiation process between the customer and the grid manager. Unlike for connections smaller than 10MVA, the grid manager can in case of connections larger than 10 MVA restrict to offering connections at those places in the grid where its capacity is sufficient. This means that when a customer is located far from a point where he can be connected to the grid, he either has to pay for a long cable to the possible point of connection or negotiate with the grid manager about sharing the upgrade costs required to enable a connection more closer to the customer.

This implies that in case of connections larger than 10 MVA, the grid manager has possibilities to stimulate the exploiter to choose a, grid technically, efficient location or to stimulate him to investments in a storage system. An example will clarify this. When a wind power operator wants to connect a wind farm with a maximal output of 15 MW, the grid managers offer a connection at a point in the grid with sufficient capacity (figure 6.3). At point A there is not sufficient capacity available. The nearest point with sufficient capacity is B, but that point is far away from the wind farm. The grid manager can charge the wind farm owner the shallow costs for a connection to the nearest point with sufficient capacity B.

It could however be financially more attractive for the exploiter to get a connection at point A and invest in a storage system to limit the maximum output of the wind farm to 10 MW.

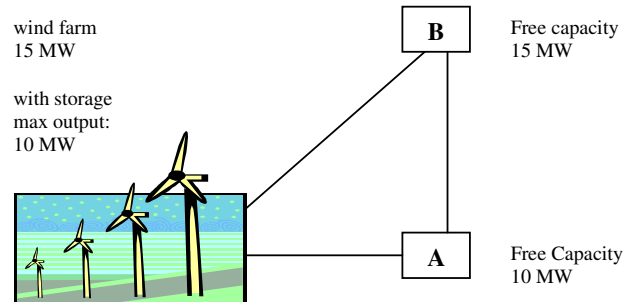


Figure 6.3: Connection options

In conclusion we find that for wind farms with an output until 10MW grid managers have no possibilities at all to provide incentives for wind farm operators to invest in storage systems. This can lead to situations where grid managers are forced to invest in inefficient options to integrate wind power in the electricity grid. For wind farms with an output of more than 10 MW the operators can voluntarily negotiate with the grid managers and choose to absorb a share of the grid investments required to connect the wind farm to the grid. While the operator can always choose to pay the shallow costs of the connection, the amount of deep costs he pays for will there never be more than extra cost caused by the fact that the grid is not close to the wind farm. The grid manager still pays for the grid investment made deeper in the grid. It is possible that the presence of stronger incentives for the wind farm owner to invest in storage systems could reduce the total costs of the electricity system.

*Extending the possibilities
for grid managers to give
incentives*

In paragraph 6.2 the advantages have been discussed of charging a customer the price that reflects as much as possible the full costs which have to be made for connecting this individual customer to the grid. This provides incentives for the customer to make his decisions regarding the location and the implementation of storage systems that are optimal for the system-wide efficiency. At the moment grid managers have no possibilities at all to give incentives to producers with connections smaller than 10 MWA. The connection of onshore wind power to the electricity grid, of which the major part has production capacities of less than 10 MW, could therefore lead to problems for the distributed grid managers. Onshore wind power is often located at remote places where large grid investments are required to enable the wind power to be connected to the grid. Since the intermittency of wind power can lead to a low utilisation rate of the grid part, the large investments are often not covered by the transportation tariffs. By lowering the limit of the connections that only have to pay the shallow connection costs, the grid managers could be enabled to provide incentives to the wind power operators to choose a location that is more favourable to the grid management. Besides the adjustment of the current regulation system, also new more sophisticated systems could be considered to introduce. In order to more and more charge private parties with the grid costs for which they are responsible, several new systems for the allocation of the cost of the electricity grid are

implemented in the electricity sectors around the world. Congestion pricing is an example of such a system. Transmission lines have capacity limits. When traders would like to use more capacity than available, the capacity has to be allocated. There are several different systems facilitating this (Nodal pricing, Transmission Rights) all aiming at pricing the available transportation capacity in a market conform way in order to have transmission tariffs that signal to both generators and consumers the full costs to the network of their operational and investment decisions (Stoft, 02). Because of the complexity of such systems however, they are not expected to be implemented in the near future in the complicated European electricity system (De Vries, 01).

Standing Offer Proposal

A less complex system that can provide grid managers the possibility to reward private parties for the supply of services locational incentives is the standing offer proposal or Request for Proposal method (Stoft, 99). Under this system, which is implemented in parts of Canada, the TSO specifies a quantity of electricity and a time when the specified quantity has to be supplied and, most important, a region in which the power has to be fed into the grid. The program is sold by auction. First the TSO posts a low offer price, which then slowly increases. All producers that are interested in supplying the offered program can take part in the auction. The first producers that accepts the offer, receives it at the price at that time. The Standing Offer proposal gives the TSO the possibilities to encourage siting of generation in locations that are favourable to the reduction of transmission upgrade costs. In a market conform way, the system provides an opportunity, fair for all potential respondents, to maximise the current electricity systems' utilisation. The standing offer system is very flexible; the grid manager can pursue the optimal configuration of generation and transmission by issuing multiple programs.

The standing offer proposal could be an effective method for grid managers to value the different benefits of electricity storage systems. Besides the supply of electricity, the programs the grid managers offer can contain schedules for reactive power supply. The ability to stimulate production capacity at specific points in the grid can be very useful for grid managers. The presence of production capacity in the grid at medium voltage level for example can be valuable for grid control. The less production capacity is connected at medium voltage level, the more electricity has to be imported from the higher voltage levels. This has the consequence that the interconnection between the two voltage levels needs to be of large capacity. Connecting a certain amount of production capacity at medium voltage level reduces the required grid investments.

The standing offer proposal could not only provide incentives for producers to invest in storage systems but also to other private parties. Large consumers that have a very high peak demand but a much lower 'base demand', must have a connection to the grid based on their peak level consumption. Peak shaving their consumption they could reduce their required connection capacity and save money on connection charges. Aside the period of their peak consumption they could use the storage system to supply services to the grid manager.

6.7 Ancillary services

The second financial relation between the storage operator and the grid manager identified in figure 6.2 consists of contracts for the supply of ancillary services.

Ancillary services are products, other than energy, that are required to ensure the secure operation of the transmission system. TenneT contracts producers on a yearly basis to oblige them to offer a certain amount of adjustment, reserve and emergency power on the imbalance market to make sure that there is sufficient adjustment and reserve power. Also black start power is an ancillary service contracted by TenneT. The costs of the ancillary services are called system costs. The system costs are passed on to the customers through the system tariffs. In contrast with the costs of the transportation services, the systems services costs are treated as 'non-accountable' within the current regulation system (DTe, 02). This means that TenneT can, under any circumstances, charge all system costs to the customers through the system tariffs.

Incentives to the producers

By offering contracts to supply ancillary services TenneT can give incentives to private parties that can contribute to the profitable exploitation of storage systems. The current regulation regarding ancillary services therefore foresees in the possibility for TenneT to stimulate the investments in storage systems. However, the system does not offer all possible incentives to do so. The costs of the ancillary services are passed on to the consumers through the system tariffs, but not to the producers. This means that the producers do not receive benefits as they lower the costs of the ancillary services they offer to the grid managers: the consumers do. If producers would profit from a reduction of the ancillary services costs this would provide them an additional incentive to look for the most cost beneficial way to supply these services. Moreover the producers are always free to refuse the contracts offered by TenneT: they are not obliged to offer ancillary services. This makes that TenneT has only limited possibilities to guide the producers to implementing storage systems to provide ancillary services.

Extending incentives to reduce ancillary services costs

A methodology for the allocation of the system costs that rewards producers when system costs decrease could create extra benefits for the implementation of storage systems. An example of such a system is 'Regulation with goals'. This system offers TenneT a fixed compensation for the execution of the system operations that is determined in advance (DTe, 02). When the final system costs turn out to be lower, TenneT gains profit, when the costs turn out higher TenneT gains losses. When the possible gains at the end of a period are distributed over both TenneT and the PRP's, the PRP's can gain extra profit if they reduce the costs of the services they offer at the ancillary market.

6.8 Balancing

The third application of storage systems that can be useful for the grid management is the implementation of storage systems as balancing power. Does the imbalance system provide incentives for the private parties to implement storage systems as balancing power? Firstly the imbalance system does so because it fines imbalance production: this stimulates the implementation of storage systems while it can reduce the imbalance costs. Secondly the system does so while it offers the possibility for storage operators to offer their storage capacity at the balancing market where they will gain benefits when it is put into action to compensate for other PRP's imbalance production. However, it is doubted whether the current imbalance system provides sufficient incentives to ensure that producers will offer all the capacity they have available for adjustment power on the balancing market.

Incentives to the producers

The Dutch imbalance market is relatively small. Large producers/suppliers like Essent, Nuon and E.on have their own production capacity and are therefore able to compensate for their imbalance to a large extent internally. This reduces the liquidity of the imbalance market and enlarges the market power of large producers. In research carried out by the Brattle group in 2001 it has been doubted whether producers have made available all production capacity to TenneT's imbalance market in 2001 (Brattle, 01). A research of the NWA (Nederlandse Mededingingsautoriteit) in 2002 concluded that in the Dutch market situations could occur in which large producers have incentives to behave strategically. In some situations they have such market power that price manipulation is possible (NMA, 02). A reason for producers to limit the available adjustment power could be that by keeping the market small, price peaks can occur, which can increase the returns for the producer. This is only possible when a producer has sufficient market power. Higher prices on the imbalance market also cause problems for suppliers that don't have much production power at their disposal. While they can't compensate for their imbalance internally they will incur high imbalance costs. This can lead to financial barriers for new suppliers and producers.

In conclusion it can be said that the imbalance system does provide incentives for producers to offer balancing power at the balancing market, but it can be questioned whether these incentives are strong enough for large producers to do so while they can have strategic reasons not to offer their balancing power at the balancing market.

6.9 Conclusions

This chapter has answered the final two sub questions:

What are the advantages and disadvantages of ownership of storage systems by grid managers compared to ownership by market parties?

Does the current regulation provide possibilities for grid managers to stimulate private parties to invest in storage systems?

Electricity storage systems could be operated both by private actors and grid managers. Either ownership structure has his consequences for the application possibilities, the required regulation systems and the grid management. What are the advantages and disadvantages of a private ownership of storage systems compared to an ownership by a grid manager? Three criteria have been used: legal compatibility, market distortion and system wide efficiency. An important fact is that three of the identified applications of storage systems, the implementation of storage systems for adjustment and reserve power supply, deferral of grid investment and reserve capacity would imply that the grid managers have to enter the electricity market.

- Legal compatibility: it is unlikely that under the current E-law regime grid managers are allowed to implement storage systems for adjustment and reserve power supply, deferral of grid investment or energy management applications. An amendment of law would be required to make these applications allowed for grid managers.

- Market distortion: the implementation of storage systems by grid managers could cause them to have conflicting interests. This could endanger a non-discriminatory grid management. Information advantages can lead to unfair competitive advantages for the grid managers when entering the electricity market.
- System wide efficiency: when grid managers have the possibility to invest in storage systems they would be able to integrate generation and grid planning, contributing to the technical efficiency to the electricity system.

	Legal compatibility	Market distortion	System wide efficiency
Grid managers	-	-	+
Private actors	+	+	0

Table 6.2: Scorecard ownership structures

The analysis shows that when the choice will be made to leave it to private actors to facilitate storage systems, extra attention has to be paid to the contribution of the storage systems to the technical efficiency of the electricity grid. In order to stimulate private actors to invest in storage systems, regulation systems should provide possibilities for the grid managers to provide private parties incentives to implement storage systems when this is cost-beneficial. Does the current regulation regarding connections charges, system charges and the balancing market offer possibilities for grid managers to incentives to private actors?

- The connection tariffs system, for connections smaller than 10 MVA, doesn't offer possibilities for grid managers to give incentives to private actors to choose an efficient location as regards the grid nor to stimulate the implementation of storage systems. For connections larger than 10 MW the grid managers have possibilities to give incentives to the customers although other regulation systems could extent these possibilities.
- The current regulation regarding ancillary services foresees in the possibility for TenneT to stimulate investments in storage systems. However, since the regulation that allocates the system charges does not provide producers incentives to minimize the ancillary service costs; parties are not stimulated to consider whether implementing storage systems could reduce the system costs.
- Although producers can gain revenues by offering their available regulation capacity on the imbalance market, the incentives to do this might not be strong enough. It can be questioned whether the current regulation regarding the balancing market provides producers enough incentives to offer all their available regulation capacity on the imbalance market that is required to have a healthy balancing market.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this master thesis the following research question has investigated:

Under which technological and institutional preconditions will it be advantageous to exploit electricity storage systems, in combination with wind farms, in the next 20 years?

The following conclusions can be drawn:

Implications of the market design on electricity storage

The current market design provides both positive and negative incentives for the implementation of storage systems. The introduction of the free electricity market has lead to the creation of incentives for producers and suppliers to respond to the fluctuating costs of electricity production: this is a major driver for the implementation of electricity storage systems. The strict unbundling of activities in the market design in contrast, can pose barriers for the introduction of technologies or changes of processes that require coordination between the links like the implementation of electricity storage. Finally the policy objective of the Dutch government to implement a large share of wind power and yet ensure the reliability of the electricity supply system, is a driver for the development of electricity storage to become an important factor in the electricity supply system in the next decades.

Available storage technologies

Currently there are several different storage technologies available, that all have specific application areas. Large-scale storage technologies can be used for the integration of renewable energy sources into the electricity supply system. A promising storage system for this application is the Poly-sulphide Bromide flow battery (PSB). The PSB system can achieve high efficiencies and is flexible with respect to discharge times and storage capacity. Though on the moment of writing this report the costs of the PSB system are still high, further development of the PSB technology is expected to result in a significant decrease of costs.

Four applications to integrate a large share wind power

There are four main applications for electricity storage systems to contribute to the integration of a large share wind power into the electricity supply system. Firstly storage system can provide balancing services. This means a storage system is operated to compensate for the (short-term) fluctuation of wind power production, which can prevent imbalance costs for wind farm operators. In time, a PSB system seems to develop to be the system that is most suited to this application.

Secondly storage systems can be used for energy management applications, for example peak shaving. Peak shaving can reduce the required generation capacity and increase the utilisation rates of the installed production capacity. Also for this application the PSB system seems the most promising option.

Thirdly storage systems can be used for the supply of power quality services. Storage systems can reduce flicker problems and harmonics caused by wind

farms. Furthermore storage systems like batteries and flow batteries can supply reactive power in order to control the voltage level.

Finally a storage system, sited close to the point where a wind farm is connected to the grid, can reduce the required grid capacity by smoothing the wind power production. This way the grid does not have to be dimensioned on the maximal amount of installed wind power capacity. This application requires large energy storage capacities, which only the PSB system is expected to be able to offer in time.

Cost-benefit analysis of the PSB system

The supply costs of the Polysulphide Bromide system (PSB) are currently significantly higher than the production costs of a gas-fired plant and a STEG unit. A case study has showed that trading on the APX with a PSB storage system, at 2003 APX prices, would have been profitable at an investment cost level of about 900 €/kW. The implementation of a PSB system for the prevention of shortage production of a wind farm is at the current imbalance prices not profitable. The combined implementation of a PSB system for both peak supply and balancing results in a significant decrease of the peak supply costs of the PSB system. At 2002 imbalance prices however, a gas-fired plant would still produce the peak supply at lower costs. At 2003 prices the PSB system supplies electricity at lower costs than a gas-fired plant when both systems are operated at a production rate of less than 1600 hours of peak supply per year; under these conditions it would therefore be cost-beneficial to implement a PSB system for the use of peak supply.

Institutional aspects

An analysis of the advantages and disadvantages of ownership of storage systems by grid managers compared to ownership by market parties shows that when it will be decided to leave it to private actors to facilitate storage systems, regulatory guiding is required that recognises and rewards the services that storage systems can provide to grid managers. This will guide the private parties to implement storage systems such that they contribute optimally to the system-wide efficiency of the electricity supply system. The regulation should offer possibilities for grid managers to provide the private actors incentives to implement storage systems when this is cost-beneficial. Current regulation regarding ancillary services does not stimulate parties to consider whether implementing storage systems could reduce the system costs. Also the incentives provided by the connections tariffs system and the regulation regarding balancing leave room for improvement.

7.2 Recommendations

First in this paragraph three topics for further research are recommended, consequently a few recommendations for the distributed network managers and the TSO the problem are given.

Recommendations for further investigation

In order to calculate the amount of shortage costs that can be prevented by the implementation of a PSB system certain assumptions have been made regarding the power capacity and the storage capacity of the PSB system in relation with the size of the wind farm. Further investigation is recommended to find the optimal relation of storage and power capacity and size of the wind farm.

This research has found that current regulation doesn't provide grid managers in every case the means to give incentives to private parties to stimulate the services they can supply with storage systems. More research is recommended to investigate whether new regulatory systems, like the Standing Offer proposal, are effective ways to provide the TSO possibilities to encourage siting of generation in locations that are favourable to the reduction of transmission upgrade costs. Furthermore the possibilities to improve regulation regarding ancillary services with for example the introduction of a 'regulation with goals' system should be considered.

Currently the distance between the location of the production of electricity and the consumption does not influence the transportation tariffs. A so-called post stamp tariff is used: a uniform price for transportation regardless of the distance that is passed through the grid. There are several different systems (Nodal pricing, Transmission Rights) that can be implemented in order to have transmission tariffs that signal to both generators and consumers the full costs to the network of their operational and investment decisions. It is recommended to investigate the impacts of these regulatory systems.

*Recommendations for the
grid managers*

In this research the deferral of grid investments is identified as an application of storage systems that could contribute to an efficient integration of a large share wind power. It is recommended to the grid managers to carry out a qualitative investigation to evaluate possibilities for the profitable implementations of storage for this application.

In the beginning of 2004 TenneT and Statnett (Norwegian TSO) have decided to invest in a 500 MW transmission cable that connects the Dutch high voltage net directly to Norwegian high voltage net. This enables the storage of electricity from The Netherlands with the pumped hydro storage systems in Norway. Further investigation could be carried out to investigate the influence of a significant increase of connections between the various (North western) European grids on the required amount of regulation and reserve power.

At this moment investigations are being carried out that consider the cost allocation of the integration of offshore wind farms into the electricity grid. One of the main dilemmas is whether offshore grids will have to be paid for by the wind farm operators or by TenneT. It is recommendable for TenneT to stress the possibilities for wind farm operators to reduce the required grid capacity by implementing storage systems and to include storage systems in the discussion regarding the allocation of the costs of grid investments.

8 REFLECTION

Perspective

This master thesis has investigated the economic and institutional aspects of the implementation of electricity storage for the integration of wind power. While the grid managers are responsible for the technical integration of wind power in the electricity grid, it was chosen to derive this investigation from their point of view. Chapter 2 has pointed out that the coordination between different links of the electricity value chain is hindered by the market design. In addition from the analysis of the Electricity Act in chapter 6 it appeared that grid managers are not expected to be allowed to carry out several applications of electricity storage systems that could be useful to grid managers themselves. This means that incentive regulation should enable grid managers to stimulate market parties to provide them storage services so that they can benefit from the advantages electricity storage can provide for the grid management. This is the principle regulatory issue considered in this research: does current regulation provide grid managers the possibilities to do so? The regulatory analysis therefore has clearly been carried out from a grid manager's perspective.

The economic aspects of electricity storage are analysed in chapter 5. In chapter 5 a cost-benefits analysis is carried out for applications that are mainly of interest for electricity producers: trading at the APX spot market, balancing and peak supply. Although there were several reasons to select these applications for the economic analysis (see the introduction of chapter 5), a cost benefit analysis of the applications that are in particular valuable to grid managers would have fitted better within the perspective chosen initially in this research: the grid managers' perspective.

Cost-benefit analysis

The cost benefits analysis of the PSB system in this research has investigated the profitability of the implementation of the system for individual applications, and for one combination of applications, balancing together with peak supply. The full picture of cost and benefits however, is not given until also possible benefits provided by grid managers to storage operators would be taken in account. These benefits can consist of a reduction of connection charges or rewards for services they supply with the storage system for the grid manager. Since in this research no attempt has been made to quantify the benefits electricity storage can have for grid managers, it therefore was not possible to include these benefits in the cost-benefits analysis. As stated in paragraph 7.2 it is recommended to quantify the benefits that electricity storage can have for grid managers. This way all benefits can be taken into account for the calculation of the profitability of a storage system, analysis, whereas the cost-benefit analysis in this research only provides a partial evaluation. In combination with this remark it can be said that the use of another than the cost-benefit analysis could have been considered to analyse the economic aspects of electricity storage. The use of a cost-benefit assessment for example would have enabled also to take into account the effects that have been identified as relevant but could not be quantified or valued in monetary terms.

Small scale/ large scale storage

This research is limited to the investigation of the implementation of large-scale storage systems. While large-scale storage technologies are still in an early stage of development, it will probably not be cost beneficial to implement these

systems within the next 5 to 10 year except in very specific situations. In my opinion if grid managers want to reduce the required grid investments on a shorter notice, the implementation of smaller scale systems by consumers offers better perspectives. Firstly small-scale storage technologies are more mature and can therefore already be implemented currently. Secondly an adjustment of the electricity tariff structure, in a way that it better reflects the difference between the costs of producing and transporting electricity at night compared during daytime, could create possibilities for consumers to profitably shift their load from day to night with as a result a reduction of the required grid capacity.

The cost-benefit analysis carried out for the implementation of a PSB system for the use of peak power supply in combination with balancing showed that the investment costs level of the PSB system will have to decrease considerable, however not to an unrealistic level, in order to be profitable. On the one hand electricity storage is the technology that could enable a large share (intermittent) renewable power in the electricity supply system in future. On the other hand however, electricity storage will not be developed on a large scale until it is clear that renewable power supply will play a significant role in electricity supply in the coming decades. In order to break this vicious circle and stimulate private parties to invest in the development of electricity storage, there has to be more certainty regarding the role storage can play in the (near) future. This master thesis has aimed to contribute to this by investigating the economic and institutional aspects of the implementation electricity storage for the integration wind power in the electricity supply system.

Ruud Hendriks

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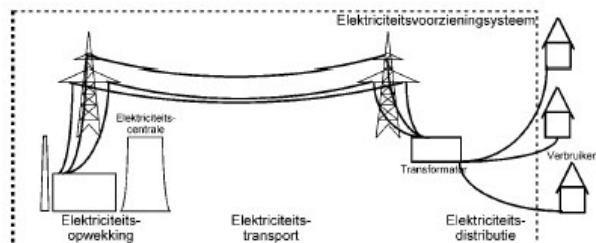
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APPENDIX A: THE ELECTRICITY NETWORK

The electricity network transports electricity from the production site to the consumer. Usually two different parts are distinguished, the transportation and the distribution grid (Kling, 00). The transportation grid has the highest voltage level and connects the large plants with the main load centres. High voltage grids operate at 50kV (partially), 110kV, 150kV, 220kV and 380kV, and are used to transmit larger quantities of electricity throughout the country and across the national borders. As the national grid administrator and Transmission System Operator, TenneT owns or administers the 220kV and 380kV grids whereas ownership of the other transmission grid sections rests with a total of eight regional grid managers.

Transformation stations are used to feed the power on a lower voltage level into the distribution grid. The electricity only flows in one direction, from the transportation grid to the distribution grid. The distribution grid subsequently distributes the electricity over the connected consumers. The distribution network consists of two types of grids, with different voltage level ranges. Firstly the intermediate voltage grids, with voltages ranging between 50kV (partially), 25kV, 20kV and 10kV: these grids are used for local distribution of transmitted electricity. Secondly the low voltage grids, with voltages in the 230V-400V range: these grids provide for the further distribution of electricity within towns or villages. There are 22 distribution network managers that control the distribution grids.



APPENDIX B: WIND TURBINES

Currently there are three main wind turbine types on the market: the fixed speed turbine, the variable speed turbine with induction generator and the variable speed turbine with direct drive generator. The first difference between the different types is the way the mechanical power is converted to electrical power (the generating system). The second difference is the way in which the aerodynamic efficiency of the rotor is limited at wind speeds higher than the nominal wind speed. This concept is discussed below. Next the three different wind turbine types are discussed, with a focus on their impact on power quality. This appendix concludes with an overview of the impact on power quality of the different wind turbine types.

Power curve

At low wind speeds the air contains little energy and a wind turbine does not generate power at all. In general wind turbines start to work at wind speeds of 3.5 to 5 m/s, which corresponds with wind force 3. This is called the cut-in wind speed. At a certain wind speed, usually between 12 m/s and 15 m/s (wind force 6/7), the nominal (or rated) power of the generator is reached. If at with wind speeds above the nominal wind value, the maximal amount of energy would be withdrawn from the wind, the generator would function at a speed higher than the nominal one, which could lead to overloading. Therefore at wind speeds above the rated speed, rotor efficiency has to be reduced. Finally wind turbines have a cut-out wind speed. At this speed the turbines has to be taken out of operation to prevent overload. In general this is at wind speeds of 25 m/s or wind force 9. The relation of wind speed and generated power is called a power curve and is illustrated in figure B.1.

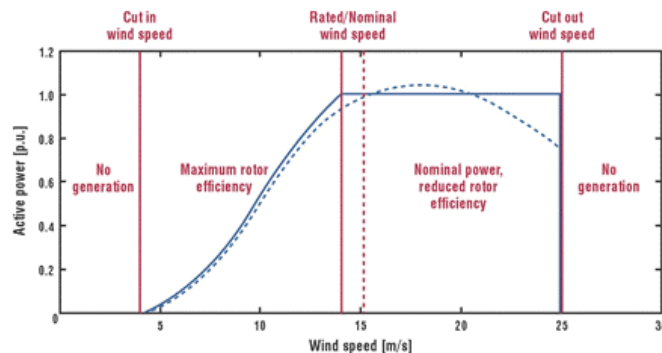


Figure B.1: Power curve

Stall control/pitch control

Reducing the efficiency of the rotor at high wind speeds can be done in two different ways. The first method is called stall control. This method enhances that the rotor blade is designed in such a way that, at high wind speeds, the efficiency of the rotor decreases automatically. The second method is an active control system. At high wind speeds the blades are mechanically turned out of the wind to reduce efficiency. This is called pitch control. Relatively new is the active stall control. This concept resembles the normal stall power limitation but the blades can also be rotated by a few (3-5) degrees in order to give better rotor control. The difference from pitch control is that the angle variation is less (about 30

degrees for a pitch turbine) and the blades rotate in the opposite direction. In addition the angle of an active stall turbine is only varied during the start-up period and the nominal speed range, while pitch control sometimes is used continuously.

Fixed speed turbine

A fixed speed wind turbine is a wind turbine with a conventional directly grid coupled induction generator. While there is a large difference between the speed of the rotor of the wind turbine and the generator, a gearbox is used to combine the systems. The slip, the difference between the actual rotor speed and the synchronous speed, varies with the amount of generated power. These variations however are as less as 1 to 2 percent. Because of the small change in speed this type of wind turbines is referred to as a fixed speed turbine. A squirrel cage induction generator draws reactive power from the grid. Especially in weak grids this is undesirable because of the problems that can occur with the grid voltage. The reactive power consumption of the generator is nearly always partly or fully compensated by capacitors. Fixed speed turbines usually use stall control, sometimes active stall control.

Fixed speed wind turbines must be mechanically robust because of the fact that the rotor speed cannot be varied and therefore variations in wind cause loads on the wind turbine that are structurally high. This ‘stiffness’ of the fixed speed turbine causes power fluctuations when the wind speed varies. In weak grids this can lead to grid voltage variations and flicker. Another disadvantage of the fixed speed turbine is the fact that both active and reactive power cannot be controlled.

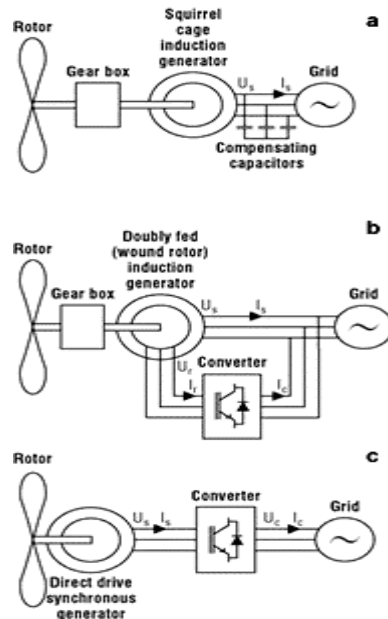


Figure B.2: Wind turbine technologies

Variable speed turbine with induction generator

The other two generators are variable speed systems. These systems are used in variable speed turbines. To allow variable speed operation the grid frequency and the frequency of the rotor have to be decoupled. This is realised by using power

electronics. A converter feeds the rotor winding which means the electrical frequency of the rotor can be varied making variable speed operation possible. The first variable speed system uses a doubly fed induction generator. Also in this concept a gearbox is installed because of the large difference between the speed of the rotor and the generator. The voltage converter on the rotor can match the electrical frequency of the stator and the rotor, independently of the mechanical rotor speed.

Variable speed wind turbines are capable of absorbing energy of variations in wind speed as it speeds up or gives back this energy to the system as it slows down. The absorption of wind gusts in the rotor speed leads to a reduction of power fluctuations. In general variable turbines therefore don't cause flicker. Because the reactive power supply can be controlled variable speed turbines can be used for grid voltage control. Variable wind turbines, because these are equipped with power electronics, can be a source of harmonics. This is the distortion of sinusoidal voltage or current waveforms characterised by either voltage or current components at multiples of the fundamental frequency. However, in case of modern power electronics converters with their filtering techniques, the harmonics issue should not be a major problem. Well-designed synchronous and asynchronous generators hardly emit any harmonics.

*Variable speed turbine
with direct drive generator*

The second variable speed concept uses a direct drive generator. This means these wind turbines have no gearbox. The generator is decoupled from the grid by a converter. The large synchronous ring generators that are used cause the specific form of the machines. Variable turbines are most of the time equipped with a pitch control system.

The advantage of a doubly fed variable speed generator compared to a direct drive variable generator is the fact that it uses a standard induction generator and a smaller power converter. The direct drive generator is more complex and expensive, but the great advantage is that it can function without a gearbox. Gearboxes need much maintenance, which especially for offshore wind farms is a problem.

*Power quality in weak
grids*

The term 'weak grid' is usually used to express that the voltage level in a grid is not as constant as in a 'stiff grid'. Put this way the definition of a weak grid is a grid where it is necessary to take voltage level and fluctuations into account because there is a probability that the values might exceed the requirements in the standards when load and production cases are considered (Binder, 99). Weak grids are usually found in more remote places. Here the power lines, often referred to as feeders, are long and operated at a medium voltage level. The grids in these places are usually designed for relatively small loads. When the design load is exceeded the voltage level will drop below the allowed minimum and the thermal capacity of the grid will be exceeded. When the designed generation is exceeded, the voltage level will be too high and the thermal capacity will also be exceeded. Only limited amounts of wind power will already cause power quality to be hard to maintain in weak grids.

Large-scale offshore power is expected to be connected directly to the high voltage grid where as smaller scale onshore wind power is mainly situated in remote areas and thus connected to weaker grids. Harmonics and the voltage level could play a role both in the integration of onshore wind power in weak grids and in the connection of large-scale offshore wind power to the high voltage grid.

Problems regarding flicker will predominantly be confined to the integration of onshore wind power in weak grids.

	Weak grid			High voltage grid		
	Fixed speed	Doubly fed	Direct Drive	Fixed sp.	Doubly fed	Direct Drive
Voltage level	Reactive power is not controllable	Reactive power is controllable	Reactive power is controllable	Reactive power is not controllable	Reactive power is controllable	Reactive power is controllable
Harmonics	Hardly of interest	In theory of interest, but should not be major problem	In theory of interest, but should not be major problem	Hardly of interest	In theory of interest, but should not be major problem	In theory of interest, but should not be major problem
Flicker	Important	Unimportant, rotor acts as energy buffer	Unimportant, rotor acts as energy buffer	Hardly of interest	Hardly of interest	Hardly of interest

Table B.1: Overview of impact of different wind turbines on power quality

APPENDIX C: COST CALCULATIONS OF THE PSB SYSTEM

Parameter values

The following parameters have been used for the calculation of the supply costs of the PSB system.

Supply capacity	100 MW
Charge capacity	80 MW
Energy capacity	800 MWh
Investment costs	800/1200 €/kW
Control and maintenance costs	4% of total investment costs
Average efficiency	70%
Discount rate	8%
Discount period	15 years
Purchase cost electricity	18 €/MWh ¹

Table C.1: Parameter values PSB supply costs calculation

1, Average 2003 APX price, from 22h to 8h

The following parameters have been used for the calculation of the supply costs of the gas-fired plant and the STEG unit.

	GT	STEG	
Production capacity	250	600	MW
Investment costs	375	650	€/kW
Control and maintenance costs	7.5	25	€/kWh
Efficiency	0,38	0,57	%
Gas price	4	4	€/GJ
Discount rate	8	8	%
Discount period	15	15	year

Table C.2: Parameter values GT and STEG cost calculations

APPENDIX D: COST-BENEFIT CALCULATIONS OF TRADING ON THE APX SPOT MARKET

Parameter values

For the PSB system the parameter values as presented in Table C.1 are used. The PSB system will be charged during the 10 hours a day when electricity prices on average are the lowest: from 22h to 08h. The average APX price during these hours was € 14.60 in 2002 and € 20.40 in 2003. The PSB system will be discharge during the 8 hours with highest market prices: from 09h to 15h and from 17h to 19h. The average APX price in these periods was € 48.15 in 2002 and € 80.14 in 2003. The 2002 and 2003 APX prices can be found at www.apx.nl.

APPENDIX E: COST-BENEFITS CALCULATIONS OF BALANCING

Parameter values

The following parameters are used to calculate the yearly benefits (prevented shortage costs) of the implementation of a PSB storage system for balancing:

Wind power capacity	1000 MW
PSB supply capacity	100 MW
PSB charge capacity	80 MWh
PSB energy capacity	800 MWh
PSB average efficiency	70%
PSB investment costs	800 €/kW
PSB control and maintenance costs	4% of total investment costs
Value of stored surplus electricity	10 €/MWh ¹
Average 2002 shortage price from 6am to 21pm	50 €/MWh
Average 2003 shortage price from 6am to 21pm	88 €/MWh

Table E.1: Parameter values of the cost-benefit analysis of balancing

1, Average 2003 surplus price from 21h to 6h

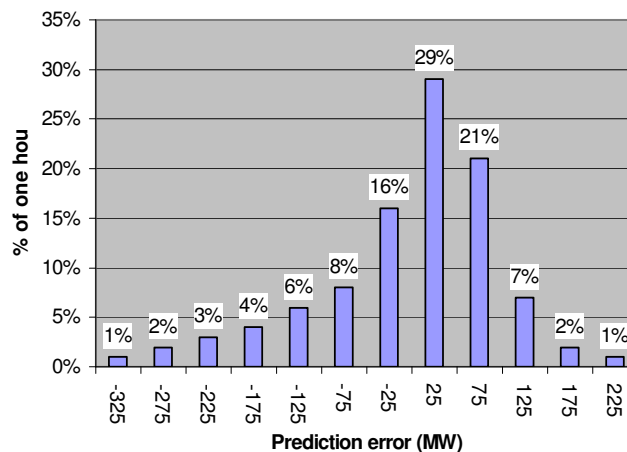


Figure E.1: Prediction errors of a 1000 MW wind farm (Source: Eltra, 02)

Explanation of the calculation

Figure E.1 shows that a 1000 MW wind farm produces on average a shortage between 0 and -50 MW during 16% of an hour. We assume that the average shortage during this 16% of an hour is equal to the average value of the interval: $(-50-0) / 2 = -25$ MW. This is assumed for every interval. We can now calculate how much imbalance the wind farm on average produces (MWh) for each prediction error interval (column shortage production in table E.2).

If the wind farm produces a shortage the PSB system can prevent the shortage by supplying previously stored electricity.

The PSB system will be operated with the following schedule:

- From 21h to 06h the PSB system will be charged when the wind farm produces a surplus to the E-program.
- From 06h to 21h the PSB system will supply stored electricity in case of shortage and store electricity in case of a surplus.

If in case of a shortage production by the wind farm, the prediction error of the wind farm production (and thus the shortage production) is less than the supply capacity of the PSB system (100 MW), all shortage production can be compensated by the PSB system. If the prediction error of the wind farm production is larger than the supply capacity of the PSB system, not all shortage production can be compensated by the PSB system (column prevented shortage in table E.2). For example, if the prediction error is -175MW, 75MW of the shortage production cannot be compensated for by the PSB system.

Prediction error (MW)	% of hour	Shortage production per hour (MWh)	Prevented shortage 06am – 21pm (MWh)
-325	1%	-3,3	-1,0
-275	2%	-5,5	-2,0
-225	3%	-6,8	-3,0
-175	4%	-7,0	-4,0
-125	6%	-7,5	-6,0
-75	8%	-6,0	-6,0
-25	16%	-4,0	-4,0
	Total	-40,0	-22,4

Table E.2: Average hourly prevented shortage

Table E.2 shows that on average 22.4 MWh shortage production is prevented per hour. This results in 122 GWh prevented shortage per year. Using the 2002 and 2003 average shortage costs between 06am and 21pm, we find that this is a shortage costs prevention of respectively € 6 million and € 11 million.

APPENDIX F: COST CALCULATIONS OF PEAK SUPPLY

Parameter values For the PSB system the same parameters values as presented in table C.1 are used. For the gas-fired turbine and the STEG unit the parameter values as presented in table C.2 are used.

Explanation of the calculation If the PSB system is used for peak supply it can annually prevent less shortage production of the wind farm. In Appendix E is calculated that the PSB system prevents 22.4 MWh per hour, 122 GWh a year. When the PSB is used for peak supply for 100 hours a year (10 GWh), it can still prevent 121 GWh shortage per year. The total yearly supply of the PSB system in this case is 131 GWh. At a supply rate of 131 GWh a year, the supply costs of the PSB system are 111 €/MWh. The calculation of the supply costs is carried out for several peak supply production rates.

	Annual supply (GWh)			Costs (€/MWh)		
Hours of peak sup.	Peak supply	Shortage prevention	Total supply	Fixed costs	Variable costs	Total costs
100h	10	121	131	96	15	111
200h	20	119	139	90	15	106
400h	40	115	155	81	16	97
800h	80	103	183	69	17	86
1600h	160	72	232	54	19	73
3200h	320	22	342	37	21	58

Table F.1: PSB supply costs: combined peak supply and balancing

In table F.1 it can be observed that when the PSB system is operated 100h per year for peak supply, the total supply costs of the PSB system are 111 €/MWh. Given the fact that the average shortage costs in 2003 were 88 €/MWh, the balancing activity will not be profitable. Only when the peak supply production rate increases to about 800h, average supply costs drop to less than 88 €/MWh and it is at this point that using the PSB for shortage prevention will be profitable.

This means that although balancing leads to a decrease of the average supply costs of the PSB system at low peak supply rates, it also creates extra costs caused by the fact that implementing the PSB system for balancing costs are higher than having the imbalance 'traded away' on the imbalance market. In order to make a fair comparison of the production costs between a gas-fired plant and the PSB system, these extra costs will be distributed over the total supplied electricity by the PSB system. However, in case shortage prevention is profitable, thus when the supply costs of the PSB system are lower than 88 €/MWh, the PSB system gains extra benefits compared to a gas turbine that would be used for peak supply only. These benefits are therefore subtracted from the supply costs. Table F.2 presents the total supply costs of the PSB system.

Hours of peak supply	Prevented shortage (GWh)	Average 2003 shortage price (€/MWh)	Prevented shortage costs (Mil. €)	Costs of prevented shortage (Mil. €)	Result of balancing (Mil. €)	Extra costs/benefits per MWh peak supply	Total costs of peak supply (€/MWh)
100h	121	88	10,6	13,4	-2,8	276	387
200h	119	88	10,5	12,6	-2,1	105	210
400h	115	88	10,2	11,2	-1,0	26	122
800h	103	88	9,1	8,8	0,2	-3	83
1600h	72	88	6,3	5,3	1,1	-7	67
3200h	22	88	1,9	1,3	0,7	-2	56

Table F.2: PSB peak supply cost, balancing results included