
# SMART GRIDS ON INDUSTRIAL AREAS

## Business models to enhance the implementation of renewable energy

**In partial fulfilment of the requirements for the degree of Master of Science in Construction Management and Engineering**



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## CONTENTS

## PREFACE

This thesis is written for the completion of the master track Construction Management & Engineering, which I have followed at the Eindhoven University of Technology. During the master, but also during my bachelor study in building engineering, the topic of energy use in the build environment has had considerable attention. For me, it is very inspiring to look for ways to switch to renewable energy and very challenging to work on solutions for this problem, which affects us all.

During the first months of this research, it was very difficult to oversee the complexity that is related to the subject of smart grids. Collaborating with researchers of the e-harbours project was very helpful, but also very fun to do. I am very glad that I had the opportunity to visit project meetings in the Netherlands, Germany, Sweden and Belgium. The knowledge gained from these meetings was vital for the progress of this study.

I would like to thank all the people from the municipality of Zaanstad and e-harbours, who have helped me with this study. Of course I would like to thank my supervisors Bauke de Vries, Brano Glumac and Bart van Weenen from the TU/e, for their advice and feedback on this work.

This research has helped me to gain a lot of understanding in the field of sustainable energy. Hopefully, others can profit from this as well, and get inspiration from this.

I hope you will enjoy reading this thesis,

Simon Lubach
Utrecht, March 2013.

## MANAGEMENT SUMMARY

The use of energy from renewable sources is growing, and a transition in the energy supply is expected. To make this transition towards an economy that is based on renewable energy, solutions have to be found to deal with the uncontrollable and intermitting supply of renewable energy.

To improve the implementation of energy from wind and solar sources, smart grids are required to match supply and demand. By using energy in a flexible and controllable way, renewable generated energy can be integrated better in the power system. A large potential for this demand side management can be found in the industrial sector.

Although the industrial sector makes a range of different products and services, flexibility can be exploited based on similar concepts. Thermal applications, pumps and production lines can consume energy flexible by optimizing the production in a smart way.

This flexibility has economic value; to exploit this, four business models are proposed, which can be applied widely. The general principle is that supply and demand can be managed by a market mechanism. Making use of variable prices of energy over the day can be used to reduce costs. The flexibility of industrial processes can also be used to avoid unbalances at a special market platform; flexibility is offered as a balancing service. Local smart micro grids can be very beneficial for consumers, who have a source of energy supply nearby. In a Virtual power plant, the production of a portfolio of renewable energy sources can be made controllable by using the flexibility of consumers.

In a case study for the industrial development location HoogTij, an example is given of a smart grid application for a collective heat/cold network. An agent based simulation model optimizes the energy use, by simulation the production of energy and the demand for heat. Result is an increase of the use of renewable energy and a vast reduction in costs. The case of the industrial development HoogTij is a good example of an application of smart grid technology. Flexibility that is present in the system of the heat network can be exploited in a smart grid. The economic benefits are so significant, that it makes the heat network profitable. Hence, this case can really improve the sustainability of the development of HoogTij.

# 1. RESEARCH FRAMEWORK

This part describes the framework of the research. First, the context of the research is described in the problem analysis. The central question and research questions are stated, as well as a framework for the research methodology is given. The relevance of the study and organisational partners are described, and the outline of the research is given in the reading guide.

## 1.1. Problem analysis

Currently, the most energy used in the world comes from fossil fuel sources such as oil, coal and gas. Yet, the use of these fossil fuels has negative environmental consequences, such as global warming. Scarcity of these resources is a growing problem, and increases the costs for energy, which demands are ever growing. Moreover, gaining these fossil fuels has been a major cause for conflicts in history: Instable regions hold vast shares of fuel resources and our cravings for energy results in undesirable dependencies and warfare.

Taking this in mind, a transition towards sustainable energy from renewable sources is a necessary and responsible step. Most countries have ambitious targets on clean energy. The European Union targets with its 20/20/20 goals for 20% reduction of $CO_2$, 20% increase in energy efficiency and 20% renewable energy in 2020 (European Commission, 2012). The Intergovernmental Panel on Climate Change (IPCC, 2012) states a $CO_2$ reduction of 80-95% compared to levels of 1990 is required for developed countries in 2050, in order to avoid disastrous climate change.

The implementation of clean energy also requires improvements in the energy infrastructure: Development of smart grids is essential for the success of clean energy. The randomness, intermittent, and the unbalanced nature of renewable energy require such a smart grid (Peng et al, 2011). A smart grid allows energy flows in two directions and is capable of matching the supply and demand of energy. Moreover, smart grids contribute to a more efficient electricity infrastructure.

Industrial areas consume vast amounts of energy for their production activities, which take place at the established companies. In 2004, industrial customers consumed 41,4% of electricity globally (IEA, 2006). Industrial energy customers are confronted with the rising prices of energy. In order to be competitive in the global market, companies should take measures to reduce their energy costs. When companies are able to purchase energy at times of the day that it is cheaper, they can have great benefits and consequently contribute to the implementation of renewable energy. Therefore, smart grids in industrial areas seem to have a great potential.

Summarising, the problem in this research is:

**A transition from an economy based on fossil fuels is emerging towards a renewable energy economy. Yet, the random and uncontrollable nature of renewable energy and the rising energy costs for industries threatens the availability of energy!**

The industrial consumers are depending on the availability of energy in order to fulfil their primary processes. Often, established companies where formed on the idea that energy is cheap and widely available. However, costs of energy are rising for decades, due to the higher demand and the depletion of resources.

## 1.2. Research questions

The ambition to make a transition towards renewable energy sources, such as solar and wind power can cause problems in the energy system: unbalances occur in the electricity grid, due to the intermitting and uncontrollable character of these energy sources. The central question in this research is: **"How can smart grids contribute to the integration of renewable energy on industrial areas?"**

An important feature of smart grids is demand management; this can be used to match the intermittent supply of renewable energy. To investigate this subject, some research questions are developed:

*Which companies or activities are flexible in energy demand and can be used to match the intermitting supply of renewable energy?*

*What business models can be found to develop smart grid applications?*

*What business opportunities can be found to develop a smart grid for the industrial area HoogTij?*

*How can multiple companies on an industrial area benefit by deploying a smart grid?*

*Can a smart energy infrastructure attract businesses to settle on an industrial area?*

### 1.2.1. Research objectives and limitations

Purpose of this study is to investigate the feasibility to implement smart grids in industrial parks and harbours. To investigate the research questions, a case study will be performed on an industrial park development. The municipality of Zaanstad and developer 'Ontwikkelingsbedrijf Haventerrein Westzaan' are developing the sustainable industrial park 'HoogTij'. The aim for HoogTij is to create a sustainable energy infrastructure: Development for wind turbines is taking place and a collective heat/cold network is planned, which is partially established. Results of this study can improve the energy concept of HoogTij, as the objective is to investigate the added value of a smart grid application for this industrial area.

## 1.3. Research methodology

To find answers on the research questions that have been set, a number of research methods had to be used. In a literature study, an investigation is made on smart grids in industrial settings. To better understand the problems concerning this, the market and the system for energy where analysed. Since smart grids are related to a number of complex problems and different interests, some reference projects where analysed, to have a better understanding of the potentials. An important factor for a smart grid application was found to be the related business model. When possible business models where discovered, an idea of a potential case for HoogTij was found.

Once a case for a smart grid was determined, this could be analysed further by developing a simulation model. The choice was made to use an 'agent based simulation' model (ABS). These simulation models are especially useful to model the behaviour of complex systems, and can cope with multiple time steps easily. The goal of the simulation study was to investigate the improvement to integrate intermitting renewable generated energy and to calculate financial benefits of the smart grid under several scenarios. Results of the simulation where used to evaluate the business case for the proposed smart grid. These results where important to give recommendations for the development of HoogTij and to conclude on the research questions. An overview of the research approach is given in the diagram in figure 1.1.

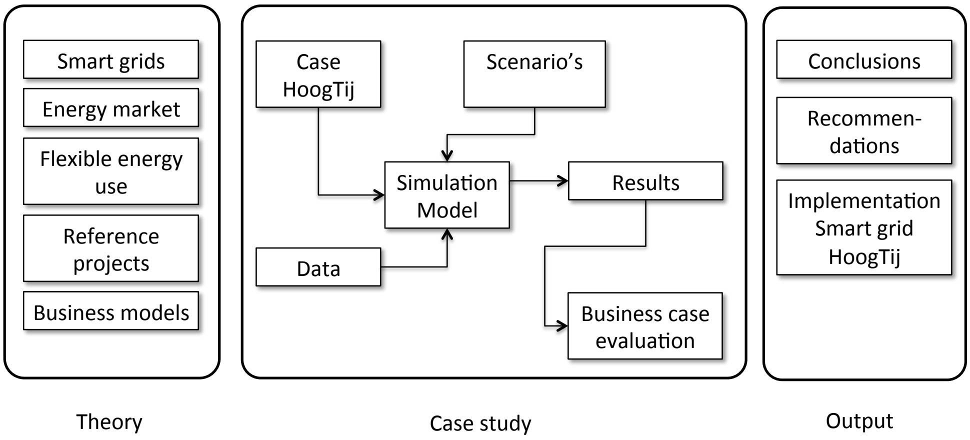



**Figure 1.1 Diagram of research methodology**

Agent based simulation models are a relatively new modelling technique in the scientific world. Due to the increasingly complex world, with all its interdependencies, traditional modelling techniques are often not able to cope with these problems. ABS models have the possibility to model individual preferences or behaviours. The 'agents' in the model are most important features. Agents are an independent component, which have the capability of making individual decisions. Agents' behaviour can range from primitive reactive decision rules to complex adaptive intelligence (Macal, 2005).

In this study, an ABS model has been developed in Netlogo. Netlogo is a programming language, which has many similarities with Java. Netlogo models consist of agents (turtles), which follow rules and interact on patches (environment). By programming behaviour of the agents, a simulation can be made on a phenomenon. Hence, different scenarios can be tested to find an optimisation.

### 1.4. Scientific and social relevance

This research is being conducted for the fulfilment of the master degree of the Construction Management & Engineering track. Yet, it is relevant for the organisational partners, the TU/e, businesses and public institutes such as the province of Brabant, who contribute with sponsoring.

#### 1.4.1. Organisational partners

This research is performed in collaboration with the European research project e-harbours and the municipality of Zaanstad. e-harbours' objective is to create a more sustainable energy model in harbour regions on the basis of innovative intelligent energy networks. Zaanstad is the lead beneficiary in this project, which is performed by eight European partners and is supported by the Interreg IVB North Sea region programme. Zaanstad is very ambitious on sustainable energy and is working hard to be an energy neutral municipality by 2020.

### 1.4.2. Relevance TU/e

Energy use is an important subject of research in the Eindhoven University of technology. Research on sustainable energy at the TU/e belongs to the top of the world. A number of faculties are interested in renewable energy. The Master track Construction Management & Engineering has special interest in the transition towards sustainable energy use, and has the focus on the implementation in the urban environment. Industrial (re)-development is a subject that is considered well within the course. More knowledge on this subject is therefore desirable. The Sustainable Energy Technology master programme has a multidisciplinary approach on sustainable energy. Smart grids are one of the research topics, as well as sustainable energy in the build environment. Industrial applications of smart grids can be a complement to the knowledge developed at the TU/e.

### 1.4.3. Relevance for businesses and public institutes

Businesses have seen energy prices rising for decades. In a globalising world it is important to stay competitive and to reduce cost where possible. Demand management can be a good way to reduce costs for energy intensive companies. Grid operators will be interested in smart grid developments; investments in more capacity could be reduced and the grid can be made more reliable. Energy producers can achieve greater efficiency and operate more profitable.

For the province of Brabant, this research and case study can be an important example of how smart industrial areas can be developed. The conclusions of the research can be helpful to develop sustainable and competitive industrial areas. Furthermore, demand management is crucial for widespread implementation of clean energy technologies. Of course, this is relevant for both businesses and society.

## 1.5. Reading guide

This research is divided in three parts. Part 1 describes the principles of the smart grid and the markets for electricity. An investigation is made on the energy consumption by industrial users, where potentials for demand management are indicated. Moreover, business models are given which can be used to gain financial benefits for application of demand management in smart grids. In part 2, a case study is performed for an industrial site that is being developed in Zaanstad. A case for a smart grid is proposed and analysed. Part 3 includes conclusions on the research questions and discussion.

## PART 1: INDUSTRIAL SMART GRIDS

## 2. THE ENERGY TRANSITION REQUIRES SMART GRIDS

Currently, a transition is starting to shift from an economy that is reliant on fossil fuels towards an economy that is based on the use of renewable energy sources. This transition is of major importance; the environmental problems related to a fossil fuel based economy are threatening the conditions of life for ourselves, and future generations. Moreover, depletion of these fossil fuels shall harm the economy sooner or later, since developed countries are more and more reliant on energy. To remain our standards of living, a shift has to be made to renewable energy.

Wind and solar power are a major source of renewable energy. Yet, it is generally accepted that the integration of intermittent energy resources like wind energy and photovoltaic into an electricity system cannot exceed a limit of around 20% to 25% (Stadler, 2008). The reason for this is that the current electricity system is demand driven. Customers, small and large can, to some extend consume energy as much as they want whenever they want. Electricity generators follow the demand, and supply energy accordingly, as illustrated in figure 2.1.

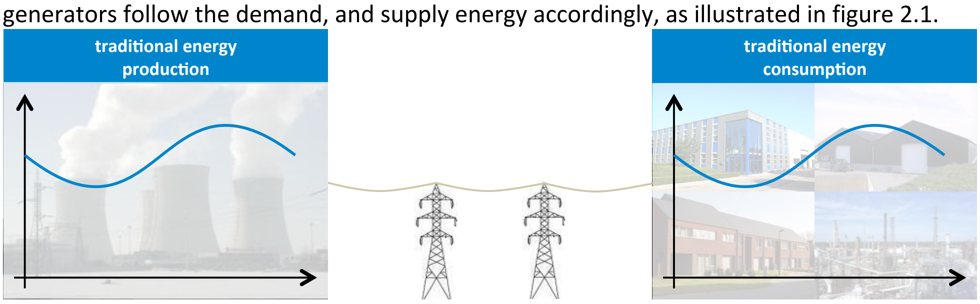



**Figure 2.1 The traditional structure of the electricity grid. Supply follows demand.**

Energy from wind and solar sources cannot be controlled and is varying over the day and over the year. When these energy sources are connected to the electricity grid, unbalances can occur; production and consumption deviates from each other (figure 2.2) and can cause problems with a safe and secure supply of energy.

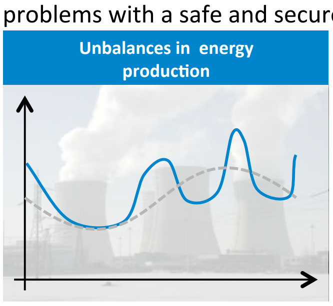
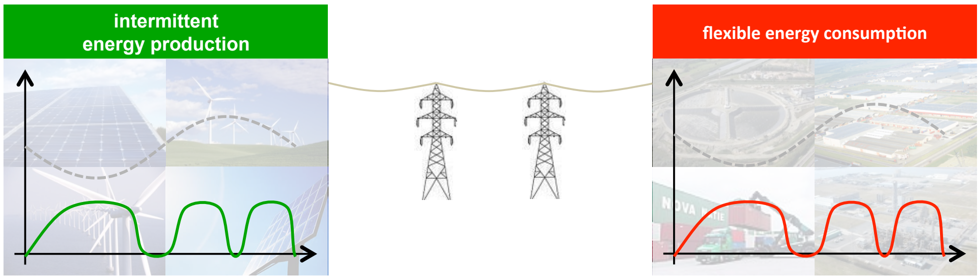



**Figure 2.2 Due to intermitting of energy from wind and solar, the production is out of balance from the consumption.**

To be able to integrate a larger share of renewable energy in the electricity system, a solution should be found in controlling the demand for energy; demand is flexible and can follow the supply of energy, as illustrated in figure 2.3. This is a radical different approach, and is the main objective of smart grids.




**2.3 Objective of the smart grid is to follow the supply of the intermitting energy production. To do so, the energy consumption should be flexible. Renewable energy can be integrated better and can form a larger share of the total system.**

Smart grids are essential for the large-scale implementation of renewable energy sources. Yet today, smart grids can already improve the efficiency of the electricity grid, and the requirement of such grids is pressing. Problems concerning a mismatch in supply and demand of electricity almost caused a power blackout in Belgium: During the Pentecost weekend in 2012, most factories where closed and people where enjoying the nice weather outdoors. The abundant sun and the strong breeze raised production of solar and wind power to a peak that exceeded the demand for energy. To avoid a blackout, Belgium had to 'sell' the excess power for minus € 18,- per MWh.

### 2.1. Smart grids in industrial areas

A vast share of literature on smart grids focuses on applications in households. The general idea is that appliances such as freezers, washing machines and air conditioners can be flexible in their use of energy. In other words, the time when they use the energy can be varied to some extend.
This research focuses on industrial users. This group has a very high demand of 41,4% electricity globally (IEA, 2006), yet the number of consumers is much smaller. Moreover, demand management and hourly varying energy prices is already seen in the sector, making the potential to operate in smart grids more viable. On the other hand, industrial processes are very different in nature, so no universal solution can be found.

The amount of energy that is being consumed in industrial areas is immense, and efficiency remains too low. The share of renewable sources is, although rising, still disappointing. Industrial areas face rising energy costs, which threatens their competitiveness in the global market. Yet, emissions of greenhouse gasses threaten the environment, which makes the call for improvement urgent.

### 2.2. What is a smart grid?

A smart grid enables to match the supply and demand of electricity in a system where renewable energy has a large share. To elaborate the functions and objectives of smart grids, the concept is explained in a brother sense.

Although the literature on smart grids is widespread, no uniform definition of a smart grid is made. Within the e-harbours project, a smart grid is defined as: "An electricity network that is adapted to the introduction of renewable energy sources." The European Technology Platform (smartgrids.eu, 2006) defines a smart grid as "An electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both, in order to efficiently deliver sustainable, economic and secure electricity supply."

***The concept of todays power grid:***
*Traditional power grids have a top-down structure, where few centralised power plants generate electricity. Power plants are controlled to follow the demand for energy. This demand is forecasted 24 hour prior to delivery. Once forecasts deviates from the actual consumption, unbalances in voltage and frequency can occur. This unbalance should be cancelled out immediately since it threatens a safe and secure delivery of energy. Therefore, reserve capacity is available to restore the balance.*

The smart grid is a modern electricity network that covers all parts from production, transmission and consumption, which is optimised by the use of information and communication technology. Decentralisation of energy production is a key aspect in smart grids. To maintain balance in the grid, advanced technology measures and coordinates both the production and consumption of energy. Advanced sensors and operating switches which are placed in a network, manage the system in a sophisticated way, so that the demand is in balance with the supply of energy. Storage of energy can be integrated in the smart energy network, to provide some buffering possibilities. In figure 2.4 the components of a smart grid are illustrated.

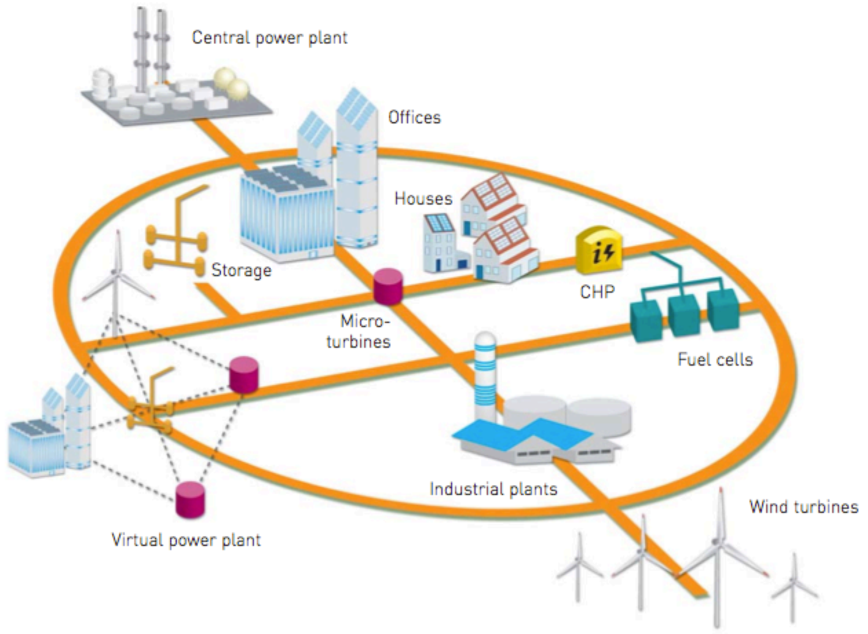



**Figure 2.4 Concept of a smart grid. Source: European Technology Platform: http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf**

Smart grids can make the electricity grid more efficient, and integrate renewable energy. But who has the benefits, and who has to invest? Answers to these questions aren't definitive, since the concept of a smart grid is still being developed. To give an illustration, an overview on different stakeholders in the energy system is given:

### 2.2.1. Energy production

Production of energy in a smart grid can come from many sources. Windmills, biomass plants and solar PV panels can generate renewable energy. Small combined heat power (CHP) plants generate energy locally and can manage production in an optimised and automated way, by interacting with the smart grid. Central power plants are connected to the smart grid as well. Energy production by intermitting renewable sources can be integrated better in the energy system. Investors in wind parks might have better revenues, since the unbalances in the power grid, which occur from the varying patterns of wind, can be managed better.

### 2.2.2. Energy suppliers

Companies that supply energy and trade it to customers will find new business models and additional services that they can sell. Their role can be very different in a smart grid, since production is decentralised and energy can be traded in local 'micro' grids.

### 2.2.3. Energy consumption

Energy consumers, like houses, offices and industry are enabled to automatically alter their demand for energy on the availability. In this way, the consumers can benefit while the availability is high, and can reduce their needs at times of the day that energy is scarce. This is done by a marked mechanism of varying prices of energy. The flexibility of energy usage is the backbone of the smart grid. Consumers who are able to shift energy demand will benefit from cheaper energy prices and consequently enable integration of renewable energy sources. To develop the smart grid, consumers play a crucial role. As the main goal of the smart grid is to adjust demand on the availability of energy, the biggest change in the system should be seen here. Consumers who can shift their energy needs can have interesting price benefits. To be able to do so, technical measures should assist consumers to use their energy flexible, without suffering loss in comfort or business conducted.

### 2.2.4. Grid operators

Transport of electricity today takes place on three different levels. On the highest level, transmission side operators (TSO) manage transport on high-voltage overhead cables from the centralised plants to the distribution grids. Distribution side operators (DSO), deal with electricity distribution on medium- and low-voltage levels. DSO's operate distribution grids in appointed regions and are responsible for an effective delivery of energy.
Smart grid technology is of great interest for distributers of energy. Once demand for energy can be managed, investments in upgrades on the capacity of cables and transformers might be postponed or deferred. Important is that the local grid is capable of energy flows in two directions. While the traditional network is designed for energy to flow in one direction, a smart grid can manage a reverse flow in direction if a local sub network generates more energy than it consumes. The distributer can arrange improving the grid assets with ICT means such as communication and measurement equipment to make the grid 'smart'. The main objective of the distributors is to have controllability on the energy flow in order to avoid overloading of the power grid.

#### 2.2.5. Energy storage
To store energy, large batteries or fuel cells can be used. Storing energy on a large scale is technically and economically challenging. Yet, storage capacity of electric cars can be a key element in a smart grid. The batteries of electric cars can be charged at the moment that there is sufficient energy. During a peak demand, the batteries of electric cars can be used as a buffer and deliver energy back to the grid. This concept is known as vehicle to grid (V2G).

### 2.3. The energy market
To better understand the problems related to the integration of renewable energy, and how the smart grid can play a role in that, an analysis is made on the energy system as it currently works.

#### 2.3.1. Energy producers
Traditionally, energy is generated in a centralised way by power plants. These plants can, to some extend, be controlled to supply energy according to the demand of all the customers. Plants powered on coal or nuclear fuels are limited in their controllability, shutting down or ramping op coal or nuclear plants takes a long time hence they are used to supply the base load for electricity (figure 2.5). Gas fired plants can be controlled well and supply electricity when demanded for. The gas plants produce the peak load of the energy demand; the part of energy demand that varies over the day on top of the base load. Production of energy is planned on the 'day ahead' according to the forecasts of energy suppliers. In the last decade, the electricity system has become much more complex. Rise of renewable sources of energy and a more distributed production network raise problems for the distribution companies. Maintaining balance in the network is vital, but growingly difficult to achieve.

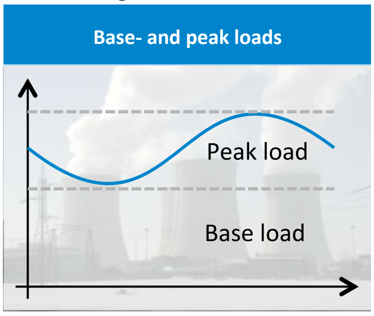


**Figure 2.5 base load and peak load of the energy production**

#### 2.3.2. Energy suppliers
Energy suppliers sell the energy from producers to the customers. An energy supplier does not necessary produce energy, but is a legal entity, which trades energy. In most cases this is done in bilateral contracts, also referred as 'over the counter'. Small end-users are often supplied on bilateral contracts with standardised terms and a fixed per unit price. Others may be linked to the market price, and face price differences over time.

#### 2.3.3. Market platforms
Many European countries have a so-called spot market for electricity. Buyers and sellers of electricity bid their offers 24 hours ahead of delivery. Prices are set on an hourly basis. After the spot market has closed, trade volumes for the following day are known. The suppliers at the spot market are not necessarily producers of electricity, since there is a lot of trade in electricity, which can be compared to the trade in the stock exchange market.

In the Netherlands, as well as for Belgium and France, spot market trade is facilitated by the Amsterdam Power Exchange (APX). Trades in the spot market represents a relatively small amount, according to Lijesen (2007), the spot marked trade is about 15% of the total electricity trade. Another marked for electricity is the Endex. This is the marked for futures; contracts involve a fixed term for a longer period.

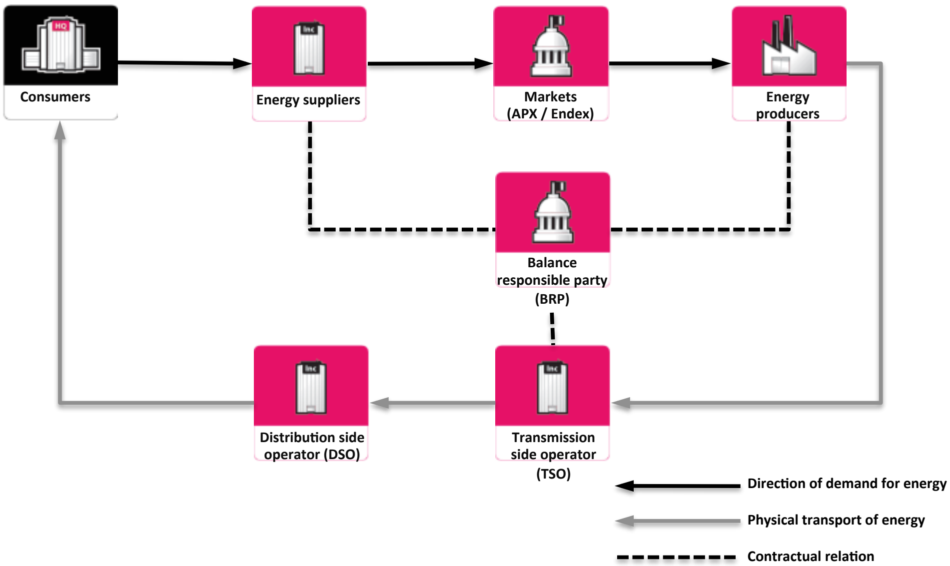
#### 2.3.4. Transport of energy

Two parties manage energy transport: The transmission side operator (TSO) takes care of transport and transmission on the high voltage overhead cables. Different distribution side operators (DSO's) deliver the electricity on the medium and low voltage network to end customers in appointed regions.

#### 2.3.5. Balancing systems

Maintaining an exact balance between supply and demand is of vital importance for the functioning of the power supply. To keep the network in balance, a number of measures are taken. First, energy suppliers make a forecast of the energy their consumers will use on the day ahead and a production schedule is made accordingly. All energy suppliers and producers have to report their forecasts to the balance responsible party (BRP), in which they have to rely. Any mismatch in the prediction will be penalized afterwards. Once a mismatch in prediction occurs, a system of reserve capacity is used to stabilise the network. This reserve capacity system consists of both generators and large consumers, which can take measures to restore the balance. If the demand for electricity is lower than predicted, large industrial plants can increase their consumption to restore the balance. If demand is higher, they can reduce their demand, or reserve generators will start up to supply additional power. The reserve capacity is arranged in a special market platform, which enables to use the most cost effective units to restore the balance. The transmission side operator (TSO), which is TenneT in the Netherlands, controls this market and oversees the different balance responsible parties.
Huge amounts of money are involved in the reserve capacity market. Some calculations show that over 10% of the total electricity costs paid by end users is due to imbalance costs (e-harbours, 2011). Large companies who have flexibility in their demand can offer this to balancing platforms and can get paid for this service.

Figure 2.6 gives a simplified illustration of the parties that act on the energy market. The consumers have a demand for energy, which they purchase from an energy supplier. These suppliers buy energy at market platforms or directly from producers. The electricity is transported from the producer via the transmission system of the TSO and distributed further by the DSO to the end user.
A balance responsible party (BRP) oversees the supply and demand forecasts of the energy suppliers and producers that participate in their portfolio. All the BRP's in the market have a mere contractual relationship whit the suppliers and producers. If actual unbalances occur in the system, the TSO arranges correction by altering the production (or consumption) of parties that operate on a special platform for unbalances (not displayed in figure 2.6). Penalties for unbalances are charged by the TSO to the accountable balance responsible party, which charge the responsible supplier accordingly.




**2.6 Overview of parties that act in the electricity market.**

## 2.4. Price composition of energy

Prices for energy vary widely, and depend on the amounts used and specific contractual arrangements. The costs for electricity is composed of thee elements; the commodity price of energy, taxes and transport costs. To have an idea of prices for electricity, figure 2.7 presents electricity prices charged to final industrial consumers. On top of the price of the electricity, energy taxes have to be paid as well.

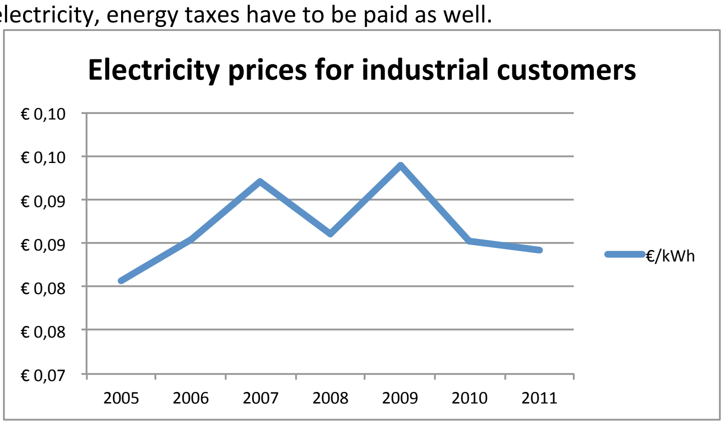



**Figure 2.7 Price development of electricity. Source: Eurostat**

Electricity prices for industrial consumers are defined as follows: Average national price in Euro per kWh without taxes applicable for the first semester of each year for medium size industrial consumers (consumption between 500 and 2000 MWh). During this period the average price was € 0,09 per kWh. Source: Eurostat

### *Taxes on electricity*

The amount of taxes that has to be paid on electricity decreases when the amounts increase. Table 2.1 gives the tax rate on energy in the Netherlands.

| Electricity per kWh | Taxes (excluding VAT) |
|---|---|
| 0 t/m 10.000 | € 0,1140 |
| 10.001 t/m 50.000 | € 0,0415 |
| 50.001 t/m 10 million | € 0,0111 |
| Above 10 million non-business | € 0,0010 |
| Above 10 million business | € 0,0005 |

**Table 2.1 Energy taxes in the Netherlands. Source: Rijksoverheid.**

If a consumer uses for instance 40.000 kWh, the highest rate has to be paid over the first 10.000 kWh, next the second highest rate have to be paid on the remaining 30.000 kWh, etc. On top of the energy taxes, also 21% value added taxes (VAT) have to be paid by end users.

***Transport costs***

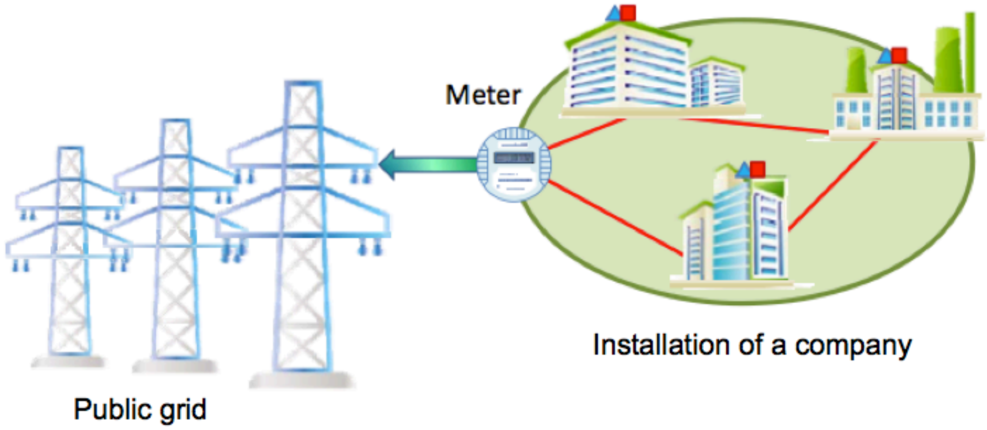
A significant share of energy cost is due to the transport over the power grid. Energy transport costs have a fixed part that is based on the capacity of the connection. For heavy users, a fee per unit of energy is charged as well. In some situations, an additional remuneration has to be paid on the maximum peak demand, which has occurred in a certain period. Industrial consumers often tend to limit their peak demand (peak shaving) in order to avoid a higher fee on transportation costs. The transport costs have to be paid to the local energy distributer (DSO).

## 2.5. Smart grids and regulations concerning energy transport

The transition towards renewable energy will have an important impact on the distribution of energy. Since a goal of smart grids is to facilitate the implementation of renewable and distributed energy sources in the power grid, regulations related to transport of energy have an important impact. Current regulations can form obstacles for smart grids. Although legal issues are not of main interest of this study, they cannot be omitted. Hence, an overview is given on most important subjects.

### 2.5.1. Role of the distributer

In the Netherlands, the energy market is liberated; in principle everybody is free to enter the marked to produce and trade energy. To ensure a safe and secure delivery of energy, the transport grids are managed by a distributer, who has the exclusive rights to do so. The distributer is responsible for the grid up to the connection (and meter) of the consumer. The consumer can install his devices on the electric *installation*, which is the part behind the meter as illustrated in figure 2.8.




**2.8 The distributer is responsible for the public grid, where the electricity connection and meter form the border. The installation is the domain of the company. If multiple companies own the buildings, this would be a private grid.**

All electricity transported over the grid is subject to energy taxes and transport fees, which are charged to the consumer. Electricity generated on the installation of the consumer, (behind the meter) for instance by solar panels on roofs is free for such charges.

### 2.5.2. Private grids

Some industrial sites can have an exception on the monopoly of distributers, and use a private grid. A private entity can develop the grid assets, and there is only one connection to the public grid for the whole site. The situation in figure 2.8 can be a private grid, if the buildings belong to different companies. If there is a lot of transport and energy trade between companies, a private grid can be beneficial, since grid usage costs can be reduced. Contrary to an installation, energy taxes have to be paid on energy consumed within the private grid. To develop private grids, exemptions have to be granted. However, draft legislation is being made, which further limits development of private grids.

### 2.5.3. Energy trade between local actors

The concept of smart grids is that electricity is generated in a distributed manner, and buildings generate energy by itself. If more energy is generated than is required at the moment, it can be sold to neighbouring consumers. Yet, if the energy is transported over the public grid, it is due to transport costs and taxes. These additional costs can be an obstacle, and deteriorate the business case for energy trade in a smart grid. For clarification, an example is given:

*A company installs solar panels on its site, but cannot use the generated power during the weekends. A neighbouring company will buy the electricity during the weekend, but if it is transported over the grid, the neighbour is charged with taxes and transport costs, which makes the energy more expensive than conventional 'grey' energy.*

Small users have a better position on this subject. Households and other small users can deliver up to 5000 kWh back to the grid and consume it some other time. The Dutch term for this is 'salderen'.

#### 2.5.4. Micro grids

Within this research, the term micro grid is used as well. A micro grid can be either a private grid or an installation, according to the definitions of the energy legislation. Micro grids can offer some more legal possibilities to trade and optimise energy usage between different local actors. Avoiding energy taxes or grid usage costs is not a main objective here, but can be necessary to find a business case for a smart grid application. The report Smart grid pilots (2011) further elaborate the legal barriers and possibilities concerning exchange of energy in smart grids.

### 2.6. Integrating renewables

Without the implementation of smart grid technologies, the amount of renewable energy sources that can become a part of the energy network is limited. Current balancing mechanisms face difficulty with the rise of renewable en distributed generated electricity and the efficiency of the grid is low. Flexibility of consumers is the enabler for large-scale implementation of renewable energy sources, and a key objective of the smart grid.

## 3. FLEXIBLE ENERGY CONSUMPTION IN THE INDUSTRIAL SECTOR

The industrial sector has a very high demand for energy, and consumption of electricity is enormous. Focussing on the industry to find flexibility seems obvious, however the development of smart grid technology is rarely seen among these heavy consumers. An explanation can be found in the fact that what is described as smart grid technology, has been seen in industry for decades. Controlling energy consumption to maintain balance in the electricity network is known in industry as demand side management, demand response or (industrial) load management. Benefits of demand management can be experienced over the entire chain of energy production, transmission and distribution. Cutting demand at critical times can avoid costly and polluting peaking capacity of the network. It can reduce costs of energy and make prices more stable over time. During critical demands peaks, the electricity price can grow exponentially. Although demand side management is a well-known phenomenon, the response from industry on energy prices is low. According to Lijesen (2007) the response on real-time prices is even lower.

With the rising production of intermitting renewable energy supply, the requirement for demand side management is growing. Technology for flexible consumption of energy is already available, however, the objective for demand management in industry was mostly to reduce peak loads. Demand management technology can be used to deal with the uncontrollable production of renewable energy as well; hence the potential to implement smart grids in industrial areas is great. To investigate flexible consumption of energy, the use of energy by industry is analysed, flexibility is defined and general concepts of flexible consumption are given. Also, a number of smart grid applications in industry are discussed.

### 3.1. Analysis of industrial energy use

The use of energy by the industry is the largest among all sectors in the Netherlands. The graph in figure 3.1 states the use of energy by different sectors. The industry (red) uses the most energy, and the demand for energy has been rising in the timeframe of the graph.

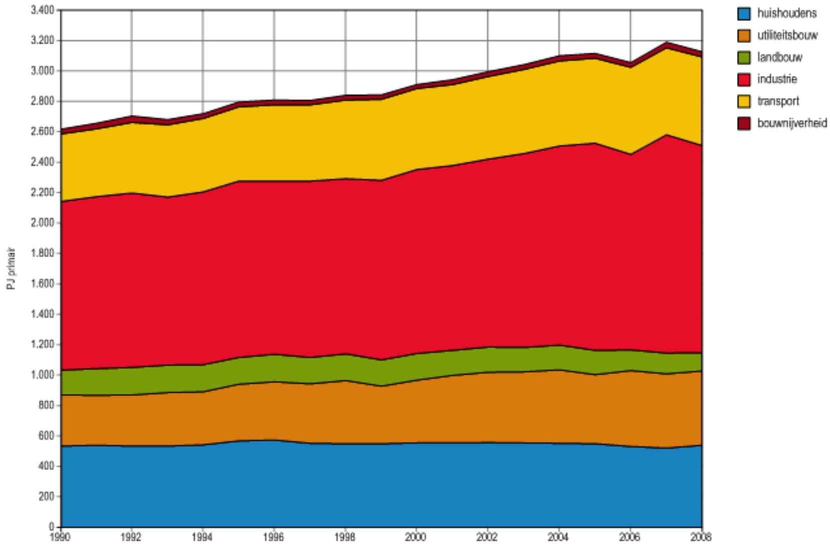



**Figure 3.1 Energy use per sector in the Netherlands. Source: senternovem.databank.nl**

Industrial consumers cover hundreds of different activities, which make it hard to investigate potentials for flexibility. Although the activities are very different in nature, their electricity use can be classified in 10 to 20 processes. Several studies have made such classifications, which makes it easier to compare processes that can be identified in industries. Meijer Energie & Milieumanagement (2008) and the study EU-Deep (2009) makes a classification, which is given in table 3.1.
Ashok and Banerjee, (2001) classify industrial loads into controllable loads that can be subjected to load management actions and fixed loads that cannot be controlled. Whether or not a load is controllable can depend per situation as well. Lightning is quite an obvious fixed load, yet lights in greenhouses could well be controlled without experiencing inconveniences. The identified loads are classified into fixed and controllable loads in table 3.1.

| EU-deep | Meijer | Load type |
|---|---|---|
| Lighting | Lighting indoors<br>Lighting outdoors<br>Lighting emergency | Fixed |
| Space heating | Space heating | Controllable |
| Water heating | Hot water preparation | Controllable |
| Process heating | Product preparation | Controllable |
| Space cooling | Cooling | Controllable |
| Process cooling | Product Cooling | Controllable |
| Cooking | Catering | |
| Computers and electronic devices | ICT centralized<br>ICT decentralized | Fixed |
| Use of motors | Pumps | Controllable |
| Electricity base processes | | Controllable |
| | Humidification | |
| | Transport | |
| | Ventilation | Controllable |
| | Other | |

**Table 3.1 Classification of electricity use and load type in industries.**

### 3.2. Classification of flexibility

Flexibility of energy use can be characterized by two basic determinants: the amount of flexible load and the flexibility over time (e-harbours, 2012). These determinants of flexibility can describe single devices or entire properties.

#### *Amount of flexible load*

The flexible load measures the total amount of electric power that can be shifted on or off at a given moment, compared to the baseline load. This usually varies over the course of the day or the week. Typical amounts in commercial and industrial properties that suit economic exploitation, reach from tens of kilowatts to tens of megawatts.

***Flexibility over time***

This indicates how long a certain amount of load can be switched without negatively affecting the process or application the device is used for. Typical time spans for flexible loads reach from several minutes to several hours, in some cases even weeks.

Janssen (2012) defines flexibility as: "Using the same amount of energy within a given period, but distributing the power usage during that period in a different way."
Now an understanding is made on what flexibility is an investigation can be made where this flexibility can be found.

## 3.3. Controllable, flexible loads

Flexible electric loads that can be subjected to load management can be divided further into independent loads, process interlocked loads and storage space constrained loads. Independent loads can be subjected to load management by taking into account constrains that are related to them, such as the time span that the loads can be switched on or off. Process interlocked loads form a part of a production process where the different loads have interdependencies. A storage space constrained load can have dependencies in a production line, but can be controlled individually.  Although all processes can be very different, an optimisation can be made based on a similar concept.

### 3.3.1. Independent loads

Five of the classified processes in table 3.1 include thermal applications, which can be seen as independent loads. These processes all have a general principle, which is similar. Products or spaces have some sort of window in which the temperature should remain. If the temperature exceeds certain thresholds, heating or cooling applications are activated to restore temperature to the desired level. These processes have potential flexibility: Without exceeding the temperature thresholds, the energy use can be optimised to the availability of energy. Stretching the limits of temperature a little can increase the available flexibility. This is often possible without disturbing the process. Moreover, heat (and cold) can be stored quite easily in storage tanks (figure 3.2), which makes it possible to shift loads for even longer periods.

**Figure 3.2 Heat storage tanks in can be used to increase the flexibility in a demand management application related to thermal applications**

### 3.3.2. Process-interlocked loads

Electrical motors are seen in many industrial applications, for instance in pumps, conveyor belts, mills, cranes, etc. Often, the motors form part of a chain of applications in a production line and the loads are process-interlocked. Interlocked processes are a number of machines that operate dependent from each other. For instance, a conveyor belt feeding material in a processing machine. These processes are linked and can only be controlled together. In figure 3.3 process 1A and 1B are interlocked.

### 3.3.3. Storage space constrained loads

Processes that have a storage space constrain are different processes, which can be operated individually but are linked to a shared storage space for material. In figure 3.3 process 1 and 2 have a storage space constrain: The handled material from process 1 is placed in the storage, afterwards it will be an input for process 2. The two processes can be controlled individual and, as long as the upper and lower level for the storage space is respected. These processes can potentially be controlled in a flexible way. The load of process 1 can be intermitted as long as it does not disturb process 2. If the amount of load and the flexibility over time are significant, the process has economic flexibility, which can be used in a smart grid.

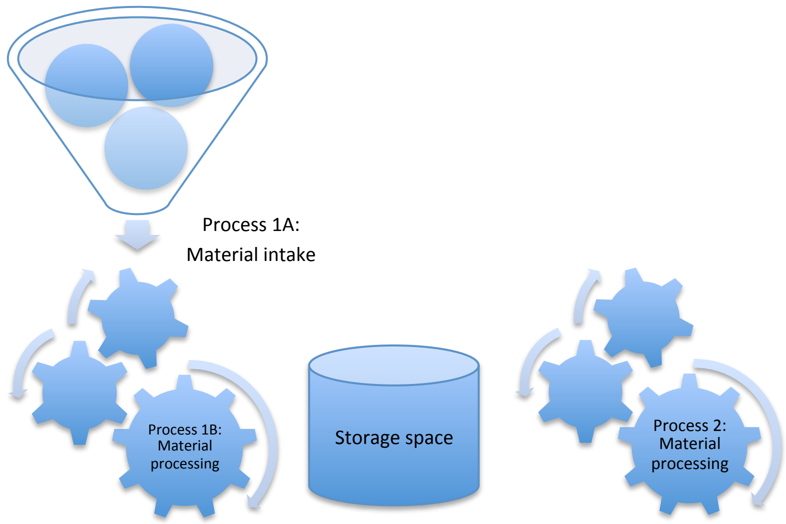



**Figure 3.3 Process 1A and 1B are interlocked, and can only be controlled together. Process 1 and 2 can be controlled individual, but are related by a storage space constraint.**

An example of a process with a storage space constraint is a water treatment tank in figure 3.4. A pump takes in raw water and pumps out the processed water. The two pumps can be controlled separately, but are constraint by the storage capacity of the tank.

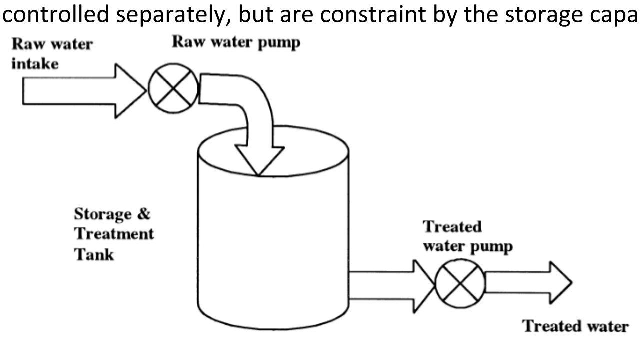



**Figure 3.4 A process with a storage space constraint. Source: Ashok, 2000.**

When additional storage space is made available, the flexibility of the constrained processes is enlarged, since the flexibility over time increases. Adding storage space can enable to split interlocked processes. This is an important measure to increase the flexibility of parts of a production process. When interlocked processes are split by a storage space, as in figure 3.3, it is important that process 1 has some overcapacity: It should be able to catch up the production after it has been stopped for a while and the material storage is at its lower limit. In this way, an optimization can be made between the desired flexibility and available space. "Controlling power consumption requires deep domain knowledge about processes" according to Samad et al (2012). To operate processes in production lines flexible, all interdependencies as well as their roles in the overall production should be understood. Optimising the power usage should hence not lead to a decrease in plant performance or safety.

### 3.4. Load shifting & load shedding

Production processes often are produced in batches. For instance, a production plant can make a few products at production lines that can be operated sequential or simultaneous. If the processes are energy intensive, plant operators can decide to schedule the processes to times when energy is cheap: They shift loads to reduce energy costs. When energy prices are at peak levels, it can be worth to shut down the production for some time. Even if it results in wasted labour costs, it can be beneficial in some cases. In literature, this is known as load shedding. Load shifting and shedding involves the whole production process and has a direct influence on the operations of the plants. Yet, some of these processes can be automated as well. Since load shedding can result in lost labour or resources, it is more suitable to prevent critical network imbalances, rather than compensating for daily peaks in demand. Load shifting can be beneficial to reduce energy costs and can have a significant effect on the balance of the power grid. Yet, this type of flexibility involves the primary process of the company and is therefore of limited use in smart grid applications, unless in can be done in a way that it does not interfere with the operations of the company.
Companies with an installed capacity exceeding 60 megawatt are obliged by the grid operator to offer possibilities for load shedding. The plant in figure 3.5 is equipped with an automated load shedding system to avoid power outages if problems in occur in the electricity supply.

**Figure 3.5 Industrial plant with automatic load shedding systems to maintain network stability. Source: Siemens**

### 3.5. Examples of flexible energy consumption in the industry

Exploiting the flexibility that companies have can result in significant savings in energy costs, while it enables the integration of renewable energy. To investigate how this can be achieved, some examples are given that are found in the e-harbours project and in literature.

***Cold storage facility: Nova Natie***

Warehouses for storage of refrigerated goods (figure 3.6) consume vast amounts of energy, and have quite some flexibility. Frozen goods are kept at a temperature around minus 20°C. At times when energy is abundant, these goods can be cooled down to -25°C to absorb the surplus of energy. When energy is scarce, the freezers can be turned of fore some time, while temperature rises gradually to the maximum level. In this way, the cold store facility can optimise energy use and help to maintain balance in the grid.


**Figure 3.6 The assessed cold storage facility Nova Natie.**

Close to the cold store, a windmill is projected. The developer of the windmill offered to sell the energy direct to the company, which can make the business case even more interesting. To investigate the business case of the cold storage, an analysis is made. In the analysis, several scenarios are calculated, considering the standard contract, buying the wind energy, buying of spot market prices and the allowed temperature variations.
The analysis made clear that even using the standard contract with day- and night-tariffs can contributes to cost savings up to 9%. The most savings could be achieved when the company purchased energy from the wind turbine. In table 3.2 cost savings in the different scenarios are elaborated.

| Scenario | Temperature variations<br>-20°C ~ -22°C | <br>-20°C ~ -25°C | <br>-20°C ~ -∞ |
|---|---|---|---|
| Standard contract without wind energy | -5,3% | -8,5% | -9% |
| Standard contract with wind energy | -12,4% | -15,4% | -16,6% |
| Spot market prices without wind energy | -7,3% | -10,7% | -11,2% |
| Spot market prices with wind energy | -7,3% | -10,3% | -10,8% |

**Table 3.2 Cost savings in percentage for the investigated cold store. Source: Vito, Jef Verbeeck**

The flexibility that is applied in this case can be categorised as an independent load. Such an application can be fully automated by smart grid technology.

***Sludge processing: Amoras***

The harbour of Antwerp has berths for large vessels that come from all over the world. To keep the waterways accessible for these vessels, they have to be dredged frequently.

Amoras takes care of the dredged sludge, by dewatering and recycling the sludge (figure 3.7).

**Figure 3.7 The Amoras sludge processing site.**

The sludge processing plant has a number of basins and a network of pipes and pumps. These pumps have an enormous consumption of energy, and can be shifted in time for many hours or even days. Moreover, the site can also be connected to a wind turbine, which is being developed.
In this situation, the site has three energy tariffs:

- Energy from the wind turbine
- Energy in day tariff
- Energy in night tariff

Without an optimisation, the site is supplied for 50% by wind energy. In an optimised situation, illustrated by the graphs in figure 3.8, the energy purchased in day-tariff is minimised and wind energy use is maximised, resulting in a cost reduction of 41%.

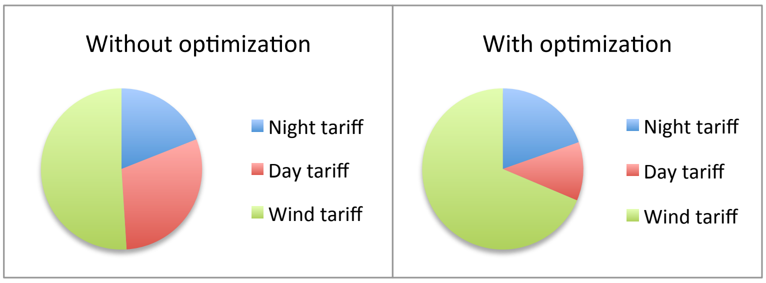



**Figure 3.8 Comparison of energy usage before and after optimisation.**

In this case, it is very beneficial to optimise the energy use, since this site has abundant flexibility. The pumps on this site have a very high capacity and the flexibility over time reaches up to a few days. The process has storage space constrains and parts that are interlocked, but it also involves load shifting operations. This load shifting has direct influence on the core business of the company, which have to reschedule their workforces. In this case this forms a barrier: To fully optimise the plant on the supply of wind energy, night shifts have to be scheduled, which results in additional labour costs. Yet the cost savings are so significant, this could be reasonable to do.

***Pumping stations***

The Netherlands is unique in its water households. Dozens of pumping stations keep water heights at desired levels, enabling us to live on lands below sea level. A float switch that activates the pumps if a certain threshold is exceeded operates these pumping stations (figure 3.9). Generally, pumping stations have a very high capacity, because they are designed to keep polders dry in a worse case scenario. Energy consumption is also significant, as can be seen in table 3.3.

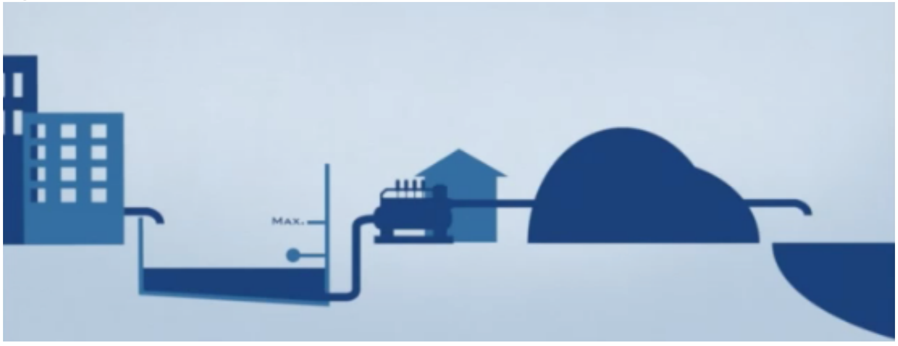



**Figure 3.9 Principle of a pumping station. The float switch activates the pumps and drains water out of the area.**

| Type | Capacity [$M^3$/minute] | Energy use [kWh/year] |
|---|---|---|
| Surface pumping stations | 1 - 10 | 100 - 20.000 |
| Small pumping stations | 10 - 50 | 10.000 - 100.000 |
| Medium pumping stations | 50- 500 | 50.000 - 1.000.000 |
| Large pumping stations | 500-3500 | 500.000 - 5.000.000 |

**Table 3.3 Characteristics of pumping stations. Source: Senternovum cijfers en tabellen 2007.**

Depending on the rainfall and characteristics of the pumping stations, they are activated a few times per day, as shown in figure 3.10. The capacity of the pumps is significant, as well as the yearly consumption. Since water boards are responsible for a number of pumping stations, the potential for a smart grid application is even better. Pumping stations can be seen as independent loads, which are influenced by weather conditions. Optimising energy use can be fully automated in a smart grid.

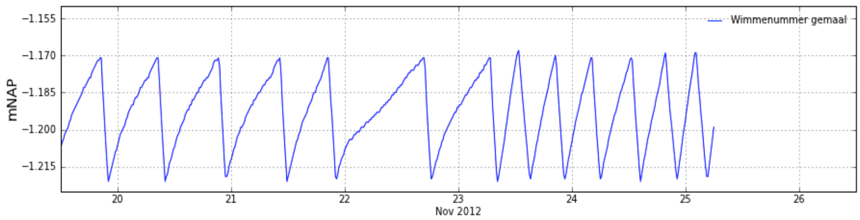



**Figure 3.10 water level controlled by a pumping station. Source: http://hhnk.lizard.net/map/workspace/peilstanden/**

### *Thermal applications*

Cooling capacity (figure 3.11) is a good example of flexible energy demand applications. Load management of refrigeration systems is investigated by Grein and Pehnt (2011). They found achievable potential of 2,8 GW in Germany. Yet, they also identified barriers, such as informational barriers, strict compliance with legal cooling requirements, liability issues, lack of technical experience, and inadequate rate of return and organizational barriers. Applications that produce heat or cold from electricity can be subjected to smart grid applications.

**Figure 3.11 Industrial cooling applications**

### *Cement mills*

Production facilities for cement (figure 3.12) consume considerable amounts of energy for crushing of clinker and mixing of ingredients. According to Paulus and Borggrefe (2011) cement mills can be regulated in a flexible way and can be shut down and ramped up again within minutes. The amount of flexible loads is high, yet the shift time is often limited. The production line of cement mills can be seen as a storage space constrained process.
Several applications of demand side management are reported in literature, yet they note the high utilisation levels and limited storage space as barriers.

**Figure 3.12 Cement production facilities**

### *Paper industry*

The paper industry produces paper and cardboard from old paper and pulp from wood (figure 3.13). Paulus and Borggrefe (2011) identified significant potentials for demand management, due possibilities to store the produced pulp. The current pulp storage volume at most paper mills is large enough to accommodate 1.5 hour at maximum capacity. This process can be classified as storage constrained. Increasing the storage space will enable longer shift times and thus more options to benefit from demand management.

Figure 3.13 Paper mills have possibilities to operate the plant flexible.

### *Chemical plants*

The chemical industry is characterized as very energy intensive, and production often takes place around the clock (figure 3.14). Although chemical plants are often operated on a very continues base, load management is frequently applied in this industry. Ashok and Banerjee, (2000) describe applications of load management of a fertilizer plant. Chemical plants often have numerous process interlocked and storage space constraint processes. Applications of demand management are common, yet the aim is often to have a very constant consumption of energy, rather than to react on spot market prices.

Figure 3.14 A chemical production plant

### 3.5.1. Conclusion on flexible production processes

Applying demand management in industries has a lot of potential to deal with the variability of renewable generated energy. Although industrial activities vary widely, classifications in processes can be made, which makes it possible to use a more generalized approach. Some examples are given for illustration, yet flexibility can be found in many industrial processes. Production can be made flexible if the process has overcapacity; to compensate for the time the production was halted or to increase production for later use. Besides capacity, the time a process can be shifted is an important constrain. To increase the shift time, adding storage space can be an option. To apply industrial load management, an optimisation should be made, which takes in account constrains of the process. Determining the financial benefits of flexible energy consumption can be hard to estimate: A simulation study can give a good understanding of the savings and can determine the most beneficial business model.
The potential of load management in industry is large, yet application is still low. Barriers as lack of knowledge, limited incentives or organisational barriers are often mentioned.

## 4. BUSINESS MODELS FOR SMART GRIDS

Consumers, who have identified a source of flexibility in their power consumption, can exploit this in various ways. A number of business models for exploitation of flexibility are proposed. These models are mainly based on the findings of the e-harbours report “Strategies and Business Cases for Smart Energy Networks” (2012). The optimal business model is depending on the characteristics of the flexibility and the preconditions of the client. The general idea of all models is that supply and demand of energy can be matched by a market mechanism; if the supply of energy is low, prices increase which will limit the demand. Vice versa, a lower price can increase the consumption. In this way, supply and demand can be kept in balance, as illustrated in figure 4.1.

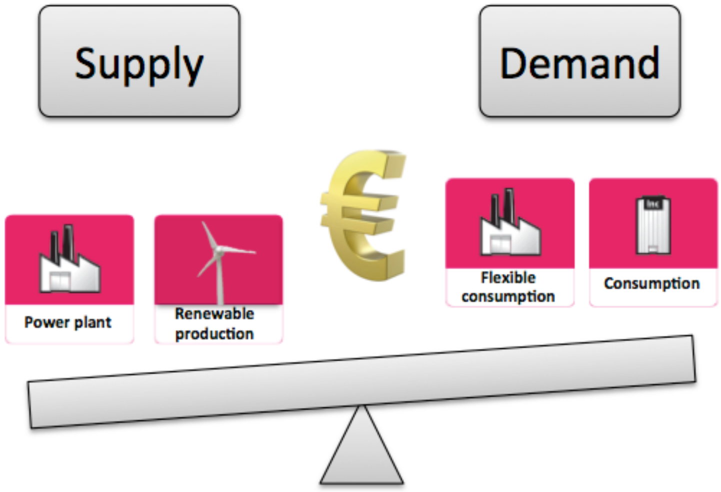



**Figure 4.1 Supply and demand of energy can be regulated by market mechanisms.**

Four models are proposed to for exploitation of flexibility: Contract optimisation can be an easy way to save money, for instance by using an off-peak energy price. Customers, who have flexibility available for very short timeframes might offer this to special balancing platforms. Micro grids can be beneficial for consumers who have energy producers in their proximity, for instance by an on-site windmill. The most advanced Virtual Power Plant model optimises energy flows between multiple sites and can trade on multiple market platforms, in order to maximise the financial benefits.
The business models for contract optimisation and trading on balancing markets are quite traditional; such tariff structures are present in the industry for years. It can be assumed that with the development of smart grids new models and markets for energy trade can be developed. The models for smart micro grids and virtual power plants are a possibility to make use of flexibility in a smart grid.

### 4.1. Contract optimisation

The simplest and most universal business case to make use of flexibility is to apply ‘time of use’ rates, such as day/night tariffs for energy. Making use of an energy contract that offers flexible rates, or real time pricing of energy are well known in demand management programs for industries and are described by Albadi (2008). A large share of energy contracts today is based on a flat tariff or day/night tariffs. Contracts with different time of use rates are still limited available. About 15 % of energy trade is done via spot markets, which offer variable prices (Lijesen, 2007).

### 4.1.1. Time of use rates


**Figure 4.2 Optimisation involves the consumer and the energy supplier.**

Optimisation based on time of use rates involves the energy supplier and the consumer (figure 4.2), who is offered an energy contract that has a peak and an off-peak price for energy. Off peak hours generally apply during nighttime, for instance between 22:00 and 07:00. Shifting loads to these off-peak hours can significantly reduce the energy costs. In some cases, four our more different prices apply per day (figure 4.3). This type of optimisation can be applied to a great number of customers. Since peak hours are predefined, planning can be done well in advance. Simple timers can enable load management to be automated.

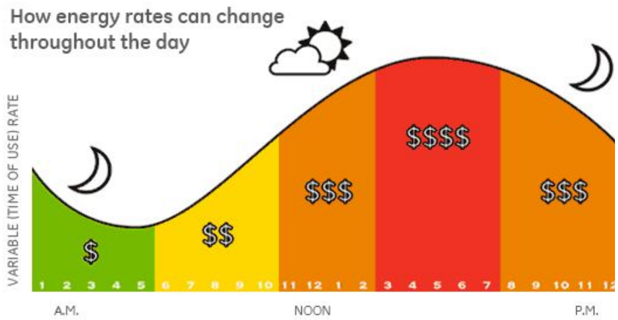



**Figure 4.3 Variable rates for energy over the day.**

### 4.1.2. Spot- and wholesale markets

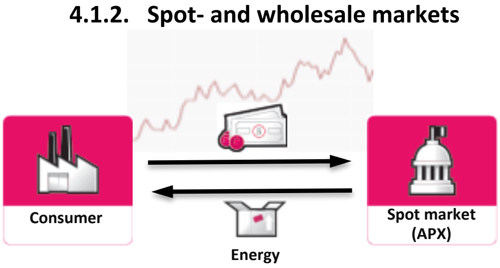



**Figure 4.4 Consumers with high demands can buy energy directly at energy markets and can make use of the variability of prices.**

In some situations customers can have energy tariffs that are linked to the spot market prices. Within the spot market, the energy price varies over hours of the day, and is announced on a day-ahead basis. Energy market platforms offer both short and long term trade in energy. Large consumers, or collectives of companies, can trade directly on these markets (figure 4.4). Although entrance and trading fees apply, it can be beneficial to operate on this market. Flexibility of the consumer in its energy demand can increase the savings, since more use can be made of the off-peak prices. At the same time, the consumer responds to the intermitting energy supply of renewables, which enhances the integration of clean energy.

#### 4.1.3. Reduce grid utilization costs

A part of the energy costs are due to utilisation of the power grid. To reduce costs for grid usage, peak shaving (figure 4.5) is a well-known phenomenon in the industry, since a share of costs for transport is based on the peak demand of the consumer. Reducing the peak load can be an objective for demand management, however this objective can be conflicting when companies want to make use of varying energy prices: If the energy price is low, consumption can be increased, which results in a larger peak demand.

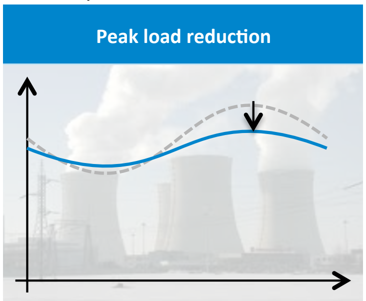



**Figure 4.5 Peak shaving can be used to reduce the cost for grid usage.**

Smart grid technology can be used for local grid management as well. The grid operator (DSO) has special interest to use flexibility of companies to reduce congestion on the local network (figure 4.6). Congestion can cause damage to the infrastructure, such as the transformers. If load management can be used to avoid congestion, the DSO can defer investments in upgrading the power grid. However, a flexible tariff structure is not present yet. It can be expected that DSO's will develop an incentive structure to use smart grid technology to avoid grid congestion.


**Figure 4.6 Optimisation is related to the energy distributor, who can offer incentives when congestion is avoided.**

### 4.2. Trade on balancing markets

In order to keep the electricity grid in balance, special parties arrange balancing services. This balancing market is of great importance for an electricity system whit a high penetration of renewable energy. In a national grid, there are several balance responsible parties (BRP's). Their role is to maintain balance of all the consumption and production of the connected users. The transmission side operator (TSO, which is TenneT in the Netherlands) is maintaining balance over the national grid. If an energy supplier in a BRP is causing unbalances, they are penalized by the TSO. The TSO deals with unbalance at a special unbalance market platform. The market for unbalance works on a very short timeframe. Corrections are made by calling in reserve capacity within seconds to 15 minutes.

Positive reserve capacity provides extra power to the grid in the form of additional generation or reduced consumption. Negative reserve capacity, in the form of reduced generation or additional consumption, is dispatched if power supply is too high (e-harbours, 2012). This reserve capacity is generally required for a quarter of an hour. Prices of energy traded on the balance market are very variable and can be negative; if unbalances occur, the price can be tenfold of the normal prices.

Consumers, who satisfy the requirements to act on the balancing market platforms, can earn money by offering their flexibility as balancing services, as illustrated in figure 4.7. Yet, the balancing market platform, which is regulated by the TSO, is only accessible for consumers with a sufficiently large consumption or production. To operate on the balancing market, bids have to be at least 5 MW and these bids have to be placed 24 hours ahead.

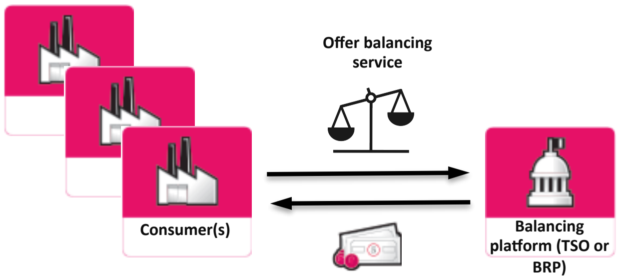



**Figure 4.7 Consumers, or a few of them in a pool, can offer reserve capacity to the balancing platform, by switchin loads on and off on demand of the TSO.**

Consumers, which do not satisfy the criteria to enter the balance market as operated by the TSO, have two alternatives: They pool together with other consumers or they can offer their flexibility to a balance responsible party.
In the first option, a number of consumers that have similar processes form a pool in order to meet the criteria of TenneT. For clarification, an example is given based on the study of Hovgaard et al (2012):

*A supermarket chain has a few hundred branches, and their power consumption is dominated by cooling needs of their refrigerators. These refrigerators have the flexibility to be turned off for about half an hour. Yet the installed cooling capacity is by average 100kW per branch, which is too little to operate on the balancing market. If all refrigerators of the supermarkets can be controlled together, they are able to enter the balancing market. Hovgaard research made clear that by entering the balance market, a cost reduction of 70% could be achieved!*

Another option for consumers, which do not meet balance market criteria's of TenneT, is to offer their flexibility to the balance responsible party. The BRP operates on a smaller scale, and can make use of the flexibility to correct his portfolio on unbalances. If the BRP is capable to manage the balance, fines for unbalance by the TSO, can be avoided.

### 4.3. Smart micro grids

A micro grid is in this research defined as an electricity network where energy is being produced and consumed without being transported over the public grid. Micro grids can be an interesting ground for developments of smart grids.
Within a micro grid, the connected users are free to make arrangements on energy prices, and more important, no taxes and transport costs have to be paid on the mutually traded energy. The micro grid, as illustrated in figure 4.8, can be beneficial for both the energy producer and the consumer; a price gap is present between energy that is sold by the windmill compared to energy bought from the grid. The owner of the windmill can sell energy for a better price to a consumer in a micro grid, compared to the revenues that can be gained if it is sold to energy suppliers. The consumer can buy energy for a lower price, since no taxes and grid utilisation costs have to be paid. In this way, a price incentive occurs to use the on-site generated renewable energy, rather than the energy from the grid.

Local generated energy from solar panels, windmills or CHP plants can be sold to the grid if it is in excess of the demand. A company, which generates on-site energy, can use its flexibility to meet the supply of the local produced energy. If the connected users in the micro grid can consume energy in a flexible way, by means of demand management, the grid becomes 'smart'.

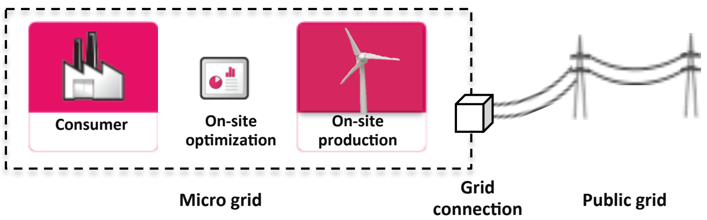



**Figure 4.8 Consumers and producers can form a micro grid, by sharing the same grid connection.**

Development of a micro grid can have legal constrains. The NMa, which regulates energy matters in the Netherlands, have to grand exemptions for development of a private grid. An alternative is to use the term *installation*. To do so, the producer and consumer should be in the same company. This construction can work if a company develops on-site generation capacity. For a group of companies on an industrial area this is not an option, they can only develop a private grid. Unfortunately, development of private grids is subject of draft legislation, which further limits these possibilities. Chapter 2.5 elaborates on the possibilities and constraints of energy transport over the grid.

### 4.4. Virtual Power Plant

The basic idea of a Virtual Power Plant is that a number of small-scale producers (and consumers) can be operated as if they where a single power plant. Individual units in the Virtual Power Plant (VPP), such as windmills and small biomass plants, can be distributed over a large area, but act as a single entity towards the power system and the market. By making use of intelligent systems and communication, the power production is optimised.
The following definition is provided by the European project FENIX (2006): "A Virtual Power Plant (VPP) is a flexible representation of a portfolio of distributed energy recourses that can be used to make contracts in the wholesale market and to offer services to the system operator".

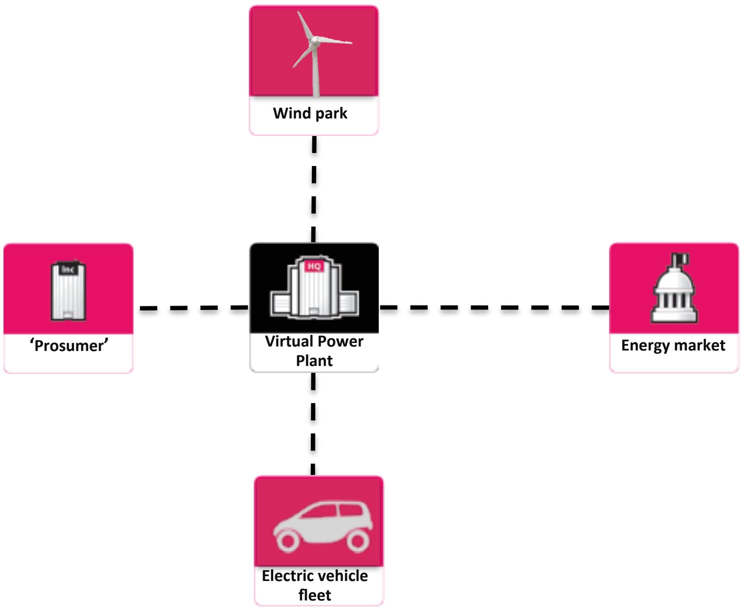



**Figure 4.9 The concept of a virtual power plant.**

A VPP, as illustrated in the example of figure 4.9, forms a collection of a wind turbine park, a building equipped with solar panels (the prosumer) and a fleet of electric vehicles. The connected units can be distributed across an area, but their power needs are centrally managed by the VPP. If the market price for energy is high, the VPP will reduce it's own consumption and sell energy that is produced. Once the market price is low, energy will be consumed, for instance to charge the electric cars that are connected. In the concept of the VPP, the energy management is not only optimised to use the produced energy in a smart way, it also interact with energy markets. The various distributed generators offer their production in a controlled portfolio to the energy market. The benefit of the flexibility that is present in the system is optimised in a broader way, since the VPP can trade on the spot market or the balancing market, besides that it can use its own renewable energy.
A VPP is strongly related to a smart grid, but differs in a way that the connected entities do not need to have a geographic proximity. A company, which has branches over the country can optimise energy usage in a VPP, and thus reduce its energy costs.

### 4.5. Comparison of the business models

The proposed business models to make use of the flexibility that is present in the processes of businesses are compared and summarised in table 4.1. Which business model will work the best depends on project characteristics, but also on developments on the area of smart grids. Contract optimisation can be seen as the easiest applicable model. The VPP model is the most advanced, but also the most complex model, since it involves multiple connected users and can make use of more (or new internally formed) market mechanisms.

| | Contract optimization | Trade on balancing market | Smart micro grids | Virtual Power Plant |
|---|---|---|---|---|
| **Principle** | -Make use of variable energy prices<br>-Universally applicable | -A consumer or producer (or a pool of them) operate on the balancing market | -Make use of local generated energy (e.g.: a wind turbine) | -Production and consumption of multiple units is optimised to form a controlled portfolio |
| **Requirements for participation** | -Energy contract with peak/off peak prices or variable (APX) prices | -Requirements on minimum capacity<br>-React on short notice for limited time (about 15 minutes) | -Geographical proximity of energy supplier (on site or via private grid) | -Advanced energy management system |
| **Related energy market platform** | -Energy contract with off-peak differentiation<br>-APX prices | -Balancing market | -Trade with local (on-site) energy supplier | -APX<br>-Balance market<br>-Energy supplier<br>-Internal energy market |
| **Barriers** | -Limited contracts with variable prices are present | -Organisational barriers | -Legal limitations to develop private grids | - Organisational barriers<br>-Technical barriers |
| **Future developments** | -Variability in prices are expected to rise when renewable energy production grows | -More balancing requirement when renewable energy production grows | -Possibility that regulations related to private grids will be limited further. | -The VPP concept will develop from theoretical / pilot phase to a practical application. |

**Table 4.1 Comparison of the proposed business models**

# PART 2: CASE STUDY SMART GRID HOOGTIJ

## 5. A SMART GRID FOR HOOGTIJ

The region of the Zaan is the oldest industrial site of Europe. During the 17th century, the area had over 900 mills and was an important player in the ship building industry. Later, food industry came up and a number of multinational companies where founded here. Since Zaanstad has a strategic location, close to Amsterdam, Schiphol and next to the Nord Sea canal, it is still an important region for industry. To enable companies to grow and to settle here, the development of a new industrial area 'HoogTij' was initiated in 2003 and forms a part of the harbour area of Amsterdam. As a quay is projected along the Nord Sea Canal (figure 5.1), it aims for cargo handling and logistics as well as food and metal industry.


**Figure 5.1 Left: A map of the region and right an aerial photograph of HoogTij.**

Today, just a small part of the 130 ha site has been issued. In order to attract companies, Zaanstad sees opportunities develop in a sustainable way and to deploy renewable energy as an establishment condition. Consequently, Zaanstad can fulfil its ambition to become energy neutral by 2020.

To facilitate this, the zoning plan offers space to develop wind turbines and there is the possibility to develop a (biomass) power plant. Buildings can connect to a collective heat & cold network, which provides their needs in an efficient way. A study on this heat/cold network (New-Energy-Works, 2011), investigated two alternatives: a biomass plant and a 'Nord Sea Canal' plant, which is a collective heat pump that subtracts heat and cold from the canal to supply it to the buildings.

To give an impression of the estimated energy consumption of the area, some figures are given in table 5.1. The area consists of two phases and a port area, phase 2 is not included since its development is takes place on the long term.

| Energy demand | Phase 1 [TJ/a] | Port area [TJ/a] | Households equivalents |
|---|---|---|---|
| **Heat >120 °C** | 49 | 2 | 340 |
| **Heat 70-120 °C** | 65 | 2 | 450 |
| **Heat < 70 °C** | 70 | 10 | 530 |
| **Cold < 10 °C** | 2 | - | - |
| **Cold >10 °C** | 3 | - | - |
| **Electricity** | 60 | 8 | 5450 |

**Table 5.1 Estimated energy demand for the first phase and the port area of HoogTij. For understanding, the energy demand is compared to household equivalents. Source: New-Energy-Works (2011).**

Unfortunately, HoogTij has known some problems as well. Land issuing has a slow pace, and the company that operated the heat grid gave its concession right back and left the project. Zaanstad hopes, that a smart grid can contribute to achieve their goals, and stimulate renewable energy development. With this in mind, the development of the industrial area HoogTij offers an interesting starting point to find a business case for a smart grid.

### 5.1. Proposed smart grid

The possible development of the 'Nord Sea Canal' plant appeared to have potential to become a smart grid application and looked like a proper case to analyse further. This heat pump looks as a more feasible alternative compared to the biomass plant, since it can be developed in phases, as more companies settle at HoogTij. Moreover, thermal appliances such as heat pumps can become 'smart' as described in chapter 3.
Currently, the Rijksgebouwendienst (RGD) has issued a tender for the construction of a new detention centre at HoogTij. In a study on the Nord Sea Canal heat pump (New-Energy-Works, 2011), the detention centre is observed as the client with the highest demand for heat. Since it is also an actual development at the moment, the detention centre can become a 'launching customer' to develop the heat grid.

#### 5.1.1. Business as usual scenario

To investigate benefits of a smart grid, a business as usual (BAU) scenario is formulated and can be used to compare the results of the study. Figure 5.2 illustrates the BAU scenario: An electric heat pump produces heat, by extracting this from the nearby Nord Sea Canal. This heat will be transported over the heat grid to the connected buildings. Consequently, a development for wind turbines is taking place, but this has currently no relation to the heating system. Zaanstad develops one of these windmills and will sell the electricity to the grid. This scenario is very realistic and forms the 'business as usual' scenario for the smart grid.

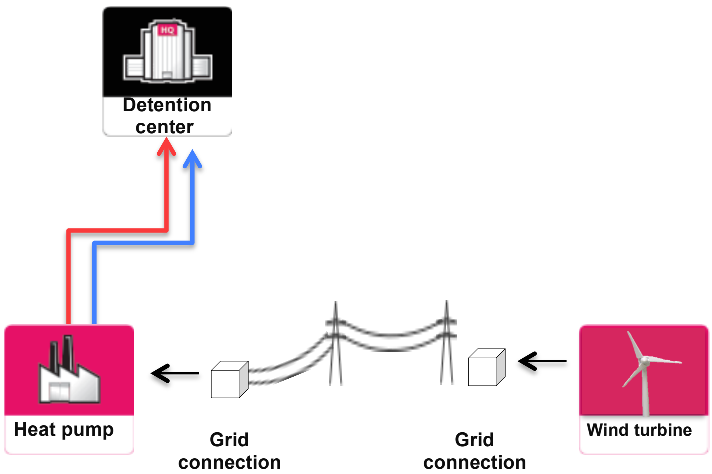



**Figure 5.2 The Business as Usual scenario.**

#### 5.1.2. Business model selection

To make use of flexibility, four business models are proposed in chapter 4. To find the most suitable business model to make use of the flexibility of the heat pump, an analysis is made in table 5.2.

| | Contract optimisation | Balance market | Smart micro grid | Virtual power plant |
|---|---|---|---|---|
| **Suitability of the business model for the proposed case** | Contract optimisation can be used. Benefit can be expected when flexible tariffs are used. | Not applicable since consumption is too low to enter the balance market | A windmill will be developed nearby. Using the wind power in a micro grid can be very beneficial | Theoretically possible, but limited revenues are expected with only two actors |
| **Scenarios to test** | -Day/night tariff<br>-Day/night tariff with demand management + heat storage | -None | -Private grid<br>-Smart grid (demand management + heat storage) | -None |

**Table 5.2 Comparing business models for the proposed smart grid.**

Creating a smart micro grid with a wind turbine and the heat pump seems as a promising scenario, with a high potential. Hence, the smart grid scenario is proposed.

#### 5.1.3. Smart micro grid scenario

The proposed smart grid is a situation where a wind turbine and a heat pump share the same grid connection (according to the definitions of the NMa, the wind turbine and heat pump are installed in the same installation). In this way, the heat pump can directly uses the energy that is generated by the windmill. The heat pump exploits its flexibility to optimise the share of wind energy: the production of heat is matched to the availability of wind energy. To do so, heat storage should be available to buffer the heat temporarily. A heat buffer tank or the mass of the building can be used to store the heat.

Besides the benefits of the better integration of wind energy in the electricity grid, there is a financial benefit. The rate for power supplied by the windmill is lower than the rates that are offered by energy suppliers. Since no taxes and transport costs apply on the energy that is supplied by the windmill, an interesting price difference applies. As seen in figure 2.7, the average price for a kWh electricity is € 0,09. When taxes are added a price of €0,10 per kWh is realistic. Developers of windmills generally gain € 0,065 (Bosch & van Rijn, 2010) to € 0,07 (Windenergie, 2012) per kWh. Supplying directly to a nearby consumer, without using the public electricity grid can result in an interesting price benefit. To do so, arrangements have to be made so that the wind turbine and the consumer share the same grid connection, as illustrated in figure 5.3. To realise this, the exploiting company of the heat grid and the windmill should cooperate in a legal entity, for instance as a local energy service company (ESCO).

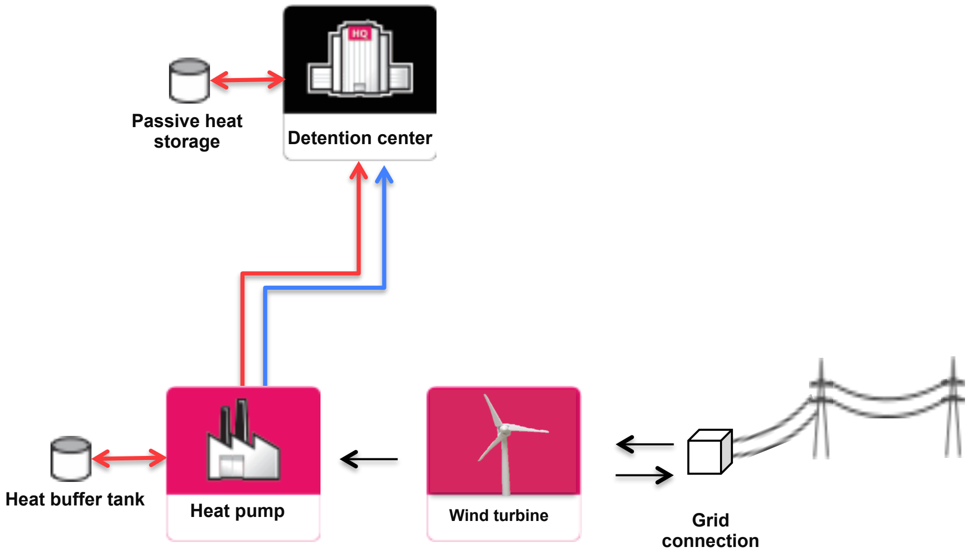



**Figure 5.3 The smart grid scenario: The heat pump and wind turbine use the same grid connection. To be able to operate flexible, the heat pump can store energy in either a heat buffer tank or by using passive heat storage in the building.**

The concept of heat pumps in smart grid applications is already present in literature. Hedegaard et al (2012) analyses the possibilities for individual heat pumps to enable integration of wind power. To operate heat pumps flexible, it should have the possibility to store heat; especially passive heat storage (using building mass) found to be a cost-effective way to enable flexible operation of the heat pumps.

In this study, particular interest is in the business case of the smart grid appliance. Can the proposed smart grid have a positive business case, and how does the heat storage capacity influence the financial benefits? Another interesting question is how much the use of wind power can be increased by the flexible operation of the heating system. To find answers on these questions, a simulation model is developed for this collective system.

### 5.2. Scenarios for simulation analysis

Analysing how well this smart grid application can function requires a simulation study. In a simulation model, the production of heat can be optimised according to available wind energy and the demand for heat over time. This can be valuable to see the economic benefits and the ability to use energy in a smart and flexible way. Figure 5.4 gives the different scenario's that have to be tested in the simulation model.

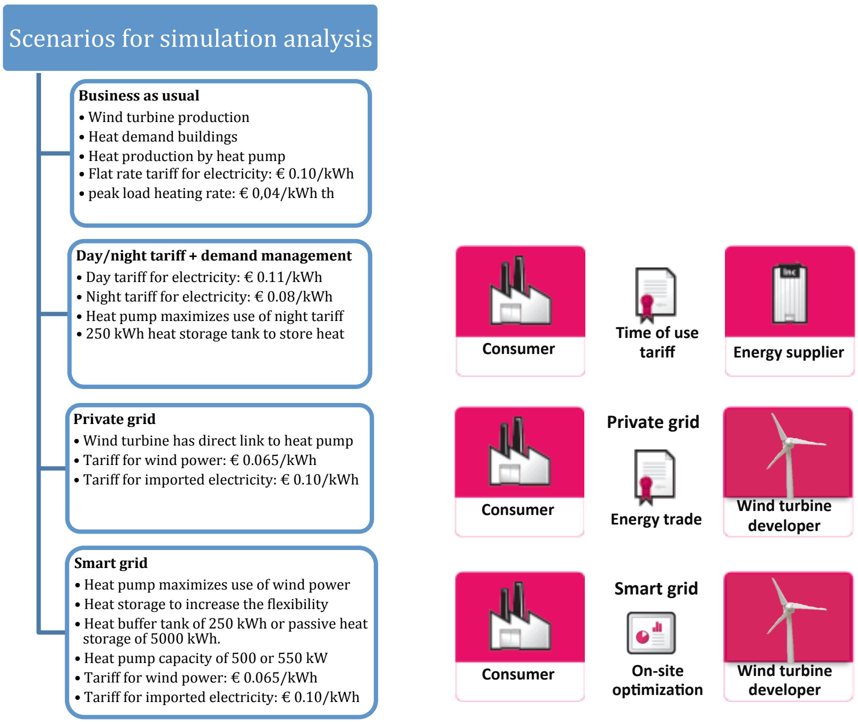



**Figure 5.4 Scenario's for the simulation model. For clarification, the actors that have a role in the business model are displayed graphical.**

The 'business as usual' (BAU) scenario calculates the consumption and costs for energy of the heating system. Electricity costs are calculated based on a fixed tariff per kWh. Production of power by the wind turbine is simulated, but has no relation yet to the heat pump. In the 'BAU + demand management' the business as usual scenario is extended with a heat buffer and a day/night tariff for use of energy. In the 'Private grid' scenario, the wind turbine is connected to the heat pump and can supply wind energy at a lower tariff. The heat pump operates in the same way as in the BAU scenario. By using the heat buffer in the 'Smart grid' scenario, the use of wind power is maximised. Constraints for the flexibility of the system are the capacity of the heat buffer and the heat pump. These can be altered to investigate the influence and to find an optimum. A number of simulations are performed to compare the influence of a larger capacity heat pump and buffer. In all the scenarios the use of gas-fired peak load heaters, which are generally added to a heat pump system is simulated as well. To be able to make a good comparison between the different scenarios, a rate for peak load heaters is set, which is based on the tariff of conventional gas fired heating.

## 6. DEVELOPMENT OF THE SIMULATION MODEL

To investigate the ability and the benefits of the proposed smart grid, a simulation model is developed. This model simulates the production of the wind turbine, the heat demand of the buildings and the heat production by the heat pump. In this analysis, the heat demand is demarcated for the buildings of the detention centre. The behaviour of these components is modelled and simulates the business as usual scenario. To assess the impact of smart grid technology, an optimisation is made, which models the behaviour for smart grid operations and maximises the use of wind energy.

The model works in 15 minutes time steps, and calculate values over an entire year. A dataset is used with hourly climate measurements of the KNMI for the nearest measuring post: Station 240 at Schiphol.

### 6.1. Research method: Agent based simulation model

In this case study, an agent based simulation model is developed to optimise the components in the smart grid. Agent based simulation (ABS) models is quite a new technique in research modelling developments. Agent based models are suitable to model complex relations in all kinds of abstraction levels. Applications range from modelling agent behaviour in the stock market and supply chains, to predicting the spread of epidemics and the threat of bio-warfare, from modelling consumer behaviour to understanding the fall of ancient civilizations (Macal, 2005). ABS models are very powerful to model phenomena in scientific research, businesses and for decision-making purposes.

Agent based systems are comprised of autonomous agents, that interact with each other and the environment. An agent can represent an independent component, such as individuals (figure 6.1), with behaviour that ranges from primitive reactive decisions to complex adaptive intelligence. The agents in simulation models can, besides following their behavioural rules and attributes, learn over time and can have 'rules to change the rules' (Macal, 2005). Modelling human social behaviour and decision-making is hence a possibility of the ABS models.

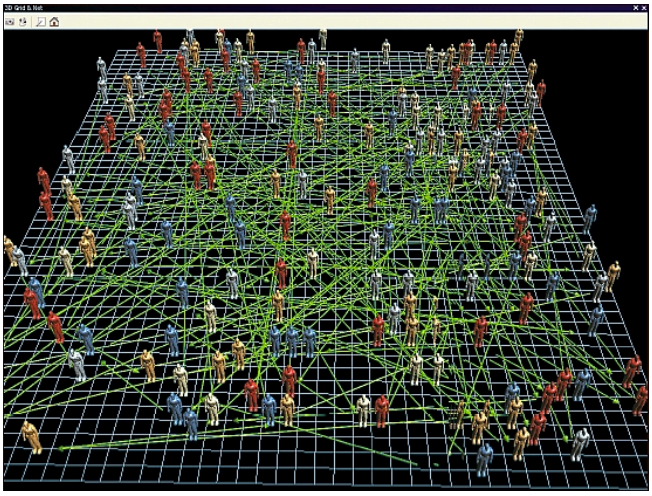


**Figure 6.1 screenshot of an agent based model. Source: www.scidacreview.org**

ABS models are very suitable in research related to smart grids. Components of the smart grid, such as generators, consumers, batteries and grid constrains can be modelled as agents and interact with each other. Moreover, the actual smart grid is likely to function based on agents that interact with the power grid and make decisions to buy or sell energy, rather than a top-down system that dispatches energy use. Jun (2011) and Dave (2011) describes agent based systems for energy management.
For this analysis, the Netlogo modelling software is used to develop the model. Netlogo is a multi-agent programming language and modelling environment for simulating natural and social phenomena. It is particularly well suited for modelling complex systems evolving over time. Modellers can give instructions to hundreds or thousands of independent agents all operating concurrently. This makes it possible to explore connections between micro-level behaviours of individuals and macro-level patterns that emerge from their interactions. Netlogo enables users to open simulations and "play" with them, exploring their behaviour under various conditions. Netlogo is also an authoring environment that is simple enough to enable students and researchers to create their own models, even if they are not professional programmers. (Tisue and Wilensky, 2004).
To learn the programming language, tutorials and demonstration models are widely available. In Netlogo, agents are called turtles and move over an environment of patches, which can also be programmed. The developed model uses formulas and descriptions in program language to simulate the system of the smart grid case of HoogTij. Also, datasets are used as an input for the simulation model. All coding of the Netlogo model is stated in appendix I, yet the general working of the model is explained in this chapter.

### 6.2. Wind turbine production

Production of energy by the windmill is variable over time, depending on the wind speed. Since data sets of turbine power output could not be obtained, (this data is treated confidential, and contacted companies would not supply these data) the data is simulated, using wind measurements of KNMI and characteristic power curves of a wind turbine.

For wind speed measurements, a dataset of 2006 is used, since this year was 'average' according to the Windex (CBS, 2011), which expresses the amount of wind per year. To convert the hourly measurements to quarter-hour values, the measurements are randomised with the hourly mean and standard deviation.
Since measurements are made 10 meters from the ground, they should be corrected to the hub height of the turbine (90 meter). The following logarithmic expression is used to do so:

$$V(x) = V(r) \cdot \left( \frac{\ln\left(\frac{x}{Z_x}\right)}{\ln\left(\frac{r}{Z_r}\right)} \right)$$

In which:

| | |
|---|---|
| $V_{(x)}$ = Wind speed at height x | = 90m |
| $V_{(r)}$ = Wind speed at reverence height | = 10m |
| $Z_x$ = Roughness length at location x | = 0,03m |
| $Z_r$ = Roughness length at reference location | = 0,03m |

The power generated by the turbine can be calculated using a power curve (figure 6.2).

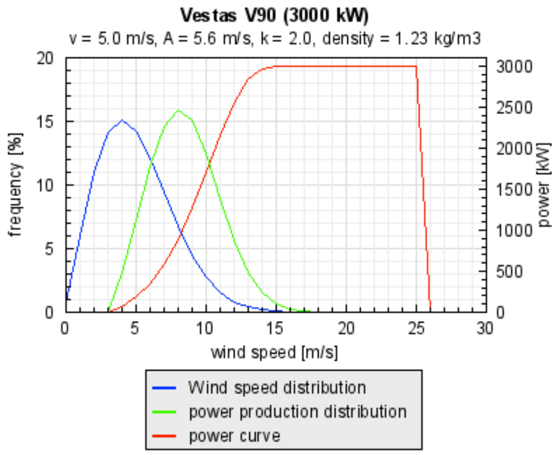



**Figure 6.2 Power curve for the projected wind turbine at HoogTij: A 3MW Vestas V90 turbine. Source: http://www.wind-data.ch/tools/powercalc.php**

An Excel spreadsheet is used to calculate the wind turbine output power. This simulated dataset gives the production of the wind turbine per 15 minutes in kWh, for one year, and is used as input for the Netlogo simulation (see figure 6.3). The simulated yearly power generated by this wind turbine accounts for 2380 maximal capacity equivalent hours, which is representative for this location.

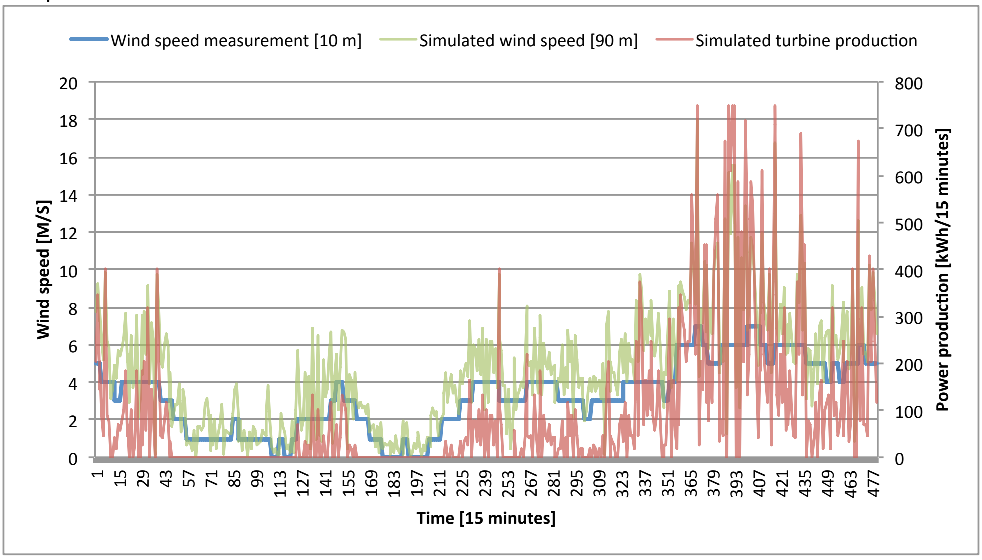



**Figure 6.3 Simulated wind speed and turbine production vs. KNMI wind speed measurements. The graph shows five days of the simulation.**

The graph in figure 6.3 shows clearly the intermitting character of the production of wind turbines. The steep power curve (figure 6.2) results in a very fluctuating output power.

### 6.3. Heat demand model

To be able to make an investigation on the flexibility of the heating system, the demand for heat should be known. Since the complex of the detention centre is in tender phase, and no information on the design was available a number of assumptions had to be made. From a simplified design of a building, the energy use can be calculated over time. To model the demand for heat several methods are available in literature: Statistical models, computer systems and simulation methods. The simulation method is the most appropriate in this situation, since it can simulate the heat demand in time steps, based on climate data. This method requires detailed information of the building, such as heat transmission coefficients, orientation to sun and ventilation losses. Assumptions on performance of building materials had to me made to calculate the heat demand.

### 6.3.1. Heat losses by transmission and ventilation

Heller (2002) estimates the significance of different parameters and reports that ambient temperature and solar radiation accounts for 83% and 7,7% of heat demand respectively.
Lü (2002) describes a method for heat and moisture transfer in buildings and compare simulated results to measurements of a test building. The used model calculates heat demand based on the ambient temperature, ventilation, building surfaces and transmission coefficients. The heat loss in a steady state condition is represented by the following algebraic equation:

$$Q_{Heat\ loss}(t) = [\eta V C_{air} \rho_{air} (T_{indoor} - T_{outdoor}) + \sum AU(T_{indoor} - T_{outdoor})]$$

In which:

| | | |
|---|---|---|
| $Q_{Heat\ loss}$ | Heat losses | [W] |
| t | Time | [s] |
| η | Ventilation rate | [h-1] |
| V | Volume | [m3] |
| $C_{air}$ | Specific heat of air | [kJ/kg/K] |
| $\rho_{air}$ | Density | [kg/m3] |
| T | Temperature | [K] |
| A | Area | [m2] |
| U | Heat transfer coefficient | [W/m2K] |

### 6.3.2. Heat gain by sunshine and occupants

In the thesis of Pennavaire (2010) heat and electricity demand is modelled for an entire district. Pennavaire also corrects heat demand by internal heat gain from sun, appliances and occupants. To improve the accuracy of the simulation, his method for internal heat gain is used. For the calculation of heat gain through sunshine, solar intensity measurements of KNMI are used in the expression:

$$Q_{Sun}(t) = O_w \cdot A_w \cdot ZTA \cdot E_{sun} \cdot I_{sun}$$

In which:

| | | |
|---|---|---|
| $Q_{sun}$ | Heat gain through sunshine | [J] |
| t | Time | [s] |
| $O_w$ | Orientation of window | [-] |
| $A_w$ | Area of window | [$m^2$] |
| ZTA | Sun accession factor of window | [-] |
| $E_{sun}$ | Accumulated solar intensity | [$J/m^2$] |
| $I_{sun}$ | Solar intensity | [$J/m^2/h$] |

The orientation of windows influences the heat gain from the sun. These factors are between 1,00 for a South facing facade and 0,33 for a North facing façade. In the simulation model, an average factor is used of 0,6125. The accumulated solar intensity is a correction factor for the amount of sun that actually accesses the building. It accounts for the solar intensity on a vertical plane, which is corrected from the KNMI measurements on a horizontal plane, the framework of the window and a reduction factor for dirt on the windows. These three aspects account for a total factor of 0,885. A more detailed explanation of the used values can be found in Pennavaires thesis (2010).

Occupants who are present in the building, accounts for a significant heating source for themselves. An average person emits about 105 Watt. Especially in a detention centre, occupants are present all the time. Assumed is that a constant amount of 1000 prisoners and 200 staff is present in the buildings.

The energy use of heating for buildings is calculated if two conditions are met: the outdoor temperature is lower than the indoor temperature and the heat gain is less than the heat loss. Once these conditions are met, the energy use for heating is:

$$Q_{Heating}(t) = [Q_{Heat\ loss} - Q_{heat\ gain}]$$

Which is:

$$Q_{Heating}(t) = \left[\eta V C_{air}\rho_{air}(T_{indoor} - T_{outdoor}) + \sum AU(T_{indoor} - T_{outdoor})\right] - \left[(O_w \cdot A_w \cdot ZTA \cdot E_{sun} \cdot I_{sun}) + (n_{occupants} \cdot Q_{heat\ from\ occupant})\right]$$

The energy use for heating is calculated for every 15-minute time step and is expressed in kWh.

#### 6.3.3. Building characteristic assumptions

To model the demand for heating of the detention centre, an assumption had to be made on the design and performance of the building. Assumed is that the complex will host four square buildings, where two buildings have three storeys and two are four storeys high. All storeys are 4 meters high, of which 1 meter is reserved for construction and building services. In total, a gross floor area of 70.000m$^2$ is assumed. Performances of building materials are assumed in table 6.1, which are representative values for new buildings.

| Building element | Value |
|---|---|
| U-floor [W/m$^2$K] | 0.35 |
| U-wall [W/m$^2$K] | 0.32 |
| U-roof [W/m$^2$K] | 0.27 |
| U-glass [W/m$^2$K] | 1.7 |
| ZTA glass | 0.6 |

**Table 6.1 Used values for building elements**

Assumed is that the building will be equipped with a heat recovery system for ventilation. These systems can reduce the heat losses by ventilation up to 95%. The ventilation rate is set in building codes, yet these depend on the function of the room. An average value for the ventilation rate is assumed to be 5, which means air is refreshed five times per hour. The surface of windows in the façade is calculated as a fraction of the façade.

Since all assumed factors have a great impact on the performance of the building, a sensitivity analysis is performed. Table 6.2 states the assumed factors for a low, normal and highly efficient building. The total energy use for space heating is stated, which is an outcome of the Netlogo model.

| Building efficiency -> | Low | Normal | High |
|---|---|---|---|
| Temperature [C°] | 20 | 19.5 | 19 |
| Ventilation rate | 8 | 5 | 3 |
| Heat recovery efficiency | 80% | 90% | 95% |
| Fraction windows | 0.4 | 0.3 | 0.2 |
| Energy use [MWh th] | 8294 | 2851 | 1197 |

**Table 6.2 Values for sensitivity analysis on the heat demand of the detention centre.**

The sensitivity analysis shows clearly that the model is sensitive for these variations. Especially ventilation seems to have a great impact on the energy performance. If we compare the values with the assumptions made in the study on the collective heat network for HoogTij, the energy use is very low. In that report (New-Energy-Works, 2011), assumed is a heat demand of 720 MJ/m$^2$/year, which is representative for hospitals and care facilities. This would account for a total heat demand of 14000 MWh. The low values of the simulation can be declared by the fact that performance of the building is calculated on today's efficiency and insulation levels. The 'normal' values are used in further calculations.

### 6.4. Heat pump production

Heat pumps are efficient systems to produce heat (and cold) to control indoor climate in buildings. Reductions in $CO_2$ emissions reach to 70% compared to gas fired heating (Salvalai, 2012). Heat pumps transfer heat from a low temperature source to a higher temperature, which is suitable to heat buildings. The heat source is often ground water or surface water; these sources have a quite stable temperature over the year and can be used to extract heat. The amount of energy that is required is much lower than the useful energy that is supplied to the building. Figure 6.4 illustrates the principle of a heat pump.

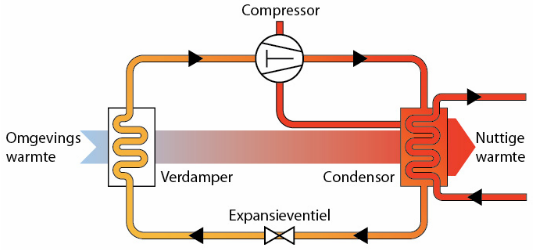



**Figure 6.4 Schematic diagram of a heat pump.**

A fluid is used in the internal system of the heat pump, which evaporates at the source, and absorbs heat from the surrounding (ground) water. Next, the vapour is compressed and condensates at the condenser, where it releases the heat. A heat exchanger at the condenser transports the heat to a heat grid or a building heating system.

The most important parameter of the heat pump is the coefficient of performance (COP), which gives the relation of required electrical energy to the produced heat. The formula for COP is given below:

$$COP = \frac{Q_{heating}}{P_{electric}}$$

The value for the COP is depending on the technical characteristics of the heat pump, the entering source temperature and the output (sink) temperature. To model the performance of the heat pump in the simulation, values given by Salvalai (2012) are used. Assumed is that the sink temperature (water temperature which goes in to the building) is 55 ° C, since this is the operational temperature of the excising heat network at HoogTij. From the graphs in figure 6.5, given by Salvalai (2012), the following formula for COP is derived:

$$COP = 0{,}05 \cdot t_{source} + 3$$

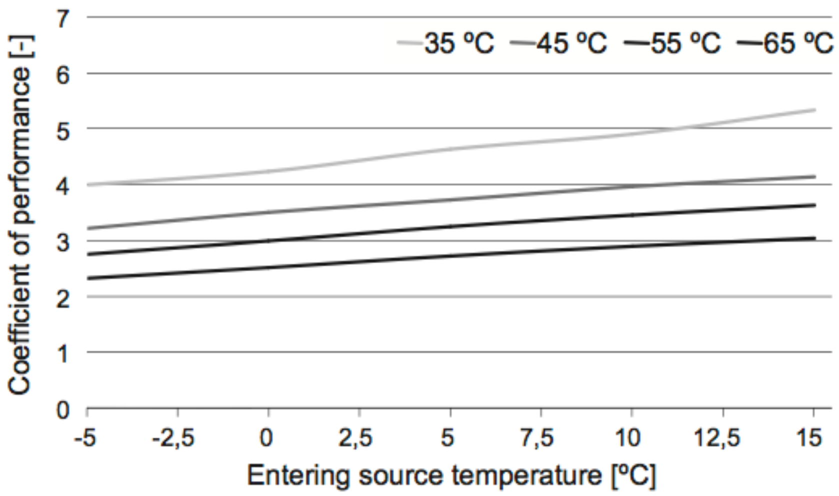



**Figure 6.5 COP values depending on source temperature. Source: Salvalai 2012.**

The heat pump itself might have a higher COP, since it can be more efficient than smaller systems described by Salvalai. On the other hand, it will also have some more losses on transferring the heat thought the network. Taking this into account, the COP value for the entire system seems reasonable.

In a study on a collective heat pump system for HoogTij, the choice is made to use the water of the North Sea canal as a source. Measurements by Rijkswaterstaat at Westzaan give the temperatures for the water near the bottom. These measurements are used as a source temperature.

Now that the COP is known, the electric consumption of the heat pump can be calculated by dividing the actual heat demand by the COP. The heat pump shall have a maximum capacity, which is determined by the electric power.

### 6.4.1. Peak load capacity

Larger heating systems with heat pumps generally have a lower capacity than the peak demand of the connected buildings. Since investment costs in the system would rise overly if the system were dimensioned to the peak load, it is often dimensioned to supply 80% of the annual demand. Figure 6.6 is an annual duration curve for a district heating system; the red line illustrates the capacity of the heat pump. Peak load heating is offered by conventional boilers, which run on gas or (bio) oil. In the Netlogo model, the demand for peak load heating is modelled as well. To be able to compare different scenarios, a tariff for peak load heating is used based on central heating boilers.

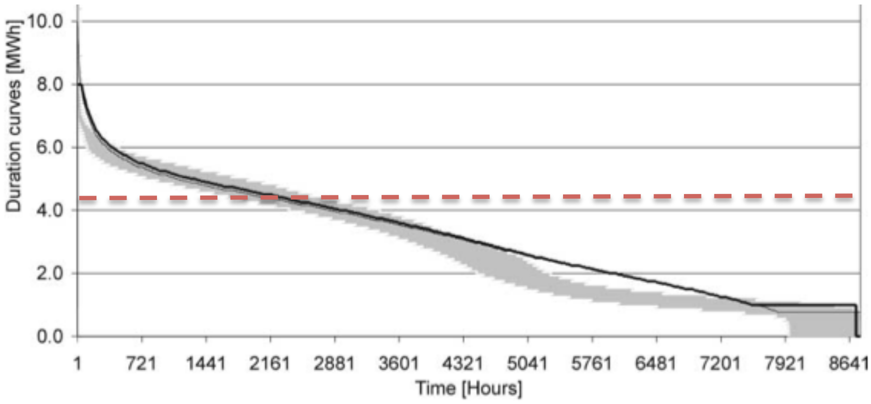



**Figure 6.6 Annual duration curve of a district heating system. The red line illustrates the capacity of the heat pump. Additional heating capacity comes from peak load boilers. Source: Heller, 2002.**

## 6.5. Heat storage

Crucial in a smart grid are energy consumers that have flexibility in to shift demand in time. Thermal applications, such as heat pumps, can operate quite flexible, since the system have some potential to buffer the heat. When heat can be stored, the flexibility op the heat pump increases. Hedegaard et al (2012) identifies two methods for heat storage: by using the thermal mass of the building and by storing heat in accumulation tanks.

In the Netlogo model a heat buffer is implemented, so that the heat pump is flexible in its energy use. The capacity of the buffer can be chosen, so that effects can be assessed. The model is programmed in a way that heat is stored when energy prices are low (when wind power is sufficient or during night-tariff) and is used again when electricity price is high (wind power is not sufficient to supply the heat pump, so energy have to be imported from the grid at a higher rate).

The strategy of the model is to use the heat buffer to maximise the share of wind power. Alternatively, a strategy could be to reduce the peak load capacity of the heating system. Although the heat buffer slightly reduces the demand on peak load heating system, this is not its the main goal, but a positive side effect. To illustrate how the heat can be stored in practise, two alternatives are described:

### 6.5.1. Heat storage in building mass

Exploiting the mass of buildings is a simple and cost effective way to store heat, which is also known as passive heat storage. The idea is that the construction itself contains heat, and will keep the spaces warm for some time, even is the heating system is switched off. The ability of storing heat is depending on the type of construction. Lightweight structures, such as sheds and warehouses have limited capacity for heat storage. Yet, concrete structures (figure 6.7) offer great possibilities for passive heat storage. Especially if the building is equipped with 'concrete core activation', the possibilities for heat storage are abundant. A small change in temperature of the building can absorb a significant amount of energy. If a temperature variation of one or two degrees can be used to store heat, the flexibility of the heating system increases significant.

Exploiting the natural heat buffer is technically and economically very attractive, but in this case it can make the situation a bit more complex. Since the heating system is part of an external heat network, an external party would control the temperature of the building. In this case, the building would form an integral part of the heat grid, and operators of the building will have to agree on this.

**Figure 6.7 Building mass of a concrete structure can be used as a heat buffer.**

The ability to buffer heat in the buildings of the detention centre is abundant. To give an impression: a floor slab of 300mm accounts for about 21000 $m^3$ of concrete for the whole building. If a variation in temperature of half a degree is allowed, over 6000 kWh of heat can be stored.

#### 6.5.2. Heat accumulation tanks

The concept of thermal storage in a demand management program is widely accepted in literature. Arteconi et al (2012) made an extensive investigation in thermal energy storage applications. A thermal energy storage system is a device that can store thermal energy by cooling, heating, melting, solidifying or vaporizing a material. Sensible heat storage occurs when a material changes in temperature, for instance by heating water, rocks or soil. Latent heat storage is used when a phase change occurs. This can be applied to paraffins, salt hydrates, ice, etc. A further category is represented by thermochemical heat storage, when the process is based on a reversible chemical reaction, which is energy demanding in one direction and energy yielding in the reverse direction. The authors state that heat storage in water tanks is the most mature technology and has a high efficiency. The disadvantage of this technique is that it requires a significantly large tank, which occupies quite some space.

A heat buffer tank of 10~20 $m^3$ seems reasonable for the proposed heating system. If the system can operate with a temperature difference of 15° (difference in supply and return temperature of the water) the capacity of the buffer is in a range of 175 to 350 kWh.

The Netlogo model simulates an 'ideal' buffer that does not have any additional losses from heat storage. If building mass is used as a buffer these losses shall be minimal, yet a heat storage tank shall has some constrains, which are not calculated in the model. The operation of the heat buffer is different in the tested scenarios. Appendix I describes this in the produce-heat procedure of the Netlogo model.

## 6.6. Netlogo simulation model

All the datasets, equations and behaviour of the proposed smart grid configuration are programmed in a Netlogo simulation model. This model will be used to test a number of scenarios, and can give an important indication on the viability of a business case. Figure 6.8 give a screenshot of the model and it's features.

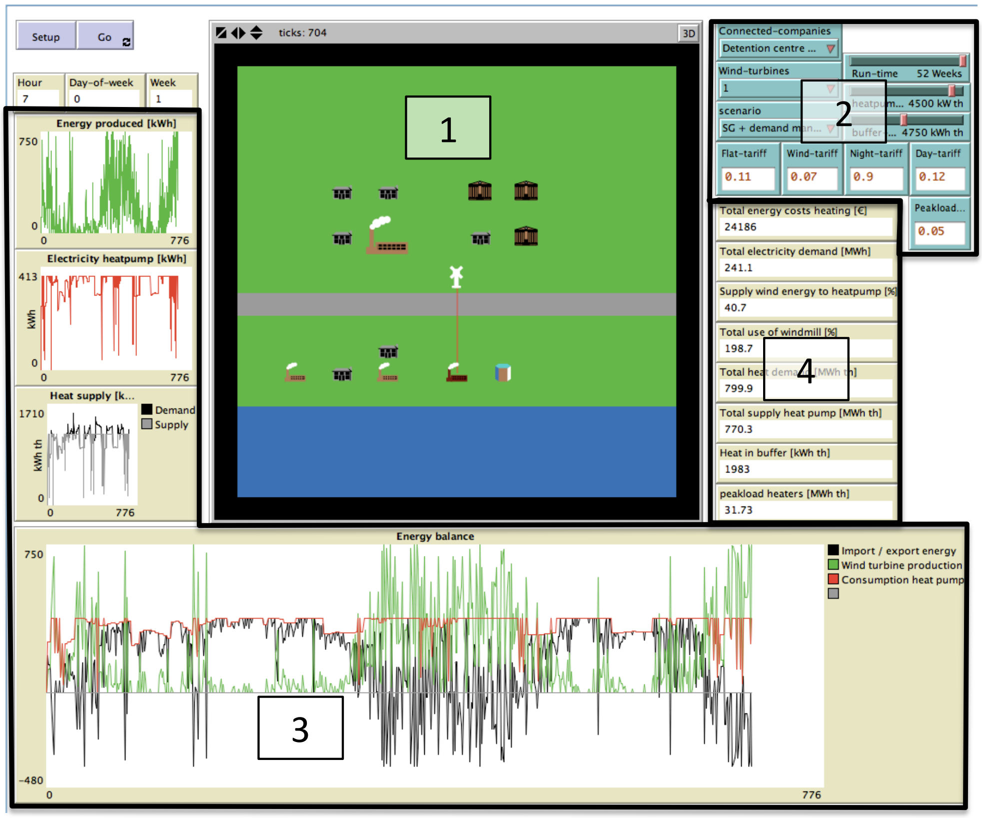



**Figure 6.8 A screenshot of the developed Netlogo simulation model**

### *Visuals*

Section 1 is a graphical representation of the industrial area 'HoogTij'. It displays a number of buildings that have a demand for heat. Windmills are present in the model, and can be directly connected to the electric heat pump (red line). Next to the heat pump, a heat buffer tank is placed to store heat temporarily.

### *Parameters*

All the parameters of the scenario's can be set in section 2. Capacity of the heat pump and buffer size can be set, the number of windmills that are connected to the smart grid and the type of scenario can be chosen (Business as usual, smart grid, etc.). To calculate financial aspects of the smart grid, different tariffs for the energy should be given. A differentiation is made for the electricity that is bought from the grid, from the wind turbine and day/night tariffs can be given. Also, a rate for energy from the peak load heaters should be given, so the total energy costs are realistic. The capacity of the heat pump and the heat buffer can be set. These are important constrains for the ‘flexibility’ of the heating system and the ability to use energy when it is available.

***Graphs***

Different graphs show the generation of wind energy (green), the heat demand of the buildings (black) and production of heat by the heat pump (grey) and the electrical consumption of the heat pump (red). The large graph below shows the ‘energy balance’ of the electricity. Again, production by wind energy is given in the green line and consumption is red. The black line in this graph shows the electricity that is imported or exported from or to the grid.

***Monitors***

Section 4 gives more insight in the cumulative results. Numbers are displayed for the total use of electricity and heat, costs of the energy (for heating) and the current amount of heat that is stored in the buffer. Two factors indicate the use of wind energy. The ‘Total use of wind mill’ indicates the fraction of wind power that is used for the heat pump of the total wind power that is generated. The ‘supply wind energy to heat pump’ gives the percentage of wind power versus the imported ‘grey’ energy from the grid, which is consumed by the heat pump.

### 6.7. Simulation results

The Netlogo simulations give clear results on the energy costs for the heat pump system and the fraction of wind power that is used. Interesting conclusion is that the costs for electricity drop significantly when the wind turbine is connected to the heat pump (the private grid and smart grid scenario). The smart grid scenario can result in cost savings up to 23%, which increases the business case for the heat pump significantly. Another interesting conclusion is that the fraction of wind power that is used can rise about 5% by using demand management technology and a relative small heat storage tank of 250 kWh. Increasing the buffer size is beneficial for the fraction of wind energy that is used; a rise of 1% is seen with any doubling of its capacity. When passive heat storage can be applied, the share of wind energy can be increased by 13%, to a total of 82% (figure 6.10). Increasing the capacity of the heat pump improves the absorption of wind power as well, yet this will require a higher investment. Therefore, a limited overcapacity of 10% (550 kW) seems realistic. A rise of the total use of the supplied wind energy (figure 6.11) and a reduction in costs is seem in the scenario’s where the heat pump has more capacity. Yet, the percentage of wind energy (figure 6.10) is remains equal with both size of heat pumps.

Just connecting the wind turbine to the heat pump (private grid scenario) results in strong cost reduction at once, but has no benefit for the integration of wind power. The smart grid scenario with passive heat storage and a heat pump capacity of 550kW has the greatest benefit for both costs as well as environmental considerations. Exploiting the passive heat storage capacity of the connected buildings can be a cost effective way to be able to operate the heat pump flexible. Findings related to operation costs are visualised in figure 6.9.

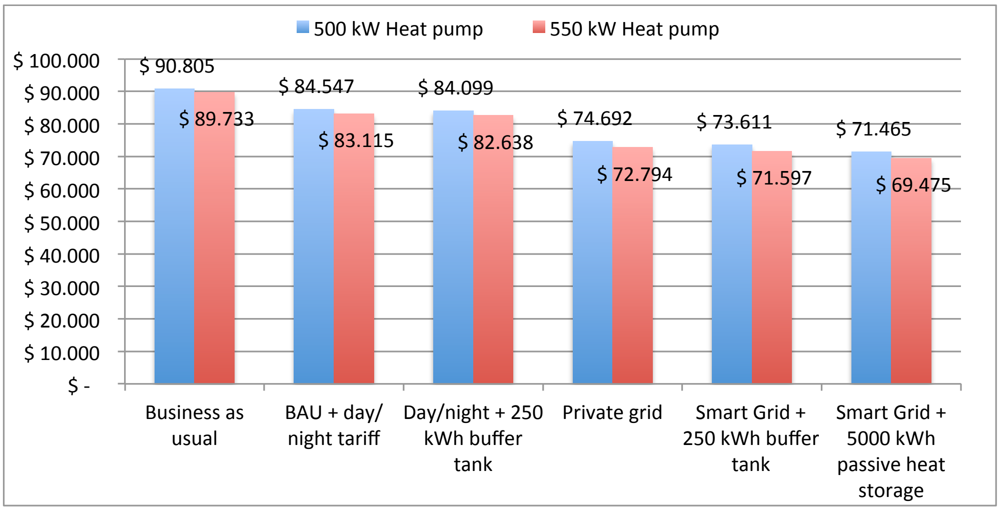



**Figure 6.9 Simulation results of the proposed smart grid from the Netlogo model, for various scenarios.**

The graph in figure 6.10 gives the fraction of wind energy of the total energy needs of the heat pump. In the smart grid scenario where 5000 kWh of heat can be stored in the building mass, the wind energy that is used reaches up to 82%, compared to 68% in the BAU scenario. The heat pump consumes around 10% of all the energy that is produced by the windmill, as given in figure 6.11. Excess wind energy will be sold to the grid by the owner of the windmill.

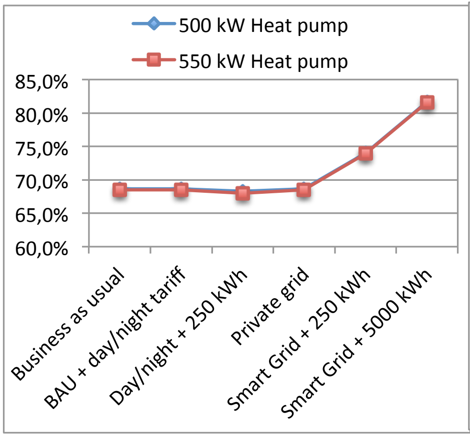



**Figure 6.10 Share of wind energy used by heat pump**

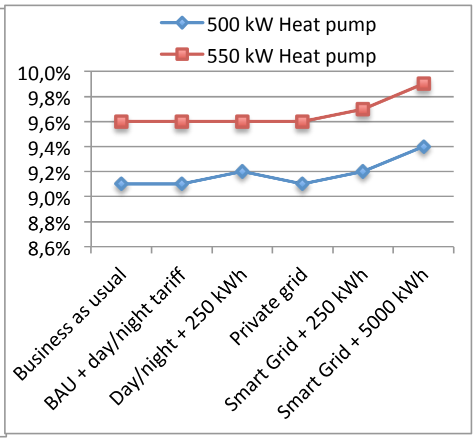



**Figure 6.11 Total use of energy produced by windmill**

# 7. THE BUSINESS CASE FOR THE 'SMART' HEAT GRID

Results of the Netlogo simulation indicate clearly that a smart grid is beneficial. Interesting question remains how this costs saving can increase the business case for the heat grid. The report of New Energy Works (2011), indicate that a this case is viable, but not particularly interesting for investors. Development of the heat grid is thus uncertain. To investigate the impact of a smart grid on the economic viability of the heat grid, the business case is calculated. Therefore, tariffs for heat are investigated, as well as investment costs and financial indicators. To highlight the environmental benefits, the $CO_2$ reduction is calculated as well.

## 7.1. Tariff structure

District heating systems are subject to the 'Warmtewet', which regulates tariffs for district heat. Currently, the 'Warmtewet' is draft legislation. The regulation is based on the idea that customers have equal costs for district heating, compared to individual gas fired heating. In the report Rekenmodel Warmtewet (2009), a model is proposed for the tariff structure. This model is used for the calculation of the tariffs. Three tariffs are used in this model:

$$Connection\ \ fee = 130{,}01 \cdot x^{0{,}9637}$$
$$Yearly\ standing\ charges = 16{,}206 \cdot x^{0{,}7762}$$
$$Heat\ tariff[€/GJ] = \frac{1401m^3 \cdot Pg - 55kWh \cdot Pe}{34{,}74GJ}$$

In which:

x = capacity of heating [kW]
Pg = gas price [€/$m^3$]
Pe = electricity price [€/kWh]

## 7.2. Investment costs

Important for the calculation of the business case is the required investment of the heating system. Estimations are made for costs of the heat pump, peak load heating, utility connections, heat grid etc. For the smart grid option, some additional costs are calculated as well, for instance for the connection to the wind turbine. All cost estimations can be found in appendix IIC.

### 7.2.1. Assumptions

Some more assumptions had to be made for the financial calculations. A rate is used for price increase of energy. As prices of energy rise, the margin between energy that is purchased and heat that is sold rises as well. Assumed is that energy prices rise with 1,5% per year, both for sold heat as for bought electricity from the grid and the windmill. Costs for maintenance are set at 3% of the investment costs and an internal interest rate is set at 7%. More details can be found in appendix IIA and IIB.

## 7.3. Results

Clearly, the smart grid scenario makes the business case attractive for investors. The business as usual scenario remains a weak case for investors to develop the collective heat grid, since it does involve some risks as well. The business case calculation also made clear that the scenario with passive heat storage and a larger heat pump capacity is the most profitable option.

The net present value method is used to express the financial performance of this case. Net present value account for the time value of money; interest is gained by the investor over the capital that is invested. A project can be marked as acceptable if the balance is positive after the period of exploitation. In the business as usual scenario, a positive balance is achieved after 15 years. Since the costs for the exploitation and the interest on the capital are covered, the case is acceptable. In the smart grid scenario, a positive net present value is achieved within 10 years and after 15 years, a profit of € 139.000, - is gained. This scenario is attractive for investors, and hence more feasible to develop. A summary of the findings is presented in table 7.1.

| | Business as usual | Smart Grid |
|---|---|---|
| **Investment** | € 414.000, - | € 472.000, - |
| **Pay back time [year]** | 11,1 | 7,6 |
| **Internal Rate of Return** | 7% | 14% |
| **Net present value [7%, 15 years]** | € 1450, - | € 139.000 |
| **$CO_2$ reduction** | 19% | 73% |

**Table 7.1 Most important findings of the business case calculation.**

On environmental performance, the smart grid scenario is preferred as well, since $CO_2$ reductions reach up to 73%, compared to gas-fired heating. Reduction on $CO_2$ is compared to conventional gas-fired heating. Energy that is generated by the wind turbine and consumed directly (smart grid scenario) is considered as $CO_2$ neutral.

### 7.4. Conclusion of the business case

The case for the proposed smart grid seems to have a strong potential. Thanks to the costs reduction of the smart grid optimisation, the business case is a more attractive, and it is likely that an investor can be found to develop this. The municipality and the shareholders of HoogTij can outsource the exploitation of the heat grid to an investor. Producing and selling energy is not the core business of the developers of HoogTij, and hence are not interested to invest or take risks in this. Yet, they are interested in a sustainable development of the area, and the smart grid can improve on the innovative character of the area.
For companies who potentially want to settle on HoogTij, such a heat grid can be a plus: They are relieved with production of heat and cold, without additional costs, and they can use the sustainable generated energy. For many companies, this can be a valuable estate as it can improve on their corporate social responsibility performance.

# PART 3: CONCLUSION & DISCUSSION

## 8. CONCLUSION

The transition towards an economy that is powered by energy from renewable sources is a necessary and responsible step, to overcome environmental problems, global warming and depletion of fossil fuels. In order to do so, a solution have to be found to deal with the uncontrollable and intermitting supply of renewable sources, such as the energy generated by wind and solar power. Flexible and controllable consumption of energy is a key element in a smart grid, and can be used to match supply and demand. The central question in this research is: "How can smart grids contribute to the integration of renewable energy on industrial areas?" To investigate this problem, some specific research questions has been set, which are answered here:

***Which companies or activities are flexible in energy demand and can be used to match the intermitting supply of renewable energy?***

Flexibility of energy usage can be found in more or less any process, yet flexible energy usage is most feasible if it does not affect the primary operations of the company. Thermal applications, such as product cooling and building heating are very suitable for smart grid applications, since they have flexibility and can be controlled in an automated way. Energy use for thermal applications has a large share of the total energy consumption, and application of electric heat pumps, which are efficient and can be controlled 'smart', is increasing. Another promising application is use of pumps, for instance in pumping stations that control water levels, or processing of dredging sludge. Energy intensive parts of production lines can be made flexible, by using or adding storage space for the produced goods. Examples of this kind of flexibility are given for cement mills, chemical plants and the paper industry, but are widely applicable to production processes.

***What business models can be found to develop smart grid applications?***

For a company that has flexibility in their processes, it is important to find a financial driver to exploit this. Four business models are proposed to use flexibility in a smart grid application: *Contract optimisation* is very universally applicable and makes use of 'time of use' energy tariffs or variable tariffs. *Trade on balancing markets* can be beneficial for flexibility that has a short time frame: financial rewards can be gained by switching large electric loads on or off for about 15 minutes. *Smart micro grids* are very suitable for companies that have an energy source nearby, for instance a windmill on their site. A *virtual power plant* is an advanced business model to cluster a portfolio of energy producers and consumers, in order to interact with energy markets in a controlled way.

***What business opportunities can be found to develop a smart grid for the industrial area HoogTij?***

An industrial site that is being developed offers a great opportunity to design a smart energy infrastructure. Yet, finding flexibility in industrial processes is hard if there are no companies present. The development of wind turbines and a collective heat grid offered an interesting chance for a smart grid application: The electric heat pump can use its flexibility to produce heat when wind power is available. The performed case study on the heat/cold network for HoogTij indicates that the share of wind power can be increased significantly, and consequently resulting in a major cost reduction. Calculations on the business case show that the smart grid alternative makes the heat grid profitable: A great opportunity to develop HoogTij in a sustainable way and a viable business case for a smart grid application.

***How can multiple companies on an industrial area benefit by deploying a smart grid?***
The case study for HoogTij deals with only two actors: A wind turbine and the collective heat pump, which forms a smart micro grid and share the same connection to the pubic grid. These two actors have to join in a legal entity in order to maximise the financial benefits. Technically, more companies can be connected to this smart grid, yet, legal constrains hinder this: Draft legislation further complicate the development of private grids, which is for a proper basis for a smart grid on industrial sites. To overcome these legal constrains, the business model of a Virtual Power Plant suits best. The connected companies can optimise their power flow in order to obtain lower energy prices, match sustainable energy production or avoid local grid congestion. In this way, the companies can reduce their energy costs, but it creates interdependencies and some organisational barriers can be expected.

***Can a smart energy infrastructure attract businesses to settle on an industrial area?***
Energy is an important precondition for industry, yet many companies consider energy supply a self-evident matter. Reducing energy costs and using renewable energy is valuable for companies, however for most companies this is not a mayor concern and they focus on their core business. A smart energy infrastructure, which offers affordable renewable energy and relieve companies with energy production, can thus be an attractive establishment condition.

The deployment of smart girds is a requirement to be able to integrate a share of more than 25% of solar and wind power in the electricity system. Although renewable energy production in the Netherlands is currently 'shamefully' low, a rapid increase can be expected. Moreover, smart grids are already very valuable to increase the efficiency and reduce costs of the energy supply. The industrial sector offers a great potential to develop smart grids, it can enable integration of renewable energy and can contribute to their competitiveness in the global market.

## 8.1. Discussion

### 8.1.1. Case study HoogTij

One of the goals for this study was to investigate how a smart grid could strengthen the industrial area HoogTij. Determining whether the proposed smart heat grid result in a positive business case is not easy to investigate but requires a detailed simulation study to calculate different scenarios. The simulation model is developed specifically for that purpose. To develop the model, a number of assumptions and simplifications had to be made. In order to draw the right conclusions from the model, various tests and comparisons are performed and research institute Vito has assisted in validating of the model. For the purpose of investigating the potential to operate in a smart grid, the developed simulation is reliable, and the feasibility of this smart grid is made clear.

In the performed case study, the technical and economic feasibility are proven. Also, feasibility in terms of legal possibilities is taken into account, yet this might need some more attention. The wind turbine and the heat pump share the same connection to the public

grid, so the financial benefits are maximal since no energy taxes and transport costs have to be paid on the energy that is consumed directly. To do so, these assets have to be owned by only legal entity. A point of attention in this construction is that the wind turbine will be subject to SDE+ subsidies (feed in tariffs), yet a part of the produced energy is already consumed on-site. Such constructions are possible, but it is on the brink of the energy laws and can be a hassle to organise.
The most beneficial scenario in this case study occurs if the building mass of the detention centre can be used as a passive heat storage buffer. Although the occupants of the building do not encounter any inconveniences of this, this should be organised with the developers of the building.

#### 8.1.2. Extension of the simulation model

Calculating cases for different buildings and heat pumps can quite easily be done, by altering some parameters. A relevant extension for further research would be to account for cooling loads as well. In this way, the model can be made more versatile and can be used to assess various thermal applications for smart grids.
The model includes the basic functionalities that are required to other smart grid simulation studies and can be used as a basis to develop more applications. Yet, flexibility in every process is different, and to assess this, a lot of constrains have to be investigated. Agent based simulation models are suitable to assess such cases, and the developed model can be extended to include different cases. Modelling applications of smart grids can be very difficult, but also very challenging.

### 8.2. Recommendations

This research has focussed on industrial applications of a smart grid, and especially for HoogTij. The investigated case for HoogTij has been developed, taking in mind that it should have added value for the area and is realistic to accomplish. Zaanstad can take a directing role in the development of this smart grid. Since Zaanstad also develops a windmill on HoogTij, they are in the position to create the preconditions to develop this smart grid in collaboration with a market party. A feasible way to accomplish this is to establish a local sustainable energy company: The development of the wind turbine by Zaanstad can be combined with a market party who deals with the development of the heat grid. In such cooperation, the smart grid will be beneficial to develop and it will contribute to a sustainable and competitive development of HoogTij.

For further research, it can be recommended to investigate a smart grid application for the municipal pumping stations. These pumping stations have a significant consumption of energy, and have flexibility as well. In cooperation with the energy supplier and the grid operator, the flexibility can be exploited and all partners can experience benefits. Such a project can contribute to the innovative nature of Zaanstad.
This leading role in the field of energy can contribute to the business climate of the area. For both existing and new companies that consider settling in Zaanstad, the knowledge and innovation on smart energy networks can be a strategic asset and contribute to economic welfare of the region.

### 8.3. Acknowledgements

This work has been carried out in fulfilment of the master degree in Construction Management & Engineering. The municipality of Zaanstad had a supporting role as a supervisor in this graduation project. Moreover, support was given from the European e-harbours project, which is part of the Interreg IVB North Sea Region Programme. The Province of Brabant took a sponsoring role by participating in the KENWIB program, which is a collaboration with the TU/e, municipality of Eindhoven and Promotie installatie Techniek (PIT). I would like to thank Jef Verbeeck from Vito for his role in the validation of the model, and all others who have supported this research.

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**APPENDICES:**





71

## Appendix I Netlogo coding

In this appendix the coding of the Netlogo simulation is described, which is used for the case study of HoogTij. This model executes a range of codes, which simulate the behaviour of the system and the optimisation. The code is build up in three parts; first, the agents and variables of the model are defined. In the setup, specific settings for the start situation are given. The Go section describes a set of procedures, which are followed by the agents.

## Model variables

Variables that are used within the model are described here:

### *Breeds*

The agentsets that will operate in the model are created in breeds. Both the plural as the singular forms are given:

```
breed [ windmills windmill ]
breed [ heatpumps heatpump ]
breed [ heatbuffers heatbuffer ]
breed [ companies company ]
```

### *Globals*

Global variables are used to set and store variables. Theses can be altered by all the different agents or can be have fixed values.

```
globals [
electricity-heatpump
energy-windmill
energy-use-heating
heat-from-heatpump
heat-in-buffer
hour-of-day
day
day-of-week
week-of-year
night
temperature
solar-intensity
total-heat
total-electric
total-supply-heatpump
total-windmill
energy-costs
energy-tariff
windfraction
peakload-boilers
]
```

### *Heatpumps-own*

These are variables that belong to the agents of a specific agent set, in this case the agent representing the heat pump.

```
heatpumps-own [
 COP
 p-electric-heatpump
]
```

***Companies-own***

These are the variables that belong to the agent set of the buildings (defined as companies). They are used to set values that influence the heat demand of the buildings, such as the thermal resistance of building materials.

```
companies-own [
  business-hours
  t-business-hours
  t-closed
  t-indoor
  area-footprint
  storeys
  storey-hight
  u-floor
  u-wall
  u-roof
  u-window
  ZTA-window
  window-wall-ratio
  ventilation-rate
  ventilation-heat-recovery
  q-heatloss
  q-heatgain
  occupants
  process-heat
]
```

## Setup

This procedure is used to setup the model. It resets some general values, and asks agents to sprout itself on the model creates the patches (environment). Depending on the scenario that is being tested, an agent for a heat buffer is created as well. In coding:

```
to setup ;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  clear-all
  reset-ticks
  file-close-all
  set total-heat □
  set energy-costs □
  set total-electric □
  set total-windmill □
  set windfraction □
  set heat-in-buffer □
  set peakload-boilers □
  set total-supply-heatpump □
  ask patches [setup-world]
  setup-agents
end

to setup-agents
  create-windmills 1 [         ;; sets shape, color size and coordinates of an agent
    set shape "windmill"
    set color white
    set size 2
    setxy 0 0
  ]
```

```
  create-heatpumps 1 [
   set shape "factory"
   set color 12
   setxy 0 -4
  ]
  if scenario = "BAU day/night" [
   create-heatbuffers 1 [
    set shape "hexagonal prism"
    set color brown
    setxy 2 -4
  ]]
  if scenario = "Smart Grid" [
   create-heatbuffers 1 [
    set shape "hexagonal prism"
    set color brown
    setxy 2 -4
  ]]
 create-companies 1 [ ;; Description of building characteristics
  set shape "building institution"
  set color brown
  setxy 3 4
  set business-hours [ 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 ]
  set t-business-hours 19.5         ;; tempeture during business hours
  set t-closed 19.5                 ;; tempeture when closed / at night
  set area-footprint 5000           ;; [m2]
  set storeys 4
  set storey-hight 4                ;; [m]
  set u-floor 0.35                  ;; [W/m2K]
  set u-wall 0.32                   ;; [W/m2K]
  set u-window 1.7                  ;; [W/m2K]
  set u-roof 0.27                   ;; [W/m2K]
  set ZTA-window 0.6                ;; factor for sun accessibility through windows
  set window-wall-ratio 0.3         ;; 0 = no windows. 1 = 100% glazed facade
  set ventilation-rate 5            ;; [1/h]
  set ventilation-heat-recovery 0.1 ;; 0 = 100% heat recovery. 1 is no heat recovery
  set occupants 350                 ;; occupants create internal heat gain of 100w
 ]
 end
to setup-world
  if (pycor < 10) and (pycor > -10) and (pxcor < 10) and (pxcor > -10)   [set pcolor green]
  if (pycor < -5) and (pycor > -10) and (pxcor < 10) and (pxcor > -10)   [set pcolor blue]
  if (pycor < 0 ) and (pycor > -2 ) and (pxcor < 10) and (pxcor > -10)   [set pcolor grey]
end
```

## Go

The Go procedure asks all the agents to execute a set of rules. Some procedures are executed by the model itself, for instance to import datasets and to keep track of the time steps (ticks). When the Go procedure is run, is starts sub-procedures that form a part of the Go procedure. After all agents have performed their tasks, the model advances a tick, which represents a 15-minute time interval.

```
to go ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
 import-data
 run-clock
 create-smart-grid
 heat-buildings
 produce-heat
 report-totals
 calculate-costs
 tick
 if ticks = run-time * 4 * 24 * 7 [stop]
end
```

***Run-clock***

The run-clock procedure defines different time intervals, such as hours, day and weeks.

```
to run-clock
  set hour-of-day floor (ticks / 4 ) mod 24
  set day floor (ticks / 96)
  set day-of-week day mod 7
  set week-of-year floor (ticks / (4 * 24 * 7 )) mod 52
end
```

***Import-data***

The model reads datasets for temperature and solar intensity. Production of the windmill is simulated in a spreadsheet, which is read as well.

```
to import-data
  file-open "Temperature.txt"
  set temperature file-read
  if file-at-end?  [file-close]

  file-open "Wind-power.txt"
  let output file-read
  if file-at-end?  [file-close]
  set energy-windmill output * wind-turbines

  file-open "Solar-intensity.txt"
  set solar-intensity file-read
  if file-at-end?  [file-close]
end
```

***Create-smart-grid***

This procedure is used to visualise the cable that connects the wind turbine to the heat pump.

```
to create-smart-grid
  if scenario = "Private Grid" [
   ask windmills  [create-links-to heatpumps]
    ask links [set color red
    set shape "link"]]
  if scenario =  "Smart Grid" [
   ask windmills  [create-links-to heatpumps]
    ask links [set color red
    set shape "link"]]
end
```

***Heat-buildings***

The heat-buildings procedure is used to calculate the losses of heat by transmission through the building façade, roof and floor and calculates the losses by ventilation. Internal heat gain by sunlight and occupants themselves is calculated and deducted from the demand for heat. The demand for heat is mainly depending on the outside temperature, which is imported from a dataset. The value for heat demand is stored in the variable energy-use-heating every time step.

```
to heat-buildings
  set energy-use-heating 0
  ask companies [  ;; calculation of heat losses through transmission and ventilation
   ifelse item hour-of-day business-hours = 1 [set t-indoor t-business-hours][set t-indoor t-closed]
   if temperature < t-indoor [
    ;; calculate ventilation losses:
    let volume ( area-footprint * storeys * (storey-hight - 1) )
    let ventilation-loss abs(temperature - t-indoor ) * (ventilation-rate / 4) * volume *
     |1.005 * 1.2041 * (3600 / 4) * 2.777 * 10 ^ -7
    let actual-ventilation-loss ventilation-loss * ventilation-heat-recovery
    ;; calculate transmission losses:
    let transmission-loss
      abs(temperature - t-indoor ) * ( area-footprint * u-floor ) * (3600 / 4) * 2.777 * 10 ^ -7
    + abs(temperature - t-indoor ) * ( area-footprint * u-roof ) * (3600 / 4) * 2.777 * 10 ^ -7
    + abs(temperature - t-indoor ) * ( (sqrt area-footprint) * 4 * storeys * storey-hight * ((1 - window-wall-ratio) *
        u-wall + window-wall-ratio * u-window)) * (3600 / 4) * 2.777 * 10 ^ -7
   set q-heatloss (actual-ventilation-loss + transmission-loss)]
    ;; calculate internal heat gain:
    let area-window ((sqrt area-footprint) * 4 * storeys * storey-hight * window-wall-ratio)
    let heat-from-sun  0.6125 * area-window * ZTA-window * 0.885 * solar-intensity * 2.77 * 10 ^ -7
    let heat-from-occupants occupants * 105 * (3600 / 4) * 2.77 * 10 ^ -7
   set q-heatgain heat-from-occupants + heat-from-sun
  ifelse q-heatloss > q-heatgain [set energy-use-heating energy-use-heating + (q-heatloss - q-heatgain) +
    (item hour-of-day business-hours * process-heat)]
    [set energy-use-heating energy-use-heating + item hour-of-day business-hours * process-heat]
  ]
end
```

***Produce-heat***

The heat pump and the peak load heating capacity produce the required heat to keep the buildings on temperature. This procedure also includes the operation of the heat buffer, and it includes optimisation rules for different scenarios.

The coefficient of performance (COP) of the heat pump determines the required electric energy, and is reliant on the temperature of the source of the heat, which is the water from the Nord Sea Canal in this case. Measurements of the water temperature are included, which changes every four weeks.

In the scenarios “BAU day/night” and “Smart Grid” the heat pump makes an optimisation to produce heat at times that cheap electric energy is available.  The overproduction of heat is stored in the heat buffer, and is used when the price for electricity is higher.

If the capacity of the heat pump is not sufficient to produce the demand of heat and the heat buffer is empty, peak load boilers are used supply the deficit.

```
to produce-heat
 ask heatpumps [
 let sourcetemp item (floor week-of-year / 4) [3.9 3.1 5.3 9.9 12.2 16.7 21.1 21.9 18.9 16.8 13.5 10.2 3.9]
 set COP (0.05 * sourcetemp + 3)
 set p-electric-heatpump (heatpump-capacity / (4 * 3))

if scenario = "Business as usual" [
  ifelse energy-use-heating  > (p-electric-heatpump * COP)
   [set heat-from-heatpump (p-electric-heatpump * COP)]
   [set heat-from-heatpump energy-use-heating ]
  set electricity-heatpump (heat-from-heatpump / COP )
  ]

if scenario = "Private Grid" [
  ifelse energy-use-heating  > (p-electric-heatpump * COP)
   [set heat-from-heatpump (p-electric-heatpump * COP)]
   [set heat-from-heatpump energy-use-heating ]
  set electricity-heatpump (heat-from-heatpump / COP )
  ]

 if scenario = "BAU day/night" [
  ifelse energy-use-heating  > (p-electric-heatpump * COP)
  [set heat-from-heatpump (p-electric-heatpump * COP)
     if sum heat-in-buffer > 0
     [set heat-in-buffer lput  (heat-from-heatpump - energy-use-heating) heat-in-buffer ]]
 [if night = 1 [
   ifelse (sum heat-in-buffer < buffer-size ) [
     set heat-from-heatpump (p-electric-heatpump * COP)
     set heat-in-buffer lput (heat-from-heatpump - energy-use-heating) heat-in-buffer ]
    [set heat-from-heatpump energy-use-heating]]
  if night = 0 [
    ifelse sum heat-in-buffer > 0 [
    set heat-in-buffer lput  ( - energy-use-heating  ) heat-in-buffer
     set heat-from-heatpump 0
     set electricity-heatpump 0 ]
    [set heat-from-heatpump energy-use-heating ]]
   ]
    set electricity-heatpump (heat-from-heatpump / COP )
  ]

 if scenario = "Smart Grid" [
  ifelse energy-use-heating  > (p-electric-heatpump * COP)
   [set heat-from-heatpump (p-electric-heatpump * COP)
     if sum heat-in-buffer > 0 [
     set heat-in-buffer lput  ( heat-from-heatpump - energy-use-heating  ) heat-in-buffer ]]
   [set heat-from-heatpump energy-use-heating ]
    set electricity-heatpump (heat-from-heatpump / COP )

 if energy-windmill > (energy-use-heating / COP)  and (sum heat-in-buffer < buffer-size ) [
   if p-electric-heatpump * COP > energy-use-heating [
   set heat-from-heatpump (p-electric-heatpump * COP)
   set heat-in-buffer lput (heat-from-heatpump - energy-use-heating) heat-in-buffer ]
   set electricity-heatpump (heat-from-heatpump / COP )
   ]

 if energy-windmill < (energy-use-heating / COP) and (sum heat-in-buffer > 0 )[
  set heat-from-heatpump (energy-windmill * COP)
  set electricity-heatpump (heat-from-heatpump / COP)
  set heat-in-buffer lput (heat-from-heatpump - energy-use-heating) heat-in-buffer
  ]]

 ifelse sum heat-in-buffer > 0   ;; use of peakload heaters (in all scenario's)
  [if energy-use-heating > (p-electric-heatpump * COP + (sum heat-in-buffer ))
    [ set peakload-boilers lput (energy-use-heating - heat-from-heatpump) peakload-boilers]]
  [if energy-use-heating > p-electric-heatpump * COP
    [set peakload-boilers lput (energy-use-heating - heat-from-heatpump) peakload-boilers]]
 ]
end
```

### *Report-totals*

This procedure keeps track of the cumulative production and consumption of energy from all different agents.

```
to report-totals
  set total-heat lput energy-use-heating total-heat
  set total-electric lput electricity-heatpump total-electric
  set total-supply-heatpump lput heat-from-heatpump total-supply-heatpump
  set total-windmill lput energy-windmill total-windmill
end
```

### *Calculate-costs*

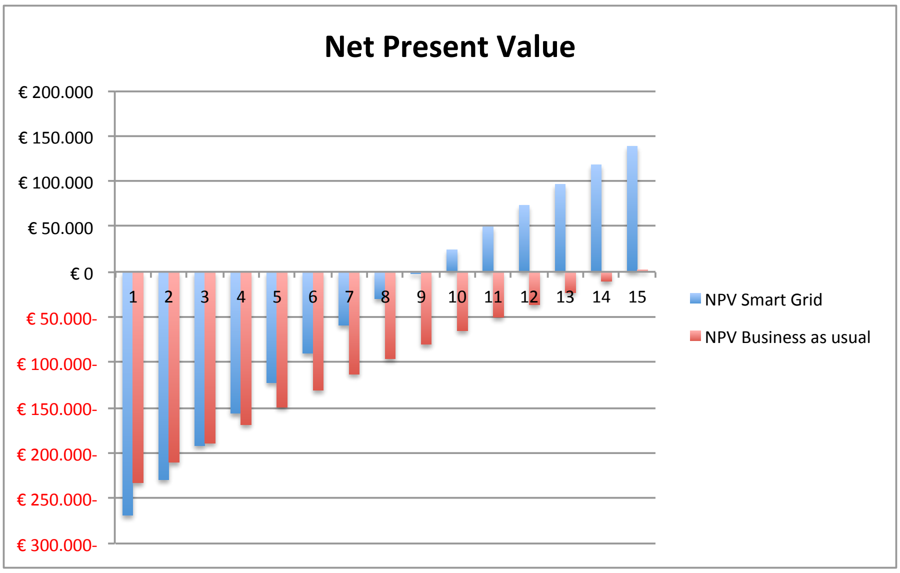
The final procedure calculates the costs, which are made for the generation of heat in the different scenarios. Moreover, the share of wind energy that is used is calculated as well.

```
to calculate-costs
  if scenario = "Business as usual" [
   set energy-tariff Flat-tariff
  ]
  if scenario = "BAU day/night" [
   set night item hour-of-day [ 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 ]
   ifelse night = 1 [set energy-tariff Night-tariff ] [set energy-tariff Day-tariff ]
  ]
  if scenario = "Private Grid" [
   ifelse energy-windmill >= electricity-heatpump [ set energy-tariff Wind-tariff ]
   [ set energy-tariff ((energy-windmill / electricity-heatpump) * Wind-tariff +
       (1 - (energy-windmill / electricity-heatpump)) * Flat-tariff) ]
  ]
  if scenario = "Smart Grid" [
   ifelse energy-windmill >= electricity-heatpump [ set energy-tariff Wind-tariff ]
   [ set energy-tariff ((energy-windmill / electricity-heatpump) * Wind-tariff +
       (1 - (energy-windmill / electricity-heatpump)) * Flat-tariff) ]
  ]
  set energy-costs lput (electricity-heatpump * energy-tariff ) energy-costs
  ifelse energy-windmill >= electricity-heatpump
  [set windfraction lput electricity-heatpump windfraction]
  [set windfraction lput energy-windmill windfraction]
end
```

# Appendix II Exploitation of the heat grid

**IIA Exploitation of heat grid**

| | | |
|---|---|---|
| Heating capacity | 1400 | kW |
| Connection fee | € 139.927 | |
| Yearly standing charges | € 4.484 | |
| Heat tariff | € 11,94 | GJ |
| Heat tariff | € 43 | MWh |
| Heat demand | 2851 | MWh/year |
| Energy costs Gas scenario | € 114.000 | |
| Energy costs BAU scenario | € 90.000 | |
| Energy costs SG scenario | € 69.500 | |
| Investment BAU scenario | € 414.180 | |
| Investment SG scenario | € 471.680 | |
| Fixed costs (% investment) | 3,0% | |
| Yearly fixed costs BAU | € 12.425 | |
| Yearly fixed costs SG | € 14.150 | |
| Internal interest rate | 7,0% | |
| Price increase energy | 1,5% | |
| | | |
| Turnover | € 127.033 | Margin |
| Difference (Gas) | € 608 | 0% |
| Difference (BAU) | € 24.608 | 19% |
| Difference (SG) | € 43.383 | 34% |



## Appendix IIB Cash flow model

**Business as Usual scenario**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turnover | € 128.896 | € 130.786 | € 132.705 | € 134.653 | € 136.630 | € 138.636 | € 140.673 | € 142.740 | € 144.838 | € 146.968 | € 149.130 | € 151.324 | € 153.551 | € 155.811 | € 158.105 |
| Expenses | € 103.775 | € 105.146 | € 106.536 | € 107.948 | € 109.381 | € 110.835 | € 112.311 | € 113.810 | € 115.330 | € 116.874 | € 118.441 | € 120.031 | € 121.645 | € 123.283 | € 124.946 |
| Cash flow | € 249.133- | € 25.641 | € 26.169 | € 26.705 | € 27.249 | € 27.801 | € 28.361 | € 28.930 | € 29.508 | € 30.094 | € 30.689 | € 31.293 | € 31.906 | € 32.528 | € 33.159 |
| IRR | | -90% | -62% | -41% | -27% | -18% | -11% | -6% | -3% | 0% | 2% | 4% | 5% | 6% | 7% |
| NPV | € 232.835- | € 210.439- | € 189.078- | € 168.705- | € 149.277- | € 130.752- | € 113.090- | € 96.252- | € 80.202- | € 64.904- | € 50.324- | € 36.429- | € 23.190- | € 10.575- | € 1.443 |
| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |

| | | |
|---|---|---|
| Pay back time | 11,1 | Year |
| CO2 emission | 549 | Tonne/year |
| CO2 reduction | 19% | |

**Smart Grid scenario**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turnover | € 128.896 | € 130.786 | € 132.705 | € 134.653 | € 136.630 | € 138.636 | € 140.673 | € 142.740 | € 144.838 | € 146.968 | € 149.130 | € 151.324 | € 153.551 | € 155.811 | € 158.105 |
| Expenses | € 84.693 | € 85.751 | € 86.825 | € 87.915 | € 89.022 | € 90.145 | € 91.285 | € 92.442 | € 93.616 | € 94.808 | € 96.018 | € 97.246 | € 98.492 | € 99.757 | € 101.042 |
| Cash flow | € 287.551- | € 45.035 | € 45.880 | € 46.738 | € 47.608 | € 48.492 | € 49.388 | € 50.298 | € 51.222 | € 52.160 | € 53.112 | € 54.078 | € 55.058 | € 56.054 | € 57.064 |
| IRR | | -84% | -51% | -29% | -15% | -6% | 0% | 4% | 7% | 9% | 11% | 12% | 13% | 14% | 14% |
| NPV | € 268.739- | € 229.403- | € 191.952- | € 156.296- | € 122.352- | € 90.040- | € 59.283- | € 30.009- | € 2.148- | € 24.368 | € 49.601 | € 73.612 | € 96.459 | € 118.198 | € 138.880 |
| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |

| | | |
|---|---|---|
| Pay back time | 7,6 | Year |
| CO2 emission | 187 | Tonne/year |
| CO2 reduction | 73% | |

**Appendix IIC investment costs**

| Subject | Number | Unit | €/unit | Total | Reference |
|---|---|---|---|---|---|
| Land acquisition | 100 | m2 | € 200 | € 20.000 | Land cost HoogTij |
| Heat pump | 500 | kW | € 350 | € 175.000 | Agentschap NL |
| Heating grid | 175 | m1 | € 220 | € 38.500 | NEW warmtenet Zaanstad |
| Heat exchanger | 1 | Pcs | € 10.000 | € 10.000 | Estimation |
| Electricity connection | 1 | Pcs | € 25.000 | € 25.000 | Liander |
| Gas connection | 1 | Pcs | € 40.000 | € 40.000 | Cost for existing connection |
| Back-up installation [1400kW] | 1 | Pcs | € 55.000 | € 55.000 | Bouwkosten online |
| Structural works | 50 | m2 | € 400 | € 20.000 | Estimation |
| Engineering & advise | 8% | | | € 30.680 | Estimation |
| Total | | | | **€ 414.180** | |

| Smart grid additional costs | | | | | |
|---|---|---|---|---|---|
| Extra capacity heat pump | 50 | kW | € 350 | € 17.500 | |
| Connection to wind turbine | 1 | Pcs | € 50.000 | € 50.000 | Estimation |
| Avoided costs grid connection | 1 | Pcs | € 25.000- | € 25.000- | |
| Software & control systems | 1 | Pcs | € 10.000 | € 10.000 | Estimation |
| Engineering | 1 | Pcs | € 5.000 | € 5.000 | Estimation |
| Total | | | | **€ 471.680** | |

## Appendix III English summary

## SMART GRIDS ON INDUSRTIAL AREAS

## Business models to enhance the implementation of renewable energy

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**ABSTRACT**
The use of energy from renewable sources is growing, and a transition in the energy supply is expected. Yet, this renewable energy is uncontrollable and can cause unbalances in the electricity system. To implement renewable energy, smart grids are required to match supply and demand. Although the industrial sector is already involved in management of the power system, a large potential can be found here. Flexibility in the consumption of energy can have economic value; concepts for flexible energy consumption are given and business models for smart grid applications are investigated. In a case study, an example is given of a smart grid application for a collective heat/cold network on an industrial site. An agent based simulation model optimizes the energy use, resulting in increase of the use of renewable energy and a vast reduction in costs.

**Keywords**: Smart grids, renewable energy, demand side management, industrial energy use, agent-based simulation.

**INTRODUCTION**
Currently, the most energy used in the world comes from fossil fuel sources such as oil, coal and gas. Yet, the use of these fossil fuels has negative environmental consequences, such as global warming. Scarcity of these resources is a growing problem, and increases the costs for energy, which demands are ever growing. Moreover, gaining these fossil fuels has been a major cause for conflicts in history: Instable regions hold vast shares of fuel resources and our cravings for energy results in undesirable dependencies and warfare. Taking this in mind, a transition towards renewable energy is a necessary and responsible step. Most countries have ambitious targets on clean energy. The European Union targets with its 20/20/20 goals for 20% reduction of $CO_2$, 20% increase in energy efficiency and 20% renewable energy in 2020. The Intergovernmental Panel on Climate Change (IPCC, 2012) states a $CO_2$ reduction of 80-95% compared to levels of 1990 is required for developed countries in 2050, in order to avoid disastrous climate change.

Transitioning to energy from sources as wind and solar requires improvements in the energy infrastructure: Development of smart grids is essential for the success of clean energy. The random, intermittent, and the unbalanced nature of renewable energy require such a smart grid, which is capable of matching the supply and demand of energy.
Industrial areas consume vast amounts of energy for their production activities. In 2004, the industrial sector consumed 41,4% of electricity globally (IEA, 2006). They are confronted with the rising prices of energy; in order to be competitive in the global market, companies should take measures to reduce their energy costs. When companies are able to purchase energy at times of the day that it is cheaper, they can have great benefits and consequently contribute to the implementation of renewable energy. Therefore, smart grids in industrial areas seem to have a great potential. Summarizing, the problem in this research is: A transition from an economy based on fossil fuels is emerging towards a renewable energy economy. Yet, the random and uncontrollable nature of renewable energy and the rising energy costs for industries threatens the availability of energy! The central question in this research is: “How can smart grids contribute to the integration of renewable energy on industrial areas?”
A vast share of literature on smart grids focuses on applications in households. The general idea is that appliances such as freezers, washing machines and air conditioners can be flexible in their use of energy. In other words, the time when they use the energy can be varied to some extend, in order to control the energy demand to match the varying supply of energy. In literature, smart grids are rarely linked to industrial energy use, however the terms demand side management or load management are used more often. This research focuses on industrial users; this group has a very high demand, yet the number of consumers is much smaller. Moreover, demand management and hourly varying energy prices is already seen in the sector, which is described by Albadi et al (2008). Paulus (2011) investigates potentials of demand side management in energy intensive industries. A top-down analysis is made on industries with high electricity demand and high costs for electricity in order to find achievable and economic flexibility. Grein et al (2011) and Hovgaard (2012) investigate potentials of demand management for refrigeration systems. Significant cost reductions are shown, yet also barriers are indicated.
Although demand management is common in energy intensive industries, it is often used to reduce peak loads, rather to integrate renewable energy supply. Gaps in literature are present on smart grids on industrial areas and business models to exploit flexibility in energy usage. In this study, activities that are flexible in energy consumption are investigated and business models to develop smart grid applications are explored. In a case study on an industrial area development, the potential for a smart grid application is investigated and the economic benefit is assessed.

**METHOD**
A number of research methods have been used in this study. A literature study is performed on smart grids and on industrial energy use. Application of demand side management and varying prices of energy is investigated. To better understand the problems related to the integration of renewable energy, the electricity system and markets are studied as well. A case study has been preformed where an application for a smart grid is investigated. For this case, an agent based simulation (ABS) model has been developed. ABS models can simulate complex behaviour of individuals or devices, and their interaction. The developed model simulates the production and consumption of energy in a process, which is optimized in the

smart grid. By using scenarios, the most beneficial case could be determined. The ABS model is developed using Netlogo.

**SMART GRIDS**

Wind and solar power are a major source of renewable energy. Yet, it is generally accepted that the integration of intermittent energy resources like wind energy and photovoltaic into an electricity system cannot exceed a limit of around 20% to 25% (Stadler, 2008). The reason for this is that the current electricity system is demand driven. Customers, small and large can, to some extend consume energy as much as they want whenever they want. Electricity generators follow the demand, and supply energy accordingly. Intermitting renewable sources cannot be controlled and can cause unbalances in the energy system. If the supply of energy deviates from the demand (figure 1), problems can occur and the electricity supply is threatened to a blackout, since it has to be in balance at all times.

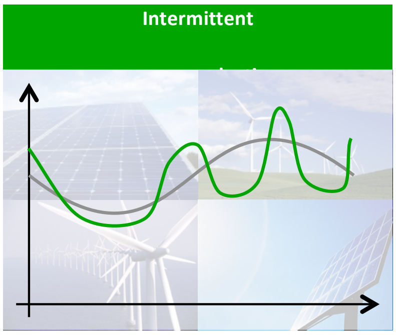


**Figure 37 intermitting energy sources (green line) can cause unbalances if the supply differs from the demand (grey line).**

To be able to integrate a larger share of renewable energy in the electricity system, a solution should be found in controlling the demand for energy; demand is flexible and can follow the supply of energy. This is a radical different approach, and is the main objective of smart grids. Although the literature on smart grids is widespread, no uniform definition of a smart grid is made. Within the e-harbours project, a smart grid is defined as: "An electricity network that is adapted to the introduction of renewable energy sources." The European Technology Platform (smartgrids.eu, 2006) defines a smart grid as "An electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both, in order to efficiently deliver sustainable, economic and secure electricity supply."

The smart grid is a modern electricity network that covers all parts from production, transmission and consumption, which is optimised by the use of information and communication technology. The market for energy is complex; production and trade in energy is done by numerous actors, who trade on different markets. Energy distribution takes place tree levels: The transmission side operator regulates the high voltage level. Distribution side operators (DSO), deal with electricity distribution on medium- and low-voltage levels. To maintain the crucial balance in the electricity system, balance responsible parties (BRP) coordinate supply and demand in advance. A market system for unbalances is used to correct unbalances in the production. All actors can experience benefits of the flexibility of smart grids, yet this flexibility is in the hands of the energy consumers, who have to adapt their energy usage by means of smart grid technology.

**FLEXIBILITY IN ENERGY DEMAND**

Controlling the energy demand to maintain balance in the energy network is applied for decades. Large industrial plants can control their energy demand by switching on and off large electric loads within a few minutes, or schedule production processes on times when energy supply is cheap. Yet, the fraction of energy use that is responsive to price changes or is controllable by the network operator is really low. In most cases, load shedding is applied, which affects the primary process of the company and resources as labour or material are get lost when plants have to shut down temporarily. In a smart grid, the goal is to adapt energy consumption in a more automated way, without resulting in lost labour or resources. This flexible energy consumption can be characterized by two determinants: the amount of flexible loads (in kilowatts or megawatts) and the flexibility over time, which can reach from minutes to hours, or in some cases even days. These determinants of flexibility can describe single devices or entire properties. Flexible loads that can be subjected to load management can be divided further into independent loads, process interlocked loads and storage space constrained loads (Ashok and Banerjee, 2001). Independent loads can be subjected to load management by taking into account constrains that are related to them, such as the time span that the loads can be switched on or off. Process interlocked loads form a part of a production process where the different loads are dependent. Such loads can only be controlled together. A storage space constrained load can have dependencies in a production line, but can be controlled individually.

A number of processes in the industry include thermal applications, which can be seen as independent loads. These processes all have a general principle, which is similar. Products or spaces have some sort of window in which the temperature should remain. If the temperature exceeds certain thresholds, heating or cooling applications are activated to restore temperature to the desired level. These processes have potential flexibility: Without exceeding the temperature thresholds, the energy use can be optimized to the availability of energy. Stretching the limits of temperature a little can increase the available flexibility. This is often possible without disturbing the process. Cold storage facilities or climate systems for buildings can be controlled ‘smart’. An example is given for a cold storage facility in the e-harbours project; when abundant energy from windmills is available, the products are cooled down a few degrees more. Afterwards, the cooling system can be switched off for up to 24 hours. In this example, a costs reduction of 15% could be achieved.

Processes that have a storage space constrain are part of a production line that can be operated individually but are linked to a shared storage space for material. In figure 2 process 1 and 2 have a storage space constrain; the handled material from process 1 is placed in the storage, afterwards it will be an input for process 2. The two processes can be controlled individual and, as long as the upper and lower level for the storage space is respected. These processes can potentially be controlled in a flexible way. The load of process 1 can be intermitted as long as it does not disturb process 2. If the amount of load and the flexibility over time are significant, the process has economic flexibility, which can be used in a smart grid.

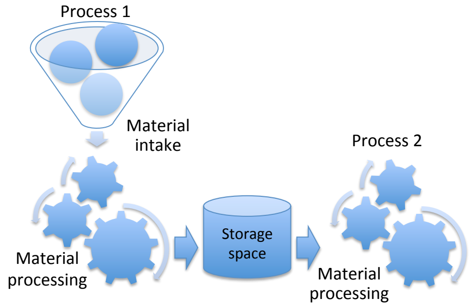


**Figure 2 Two processes are linked by a storage space constrain and can be operated flexible.**

When additional storage space is made available, the flexibility of the constrained processes is enlarged, since the flexibility over time increases. Adding storage space can split interlocked processes, such as the material intake and processing in figure 1 up. This is an important measure to increase the flexibility of parts of a production process. When interlocked processes are split by a storage space, as in figure 2, it is important that process 1 has some overcapacity: It should be able to catch up the production after it has been stopped for a while and the material storage is at its lower limit. In this way, an optimization can be made between the desired flexibility and available space. Examples of storage space constrained processes, which are subjected to load management can be found in cement industry, production of paper, flour mills, etc. Application of pumps, for instance in sewer systems, sludge processing or pumping stations can have significant flexibility. Although industrial activities vary widely, flexibility can be found in many industrial processes.
To use energy in a flexible way, an optimization should be made that takes in account constrains of the process. The potential of flexible energy usage in industry is large, yet application is still low. Barriers as lack of knowledge, limited incentives or organisational barriers are often mentioned.

**BUSINESS MODELS**
Identified flexibility in energy use can be exploited financially in a number of ways. The general principle is that supply and demand of energy can be matched by a market mechanism. Four business models are proposed, which are based on the findings of the e-harbours report “Strategies and Business Cases for Smart Energy Networks” (2012).
**Contract optimization** is the most universal applicable model to exploit flexibility. Prices of energy can vary over time, for instance by using time of use tariffs, such as a cheaper energy fairs during the night. In some cases, hourly varying prices can be offered, or energy can be purchased directly on the spot market, where energy is traded for the day ahead. By using energy when it is cheaper, significant savings can be made.
Another business model is to **trade energy on the balance market**. This is a market mechanism to maintain balance on the high voltage electricity network, which is regulated by the transmission side operator (TSO). On short timeframes of 15 minutes, the system is kept at balance by adjusting the demand of consumers or the supply of producers. Consumers, or a pool of them who satisfy the requirements to act on the balancing market platforms, can earn money by offering their flexibility as balancing services, as illustrated in figure 3.

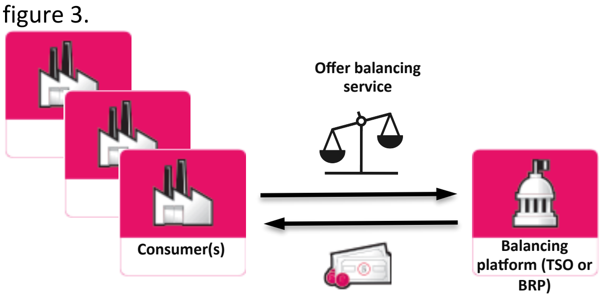


**Figure 3 The flexibility in energy use of large consumers can be offered as a balancing service to the transmission side operator or the balance responsible parties.**

**Smart micro grids** are privately developed energy networks where energy can produced and consumed without being transported over the public grid. The connected users are free to make arrangements on energy prices and, since transport costs and in some cases taxes can be avoided, a price benefit can be achieved. Local generated energy from solar panels, windmills or CHP plants can be used local or sold to the grid if it is in excess of the demand. A company within this micro grid can use its flexibility to meet the supply of the local produced energy. If the connected users in the micro grid can consume energy in a flexible way, by means of demand management, the grid becomes ‘smart’. These micro grids, as illustrated in figure 4 can be interesting breeding grounds for smart grid technologies and can have significant financial benefits for participants.

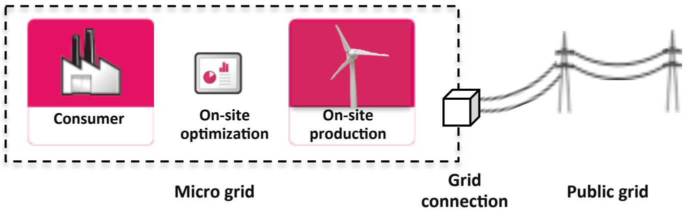


**Figure 4 Production and consumption of energy is optimised within a smart micro grid.**

The business model of a **Virtual power plant** (VPP) is an advanced optimization between a portfolio of small-scale produces, such as windmills and solar panels and several flexible loads. All these agents can be distributed over a large area, but the VPP is operated as if it where a single power plant. Since the energy production is more controlled, by having flexibility of consumption within the VPP, the energy can be managed better in the power grid and markets. To clarify this concept, an example is given in figure 5.

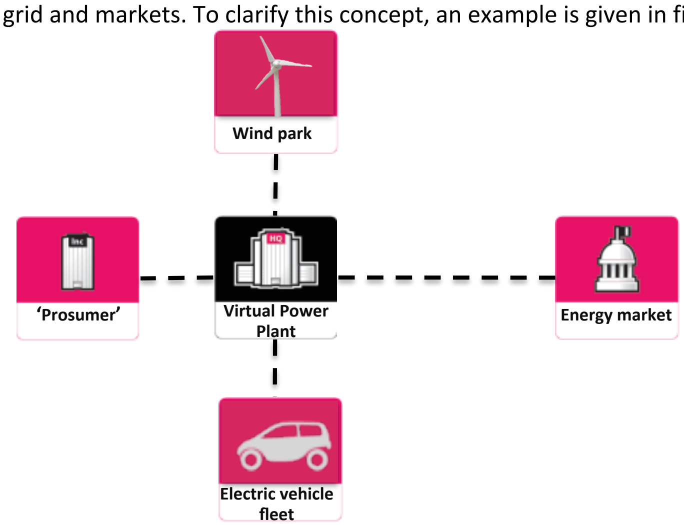


**Figure 5 In a virtual power plant, the production of renewable energy is made controllable by using flexible loads**

The VPP in figure 5 consists of a windmill park, a building equipped with solar panels (prosumer) and a fleet of electric cars. The production of the renewable energy is intermitting and uncontrollable, but by using the batteries of the electric cars that are connected to the grid as a buffer, the production becomes controllable. Hence unbalances in the grid can be avoided and better revenues can be made from the produced energy.

**CASE HOOGTIJ**

In this research a case study for a smart grid application has been preformed. The municipality of Zaanstad, who is a partner in this study, requested to investigate the added value of a smart grid for the industrial development area HoogTij. The aim for HoogTij is to create a sustainable energy infrastructure: Development for wind turbines is taking place and a collective heat/cold network is planned. One of the alternatives is to produce heat and cold for the heat grid by a collective heat pump. Heat pumps are efficient devices, which use heat from the surrounding air or (ground) water to produce heat. These heat pumps can have flexibility in their operation, together with the projected wind turbines, the ingredients for a smart grid application are identified. To be able to operate the heat pump in a flexible way, heat storage should be available to buffer the heat temporarily. A heat buffer tank or the mass of buildings can be used to store the heat, so that the production of heat can be optimized on the availability of electric energy.
Currently, only a few companies have settled on HoogTij, however, the Rijksgebouwendienst has issued a tender for the construction of a new detention centre at HoogTij. In a study on a collective heat grid, the detention centre is observed as the client with the highest demand for heat. Since it is also an actual development at the moment, the detention centre can become a 'launching customer' to develop the heat grid.
To assess the economic benefits of the potential smart grid for HoogTij, a few business models where selected. The model for contract optimization can be used; benefits of using day/night tariffs are tested. Creating a smart micro grid seems as a promising scenario as well. The wind turbine and the heat pump can be placed in a micro grid, and thus share the same connection to the public grid (figure 6). In this way, the heat pump can directly uses the energy that is generated by the windmill. The heat pump exploits its flexibility to optimise the share of wind energy: the production of heat is matched to the availability of wind energy.
Besides the benefits of the better integration of wind energy in the electricity grid, there is a financial benefit. The rate for power supplied by the windmill is lower than the rates that are offered by energy suppliers. Since no taxes and transport costs apply on the energy that is supplied by the windmill, an interesting price difference applies. In this case, the use of a heat buffer tank and passive heat storage are tested.

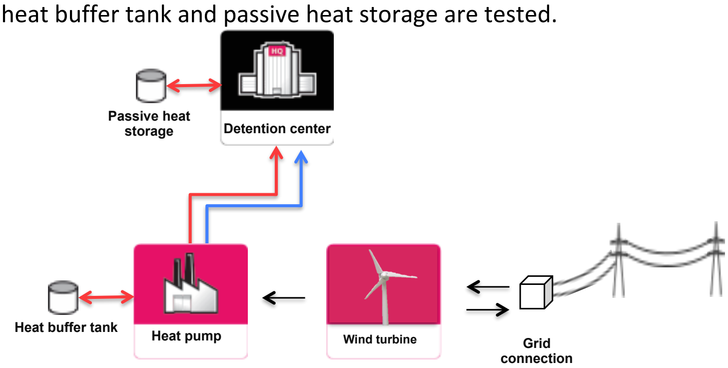


**Figure 6 Proposed smart micro grid scenario. Production of heat is optimised to the availability of wind energy, by using heat storage in building mass or heat buffer tanks.**

To assess the financial benefits and the improvement of integration of wind energy in this smart grid, an agent based simulation model has been developed to test the various scenarios. The agents in this model represent the wind turbine, the buildings, heat pump, and the heat buffer. To simulate the production of the wind turbine, a KNMI dataset of hourly wind speed measurements is used and converted to wind speeds that occur at the hub-height (90 meter) of the wind turbine, and randomized to 15-minute time slots. By using a typical power curve of a wind turbine, the energy production is simulated.

Using a model for losses by transmission and ventilation simulates heat demand of the building. The heat demand is corrected by the internal heat gain by sunshine and the presence of occupants. To calculate heat demand, a dataset of outdoor temperature and solar intensity is used. A number of assumptions had to be made on the building characteristics, such as the shape and the performance of building materials.

Heat pumps transfer heat from a low temperature source to a higher temperature, which is suitable to heat buildings. As a heat source, the water from the nearby canal is used. The production of the heat pump is calculated based on the coefficient of performance (COP), which gives the relation of required electrical energy to the produced heat. To operate the heat pump flexible, an optimization is made by using heat storage capacity. This heat buffer can simulate the optimization in the various scenarios. The capacity of the heat pump and the heat buffer turned out to be the determinants of the flexibility of the system. In figure 7, a screenshot of the developed Netlogo simulation model is given.

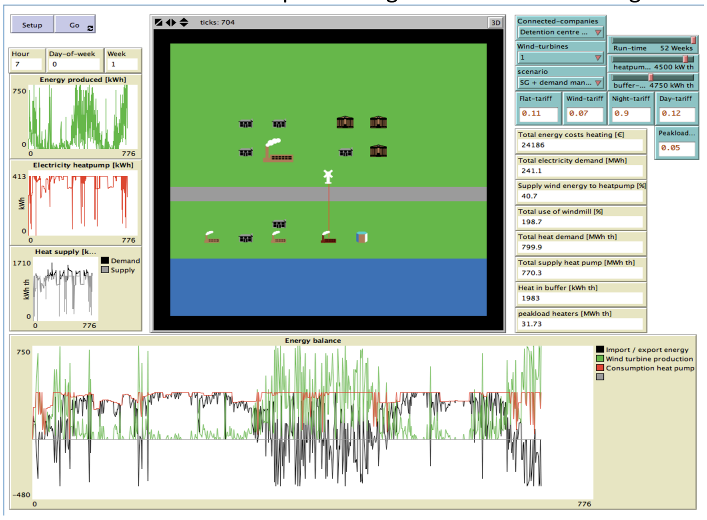


**Figure 7 The model simulates the production of the wind turbine and the flexibility of the heat pump is used to match this.**

## RESULTS

The simulation study indicates a significant saving in energy costs for the heat network. In the scenarios for contract optimization (day/night tariffs) cost savings of 7% can be made. The scenario of the micro grid is more interesting; just connecting the wind turbine to the heat pump can result in a 18% cost saving but has no benefit for the integration of wind power. The smart grid scenario with passive heat storage and has the greatest benefit for both costs as well as the integration of wind energy. A cost saving of 23% can be achieved, and the heat pump is supplied by 82% of wind energy (figure 8). The heat pump can consume about 9% of the total supply of the wind turbine to heat the buildings of the detention centre.

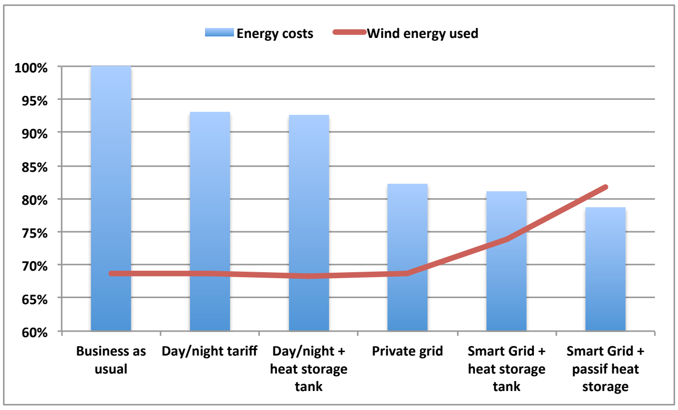


**Figure 8 Results of energy costs and the fraction of wind energy that is used in different scenarios of the simulation**

The smart grid significantly reduces the energy costs for the heat network, and hence improves the business case for this heat grid. To find out how much the business case is improved, the exploitation is calculated as well. In the business as usual scenario, the project is acceptable, but not very attractive for investors to develop. Yet, the smart grid alternative makes the exploitation very profitable! Some key facts of the business case of the heat/cold network are given in table 1.

| | Business as usual | Smart Grid |
|---|---|---|
| **Investment** | € 414.000, - | € 472.000, - |
| **Pay back time [year]** | 11,1 | 7,6 |
| **Internal Rate of Return** | 7% | 14% |
| **Net present value [7%, 15 years]** | € 1450, - | € 139.000 |
| **$CO_2$ reduction** | 19% | 73% |

**Table 1 Most important findings of the business case calculation of the heat/cold network.**

**CONCLUSION**

To make a transition towards an economy that is based on renewable energy, solutions have to be found to deal with the uncontrollable and intermitting supply of renewable energy sources. Industrial processes can have flexibility in demand that can be used to match this intermitting supply. Although the industrial sector makes a range of different products and services, flexibility can be exploited based on similar concepts. Thermal applications, pumps and production lines can be used flexible by optimizing the production and using the available storage spaces in a smart way. The identified flexibility has economic value; to exploit this, four business models are proposed, which can be applied widely.

The case of the industrial development HoogTij is a good example of an application of smart grid technology. Flexibility that is present in the system of the heat network can be exploited in a smart grid. The economic benefits are so significant, that it makes the heat network profitable. Hence, this case can really improve the sustainability of the development of HoogTij. A feasible way to accomplish this is to establish a local sustainable energy company where the different stakeholders collaborate, and the benefits can be shared.

The developed simulation model can be used in further research on thermal applications in smart grids. Extensions can be made by adding agents for different processes; an interesting study would be to operate the municipal pumping stations in a smart grid. These pumps generally operate a few hours per day, hence flexibility could be found here.

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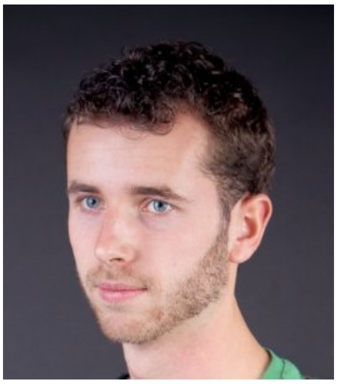

**F.S. (Simon) Lubach**

*'Every clarification breeds new questions'*

The development of smart grids is a complex problem, and a great challenge to investigate!

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91

# Appendix IV Dutch summary

## SMART GRIDS VOOR INDUSTRIEGEBIEDEN

## Verdien modellen voor de implementatie van duurzame energie

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Construction Management and Urban Development 2012-2013

**Afstudeer committee:**
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**Datum van afstuderen:**
12-03-13

**ABSTRACT**
Het gebruik van energie uit hernieuwbare bronnen groeit en een transitie in de energievoorziening wordt verwacht. Duurzame energie uit zon en wind is echter oncontroleerbaar en kan onbalans veroorzaken in het elektriciteitssysteem. Om duurzame energie te implementeren zijn smart grids nodig om vraag en aanbod af te stemmen. De industriële sector bied een groot potentieel om vraagsturing toe te passen en in te spelen op het wisselende aanbod van energie. Concepten voor flexibel gebruik van energie zijn onderzocht. Deze flexibiliteit heeft ook economische waarde; verdienmodellen voor smart grid toepassingen zijn gegeven. In een case studie is een voorbeeld gegeven van een smart grid toepassing voor een collectief warmte/koude-netwerk op een industrieterrein. Een agent based simulatiemodel optimaliseert het energieverbruik, wat resulteert in toename van het gebruik van hernieuwbare energie en een substantiële daling van de kosten.

**Keywords**: Smart grids, duurzame energie, vraagsturing, industrieel energiegebruik, agent-based simulatie.

**INTRODUCTIE**
Het gebruik van duurzaam opgewekte energie is groeiend en het is te verwachten dat er een transitie komt van energiegebruik van fossiele brandstoffen naar duurzaam opgewekte energie, bijvoorbeeld door gebruik van de energie van de zon en wind. Dit is belangrijk om klimaatverandering tegen te gaan, maar ook omdat fossiele bronnen opraken, kosten stijgen en het winnen ervan ongewenste afhankelijkheden van instabiele regio's met zich meebrengt. Om een transitie naar duurzame energie te maken, is er ook een omschakeling nodig in het elektriciteit netwerk. Het willekeurige en oncontroleerbare karakter van duurzame energiebronnen geeft problemen in het netwerk en zonder aanpassingen kan er niet meer dan 20 tot 25% duurzame energie worden gebruikt (Stadler, 2008). Het toepassen van smart grids is noodzakelijk om de energietransitie mogelijk te maken; in een smart grid kunnen vraag en aanbod met elkaar worden afgestemd en kan energietransport op efficiënte wijze plaatsvinden. De industriële sector heeft grote potentie voor smart grids; vraagsturing en variabele energieprijzen zijn van oudsher bekend en kosten kunnen worden

bespaart. Om de centrale vraag “Hoe kunnen smart grids bijdragen aan de integratie van duurzame energie op industriegebieden” te onderzoeken is een literatuurstudie uitgevoerd naar smart grids, de energie markt en vraagsturing in de industrie. Een case studie is uitgevoerd naar een smart grid toepassing voor een bedrijventerrein wat in ontwikkeling is. Hiervoor is gebruik gemaakt van een agent-based simulatie model, wat de business case van het smart grid inzichtelijk heeft gemaakt.

**SMART GRIDS**

De toepassing van energie uit zon en wind geeft problemen op het elektriciteit netwerk. Het wisselende aanbod geeft onbalans, wat fataal kan zijn voor de energievoorziening. Om duurzame energie beter in het netwerk op te nemen is vraagsturing noodzakelijk; dit is een radicale verandering van het systeem en het hoofddoel van smart grids. Hoewel er geen eenzijdige definitie is van een smart grid, geeft de definitie van het Europese technologie platform (smartgrids.eu, 2006) een goede indicatie. Zij definiëren een smart grid als “een elektriciteit netwerk dat intelligent de acties van alle aangesloten gebruikers integreert – producenten, consumenten en zij die dat beide doen, om efficiënt, duurzaam, economisch en veilig elektriciteit te leveren”. Alle actoren die een rol hebben in de voorziening van elektriciteit kunnen voordelen ondervinden van de flexibiliteit van smart grids, maar deze flexibiliteit is in handen van de consumenten, die hun energievraag aan kunnen passen door middel van smart grid techniek.

**FLEXIBEL ENERGIE GEBRUIK**

Vraagsturing om het electriciteitsnetwerk in balans te houden vind al sinds jaar en dag plaats in de industrie. Grote industriecomplexen kunnen binnen enkele minuten hun verbruik aanpassen om de balans op het netwerk te behouden of plannen productieprocessen wanneer de energie goedkoop is. De fractie van het energiegebruik dat reageert op prijsverandering of door de netbeheerder gestuurd kan worden is echter zeer laag. In veel gevallen komt de productie ook tijdelijk stil te liggen en gaan materiaal en manuren verloren. Het doel van smart grids is om energiegebruik intelligent te sturen, zonder dat dit het primaire proces beïnvloed. De flexibiliteit van energiegebruik word bepaald door de hoeveelheid vermogen en de tijdsspanne waarin deze gestuurd kan worden. Hoewel er vele productieprocessen in de industrie plaatsvinden, kunnen er wel classificaties gemaakt worden van universele processen. Flexibiliteit in energiegebruik kan bijvoorbeeld worden gevonden in thermische processen (Grein (2011) en Hovgaard (2012)); producten of ruimtes hebben een bepaalde bandbreedte waarbinnen de temperatuur moet blijven. Zonder deze te overschrijden kan het gebruik geoptimaliseerd worden. Warmte en koude is ook goed op te slaan, waardoor de flexibiliteit aanzienlijk kan worden vergroot. Vrieshuizen kunnen goed gebruik maken van dit principe; door de temperatuur iets te verlagen als er veel energie beschikbaar is, kan de koelinstallatie daarna enkele uren uitgeschakeld worden, waardoor het goed kan inspelen op een wisselend aanbod van energie. Toepassingen van pompen en productieprocessen waarbij er opslagruimte beschikbaar is hebben ook de mogelijkheid om op hun energievraag af te stemmen in een smart grid. Voorbeelden kunnen worden gevonden bij gemalen, rioolverwerking, cement industrie, papier productie, voedselbereiding, etc. Wanneer delen van productieprocessen niet continue in werking zijn, kunnen deze slim worden aangestuurd.

**VERDIENMODELLEN**

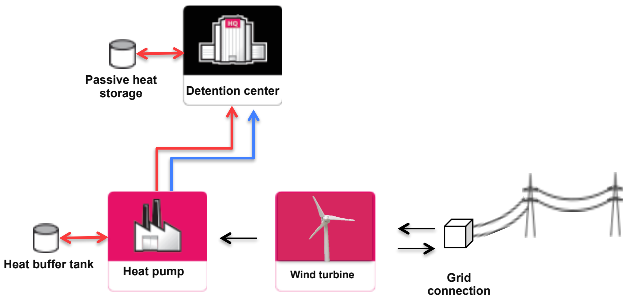
Flexibiliteit in energiegebruik heeft een economische waarde, welke benut kan worden. In een smart grid kunnen vraag en aanbod met elkaar worden afgestemd met behulp van een markt mechanisme. Hiervoor zijn vier verdienmodellen gegeven, gebaseerd op onderzoek van e-harbours (2012): **Contract optimalisatie** is een universeel toepasbare manier om energiekosten te verlagen. Door gebruik te maken van variabele tarieven, zoals dag/nacht tarieven of uur prijzen, kan worden ingespeeld op het wisselende aanbod. Een ander verdienmodel is het **handelen op de onbalansmarkt**. Hier wordt per kwartier vraag- en aanbod op elkaar afgestemd op een speciaal marktplatform. Dit is echter alleen toegankelijk voor klanten met een aanzienlijk groot vermogen. Een alternatief is om de flexibiliteit aan te bieden aan de *programma verantwoordelijke partij*. Deze partijen hebben een contractuele rol in het in balans houden van vraag en aanbod en kunnen de flexibiliteit in energiegebruik benutten. **Smart micro grids** zijn lokale, privaat aangelegde electriciteitsnetwerken welke buiten het zeggenschap van de netbeheerder vallen. Binnen een micro grid zijn er meer mogelijkheden om onderling energie te verhandelen en kan het lonend zijn om lokaal opgewekte energie, bijvoorbeeld van een windturbine te gebruiken. Het meest geavanceerde verdienmodel is dat van een **virtual power plant**. Hierin wordt er een cluster gevormd van kleinschalige producenten en consumenten met een stuurbare energievraag. De oncontroleerbaar opgewekte energie uit zon- en windkracht kan zo betrouwbaarder en voorspelbaar aan het netwerk en aan de energiemarkt worden geleverd.

**CASE STUDIE HOOGTIJ**

In dit onderzoek is een case studie uitgevoerd naar een smart grid toepassing op het in ontwikkeling zijnde industrieterrein HoogTij. Dit terrein wordt duurzaam ontwikkeld, waarbij er windturbines worden geplaats en een collectief warmte/koude netwerk wordt aangelegd. Een optie voor de opwekking van deze warmte en koude is door gebruik te maken van warmtepompen. De ontwikkeling van windturbines en het warmtenetwerk geeft een interessante optie voor een smart grid: Productie van warmte heeft enige flexibiliteit kan zo inspelen op het fluctuerende aanbod van de windturbine. De mogelijkheid om warmte op te slaan, bijvoorbeeld in een buffervat of in de massa van gebouwen die worden verwarmd vergroot de flexibiliteit van de warmtepomp. Het toepassen van een smart micro grid, waarbij de windturbine en de warmtepomp dezelfde aansluiting op het netwerk delen geeft een prijsvoordeel voor het gebruik van de lokaal opgewekte energie, waardoor er een prijsprikkel is om het gebruik van windenergie te optimaliseren.

Hoewel er nog weinig bedrijven zijn gevestigd op HoogTij, is er een ontwikkeling gaande van een gevangeniscomplex. Dit complex heeft een aanzienlijke warmtevraag en vormt daardoor een belangrijke rol in het warmtenetwerk. Het smart grid scenario, welke is onderzocht voor HoogTij is weergegeven in figuur 1.

Om de business case van dit smart grid te onderzoeken is een agent-based simulatie model ontwikkeld. De werking van de windturbine, warmtepomp, gebouwen en warmtebuffers word gesimuleerd door ‘agents’. In verschillende scenario’s worden optimalisaties gemaakt waarbij de verdienmodellen voor contract optimalisatie en smart micro grids zijn getest.




**Figuur 1 Smart micro grid scenario met een windturbine en een warmtepomp, welke flexibel is door gebruik van warmte opslag**

## RESULTATEN

De simulatie geeft duidelijk aan dat er een haalbare business case is voor een smart grid toepassing: Kostenbesparing voor de warmtepomp kan oplopen tot 23%. De integratie van windenergie verbeterd ook, de warmtepomp kan voor 82% worden voorzien van duurzame energie, wat ongeveer 9% is van de totaal opgewekte energie. De besparing op kosten voor de warmtepomp is dusdanig, dat dit een groot effect heeft op de exploitatie van het warmtenetwerk. Uit berekeningen van de exploitatie, blijkt dat het business as usual scenario een zwakke business case is en dus lastig te realiseren. Door de optimalisatie van het smart grid wordt het warmtenetwerk een lucratieve investering.

## CONCLUSIE

Om een transitie te maken naar duurzame energie is noodzakelijk een oplossing te vinden om met het wisselende en oncontroleerbare aanbod van energie om te gaan. De flexibiliteit van industriële processen kan hierbij een belangrijke rol spelen. Hoewel energie wordt gebruikt in talloze processen zijn er wel groeperingen te maken waarbij flexibiliteit op vergelijkbare wijze kan worden benut. Deze flexibiliteit heeft een economische waarde, deze kan met de voorgestelde verdienmodellen worden gebruikt om kosten te reduceren. De case naar het smart grid voor HoogTij laat zien hoe de flexibiliteit van het warmtenetwerk kan inspelen op het wisselende aanbod van energie. De kostenbesparing die hierbij kan worden gevonden is dusdanig, dat het netwerk rendabel wordt. Zo kan dit smart grid echt bijdragen aan de duurzame ontwikkeling van HoogTij.

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