Energy Self-Sufficient Neighborhoods in the Netherlands*: a technical framework on the energy storage & land usage requirement for intermittent renewable energy systems*

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Colophon

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Executive Summary

A societal scale shift towards a renewable energy production system is necessary in order to reduce dependency on limited natural resources and address climate change. While countless social, political, and economic barriers limit the development of such a system, from a technical perspective the problem of intermittency is central. Intermittency, in this case, refers to the partially predictable variability of power production due to the effects of weather, seasons, and limited daylight hours. Energy storage is the solution to this problem, and therefore essential to the widespread implementation of renewable energy production.

It is proposed that large interconnected systems such as a European Super Smart Grid offer one potential solution to intermittency, which is in effect a partial continuation of our existing large-scale centralized energy system paradigm; the opposing local, decentralized energy production systems paradigm has been gaining support in the Netherlands and beyond. In such systems, residential neighborhoods limit production of energy to within their own boundaries, and regulate supply and demand without reliance on external grid connections.

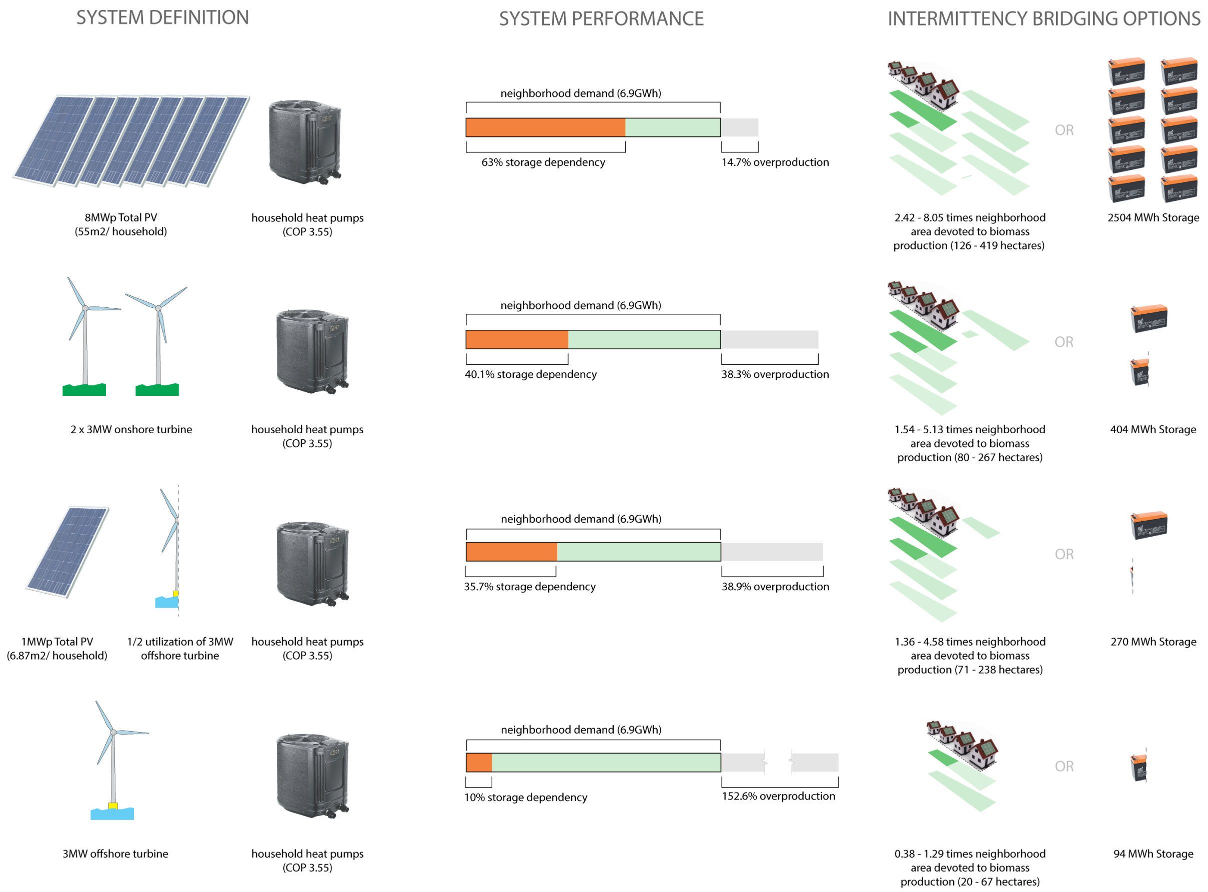
Despite this increased interest, current research has limited applicability to such a system in the Netherlands. Knowledge gaps exists because either existing research focuses on systems that are too highly idealized, and therefore unrealistic: energy demand that is too low, land intensity that is too high, very favorable climatic conditions, or an exclusion of energy storage from the system. Furthermore, current literature and practices related to energy storage and renewable energy systems, is of limited applicability to the Dutch context as energy storage capacity is bound to characteristics of the location at which the energy is produced and consumed by virtue of its dependency on wind speed, solar irradiation, and air temperature.

To address this knowledge gap, this thesis poses the primary research question, “To what degree could a self-sufficient and stable decentralized renewable energy system without a grid connection, be created today within the context of a Dutch residential neighborhood, and what form and quantity of energy storage would be required?” In addition to this main research question, sub-questions concerning the size of the intermittencies, the land required for biomass production as an alternative to energy storage, and the effect of flexible demand on the amount of energy storage are posed to better characterize the design and operation of such a system.

To answer these questions, we characterize and model a prototypical Dutch residential neighborhood of 1038 houses and 2279 inhabitants spread over an area of 52 hectares, 3 hectares of which are available for agricultural/biomass production. The energy demand profile of the neighborhood, extrapolated from historical data for the years 2004 – 2011, is used as an input for the EnergyPlan model which is able to calculate the hour-by-hour operation of the energy production system, and to examine the operation and effectiveness of different generation technology mixes including onshore and offshore wind, PV and heat pumps.

Using this model, the main research question was analyzed by simulating the operation of a Compress Air Energy Storage (CAES) system with 70% round-trip efficiency operating to allow for a self contained, 100% renewable system. This simulation produced detailed figures on the hour-to-hour operation of the system, including maximum capacity and usage through time, and the relationship between energy storage usage and specific generation technologies. Additionally, the land-area needed for biomass production is calculated, if biomass where to be

used in place of energy storage as a means to address the intermittency of generation. The results from four system configurations can be seen in the figure below.



The degree of intermittency, here represented as the percentage of the total energy demand drawn from storages, ranges from 10% for an offshore wind turbine based system located in Vlieland, to 63% for an all PV system located in De Bilt.

Storage requirements decrease noticeably when energy systems consist of a mix of sources: in a hybrid wind/PV systems, storage capacity is decreased almost 10% relative to a wind only system, and storage usage is decreased 10-15% for each additional 1 MWp in PV capacity. This effect, however, diminishes as PV capacity is increased further. In PV and onshore wind based system, energy storage capacity is required primarily for seasonal differences in demand and production, while in offshore wind systems, storage capacity is determined primarily by the need for balancing on the scale of several hours, and not days or seasons.

Another key variable that determines the amount of storage required is the capacity sizing of the renewable energy technologies. Oversizing of the system reduces the amount of storage needed, but increases surplus production. All of the energy systems exhibit surplus production, with values ranging from 20% to more than 100%. This balance is primarily a matter of economic optimization, with the cost of building additional storage capacity weighed against the cost of increasing the energy supply capacity. The technical and operational advantages of production biased and storage biased systems, however, are a topic that must be explored in future research, especially given that as penetration of electrical vehicles increases, additional production will be required to meet increasing electricity consumption. While flexible charging may allow for the useful consumption of this production on a hour-to-hour scale, an increase in seasonal storage will also be required because electrical vehicles, similar to demand response, can only delay consumption for a matter of hours, and therefore cannot decrease seasonal production imbalances, and may in fact increase them in absolute terms due to increased total consumption.

In addition to simulating the operation of multiple generation technology mixes, the model developed was also used to quantify the impact of energy savings and demand response in decreasing storage requirements. Energy savings of 30% are shown to be extremely effective, with a reduction in required storage capacity of between 45 – 65% and a reduction in usage of between 30 – 40%. However, demand response (with the assumption that 30% of the electricity demand is flexible), shows only limited effectiveness, with a decrease in required storage capacity of only around 5% in most cases.

Finally, as clearly shown in the diagram above, the land area required for biomass generation is in all cases significantly greater than the total land area of the neighborhood, and astronomically larger than the available agricultural land. As such, it is demonstrated that biomass is not a feasible option for self-contained renewable energy systems when production is limited to the neighborhood footprint and the question should be pondered to what extent purely decentralized renewable energy systems make actual sense.

All the above describe results are derived from modeled data based on detailed assumption. As with all results based on models, these need to be treated with extreme care, for models only provide a sense of direction for the truth but not an absolute truth. The primary purpose of this research was to create a technical framework to uncover the preconditions in terms of storage capacity requirement needed for different types of renewable energy systems. To look for a sense of consistency in an extremely dynamic relation between energy demand and intermittent renewable energy supply.

These findings strongly suggest that when striving for 100% renewable energy systems and energy storage minimization, Dutch energy policy should focus on supporting (financially) energy savings and offshore wind, and leave the development of PV and onshore wind to civil and market initiatives.

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Section I: INTRODUCTION

Chapter 1: Introduction

1.1 Background

At present humanity is confronted with large-scale environmental and economic problems as a result of our current fossil fuel based energy system. Carbon dioxide emissions are contributing to climate change, while the growing demand for fossil fuels and limited supply has resulted in rising fuel prices resulting in a growing (societal) interest in renewable energy resources as a substitute (Bouffard, 2008).

Renewable energy sources do not result in direct carbon-dioxide emissions, nor do they require the constant input of finite resources. At the same time, if produced locally, renewable energy contributes to energy security for countries with limited fossil fuel resources. However, considerable technical limitations and social-economic barriers limit the large-scale implementation of renewables. The single biggest technical challenge is the *intermittency* of power production by renewable technologies .

Intermittency, in the context of renewables, means that energy sources cannot always be dispatched as needed, and energy production is dependent on external variables such as the weather, causing problems with the balancing of supply and demand, on minute-to-minute, day-to-day, and weekly and seasonal time scales. These intermittencies can be regulated through energy storage, demand response or backup generation (biomass in a fully renewable system). Each of these three solutions faces severe techno-economic and societal limitations (Eyer, 2010).

In 2010 the European Renewable Energy Council (EREC) – a collaboration between European industrial associations of different renewable energy technologies – developed a vision for 100% renewable energy production that revised growth potential for different renewable energy technologies and proposed that within different European climatic zones, different technologies would be deployed: wind around the North Sea, photovoltaic (PV) & concentrated solar power (CSP) around the Mediterranean and biomass in Central Europe. By connecting all of Europe through a European Super Smart Grid, intermittencies would be dealt with through variations in geographical and climatic conditions and the different production profiles of each renewable energy technology. In addition, hydropower plants in Norway and Switzerland would act as batteries, biomass would act as back-up power, and “flexible demand” would aid in bridging (EREC, 2010). The combination of these technologies to harness aggregation and a scale to solve the problem of intermittencies sounds like a logical solution. However, the European “smart grid” vision has not yet been quantified, hence it cannot be stated with any certainty that such a super smart grid would be capable of providing a guaranteed *stable* energy supply. Because it is not guaranteed that the problem of intermittency would be solved, the amount of land required for the energy supply technologies or agricultural lands needed for backup generation also remains uncertain. This, and a myriad of other important questions, remain unanswered.

Such a renewable energy systems vision falls within the same energy system paradigm of large-scale centralized production systems that our current fossil fuel dominated energy system has defined. This energy system proposed by EREC will, however, require an extensive expansion of the grid to compensate for intermittencies and as a result of the lower energy density of renewables, will result in considerable opposition from civilians, who generally do not want more power lines in the landscape (Bouffard, 2008). The opposite approach is small-scale decentralized systems (often referred to as microgrids) that require substantially fewer interconnections. In such a system most of the energy is both produced and consumed locally and in theory could be better balanced. Furthermore, decentralized systems are less vulnerable to disturbance in the supply chain than centralized systems and are therefore less risky (Bouffard, 2008). Furthermore, decentralized systems fit nicely into the current movement romanticizing localization that has been gathering media attention over the last few years.

1.2 Problem Definition

In the centralized renewable energy vision of EREC, the degree to which a renewable energy system would be able to deal with intermittency while remaining completely free from fossil fuels has not yet been quantified. This remains difficult as a result of the high degree of uncertainty and speculation concerning the effects of a European Super Smart Grid. This draws into question the degree to which the opposing vision of a decentralized energy system would be able to be self-sufficient without fossil fuel inputs and stable/reliable, able to deal with the inherent intermittency of renewables, and whether this can be determined and implemented under present levels of technology and knowledge.

In order to investigate the possibility of such a decentralized system, the size and scope of a (residential) neighborhood was chosen. At this level it is possible to quantify the degree to which actual local demand can be met by local renewable energy supply independent of the grid. The Netherlands was chosen as a context for this research.

Based on an extensive literature review of both scientific articles and web-based searches, it can be concluded that in existing literature and practices there is a knowledge gap when it comes to the sort of decentralized stable, self-sufficient energy systems appropriate for neighborhoods in the Netherlands. It must be noted that these are generally small-scale projects or models of possible decentralized systems, not analysis of the operation of actual systems, or simulations of the operation of proposed systems in empirical contexts. As such, there are significant gaps in existing literature and practices that limit their applicability to Dutch neighborhoods. This is the case for the existing and theorized examples that exhibit:

- Too low levels of energy demand
- Too beneficial local weather patterns
- Too high levels of land intensity
- Reliance on external sources for regulation of intermittent sources

In the following paragraphs each point is elaborated and examples are used to explain why existing research cannot be compared to the Netherlands or cannot be considered a stable self-sufficient energy system.

1.2.1 Too low levels of energy demand

Self-sufficient, or autarkic, renewable energy systems have been set up in a number of developing countries for the purpose to prototyping rural off-grid electrification for implementation in countries such as China, Mexico, Kenya and Bangladesh. These energy systems often consist of photovoltaics with battery packs, or even backup diesel generators, and are located in tropical regions (Urmee, 2009). A number of studies have also been completed, including one in Cameroon, examining the potential of systems which combine PV, pico-hydro, wind and biogas, demonstrate that it is indeed possible to set up self-sufficient and stable system. However, the load for these systems is extremely low, only be equal to that of a couple of average Dutch households (Nfah, 2009). Hence, these examples cannot be compared to a Dutch neighborhood, comprised of hundreds or thousands of households. Generally, Dutch households have a much higher electricity demand, both as a result of higher affluence and the higher heat demand necessary in a much cooler climate.

1.2.2 Too beneficial local weather patterns

Other examples have exhibited extremely favorable climatic conditions or a set of unique conditions, which means that the output of renewable technologies is considerably higher than can be expected in real-world situations, thus making a decentralized self-sufficient system appear more effective than would otherwise be possible. Existing examples are for locations such as Turkish, Greek and Croatian islands, all of which exhibit extremely favorable wind speed and solar irradiation conditions, resulting in much higher system output than would be achieved in the Netherlands (Demiroren, 2010; Zafirakis et all., 2010; Duic, 2008). In the Netherlands itself, one example of a so-called "*energy neutral*" system exists: Duindorp in Scheveningen. It is a project consisting of 790 new houses. Two wind turbines of 2.6 MW and 3.2 MWth is extracted from seawater. When the temperature of the seawater is below 11 degrees, a central heat pump is used to increases the temperature. All houses have individual heat pumps, which increase the temperature for floor heating and warm tap water. Looking at the whole year, the area as a whole is energy neutral; however, a grid connection is needed for balancing, and the system therefore not self-sufficient (Cogen Projects, 2008). The conditions at Duindorp are rather unique conditions due to the proximity to the sea, and resulting higher than average wind speeds. Moreover, as the outside grid is used for balancing, there is a lack of internal balancing capacity. Hence, both examples depend upon considerable beneficial weather patterns which limit the transferability of results to more average Dutch decentralized energy system which would be confronted with lower solar irradiation, lower wind speeds, and no access to the sea.

1.2.3 Too high levels of land intensity

Combined heat and power (CHP) fuelled by biomass can act as carbon neutral backup for intermittent renewables, or even as a base-load. In combination with district heating it can act as a storage method or virtual power plant. However, the question then arises of where the biomass originates from; whether it originates from within the boundaries of the decentralized energy system or is, in fact, imported.

In most of the examples of countries or cities trying to achieve energy independence, biomass plays a substantial role. Lund et al. modeled the possibility for Denmark being energy independent by 2050. In order to achieve this, biomass production had to increase significantly, altering most of the Danish agricultural system from a wheat/rye to a corn based system. This would in a dramatic fashion increase the biomass production, but would also have major dietary and spatial consequences (Lund, 2009). A number of Danish cities have made more detailed plans to become energy self-sufficient, Frederikshavn, a city of 25,000 inhabitants, has proposed energy independence as early 2015 (Lund, 2010). However, this is dependent on both a connection to the grid for regulation, and the import of biomass for energy generation. A model was also made for the municipality of Aalborg, a city with 120,000 inhabitants. In contrast with Frederikshavn, Aalborg includes both the urban areas of the municipality and the extensive rural areas, allowing for the possibility of self-contained biomass production (Østergaard, 2010). Therefore, it can be concluded that, as a result of the import of biomass, the footprint of the energy system is considerably bigger than that of municipality itself, and that biomass production might be in competition with other spatial functions and may even have negative environmental effects, similar to those experienced with the development of palm oil production in Indonesia. This then raises the question: how much land is actually needed in order to provide a self-sufficient and stable energy system, and how can this be minimized? This is an important consideration, especially in the Netherlands, where population density is already very high and land available for biomass production is limited.

1.2.4 Reliance on external sources for regulation of intermittent sources

Intermittencies are one of the primary obstacles to implementation of 100% renewable energy. There are a number of neighborhoods in Malmo, Sweden and Freiburg, Germany (Malmo Stad, 2012; Vauben District, 2012) that are already claiming to be energy independent or energy neutral. Indeed these neighborhoods are producing enough energy to be deemed energy neutral, but are using the grid – still run on fossil fuels – for dealing with intermittencies. Because of this reliance on the grid, these systems are lacking storage capacity and hence are not dealing with the biggest obstacle of intermittent renewables: delivering energy as it is needed. Furthermore, as such systems rely on an energy system which itself still heavily reliant on fossil fuels, they are therefore also not CO_2 neutral. Other examples of 100% renewable energy system that deal with the intermittencies are backed-up by pumped-hydro, an option which is not available to the Netherlands (Krajacic, 2011).

In conclusion, there is a gap within the present literature based on the points mentioned above. What is evident in existing research is that different levels of aggregation are used to prove whether an energy system is self sufficient and stable. The one most commonly used is, in fact, the neighborhood level. In theory, if a neighborhood could be made energy self-sufficient, this could then be extrapolated to a country as a whole, at least in terms of heat and electricity demand for residential usage.

The preconditions are then that such a system is based on renewables, land intensity is minimized and the intermittencies are dealt with without interconnection to a larger grid. Otherwise the generalizability and applicability of such a model cannot be made. Through this it can be demonstrated if a decentralized system can, in theory, be possible within the Dutch context, and the extent to which such a system is preferred from a practical and cost perspective over a more hybrid centralized-decentralized system.

1.3 Aim

The aim of this thesis is to address the knowledge gap existing of whether it would be possible to create energy self-sufficient neighborhoods in the Netherlands using current technology, what such an energy system would look like, and what technical barriers limit the development of such a system.

1.4 Research question

The main research question is:
"To what degree could a self-sufficient and stable decentralized renewable energy system without a grid connection be created today within the context of a Dutch residential neighborhood, and what form and quantity of energy storage would be required?"

Associated with this main research question are number of main sub-questions:

i. What is the size of the intermittencies: discrepancy between the energy production of technologies such, as wind and PV, and energy demand, including both electricity and heat demand?
ii. What is the effect of demand response or flexible demand on the need for energy storage?
iii. As an alternative to energy storage, how much land would be required to produce the biomass for back-up capacity?
iv. To what extent can or should, energy supply technologies and storage facilities be located within the confines of the neighborhood?

The context of this research, the residential neighborhood primarily serves as a concrete context in which these abstract notions can be quantified. This residential neighborhood, it should be noted, is not based on any existing neighborhood, but is instead a hypothetical "average" neighborhood, and is therefore broadly applicable to existing neighborhoods. The focus of this research is on market-ready and near-to-market energy supply, storage and demand shifting technologies in combination with average electricity and heat demand levels. Electric vehicles and other potential future technologies are therefore not taken into account, nor are the energy demands of utilities, government services, industry or agriculture.

Using an average neighborhood serves the purpose of generalizability and scalability of results. This would not be possible if, for example, an entirely new energy efficient neighborhood would have been chosen as the context of this research, applicability would then be limited to entirely new neighborhoods. Also, the context of a neighborhood with a lower than average energy consumption was considered, but this is would negatively affect generalizability, partially due to the fact that the implementation of energy savings measures is low and is consistently below policy targets. In conclusion, the framework of this research is an average Dutch neighborhood, as it allows for maximum generalizability and scalability of results.

1.4 Methodology

In order to answer the main research question, the different components of the proposed energy system were researched individually, namely energy demand, supply and storage. The results of these sub-sections were then modeled using the EnergyPlan model in order to determine the degree of intermittency and calculate the necessary energy storage or bio-mass based back-up capacity required. In this section, the choice for the EnergyPlan model is explained, followed by an overview of the methodology of the research as a whole.

1.4.1 EnergyPlan

There are a large number of different energy models available. Based on the review of a number of articles and web-based searches, in combination with the necessary technical requirements, namely modeling intermittent sources, energy demand and energy storage, for both heat and electricity and demand response; it was concluded that the EnergyPlan model developed by Hendrik Lund from the University of Aalborg, is the most useful for this particular research (Lund & Duic, 2007; Duic, 2008; Connolly et all. 2010; Lund, 2007). Other options, including the HOMER and H2RES models, were considered, but EnergyPlan was chosen because of its increased prevalence in peer-reviewed research and ability to easily model the desired variables. EnergyPlan also allows for easy scaling of the energy system from a local to national level, thus offering opportunities for future research.

The EnergyPlan model is extremely accessible and allows for an hour-to-hour simulation of a defined energy system over the period of one year. In this research, the focus is on renewable energy, residential electricity and heat consumption, and energy storage; however, a large number of other components of the energy system such as transportation and cooling can be modeled, as can be seen in figure 1.1. In addition to technical optimizations, economic optimizations are also possible.

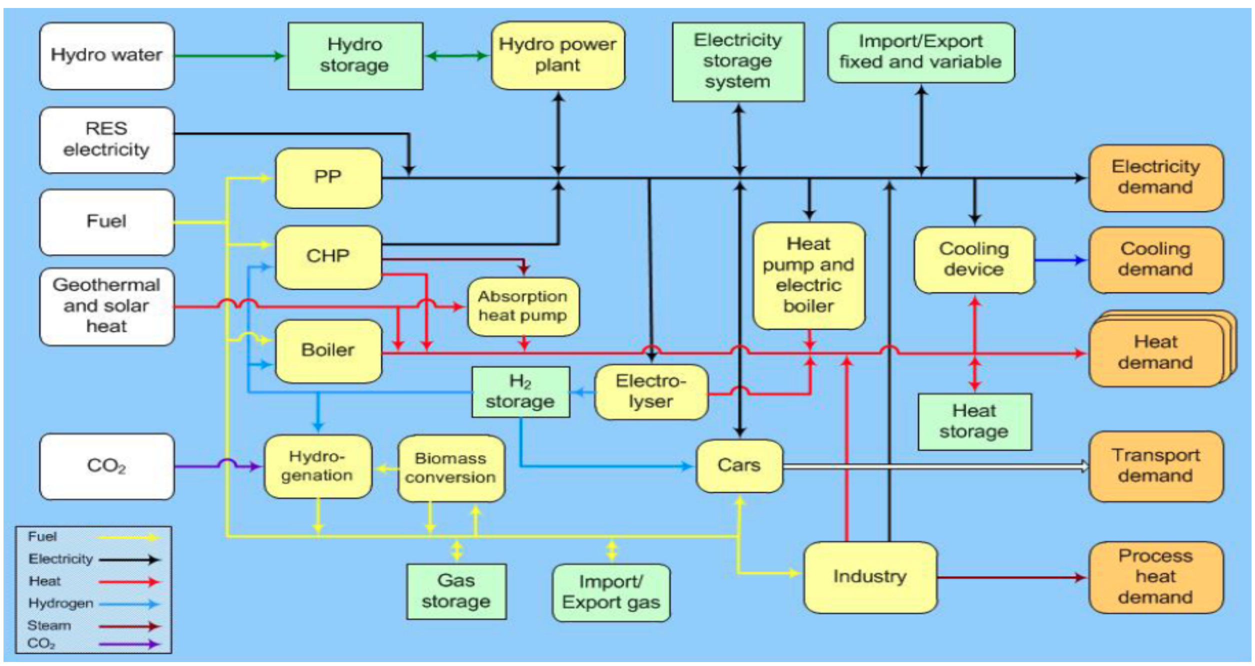

Figure 1.1: Overview of EnergyPlan variables (Lund, 2012)

The input parameters for each of the individual components generally consist of two variables: the *distribution* on an hour-to-hour basis for 1 year of either consumption or production, and the *total* demand or installed capacity. Graphically, the distribution represents the shape of the curve, while total demand or capacity represents the scale of the curve. In the case of energy storage, parameters such as storage efficiency, storage capacity and the capacity of the storage device are also required as input. Based on energy demand and supply profile, inconsistencies are then calculated, and from these calculations storage usage and storage capacity are derived. The EnergyPlan output is either a technical or cost optimization, and shows how both the electricity and heat demand are met, and the amount of energy storage and the energy imports/exports that occur on an hour-to-hour basis.

As has been pointed out earlier, the two primary problems with renewable energy are land intensity and intermittency. In order to determine the extent of these hurdles a large number of different scenarios were run in the EnergyPlan model. Results were based on the years 2004-2011, a number of locations within the Netherlands, and multiple mixes of energy production technologies. The number of variables used are far fewer than can in fact be run in EnergyPlan. Figure 1.2, depicts the different variables and the relation they have to one another. A number of difficulties arose when modeling the potentially important technologies of Combined Heat-Power plants (CHP) and heat storage, and for this reason these technologies were not modeled. Instead, they are shortly discussed in Chapter 8 & 10.

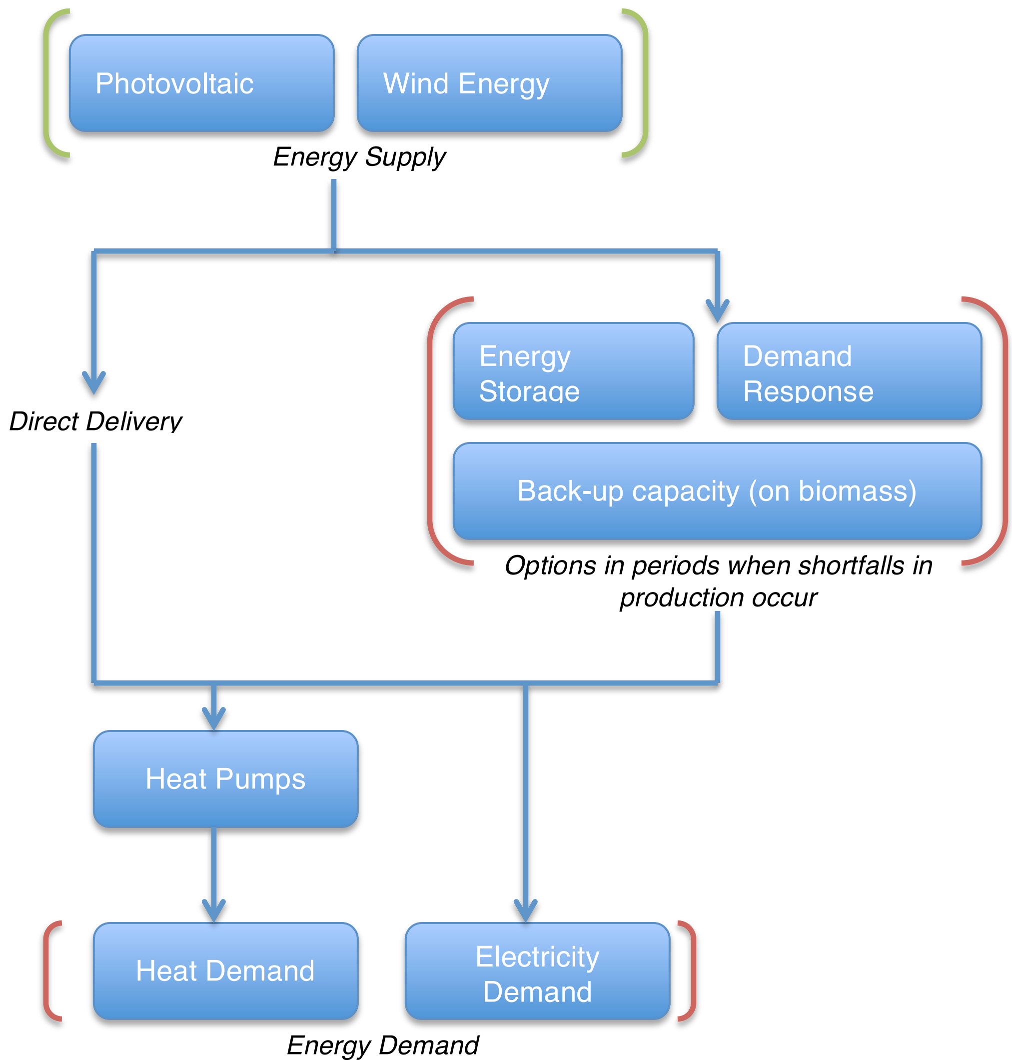

Figure 1.2: Overview of components modeled in EnergyPlan

1.4.2 Research Steps

The first step in this research was defining the model neighborhood, both in terms of population/household size and land usage. (Section II), this was done by running a statistical analysis of the "*Kerncijfers wijken en buurten 2004-2011"* database made available by the Central Statistics Agency (CBS). The energy demand, subdivided in the electricity and heat demand is discussed in Section III. For both types of demand, both total demand and distribution of the demand throughout the year had to be gathered. Data for this chapter was collected through desk research, CBS data, data from the grid operator Tennet, interviews at TNO, and temperature data from the Royal Netherland Meteorological Institute (KNMI).

Section IV is concerned with the different energy supply technologies, namely wind, PV and heat pumps. At the beginning of this section it is also explained why these specific technologies are chosen. For wind and PV, the inputs in EnergyPlan were installed capacity and the distribution of energy production. The data for these factors was generated through weather data from the KNMI and modeling methods found in literature. For heat pumps, the inputs are the earlier mentioned distribution of the heat demand and the so-called coefficient of performance (COP) as found in existing literature.

The technologies that help in bridging the intermittencies resulting from fluctuations in the energy supply are discussed in section V, namely energy storage, back-up capacity based on biomass and demand response.

In section VI, the results, based on the above-mentioned inputs, are presented for a number of energy systems with different compositions. For each energy system the maximum required storage capacity, storage usage and surplus production are presented, as well as the effects of demand response and the amount of land required if instead of storage, biomass based back-up capacity was used. These results are followed by a sensitivity analysis that examines the strength of these findings when faced with reasonable variation in the values of key variables

1.5 Reading guide

Figure 1.3 shows a reading guide of the different sections and chapters. Sections II – V contain the methodology and assumptions that have been used for the different scenarios. In the beginning of Section VI an overview of these assumptions is presented.

Section I: Introduction	•Chapter 1: Introduction
Section II: Framework	•Chapter 2:Population & Spatial characteristics of an average residential neighborhood
Section III: Energy Demand	•Chapter 3 Energy Demand
Section IV: Energy Supply	•Chapter 4: Overview Energy Supply Technologies •Chapter 5: Wind Energy •Chapter 6: Photovoltaic •Chapter 7: Heat Pumps
Section V: Overcoming Intermittencies	•Chapter 8: Energy Storage •Chapter 9: Back-up Capacity on Biomass •Chapter 10: Demand Response
Section VI: Results	•Chapter 11: Overview assumptions •Chapter 12: Results •Chapter 13: Sensitivity Analysis
Section VII: Discussion & Conclusion	•Chapter 14: Discussion & Conclusion

Figure 1.3: Reading guide

Section II: the Framework

Chapter 2: Population & Spatial characteristics of an average residential neighborhood

In order to be able to determine the feasibility of a 100% renewable energy system within the context of a Dutch neighborhood, the parameters and characteristics of an 'average' neighborhood first need to be determined; in other words the scope. The most important sets of parameters are the population size, the amount of (available) land and land usage, which will be discussed below, including a sensitivity analysis.

These characteristics of an average neighborhood were determined by using the data-set "*Kerncijfers wijken en buurten 2004-2011"* from the Central Statistics Agency (CBS, 2012). This data-set is very comprehensive, comprising of information ranging from demographics, housing stock, average energy consumption, economy, services and space usage, for every municipality, district and neighborhood in the Netherlands for the period 2004-2011. Although most of the data has been measured every year, some of the data points have only been measured in specific years. The year that contained most relevant and recent data points was the year 2008. This is primarily the result of including, information concerning the space usage, hence all tests in this chapter have been based on 2008.

The statistical program that was used in the determining the means and standard deviations in this chapter is IBM SPSS Statistics© Version 20.

2.1 Defining a "neighborhood" – average population size

There are a multitude of definitions for what constitutes a neighborhood, and average size often differs per country; in countries with lower population density (e.g. in the United States), the subdivision neighborhood often contains fewer inhabitants than in countries with higher population density (such as the Netherlands) (Kaplan, 2008).

Based on the information and definitions of the CBS, there are three "local" subdivisions: municipalities/counties, (city) districts/boroughs and neighborhoods. The municipalities (*gemeente)* can be found in many shapes and sizes, but often consists either of a city and the surrounding areas or of a collection of villages. Within a municipality there are another two subdivisions, namely districts or boroughs (*wijken)* and neighborhoods (*buurten*). Neighborhoods are the smallest local subdivision; the boundaries of the neighborhood are often the result of landscape characteristics or (historical) social-economic structures. *Wijken* comprise of the aggregate of a number of connected *neighborhoods*.

The subdivision 'neighborhood', as defined by the CBS, offers the 'cleanest' data, because municipalities often comprise of distinctive villages or towns, these are defined within the dataset of the CBS as "wijk", but this might also include the surrounding countryside. Therefore villages are also subdivided in "buurten", for example between the village "proper" (*bebouwde kom)* and surrounding houses which are not located within the confines of the village are often referred to as " *verspreide huizen",* the aggregate of the village proper and surrounding houses equates to the "wijk" level (CBS Dataset, 2012; CBS, 2012). [1]

Selecting an average population (density) for a "neighborhood", determines to a large extent the scalability and should resemble a real Dutch neighborhoods as much as possible, for in Chapter 3 it will be shown that household size and population density influence the demand for electricity and heat. In 2012, the overall population size of the Netherlands is 16,655,800 inhabitants, with a population density of 494 inhabitants per km^2, which is one of the highest in the world. As a result of the high level of urbanization (83%), local population densities are even much higher; hence an average neighborhood has a far higher population density than the national average.

The CBS depicts this higher density and the degree of urbanization/human activity through the usage of the metric "*density of addresses per square kilometer*", and has been subdivided in 5 categories, as shown in table 2.1. This metric does not only contain residential buildings, but also offices, shops, government buildings and industry. This metric gives a good specification of the availability and usage of land within a neighborhood.

Table 2.1: Categories address density

Category	**Degree of urbanization**	**# addresses per km^2**
I	Very high	>2500
II	High	1500 - 2500
III	Intermediate	1000 - 1500
IV	Low	500 - 1000
V	Non-urban/rural	<500

On average most Dutch citizens reside in a Category-II neighborhood with high degree of urbanization according to the CBS, with an address density of 1908 per km^2 in 2011 (CBS Dataset, 2012). In order to give a representative view of space usage in the Netherlands and the degree of scalability for this study, the CBS dataset was subdivided in these different address categories in SPSS in order to be able to find the specific average population size, land availability and usage. Subdividing the dataset based on mere population density does not portray a representative view of the available non-build environment within a neighborhood; while address density can be considered to be more illustrative of the actual 'free' space. Space usage is an important facet in determining the amount of biomass a neighborhood will be able to produce for energy production. Separate descriptive analyses were done for each of the categories for the relevant variables. The results for the average number of inhabitants and households and can be seen in table 2.2. Dividing the means of the number of inhabitants and households results in an average household size of 2.2, this is the same as the national average. The mean of the address density is also close to the national average, thereby reaffirming that the Category-II neighborhoods are able to provide a representative view. .

[1] During the last decade, a number of municipalities have merged into new ones; although the borders of the municipalities might have changed, those of neighborhoods and districts were not impacted by these changes, and hence have not impacted the datasets of the CBS.

Table 2.2: average population size in 2008 in a category-II neighborhood

	N	Minimum	Maximum	Mean	Std. Deviation
# inhabitants	1712	0	21640	2279	2160
# households	1712	0	9810	1038	969
address density (per km^2)	1712	1500	2497	1926	282

2.2 Space

One of the key questions this research is trying to determine is the amount of space required to satisfy the energy demand and determine to what extent a neighborhood could satisfy its own energy needs, within its own confines, therefore the amount of available space was analyzed to determine the possible production of biomass, as well as the available space for other methods of renewable energy production such as wind and solar, while keeping in mind that within the Netherlands there is heavy competition for the available space.

Table 2.3 shows the overall land use in the Netherlands, in which the urban environment uses 18% of the available space, while agriculture takes up 68%.

Table 2.3: National average land usage (2008)

		% of total
Urban Environment	Infrastructure	3%
	Build environment	10%
	Semi-build environment	2%
	Recreational land usage	3%
Non-Urban Environment	Agriculture	68%
	Nature	14%

Land usage in category-II neighborhoods differs significantly compared to the national average as can be seen in the tables below. As table 2.4 shows, an average neighborhood covers only 55 hectares of land and 2.5 hectares of water. The water surface area, includes all water bodies wider than 6m and that are not subjected to tides, e.g.: canals, lakes, rivers, which are officially part of the neighborhood.

Table 2.4: Surface Area

	N	Minimum	Maximum	Mean	Std. Deviation	Mean in % of total
Total Surface Area (ha.)	1712	2	587	54.96	61	100%
Land Area (ha.)	1712	2	584	52.48	55.57	95.5%
Water (ha.)	1712	0	150	2.48	9.50	4.5%

The overall land use is sub-divided into urban and non-urban land use. As can be seen in table 2.5, the average urban land size of a +/- 1000 household neighborhood is around 46 hectares, while non-urban land use only occupies around 4 hectares. The surface area and specific spatial functions were derived from land and cadastral surveys.[2]

Table 2.5: Urban & Non-Urban Land Use

	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**	**Mean in % of total**
Urban Land Use (ha.)	1712	1	463	48.09	46.28	96.02
Non-Urban Land Use (ha.)	1712	0	348	4.27	17.71	3.98

As national figures depict, urban land use can be subdivided into a number of different sub categories for neighborhoods. Infrastructure, consisting of roads, parking lots, cycling lanes, airports, and railroads, on average takes up 3.48 hectares in Category-II neighborhoods. The build environment comprises of land allocated to amongst others houses, offices, shops, factories, cultural and government services. The build environment takes up the largest part of the urban space, namely 35.49 hectares. The semi-build environment consists of "hardened" terrain, which does not fall in the infrastructure or build environment categories; these include cemeteries, junkyards, and construction sites with a mean size of 1.60 hectares. Recreational space is used for sports, playgrounds, camping sites and other recreational activities. On average 7.48 hectares are used for recreational purposes within urban areas. This also includes parks it is however unknown what the distribution is between these different recreational purposes at the neighborhood level, the only specifications are available at an overall provincial and national level, but these figures are heavily skewed resulting from the inclusion of areas with lower population densities. It needs to be noted that it is unclear under which categories residential gardens fall, based on the sources of data used, it is most likely that these fall in the build environment category.

Table 2.6: Urban Land Use subcategories (in hectares)

	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**	**Mean in % of total Land**
Infrastructure Land Use	1712	0	88	3.48	5.795	6.60
Build Environment	1712	0	287	35.49	30.979	75.15
Semi-Build Environment	1712	0	90	1.60	5.409	2.56
Recreational	1712	0	277	7.52	16.098	11.69

[2] Within the CBS dataset there were two separate categories for land usage, one giving the exact land (use) area in hectares and the other in percentages. The category "mean in % of total" is the mean of the later category and does not equate precisely to mean of the exact precisely. Overall there is a margin of error of about 0.5 hectare, or around 1% when converting the exact means in percentages. Explanations for these differences could not be found, the exact figures will be used in future calculations.

Non-urban areas are rather small in category-II neighborhoods with 4.27 hectares. As a result of high density in the number of addresses, it makes sense that the actual space of the non-urban environment is so little. Land allocated for agricultural purposes, consists of greenhouses, grasslands, orchards and croplands and occupies around 3 hectares. Nature areas consist of either forests, dry and wet natural lands occupy a little over a hectare of land.[3]

Table 2.7: Non-Urban Land Use subcategories (in hectares)

	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**	**Mean in % of total Land**
Agricultural Land	1712	0	180	3.05	13.13	2.98
Nature	1712	0	195	1.22	8.26	.99

2.3 Sensitivity Analysis

In this section the validity of the obtained results specifically for the category-II neighborhood will be discussed on the basis of the parameters population and space. Neighborhoods with a higher (category-I) and lower (category-III) address density will also be discussed based on these parameters.

2.3.1 Sensitivity Analysis – Category II neighborhood

The problem with using the subdivision based on address density instead of population density is, that a number of neighborhoods that fall within category-II of address density, have in fact no inhabitants as a result of being classified as either industrial areas or business districts but do contain a high address density in terms of offices, shops and factories; inclusion of these areas of course results in a drop in the mean of the total population. The CBS data does not specify whether the neighborhood is classified either as a residential neighborhood or business district, therefore these cases could not be excluded. Applying random sampling of both 10% and 25% of the cases shows that the mean of the number of inhabitants only rises to about 2450 with little alterations in the standard deviation. Eliminating all cases with fewer than 100 inhabitants accomplishes the same, the number of cases included drops from 1712 to 1642; while eliminating all neighborhoods with fewer than 500 inhabitants raises the mean to 2650, the number of cases included drops from 1712 to 1477.

Seeing that the differences between the random sampling, excluding of outliers and the data set without corrections are limited; the dataset without configurations will used in the rest of this study. For data correction could harm the validity and scalability of this study and could also impact other factors such as space, while the gain in accurate representation of a neighborhood is negligible.

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[3] It needs to be noted that within the data set a large number of values were missing; percentages and totals did not add up. By replacing the missing values with zero this was corrected, this was applicable to the variables: Water area, non-urban land use and a number of sub categories. Looking at a number of these neighborhoods with missing values, it really looked like these categories did not occupy space within those neighborhoods.

Turning to what the impact of the outlier neighborhoods with few inhabitants on the means for space availability and usage, is done based on the hypothesis that lack of inhabitants would influence the size and actual land usage and land use intensity. In investing these concerns the metrics population density and household density were used.

The average population density in table 2.2 is 43.4 inhabitants per hectare of land (or 4340 per km2). When all cases with fewer than 100 inhabitants are excluded the density rises to 44.9 inhabitants per hectare. If all cases bellow 500 inhabitants are excluded, the population density is 47 inhabitants per hectare, accompanied by a substantial drop in included cases. Logically, neighborhoods with fewer inhabitants, but similar densities, are of a smaller size. The impact of the exclusion of the outliers on the total surface area is a rise in total surface area is around 0.5 hectare. In conclusion, the outliers are still included, for differences do not seem to be significant

2.3.2 Sensitivity Analysis – Population comparison

As a mean of comparison and identifying the differences with neighborhoods of higher and lower address density neighborhoods a sensitivity analysis has been conducted for category I and III neighborhoods. As table 2.8 shows, higher density areas have more inhabitants and households, what is interesting to note is that the average household size 1.85 in comparison to the 2.2 for category II. This can be explained by the fact that higher density neighborhoods contain on average more one person households, as well as more households without children.

Table 2.8: Neighborhood Category I – Average Population size

	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
# inhabitants	991	0	26960	3163	3402
# households	991	0	13530	1712	1832
address density (per km^2)	991	2500	12067	3741	1510

In contrast the category III neighborhood has a lower population density, but a higher average household of 2.4, indicating a higher number of households with children.

Table 2.9: Neighborhood Category III – Average Population size

	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
# inhabitants	1345	0	17730	2382	2315
# households	1345	0	6950	992	950
address density (per km^2)	1345	1000	1499	1239	144

2.3.3 Sensitivity Analysis – Space comparison

As table 2.10 shows that neighborhoods with higher densities have a smaller surface area, but most importantly the non-urban land use is a factor 5 lower than in category II, recreational land usage are also a third smaller.

Table 2.10: Neighborhood Category I – Space Usage

	N	Minimum	Maximum	Mean	Std. Deviation
Total Surface Area (ha.)	991	2	583	44.93	52.91
Land Area (ha.)	991	2	578	42.20	48.41
Water (ha.)	991	0	216	2.72	10.06
Urban Land Use (ha.)	991	2	576	41.29	46.07
Non-Urban Land Use (ha.)	991	0	73	0.81	5.80
Recreation Land Use (ha.)	991	0	164	5.12	12.37
Agricultural Land (ha.)	991	0	67	0.45	3.93
Nature (ha.)	991	0	72	0.36	3.89

The category III neighborhood, has a considerable larger surface area, resulting both from a larger urban and non-urban area. Especially the larger surface for agricultural space is noteworthy.

Table 2.11: Neighborhood Category III – Space Usage

	N	Minimum	Maximum	Mean	Std. Deviation
Total Surface Area (ha.)	1345	4	955	86.12	99.52
Land Area (ha.)	1345	4	944	82.76	95.08
Water (ha.)	1345	0	361	3.33	13.89
Urban Land Use (ha.)	1345	0	540	63.45	58.28
Non-Urban Land Use (ha.)	1345	0	843	19.17	59.20
Recreation Land Use	1345	0	167	9.62	14.96

(ha.)					
Agricultural Land (ha.)	1345	0	732	14.64	46.93
Nature (ha.)	1345	0	812	4.53	32.24

2.4 Conclusion

In table 2.12, the average size, land use and number of inhabitants of an average Dutch neighborhood are outlined; these figures will be used in chapters to come to offer a framework. These averages give a good representation and overcome some of the earlier mentioned critiques on existing studies in the literature review in which so-called averages gave distorted views of reality especially concerning the average amount of space available within the neighborhood. In Appendix I the complete sensitivity analyses of Category I and III neighborhoods are included, in Chapter 14, it is also discussed whether selecting a different neighborhood category would actually have an impact on final results.

Table 2.12: An average Dutch neighborhood

Category	**Average**
inhabitants	2279
households	1038
average household size	2.2
address density	1926
average land size (ha.)	52.36
urban (ha.)	48.09
Infrastructure (ha.)	3.48
build environment (ha.)	35.49
semi-build environment (ha.)	1.60
recreational (ha.)	7.52
non-urban (size)	4.27
agriculture	3.05
nature	1.22

Section III: Energy Demand

Chapter 3. Energy Demand

The residential market in the Netherlands is responsible for 24% of the electricity consumption and 20% of the natural gas consumption in year 2010 (Energie-Nederland, 2011). In the context of energy use on a neighborhood level, there are a number of key questions that need to be addressed for modeling in the Energy Plan model:

- The total energy demand over the course of a year
- The distribution of the demand over a year, week and day, differences on an hour to hour level

The total energy demand in this research is subdivided in the electricity demand and heat requirement, both of which are subdivided in the total demand and the distribution of the demand.

In order to determine the total demand there are two main approaches, a *top-down* or *bottom-up* approach. In the first approach, one would simply be determining the demand and fluctuations in the demand based on national statistics and making these statistics applicable to a typical neighborhood. While in *bottom-up* models data is collected at an individual household level, and their consumption patterns, while at the same time other variables are included within the analysis, that influence the energy consumption, to be able to derive corrections. An intermediate approach is either a combination of these two types of data collection models, which would be done at either a city, village or neighborhood level, in combination with the relevant social-economic and demographic data. A fourth alternative is the *engineering model* in which based on appliance ownership, occupancy rate, load profiles are constructed. In this case no historical data is used.

Initially a bottom-up approach was envisioned, but during the course of this research a number of things became apparent, primarily surrounding the electricity load profiles of individual households and neighborhoods, that there is an utter lack of data in this area. Therefore the approach that is used can be classified as a top-down approach.

3.1 Electricity

3.1.1 Total Electricity Demand

In 2010, the average electricity consumption per household was 3,480 kWh. During the period 1997-2008, household electricity consumption has risen by around 1% annually. Over the years the electricity consumption has been increasing as a result of higher penetration of household appliances, such as washers, dryers, but also the usage of computers and plasma TVs as can be seen in figure 3.1. As a result of the economic crisis, household consumption has fallen by more than 5% (VROM, 2012).

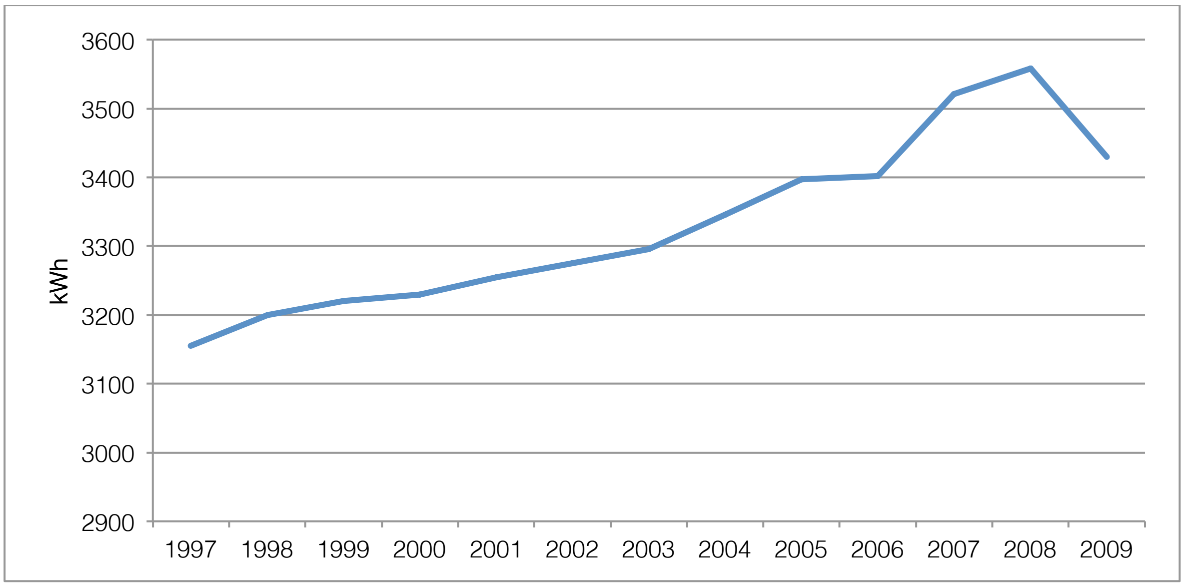


Figure 3.1: Annual average electricity demand per household (VROM, 2012)

The CBS database contains the average electricity consumption per dwelling type per neighborhood and also subdivides the consumption based on the type of house – apartment, row house, detached, semi-detached, corner house and of which the types are unknown. However, the amount of data concerning consumption per neighborhood differs substantial per year, the most recent year with an almost complete dataset was 2008, therefore this year is used in order to determine the energy consumption of the framework neighborhood. As can be seen in the figure 3.1, the electricity consumption in that year was highest as a result of economic considerations and is currently lower.

On average the Category-II neighborhoods used per household 3,165 kWh in comparison to 3,575 kWh for national consumption in that year. Looking at the breakdown per dwelling type apartments require a third less electricity, while detached houses require 50% more. The exact breakdown per dwelling type can be found in Appendix II (CBS, 2012).

There are a number of possible social-economic reasons explaining this lower level of electricity consumption. McLoughlin et all, determined based on a literature review and results from their own study based on social-economic and smart meter data of 4200 Irish households that in particular the dwelling type, the number of bedrooms, the age of the head of household, household composition/size, social class, water heating and cooking type all had a significant influence on total domestic electricity consumption (McLoughlin et all, 2012). The most obvious reason for this lower electricity consumption would be the type of dwellings and size, as a result of the higher than average dwelling density. This lower consumption can most likely be explained by a lower number of detached and semi-detached houses and a higher number of apartments and row houses. Seeing that average household size is similar between the national average and a Category-II neighborhood, factors such as the age of the head of the household, composition and income probably played a role in the lower consumption, although nothing can be said with certainty. Quite a number of data points for both the exact demographic composition and income level were missing, therefore it was not possible to conclude to what degree these factors play a role in the lower than average electricity consumption.

3.1.2 Distribution of electricity consumption

Uncovering the distribution of the electricity demand in a neighborhood has been extremely complicated. Initially, it was expected that load profiles would be available for a number of neighborhoods, or at least of a city district, for example based on data from transformer stations. However, at present this data does not exist in the Netherlands, as became apparent during my interview with Olaf van Pruissen from TNO/ECN (Pruissen, 2012). Measurements are not made at these sub-stations to determine the energy demand in a neighborhood, but are only based on a combination of statistical models and the annual gathering of the total household consumption. The only historical hourly distribution data that is available is the national load profile provided by Tennet. This distribution therefore had to be used in the EnergyPlan model (Tennet, 2012).

This of course results into a considerable difference in obtained results between the real distribution of electricity consumption in a neighborhood and the model used; a difference, which unfortunately was not quantifiable, nor was it possible to apply correction factors in the initial model. However, based on the interview with Olaf van Pruissen from TNO/ECN and literature some noteworthy difference and similarities between the two distributions can be pointed out. McLoughlin et all. analyzed the household consumption patterns based on the following factors: *maximum demand*, *load factor* and *time of use* (ToU). In the following paragraphs each of these factors will be discussed, followed by a discussion on the similarities and contrasts between the national electricity distribution and a load profile of a neighborhood. This information in turn was used in the sensitivity analysis to construct two more neighborhood like load profiles.

The *maximum electricity demand* over the course of a day is significantly influenced by household composition, as well as water heating and method of cooking. A strong relationship also existed between maximum demand and energy intensive household appliances namely, tumble dryers, washing machines and dishwashers (McLoughlin, 2012). These appliances also have the greatest potential for a shifting in the demand over the course of either a day or week, but this will be discussed more in depth in Chapter 10.

The *load factor* is defined as the average electricity load divided by the peak load at a moment in time. A low load factor indicates that the electricity consumption pattern is high for short periods of time, whereas a higher load factor indicates a more constant use of electricity during the day (McLoughlin, 2012, p 246). Larger households have a higher load factor and hence a more stable consumption pattern during the day (and also higher consumption), because more household members mean more actors demanding electricity for different purposes.

Lastly, the *time of use* for maximum electricity demand was found to be strongly influenced by occupant characteristics, such as age and household composition. Younger households were more inclined to use electricity later in the evening than older occupants. Moreover, households with children tend to peak in their usage later in the evening than those living alone. While households were their children have already moved out tend to see their peak earlier, as a result of retirement, reduced working hours or lower number of occupants (McLoughlin, 2012). In the following paragraphs, the above mentioned terms are used to explain the differences between the national distribution and a load profile of a neighborhood.

The national distribution (figure 3.2) over the course of a day, shows that the maximum demand occurs around midday and declines by around 15% from the day peak, to an intermediate day low at around 18:00 after which another peak is reached between 20:00 – 21:00 when demand is around 7% higher in contrast to the day low, from this last peak the demand drops in a quite linear fashion to the day low at around 03:00 when demand is approximately 40 - 50% below the day peak.

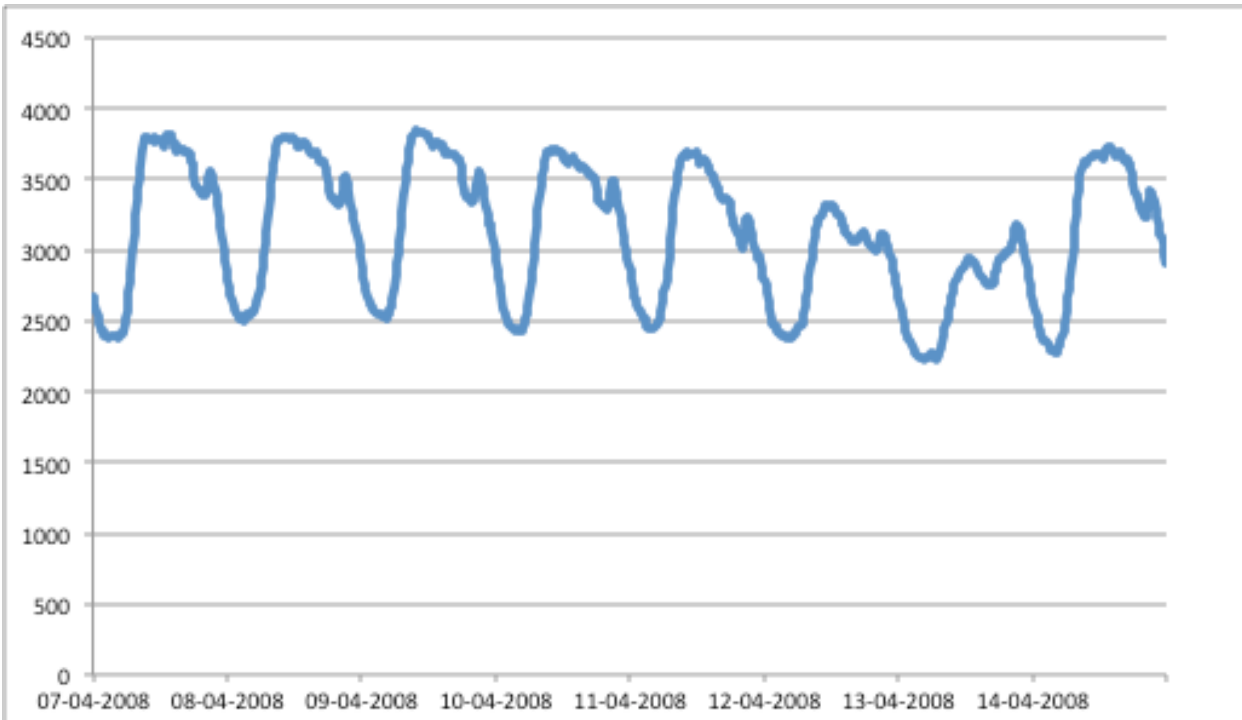


Figure 3.2: Example of the distribution of Dutch electricity consumption a week in April (Tennet, 2012)

Based on McLoughlin's analysis some interesting differences can be pointed out. While the national demand peak occurs around mid-day, in a residential neighborhood this peak would most likely occur somewhere between 17:00 – 21:00, when most household occupants are at home and have returned from their jobs. In addition, the national distribution still indicates a quite high consumption during the nights resulting from a base load from industrial complexes, green houses and street lighting. While at a household level, substantial lower consumption is to be expected, equating primarily to the demand of the equipment that is on stand bye, freezer/fridge and electric heating, factors which are responsible for roughly a third of the total annual consumption (Leguijt, 2009). The time of use and load factor in a neighborhood differ therefore quite substantially from the national distribution.

Another noteworthy difference is the level of consumption between working days and the weekend. The national distribution shows a lower consumption during weekends, while on a household level a higher consumption is to be expected, for occupants tend to be more at home and would use more electricity. Higher household consumption is also expected on Fridays when either more people work from home, or do not work at all. Hamidi et all. compared the domestic load profile of a UK household during a weekday, Saturday and a Sunday as percentage of the peak demand. Three points of interest are to be noted, demand for weekdays during the morning rises much faster that during the weekend; the demand around midday is on Sunday 50% higher than on a weekday and on Saturday around 25% above the demand of a weekday; interestingly enough the domestic profiles match evenly for all days between late afternoon and midnight, although on a Saturday night overall demand is slightly higher than on a weekday or Sunday (Hamidi, 2009). Similar differences in consumption between weekdays and the weekend for Finnish household (without electric heating) were shown by Paatero and Lund (Paatero, 2005).

It is unfortunate that there are not many examples of the distribution of electricity consumption available for whole neighborhoods. This will change in the years to come with the roll-out of smart meters, but also load profile generators for neighborhoods are being developed. A load profile generator is an example of an engineering model. The distribution is constructed through a bottom-up approach, starting at the appliance level and combining the physical characteristics with data on usage. Unfortunately, these profile generators were not publically available. It is also questionable whether in this research, such a generator would have increased the validity of the research, for the distribution of such a generators are not tied to the outside temperatures and hence not to the heat requirement and production of solar or wind energy; for the Tennet distribution this is at least partially the case. In the sensitivity analysis in the discussion the impact of the load profiles on the results is assessed through the construction of two additional load profiles.

3.1.3 Results

In EnergyPlan the following total electricity demand of a neighborhood will be used: 3.285 GWh (3.165 kWh/household* 1038 households). Although differences in demand between years can be noted; it was decided to keep this level of electricity consumption constant, for primarily social-economic reasons are behind the changes in consumption and to a lesser extent weather conditions. The latter differences in monthly distribution can be seen in figure 3.3. It shows, that consumption is higher during the winter months; in these months there is also a higher differentiation in between years, which is most likely the result of differences in electric heating demand and lighting. Therefore the Tennet national distribution linked to each researched year is used, to overcome these differences in consumption patterns. Lastly, it needs to be noted that a more in-depth breakdown of the household electricity consumption will be discussed in Chapter 10.

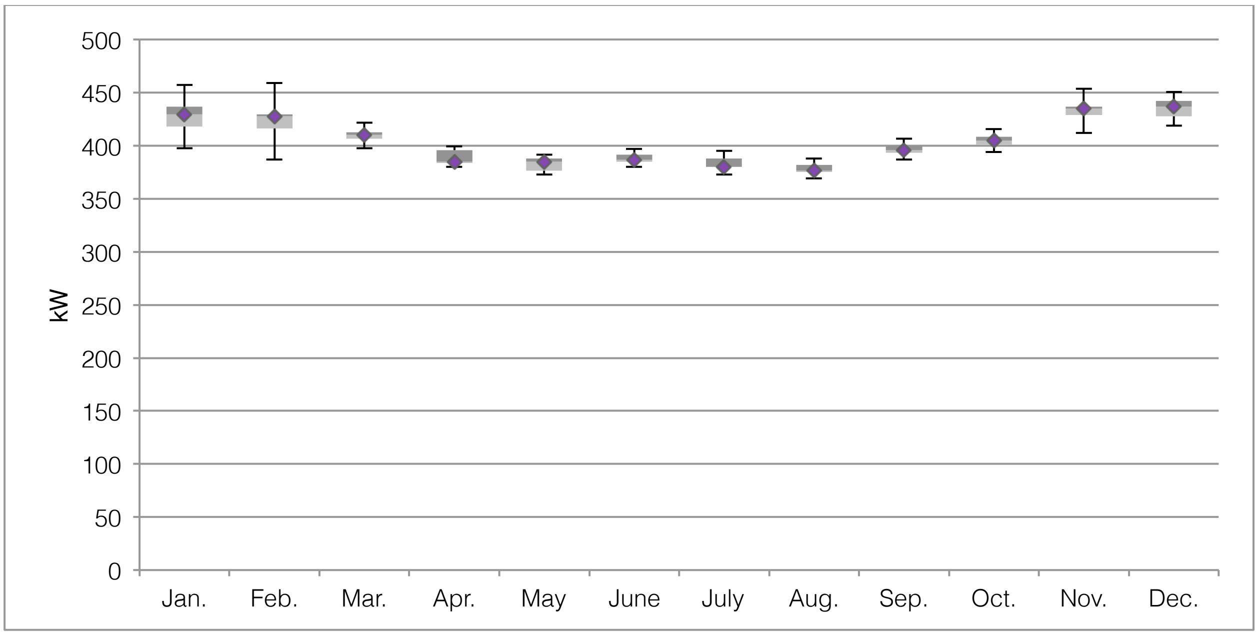


Figure 3.3: Distribution of Average Total Electricity Demand of the neighborhood per month in kW [period 2004 – 2011]

3.2 Heat Requirement

3.2.1 Total Heat Requirement

The primary source of heat provision in households are natural gas-fired boilers. Electric heating and district heating play a secondary role of which the later is only used in 4% of the households. The natural gas usage has almost halved since the 80s as a result of increased insulation, double glazing and more efficient boilers, dropping from 3.145 m^3 in 1981 to 1.617 m^3 in 2010. Graph 3.4 depicts a breakdown of the gas consumption Based on the data from the former Ministry of Housing (VROM, 2012), over the period between 1997 – 2009, average gas consumption dropped annually by 1.7%, overall consumption has dropped by 20%.Gas consumption for cooking and warm water, have both remained constant (VROM, 2012). This drop can also partially be explained by the reduction in household size and a threefold increase in the number of one person households; on a whole this is not necessarily a positive development for households with more occupants, use less gas per occupant in contrast with households with fewer occupants.

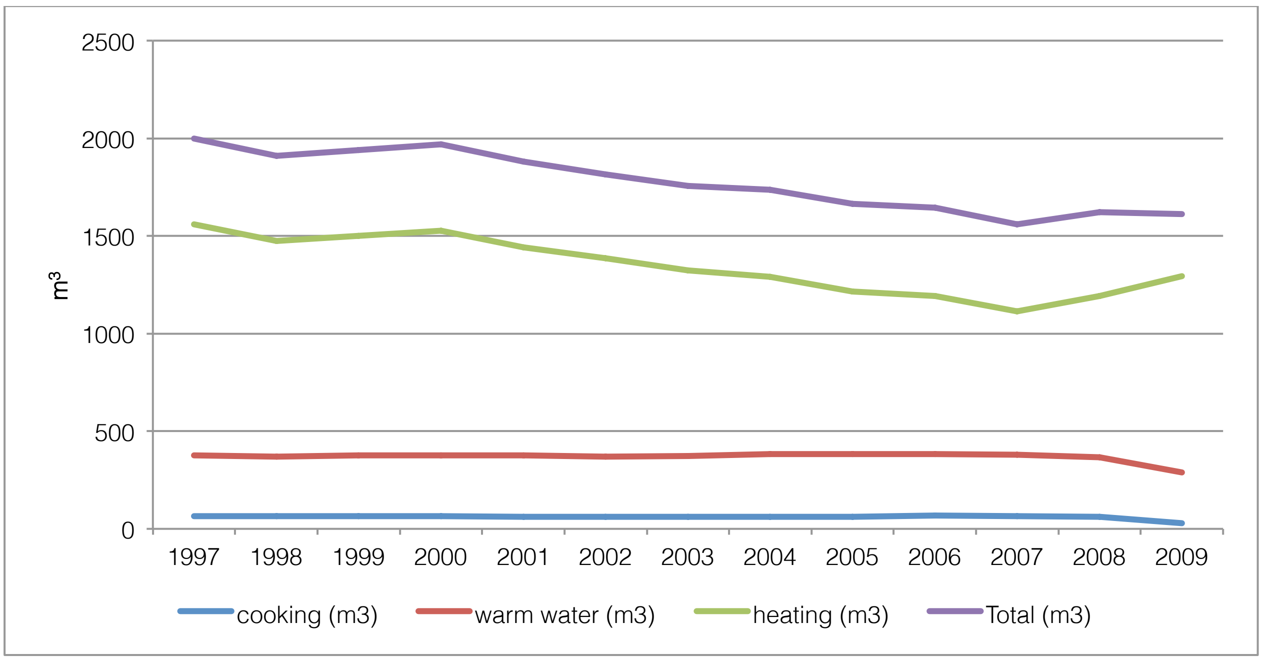


Figure 3.4: Development of Gas consumption over the year (VROM, 2012)

Assuming a caloric value of 31.1 MJ/m^3 (Blok, 2007), the caloric value for 2008 per function for gas usage was as followed:

Table 3.1: Breakdown of gas consumption (VROM, 2012)

Activity	Gas usage (m^3)	Caloric value (31.1 MJ/m3)
Space Heating	1192	37.01 GJ
Hot water	366	11.82 GJ
Cooking	63	1.96 GJ
Total	1621	50.41 GJ

The mean gas consumption for a household in the Category-II neighborhood was 1575 m^3 in 2008, thus 48.98 GJ, the exact breakdown of consumption is unknown. Gas consumption for apartments was around 1/3 lower, while consumption in detached houses was double the amount.

It is assumed 63 m^3 of gas are used for cooking such as the breakdown shows. This is of course not part of the heat requirement and therefore will be converted to electricity demand. It will be assumed that instead of gas, induction is used as a cooking method. Gas cooking has an efficiency factor of $\eta = 40\%$, so the total energy requirement for cooking is 63 m^3 * 31.1 MJ/m^3 * 0.40 = 783.72 MJ. Induction cooking has a much higher efficiency namely $\eta = 84\%$ (Lawrence Berkley Laboratory, 1993), the energy losses are thus much lower, the electricity consumption for induction cooking is thus 783.72 MJ * 1/0.84 = 933 MJ = 259 kWh. The total electric consumption per household therefore rises from 3,165 kWh to 3424 kWh, while the total neighborhood uses rises to 3, 55 GWh / year. Subtracting the cooking gas consumption from the total gas consumption, results in a drop of gas consumption to 1512 m3, with a caloric value of 47.02 GJ.

3.2.2 Distribution of the Heat Demand

The distribution of the heat demand is primarily depended on the requirement for space heating and hot water. In constructing the heat distribution curve, it was assumed that the demand for hot water remains constant throughout the year. Although in reality this is not the case, it was not possible to construct the distribution of the demand. The requirement for space heating was modeled, by modeling the heat loss of a building for which formula 3.1 forms the basis (Blok, 2007). The heat loss of a building is determined by a combination of insulation values of the building envelope and ambient temperatures in relation to the desired indoor temperature (degree-days). Seeing that the insulation values are already included in the total consumption, the degree days are the factor in influencing the distribution. As a baseline, 19 degree Celsius was assumed between 07:00 – 23:00 and 15 degree Celsius between 23:00 – 07:00 (Folkert, 2012) and on an hourly-basis the difference between these baselines and the outside temperature was calculated and the distribution constructed. Initially a constant baseline temperature was assumed, however, a differentiation between night and day indoor temperatures was assumed for this would better capture real household consumption patterns.

Formula 3.1 (Blok, 2007, p 115): Annual heat loss of a building

$$Qa = k*A*D*(24/3600 \text{ s/day}) + Cp * N * V * \rho * D * (24 \text{ h/day})$$

Where:

Qa = the annual heat loss of the building (J)
*K = the average heat transfer coefficient of the building envelope (W/m2 *K)*
A = the surface area of the building envelope (m2)
*Cp = the specific heat of air (cp = 1.0 kJ/kg*K at 20 C)*
N = the ventilation rate (h-1)
V = the air volume inside the building (m3)
ρ = the specific mass of air (1.20 kg/m3 at 20 C)
D = the number of degree- days (C – days)

3.2.3 Results

The total heat requirement of a neighborhood is equal to the caloric value of the natural gas multiplied by the efficiency of the boiler multiplied by the number of households. Assumed is that the efficiency of the natural gas boiler is 90%, this efficiency was assumed for there were no overall average figures on the efficiencies and this seemed to be an intermediate solution between less efficient boilers (80%) and high efficient boilers (105/107%)(Folkert, 2012).

This means that the total heat requirement = (47.02 GJ * 0.90 * 1038) / 3600 = 12. 20GWh

The distribution was modeled for the period 2004 -2011 for 5 locations in the Netherlands: De Bilt, Vlieland, Twenthe, Cabauw and Berkhout. The choice for these locations is further explained in Chapter 5. A boxplot of difference in the distribution for De Bilt can be seen in figure 3.5. This boxplot shows, that demand is highest during the winter months and lowest during the summer months, when heat is primarily required for warm water. The differentiation between heat required during the winter months is also considerable larger, resulting from differences in outside temperatures during these months. Differences between De Bilt and the other locations, in terms of what can be identified in the box plots are not evident. Therefore the graphs for these locations can be found in Appendix II.

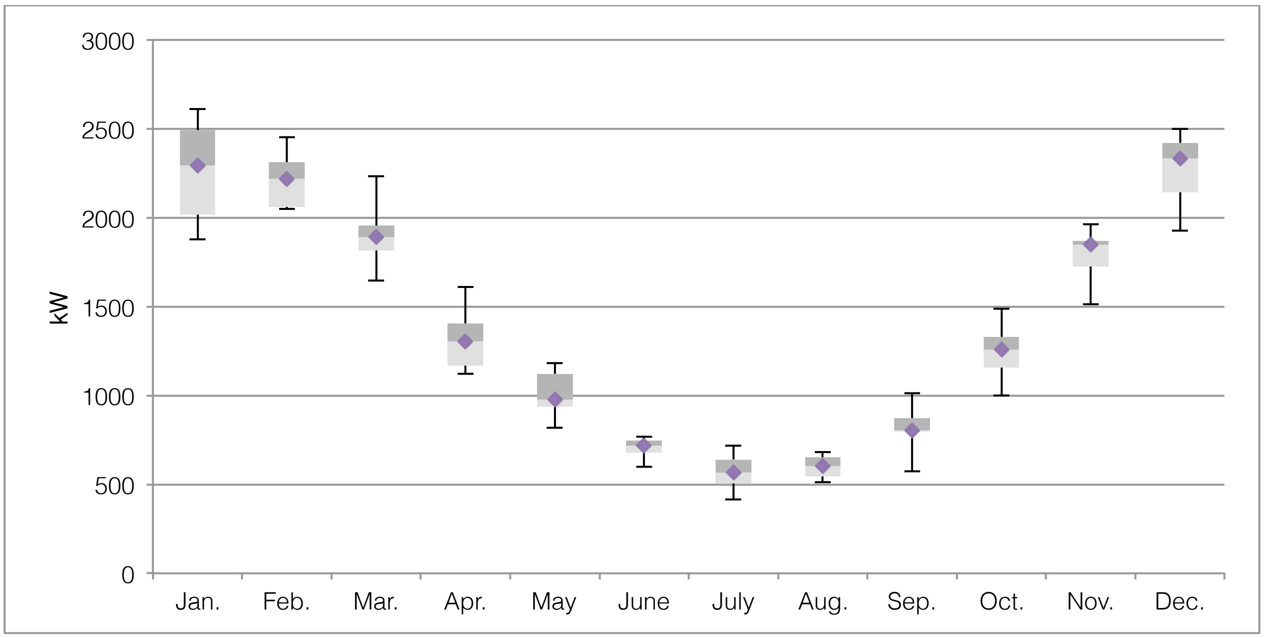


Figure 3.5: Distribution Average Heat Requirement per month [period 2004- 2011, De Bilt]

3. Critiques & Comments

- Data is lacking concerning the electricity distribution of neighborhoods
- Electric heating demand is not included in the heat requirement, but kept in the electricity section, for there was insufficient information concerning the subdivision of this category in terms of usages, e.g. heat pumps, electric heating etc.
- The way in which the heat requirement distribution is modeled fails to depict buffer capacity of the building envelop and associated time delay. In order to be able to this, far more details need to be known concerning the characteristics of the building in question.

4. Overview final figures

In conclusion, the total electricity requirement of the neighborhood is 3.55 GWh/ year and the total heat requirement is 12.20 GWh.

Section IV: Energy Supply Technologies

Chapter 4: Overview of Chosen technologies:

The energy supply technologies that were chosen for delivering electricity are: wind energy, photovoltaic (PV) and for delivering the heat: heat pumps. Each of these technologies will be discussed in the following chapters in more detail.

Wind energy and photovoltaic were chosen for these technologies are technologically ready and could be implemented in a neighborhood in the Netherlands. Other technologies that could deliver electricity in renewable fashion either are not suitable for the Netherlands or a neighborhood or technologically not yet matured, such as concentrated solar power (CSP), geothermal electricity, tide, wave or osmotic power.

Heat pumps are able to deliver heat through by consuming electricity. It is widely believed that in a renewable energy future an electrification of the heat supply will occur (IEA Heat Pump Center, 2012). Technological readiness of alternatives to heat pumps was not the issue for the exclusion of other heat supply technologies, but more the possibility of modeling these in EnergyPlan, for example geothermal heat. Solar thermal was excluded for already another solar technology, namely PV, had already been included. Combined Heat and Power (CHP) on biomass was not included some issues arose when modeling a CHP plant in EnergyPlan, as well as that a CHP plant would have to be connected to a district heating system and a present only 4% of the Dutch household is connected to such a system and therefore seemed limited in scalability for this specific research. (CBS, 2012).

Chapter 5: Wind Energy

Wind energy has been identified as being one of the key technologies for renewable energy production in the Netherlands, both in terms of onshore and offshore wind. This is the result of relative high and near the seashores constant wind speeds. Wind applications are therefore also the key technologies for a 100% renewable energy neighborhood. Onshore wind, can also be subdivided into urban and non-urban wind turbines, which differentiate in terms of size.

5.1 Data Collection

In order to model the wind energy production in the EnergyPlan model, the parameters that are needed are the total installed capacity and the wind energy distribution of the production. These parameters are dependent on both the type of wind turbine and the hour-to-hour wind speed at the specified locations.

5.1.1 Location: Wind Speeds

Only certain regions are suitable for wind development. Manwell et all. use different wind power classes in order to indicate the suitable locations for wind turbine applications based on the annual average wind speeds and associate power densities per m^2. Locations with average annual wind speeds of more than 5.6 m/s are suited for wind production (so-called class 4). Class 3 regions with wind speeds between 5.1-5.5 m/s, require taller towers to be used. Class 2 with wind speeds between 4.4-5.1 are considered to be marginal and those below 4.4 m/s unsuited (Manwell, 2009). *Figure 5.1,* show the measured average annual wind speeds and the weather stations in the Netherlands for which detailed data is available measured at a height of 10 meters (left), while computed average wind speeds at a height of 100 meters are shown on the right. As can be seen there are quite significant differences in terms of wind speeds within the Netherlands, areas closer to the North Sea have higher wind speeds, while more inland areas have lower wind speeds. The urban landscape also has a wind speed reducing effect, this is the result of the so-called surface roughness, increased roughness/friction decreases the wind speeds. With increased height frictional forces decrease, while wind speeds increase. This explains the difference between the two figures below. In addition, based on Manwell's wind classification it can be concluded that most areas in the Netherlands are suited for wind energy production, although in some areas higher turbines are required.

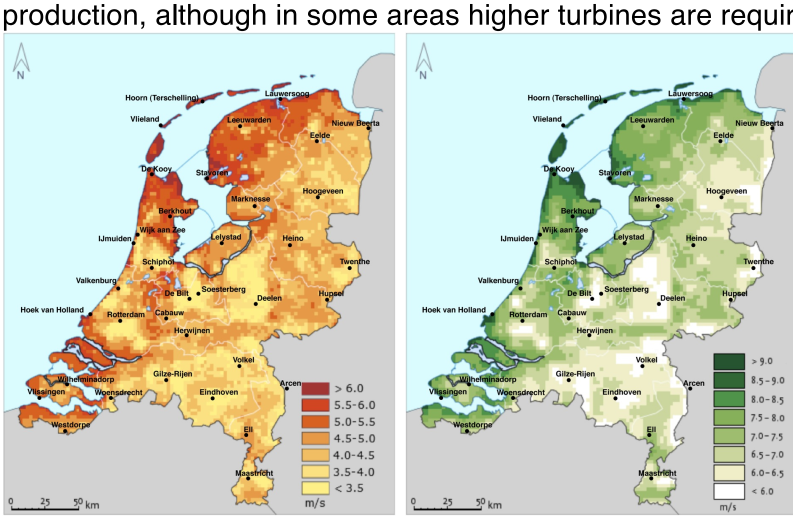


Figure 5.1: Average annual windspeeds in the Netherlands, (left at 10m; right at 100m) (KNMI, 2012)

Average hourly wind-speeds are available for a number of decades, but only the period 2004-2011 has been selected, for the wind data needs to be linked to other datasets, such as the electricity and gas demand for which only a limited number of years are available. The locations: De Bilt, Cabauw, Berkhout, Vlieland, and Twenthe were selected. These locations were selected for differentiation of wind availability and all being suited for wind, but also as will be shown in Chapter 6 for differentiations in solar irradiation. Initially only the data points, De Bilt, Twenthe and Vlieland were selected as a cross-section of the country, but as became apparent (as will be shown later on in this chapter), both the production at Twenthe and De Bilt were more or less equal, while production on Vlieland was three times higher. Therefore, as “intermediate” data points Berkhout and Cabauw were selected for these are located in regions were there are higher average wind speeds. Of all the locations, the De Bilt station is located in the area with the highest degree of urbanization, as a result of the proximity to the city of Utrecht, which also has the lowest wind speeds (KNMI, 2012).

5.1.2 Selecting the Wind Turbine

Horizontal Axis wind turbine, with a three blade rotor spinning in a vertical plane attached to a nacelle are the most widely used type of wind turbines. As an example the Vestas V112 – 3.0 MW is used in this research. This turbine was selected for it is suited for both the locations with lower wind speeds as well as higher wind speeds, based on the international IEC standard for wind turbines. The characteristics of the wind turbine are described in table 5.1. (Vestas, 2012; IEC, 2012).

Table 5.1: Characteristics of Wind Turbine used in EnergyPlan (Vestas, 2012)

Vestas V112 – 3.0 MW	
Installed Capacity	3,000 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Re cut-in wind speed	23 m/s
Hub height	84 m
Rotor Diameter	112 m
Swept area	9,852 m^2

5.1.3 Adjusting the wind speed

The KNMI measures the wind speed averages at a height of 10m; most wind turbines have a height of about 100m, a level at which the average wind speeds are much higher. In order to convert the measured wind speeds to the wind speeds necessary to be able to calculate the hourly production of the wind turbine, the following formula has to be used: $V_2 = v_1 \ (z_2/z_1)^p$, in which v2 is the wind speed at the height, which is unknown. V1 is the wind speed at the know height, in all cases at 10m. Z2 = is the hub height at which the wind speed needs to be calculated, while z1 is the 10 meters. P or sometimes referred to as α_S, know as the wind shear factor is 1/7. The hub height for this wind turbine 84m. Landscape roughness factors are assumed to already be in the measured data, seeing that existing wind data is being used, roughness of the terrain is already taken into account (KNMI, 2012; Manwell, 2009; Andrews, 2007).

Method of Calculating the Wind production

1. Computation of wind speeds from 10m to 84m
2. Turbine only produces energy between the cut-in wind speed of 3 m/s and the cut-out wind speed of 25 m/s
3. Based on the production curve (figure 5.2) values are assigned to the calculated wind speeds
4. If wind speeds exceed 25 m/s, turbine produces output in the hour in which wind speeds are below the re cut-in wind speed of 23 m/s.

This method of calculation does give a rather representative view of reality as shown by Esteban et all., who used a similar method although they considered production to be linear between the cut-in and rated wind speed and the cut-out speed was considered to be 30 m/s (Esteban et al., 2010).

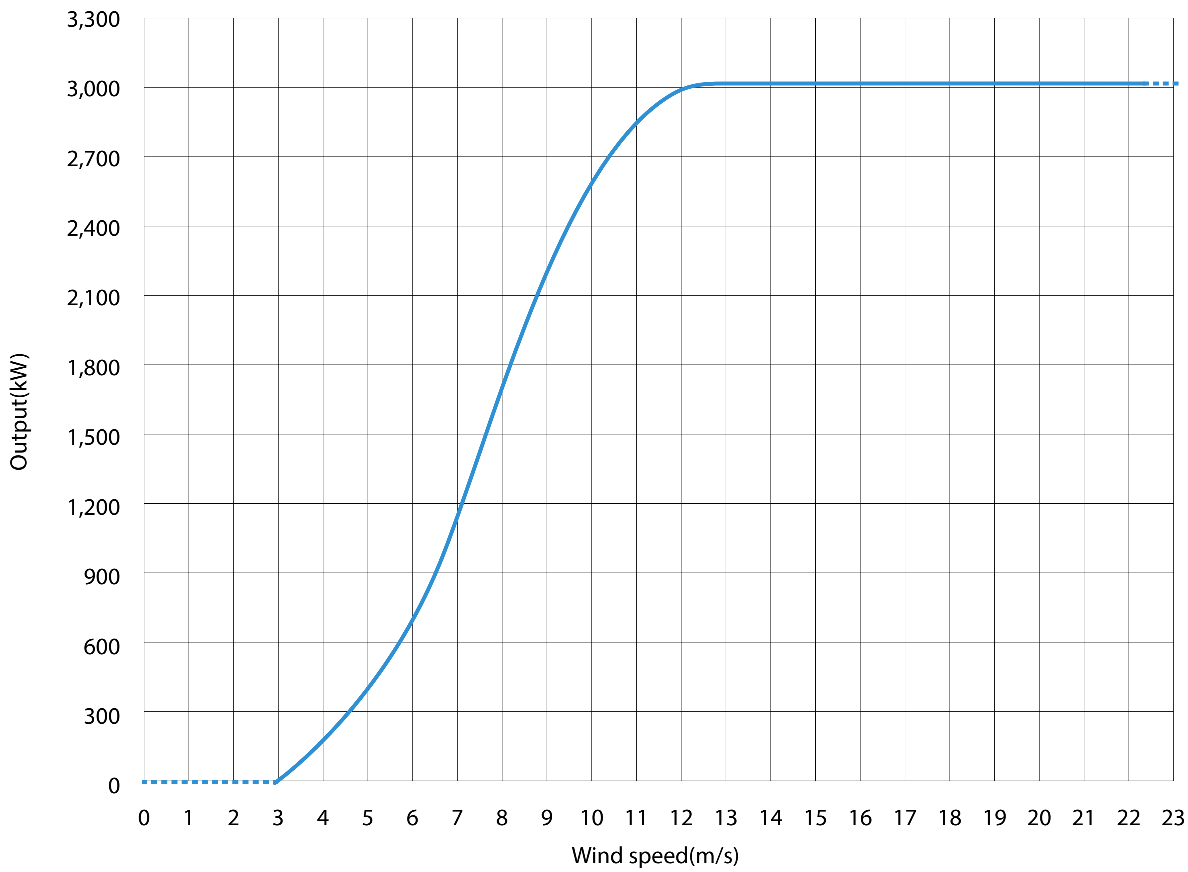


Figure 5.2: Reconstruction of Power Curve Vestas V112- 3,000 kW (Vestas, 2012)

5.2 Micro Wind Turbines

Next to the conventional horizontal axis wind turbines, micro or urban wind turbines are smaller versions of these conventional wind turbines, often producing in the range between 1,000 to 3,500 kWh annually. These micro wind turbines come in many different shapes and sizes, but still only corner a marginal part of the wind energy market. Seeing these wind turbines would fit on the roof of a house and cover a quite substantial part of the electricity consumption, it initially was assumed that these would be included in this research. However, in-depth research showed that micro-wind turbines could not be incorporated into the model, without greatly harming the validity of this research.

Although power curves for micro wind turbines from manufacturers are available, and therefore could be modeled. The available power curves, are not available with references to any standards, and claims could therefore not be verified. The literature review of a number of studies by Walker showed that the power curves provided by manufacturers often overestimate the power output at certain wind speeds. In addition, the performance of the micro-wind turbines are extremely tied to the location within the urban environment, meaning the height of the building on which the turbine is located and the effect surrounding buildings might have on the air flows. Therefore, the available hourly data, does not correspond with the wind speeds within the urban environment, where wind speeds are lower, actually somewhere between 20-60% depending on the urban roughness (Walker, 2011). In addition, Glass and Lehmore showed the difference the simulated and actual between a five different types of micro wind turbine. They concluded that for a number of the turbines, actual power production was not positive (meaning that production was not above the energy usage of the invertor used), while the modeled production did indicate that there was substantial production (Glass, 2011). Moreover, it unknown what the effect would be in a scenario in which micro-wind turbines are located on roofs of every building, which based on the level of energy production would probably be required in a 100% renewable energy neighborhood. Microwind turbines might be interesting energy solutions for buildings in rural areas, but at present levels of knowledge do not seem to be an option for large scale implementation in neighborhoods, and therefore were not used as a potential energy source in this research (Walker, 2011).

5.3 Offshore Wind

At present there is no public data hour-to-hour wind data available for Dutch terretorial waters and therefore can not be moddeled. A new measuring station has been set up by ECN, but data is not yet available. The dataset from Vlieland will be used as the example of offshore wind, in some of the scenarios. As can be seen in figure 5.3, at a height of 100m, the average wind speeds on Vlieland are comparable with offshore locations, although wind speeds are slightly lower as a result of the heigher surface roughness near the Vlieland meteo measuring station.

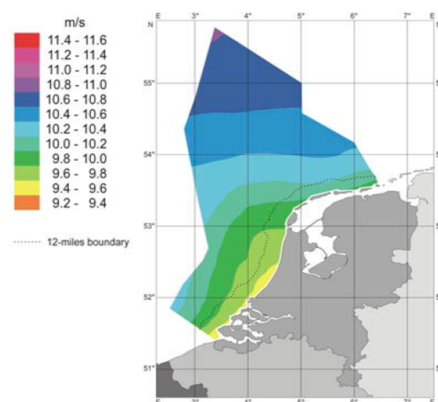


Figure 5.3: Off-shore wind speeds (KNMI, 2012)

5.4 Results

Figure 5.4, depicts the average monthly production for the 3,000 kW Vestas wind turbine; in order to provide a better overview and for reasons of simplicity the production has been divided by three, thus the graph depicts the production per 1,000 kW installed capacity. These figures also coincide with the so-called capacity factors for the previously mentioned sites. Capacity factors are defined as "*the ratio of the energy produced in a year to the energy that would be produced if the turbine operated at its rated power* (Andrews, p 118, 2007). The average annual capacity factors for a wind turbine in de Bilt would be 20.4%; Vlieland 68.2%; Twenthe 22.2%;

Cabauw 31.2% and Berkhout 39.4%. There is thus a considerable difference in the output, which looking on an annual basis would mean that in order to roughly receive the same overall output 3.5 wind turbines need to be placed in de Bilt, for 1 turbine on Vlieland. This difference is the result of considerable higher wind speeds, which often result in production being as high as the installed capacity, but also considerable fewer periods in which there is no production at all. These differences can be explained as a result of de Bilt being located more inland and also being in a considerable more urban environment and associated “urban roughness” reducing wind speeds. The results for the other locations can be explained as a result of a distance to sea and the urban density. Although Twenthe is more inland than de Bilt, it has higher annual wind speeds probably as a result of the differences in roughness of the terrain. What really needs to be emphasized is that these results represents the technical potential or optimal production patterns based on the dynamic variations in wind speeds; the found capacity factors are especially in the case of Vlieland higher than what in reality would be encountered, because factors such as down-time for maintenance are not taken into account.

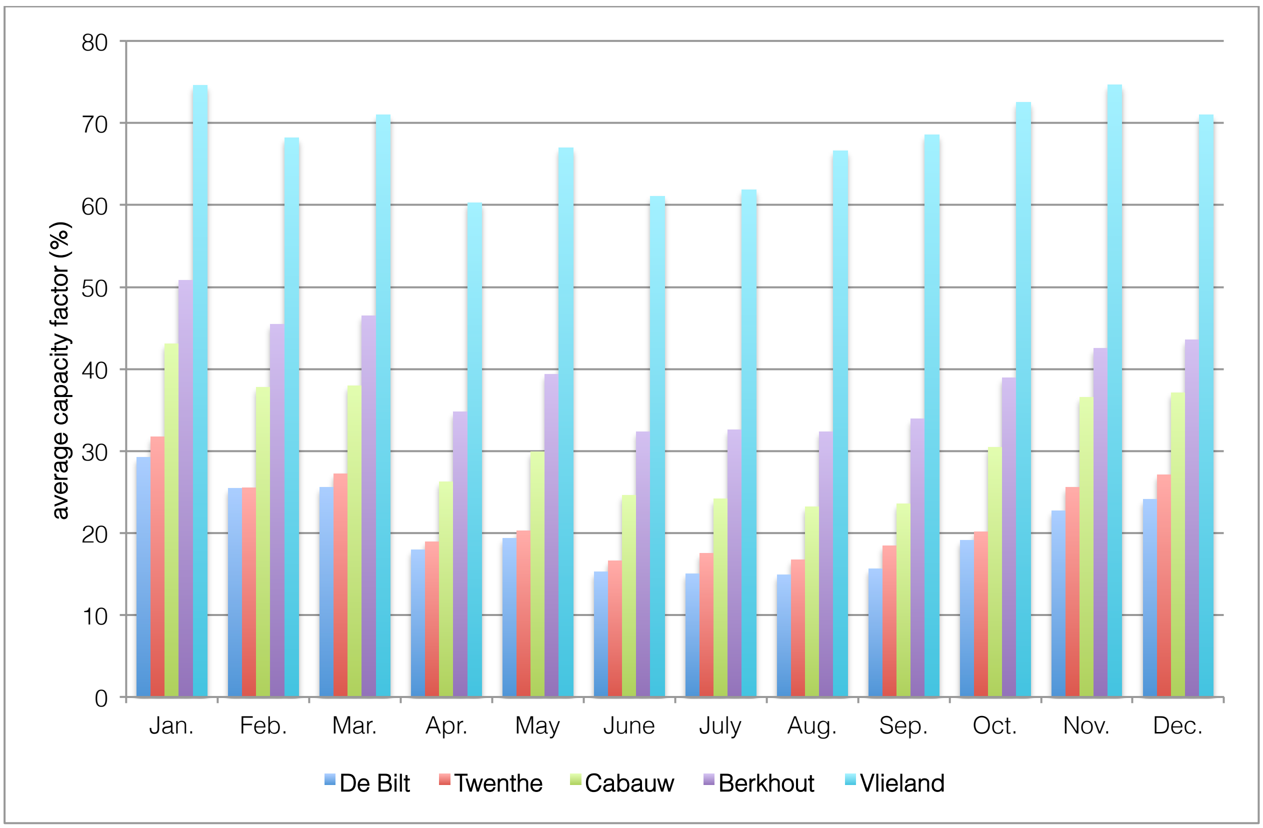


Figure 5.4: Modeled average capacity factors in % for the period 2004 – 2011

Detailed graphs and tables can be found in Appendix III. All production figures, have been modeled based on the average hourly wind speeds from the KNMI for the period 2004 – 2011 (KNMI, 2012). In contrast with solar energy, there are less noteworthy differences between the wind production over the course of a day. Manwell does claim that overall wind speeds are higher during the night than during the day (Manwell, 2009), although these differences seemed to be evident for the researched locations and quite often was the other way around.

5.4.1 Wind Output Differences: within a year

During the winter months, wind production is in all cases higher than during the summer months, but the degree differs per location.

- De Bilt: capacity factors differ a factor 2 within a year; in January the capacity factor is 29.2%, while between June-September around 15%.
- Vlieland: During the winter, autumn and early spring the capacity factor is around 70 – 75%, while during the summer and late spring this is between 60 – 65%.
- Twenthe: Capacity factors in Twenthe are slightly above those in De Bilt, during the winter, early spring and late autumn between 25 -31.7%, while during the other months this is between 17 – 21%.
- Cabauw: Average capacity factors between November – March are between 37 – 43%, October and May around 30% and the other months between 23 – 26%.
- Berkhout: October – March and May capacity factors are between 40 – 50%, other months are between 33 – 35%.

5.4.2 Wind Output Differences: between years

The differences in capacity factors between years are quite substantial. Figure 5.5 shows the example of de Bilt in a boxplot. The purple dot is the average production; the gray areas indicate the 2nd and 3rd quartile, while the whiskers depict the outliers. Most months show a difference in capacity factor of about 5% in the 2nd and 3rd quartile range, while December and January depict differences above 10%. The outliers in a number of months are also quite substantial, especially the upper outliers; some of the lower outliers show capacity factors below 10%. Between the extreme outliers there is a difference in most months of a factor 2, but some months (e.g. November), it is close to a factor 3-4 difference in output.

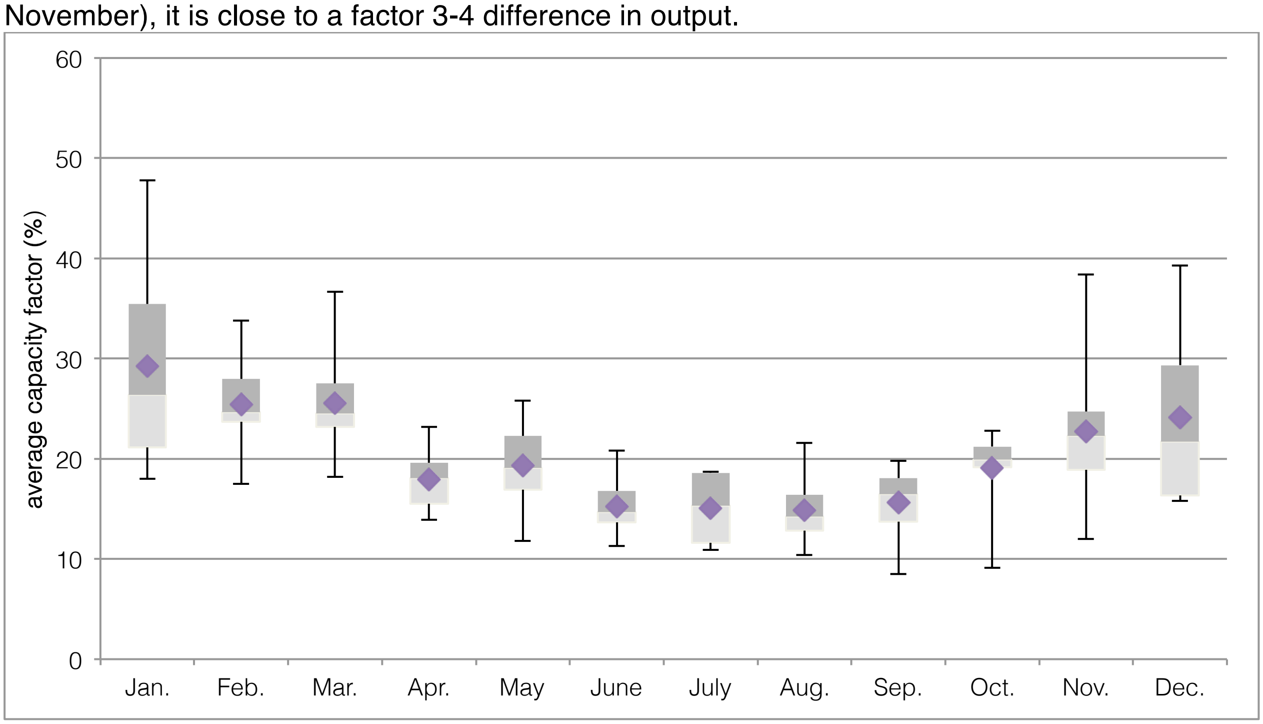


Figure 5.5: Average simulated wind capacity factor [2004 – 2011, De Bilt]

Looking more closely and the differences in the total annual production for de Bilt, the disparity between years is less extreme, but still there is a difference in annual capacity factors of 30% in a range between 14.9% - 21.2%.

Figure 5.6 shows the monthly capacity factors for Vlieland. The difference in capacity factors for the range covered by 2nd and 3rd quartile encompasses between 5% – 10% difference. The outliers are overall less extreme and appears to be more "constant" in comparison to the the example of de Bilt. This partially an optical illusion for the differences in production is larger for Vlieland than de Bilt. Percentage wise the difference in total annual production is only 10% between the year with the highest and lowest production, the range is thus far smaller than for de Bilt, which is the result from the more constant higher wind speeds.

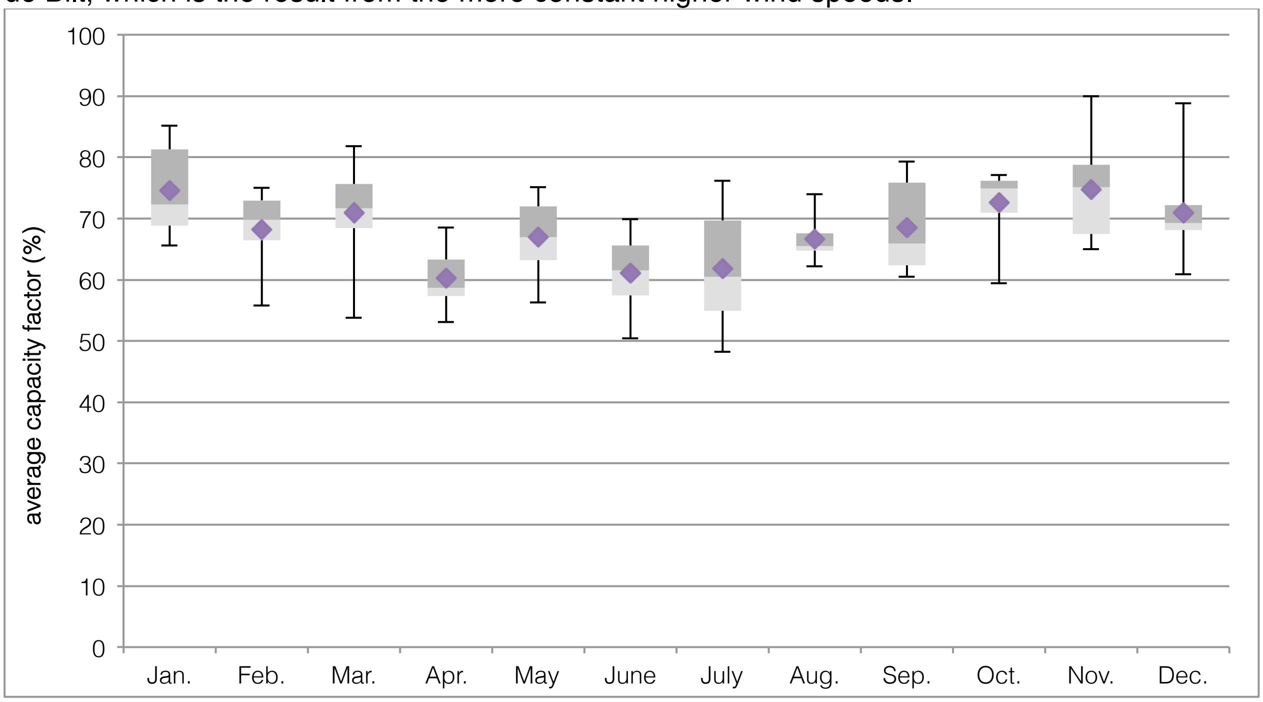


Figure 5.6: Average simulated wind capacity factor [2004 – 2011, Vlieland]

The result of the other locations can be found in Appendix III.

What can be concluded is that natural variability in the Netherlands is quite large along the coast – inland/West - East axes. Esteban et all. concluded that in larger countries such as Japan or the UK, variability in terms of location would be able to smoothen/compensate for variation in production (Esteban, 2010). This also seems to apply to the Netherlands, although this is only a compensation for shortfalls for inland wind energy production by coastal wind turbines, but not vice versa, which is in fact the case in the examples of larger countries. In the case of Denmark, which is of similar size as the Netherlands and similar overall climatic difference, a comparison between wind different geographical locations showed virtually no differentiation within the country, the result of all wind turbines being located in close proximity to the sea and an overall lower urban roughness, resulting from lower population density (Østergaard, 2008).

5.5 Critiques on estimates and room for improvement

- Average hour-to-hour data is used in the previous simulations, while more precise minute to minute would give an even better indication of the actual production, it is now assumed that there is a constant air flow at a constant speed, while different wind speeds are registered within an hour as a result of gusts of wind or reduction in the wind speeds, this consequently has an effect on the production. It is unfortunately unknown to what extent a higher or lower production in this instance

- Furthermore, the data from the KNMI, only consists of round numbers instead of more precise numbers. Seeing that the 10m data is computed to the height of the hub, the cut-in/out speed could be either over or under-estimated. This ties into the issue that the inertia of the rotor has not been modeled, referring to the momentum force/centripetal acceleration that is build up. The inertia could mean a difference between reaching the cut-in/out speed, and again lack of taken into account the inertia could result in an under or overestimation of production (Manwell, 2009).

- The number of hours that there is no production as a result of too high wind speeds are only evident for Vlieland, and there are only a few hours when this is the case. This number might be higher as a result of strong gusts of wind exceeding 25 m/s, within an hour.

- A wind turbine adjusting to shifting wind-directions results in power production losses, these have not been taken into account (Manwell, 2009).

- Down-time for maintenance was not included, down-time is especially relevant for off-shore wind turbines (Manwell, 2009).

5.6 Space requirement

The amount of space required for a wind turbine depends primarily on the height and diameter of the turbine both in relation to other turbines and the build environment.

Until a number of years ago a wind turbine was supposed to have a distance of 1 to 1.5 km in relation to the build environment, for fear of the rotor becoming detached of the hub during periods of high wind speeds. As technology has progressed and the reliability of turbines has increased, this legal requirement has been altered. Now a wind turbine should not cast a shadow on a house, nor should the turbine produce more than 47 decibels of noise (Rijksoverheid: Wet Milieubeheer, 2012). Those equates to a minimum distance of often 3 times the height of the turbine, which would equate in a 450m distance in relation to the build environment, for the turbine used in this research.

Spacing between turbines is dependent on the location of the turbines in relation to the direction of the prevailing wind. As a rule of thumb, distances vary between 5 to 10 times the diameter of the rotor (between 560 and 1120 m), often around 8 diameters for downwind and 5 diameters for cross wind (Andrews, 2007).

Chapter 6: Photovoltaic

Photovoltaic (PV) convert energy radiated from the Sun into electrical energy. The amount of light/energy that reaches the Earth's surface from year to year varies and within a year, as a result of changes in the Earth's elliptical orbit and changes in the solar declination, the angle of the Earth's axis relative to the Sun. The axis is inclined away from the Sun during the winter, while inclined towards the Sun during the summer. Consequently the amount of radiation the Earth's surface receives over the course of a year is dependent on the latitude and declination.

Radiation in the atmosphere is scattered, absorbed and reflected. Cloud cover and atmospheric haze determine the "clearness" and the amount of radiation that is diffused through the cloud cover. As a result the radiation that reaches surface is considerably lower and thus the radiation that can be converted by PV cells into electricity.

The primary factors that determine the eventual production of electricity are the amount of solar irradiation, the characteristics of the PV cell such as the conversion efficiency, the angle of the PV cell in relation to the sun and the outside temperature (Haberlin, 2012). In this chapter, first these primary factors will be discussed, followed by the methodology of calculation of the PV production, the results of the solar irradiation and simulated PV production for the locations and time period. Concluding with critiques on the method of PV modeling and the space requirements.

6.1 Data Collection

6.1.1 Solar Irradiation

The level of solar irradiation in the Netherlands as a result of the high latitude is low in comparison to regions at lower latitudes. On average the Netherlands receives around 1000 kWh/m^2/year, Mediterranean countries receive more than double that amount (Haberlin, 2012). As can be seen in figure 6.1, there are also distributions within the Netherlands; provinces in closer proximity to the North Sea receive more irradiance resulting from lesser cloud cover, in contrast to more inland regions (KNMI, 2012).

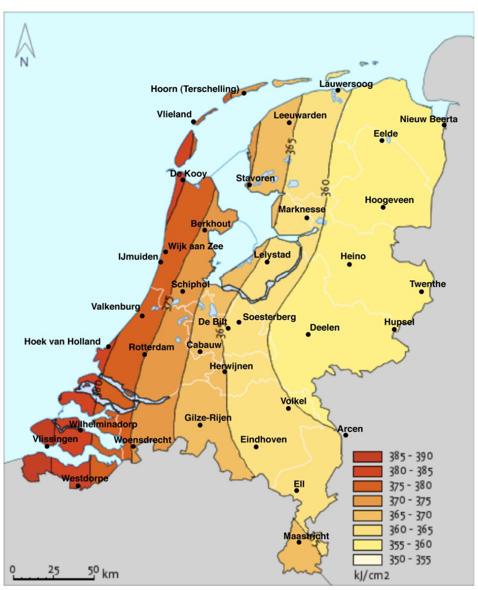


Figure 6.1: Solar irradiance in the Netherlands (KNMI, 2012)

Looking at the results for the meteo weather stations: De Bilt, Twenthe, Berkhout, Cabauw and Vlieland, these differences in level of irradiance can be spotted. In this chapter, the same measuring stations as in the wind turbine chapter are used, with the exception of Vlieland, for no irradiation data was available for that station. Instead, de Kooy has been used, a station close-by and with similar levels of irradiation.

6.1.2 Solar Cell Characteristics

Under present levels of technology, which are used for commercial purposes, the conversion efficiency of a PV cell in non-laboratory conditions is between 12 – 15 %. These efficiencies differ however per cell and manufacturer. The cell chosen for this modeling exercise is the mono crystalline Sunmodule SW 260 from SolarWorld, Germany's biggest manufactor of PV modules. The efficiency under standard laboratory testing conditions (STC) of the entire module is 15.56% [T = 25 Celsius, 1000 W/m^2], while under nominal operating cell temperature (NOCT) [T= 20 C, 800 W/m^2], module efficiency is 14.02%. The later efficiency (and other parameters) was chosen for in practice module efficiency is often around 1 – 1.5% below the STC (Solarworld, 2012). The characteristics of this cell were also in accordance with the examples of cells mentioned by Hablin (Hablin, 2012). It needs to be noted that these efficiencies are often derived from Peak power Pmax, which is the Maximum output power (voltage x current) of solar modules at a specific insolation and solar cell temperature (usually under STC) at the maximum power point (MPP). Watt peak (W_p) is also an important metric for indicating the installed capacity.

Table 6.1: PV Characteristics (SolarWorld, 2012)

Dimensions	
Length	1675 mm
Width	1001 mm
Height	31 mm
Surface 1 module	1.68 m^2

	STC 1000w/m^2	**NOCT 800w/m^2**
Maximum power (P_{max})	260 Wp	260 Wp
Open circuit voltage (U_{oc})	37.9 V	34.1 V
Maximum power point voltage (U_{mpp})	31.6 V	28.5 V
Short circuit current (I_{sc})	8.73 A	7.05 A
Maximum power point current (I_{mpp})	8.24 A	6.59 A
Module Efficiency (η_{module})	15.56%	14.02%
Max production per m^2	155.6 W/m^2	140.2 W/m^2

6.1.3 Angle of PV cells in relation to the Sun

During the course of the year the angle between the sun and the PV module changes, as a result of the latitude, declination and orbit of the Earth. This tilting of the PV in an optimal angle increases the energy yield. In addition, an optimal angle of the PV panel can increase the amount of diffused radiation that reaches the panel through e.g. cloud cover. Tilting of the solar cells increases the energy yield during the winter and days with overcast significantly.

Having a tracking system in place, which optimizes the angle of the panel with the incoming radiation can increase the energy yield by roughly 25 – 40 % (Haberlin, p 41, 2012). These tracking systems come with both higher upfront and maintenance costs; at present is economically more interesting to invest in more solar modules in the case of a Northern European country. Most solar systems are therefore set at a fixed inclination, although with some systems the inclination angle can be seasonally adjusted, which result in the increases of a few percent.

The measured solar irradiation needs to be multiplied by a factor, which would represent the gains made in received irradiation by the PV module. Studies have shown that the highest output for a non-tracking PV module at the latitude where the Netherlands is located is achieved when the module faces the south ($\gamma = 0^{o}$) and when the inclination $\beta = 35^{o}$. Baring this in mind Haberlin presented correction factors as depicted in table 6.2. These correction factors were devised for Giessen in Germany but also are representative for the Netherlands. These correction factors result in an increase in received irradiation from September – April, but a decrease during the months with highest irradiation. These factors increase the energy yield but also result in a more equal distribution throughout the year (Haberin, 2012).

Table 6.2: Irradiation correction for a module with $\beta = 35^{o}$, facing the south (Hablin, p 43, 2012)

Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
1,33	1,23	1,12	1,01	0,93	0,90	0,91	0,97	1,07	1,20	1,31	1,37	1,06

6.1.4 Ambient Temperature

The outside temperatures influence cell voltage, lower temperatures result in higher production. Seeing that the testing conditions often entail a temperature of 25 degrees, corrections need to be applied. These correction factors are depicted in table 6.3.

Table 6.3: NEC table 690.7–Ambient Temperature Voltage Correction Factors (Marion, 1999)

Ambient Temperature (°C)	Correction Factors
25 to 10	1.06
9 to 0	1.10
-1 to -10	1.13
-11 to -20	1.17
-21 to -40	1.25

6.2. Method of calculating simulated PV production

1. Initial irradiation data was presented in J/cm^2; conversion to kWh/m^2 :
$J/cm^2 * 10{,}000\ cm^2/m^2 = J/m^2 : 1000 = kJ/m^2 : 3600 = kWh/m2$

2. Correction factors for the tilting of the solar panel are applied, it is assumed that the solar panels are optimally placed, facing southward with a slope of 35^{o} and no shading occurs either from other panels, buildings or vegetation.

3. The resulting production was then multiplied by an overall model efficiency of 14.02%.

4. In conjunction with efficiency multiplication a voltage correction for the ambient temperature was applied, this was done on an hourly basis, based on the outside temperature data and temperature correction factors.

5. The resulting production is the amount of kWh per m^2, however the distribution of production needs to follow the production per kWp capacity installed, this is the result of the set-up of the Energy Model. Hence the found production needs to be converted. The Wp per m2 is 140.2, 1000 Wp divided by 140.2 results in 7.14, the factor used to multiply the found yield to get the yield per 1 kWp.

This also implies that a PV cell surface area of 7.14 m^2 is required for 1 kWp capacity.

6.3. Results

In this section, the results for both the measured solar irradiation and simulated PV production will be presented for the period 2004- 2011 in order to see the impact that the corrections have on the output. For the purpose of brevity the majority of the result are presented in Appendix IV.

6.3.1 Differences between locations

While there are substantial differences in wind production between different parts of the Netherlands, these are less extreme results for both the solar irradiation and simulated PV production. The average annual measured solar irradiation between the extremes Twenthe (1021 kWh/m^2) and de Kooy (1094 kWh/m^2) is a bit under 7%. The differences in the simulated production are of the same magnitude (CBS Dataset, 2012).

6.3.2 Differences between years

The total annual solar irradiation differs for the years researched, between 5 – 7%. In contrast to wind, the irradiation seems to be more constant.

6.3.3 Differences within a year

While there is limited variance in total irradiation between years, there are significant differences within a year, as can be seen in Figure 6.2, showing the measured solar irradiation in de Bilt over the course of a year, the curve has a perfect sinusoid shape . The average irradiation between December and June differs by a factor of 10. As can be the irradiation intensity between the outliers differs between 25% during the summer months, versus 50% during the winter months. Although during the winter the actual $2^{nd}/3^{rd}$ quartile spread is considerably smaller. This spread is the result of the number of hours in which irradiation is received and the intensity of the irradiation.

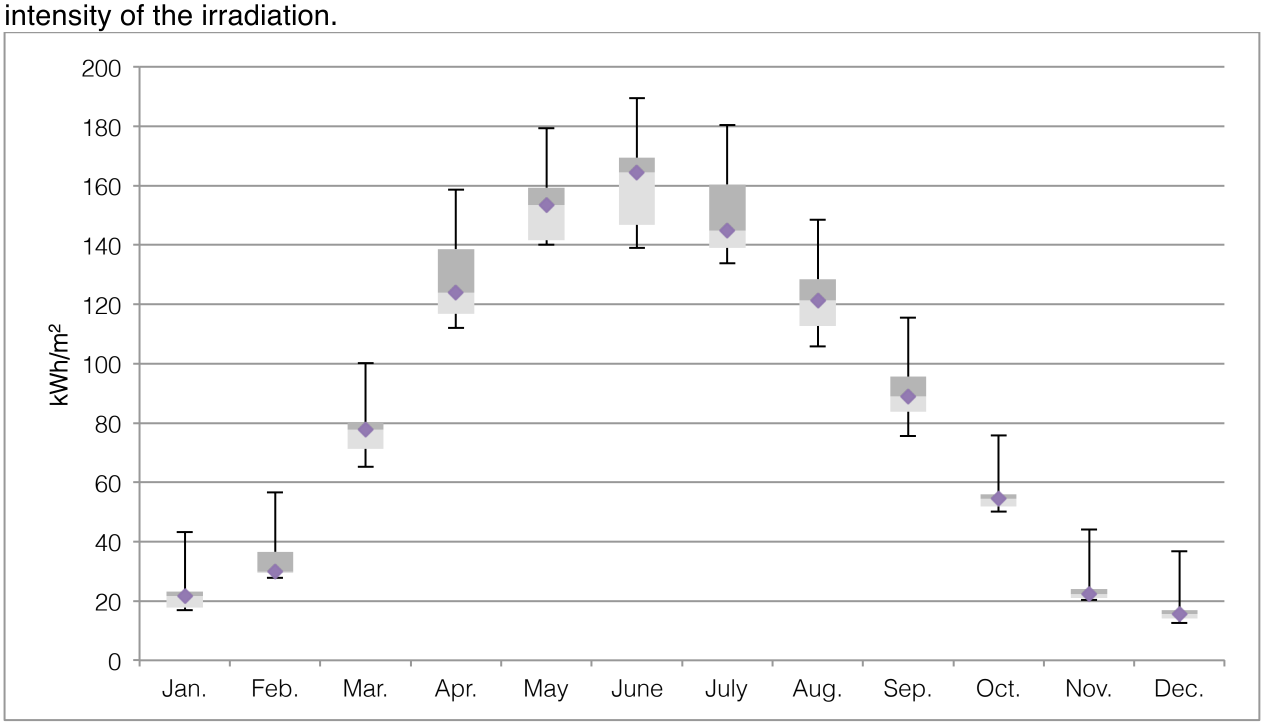


Figure 6.2: Measured Solar Irradiation, De Bilt (2004 – 2011)

For the Kooy (Figure 6.3), a similar shape can be spotted, although the distance between the outliers is smaller than in de Bilt as well as the spread of the 2nd/3rd quartiles.

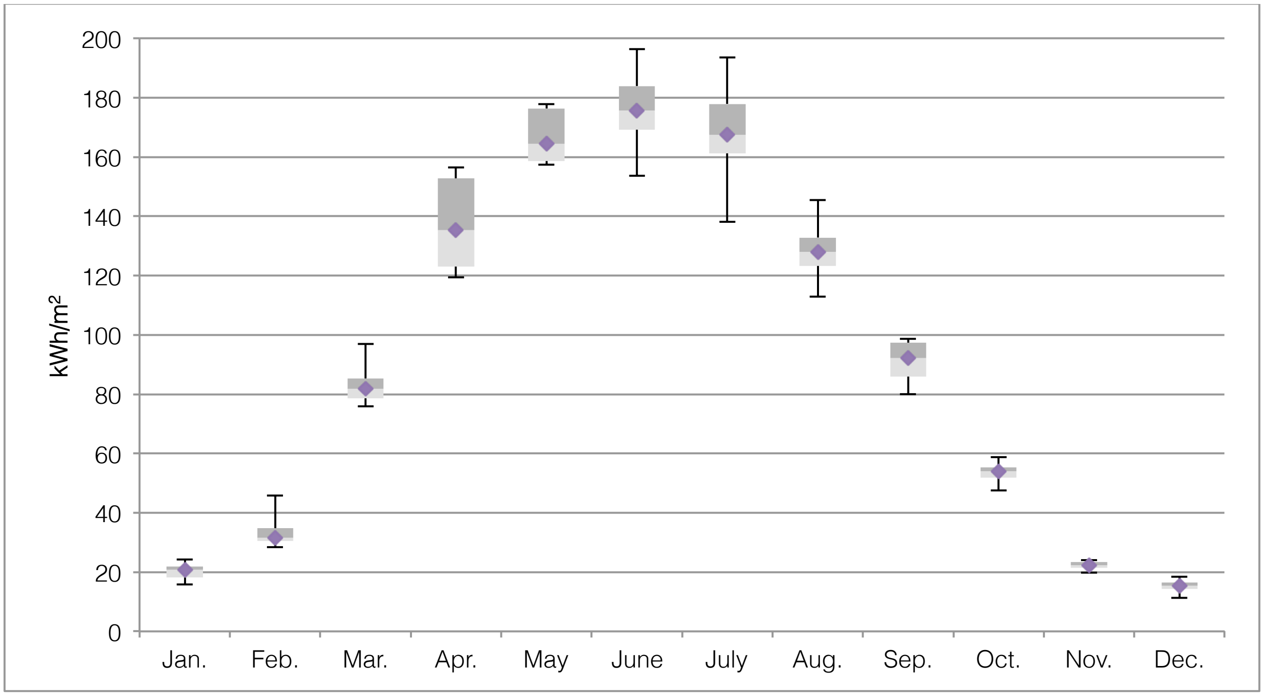


Figure 6.3: Measured Solar Irradiation De Kooy (2004 – 2011)

The other sites showed comparable outcomes as both De Bilt and De Kooy. Although there were differentiations in the spread, but of similar size and those presented in the given examples. The detailed graphs and tables can be found in Appendix IV.

Adding the previously mentioned correction factors to the solar irradiation results in the simulated PV production for a 1.5 kWp installation as can be seen in figure 6.4. What is evident is that the sinus shaped curve, is more flattened. The difference between the extremes December and June decreases to a factor 6/7. The spread between months April – July/August with maximum production the production is more equalized than the measured irradiation. The higher irradiation in June is reduced as a result of the higher temperatures, which reduce the output, as well as a reduction as a result of the angle of the solar panel; while in comparison the combination of the irradiation, angle and temperature raises the output in the other (summer) months. What can be concluded is that the corrections primarily result in a change in distribution but less into a change in overall output.

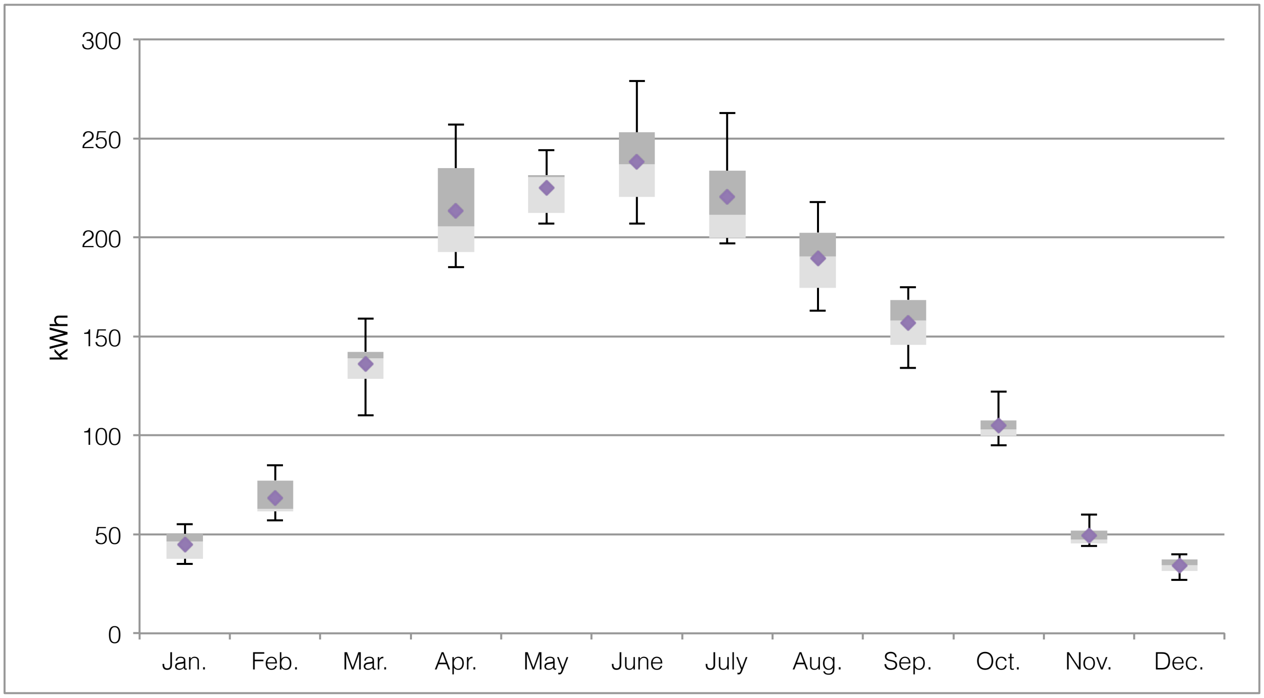


Figure 6.4: Simulated PV production De Bilt (2004 – 2011) for a 1.5 kWp installation per month

6.4. Critiques & Comments

- Additional factors such as other weather conditions (wind, humidity) are not taken into account.

- The tilting correction factors could be more exact, as well as the temperature correction factors

- indirect irradiation is not included in this models a result of the method in which the irradiation is measured by the weather instruments. Indirect irradiation would increase the produced energy yield. This primarily applies for the reflection of radiation from the ground surface, which is dependent on the absorptive capacity of the surface area, snow for example is highly reflective, reflecting between 4 and 8 times as much radiation as a regular grass surface. This means that during periods with snow cover and clear skies the irradiation that reaches the panel can be close to that of a summer's day (Haberlin, 2012).

- Although most simulations of PV production give a rather similar outcome in energy yield; actual measured production would of course have been most preferable.

6.5. Spacing: Land Usage

The average surface area for 1 kWp 7.14 m^2, when placed on a south-facing tilted roof. PV installation can also be placed on a surface area when not enough roof-space is available area. The area that is required for PV installations increases in such instance, in order to prevent that PV installation cast a shade on each other. The needed surface area is calculated by multiplying the space needed for PV on a rooftop by a land-factor, as shown by the following formula:

$A_L = LF * A_G$

A_L = *space required for a ground- based or rooftop solar generator field*
A_G = *total solar generator field area*
LF = *Land factor (between around 2 and 6 in Central Europe) for avoidance of shading of solar module*

This land-factor is in Central-Europe between 2-6 (Haberlin, 2012). In the results section, a range will be depicted, for it was unknown, what the land factor in the Netherlands would be.

Chapter 7: Heat Pumps

There are two primary methods in providing heat from renewable energy sources that can also be modeled within EnergyPlan: heat pumps and combined heat and power (CHP) plants running on biomass. In addition there are two "scales" at which heat can be delivered and modeled, either at a household level or via a district heating systems. At present, only 4% of all Dutch households are connected to district heating systems. The primary advantage of the district heating system is that heat can be produced centrally and heat can be stored at higher efficiencies. Although the disadvantage is that it is much more costly. The problem that was encountered with modeling CHP and heat pumps at the district heating systems within EnergyPlan, was that results for comparable systems were found to give different sizes in terms of the storage requirement. However, when modeling heat pumps at individual households, the results that were gathered seemed to be correct. Therefore, heat pumps were considered to be the only method of delivering heat to households and located at individual households. Heat storage therefore could also not be modeled. This method of modeling the heat pumps at individual households also seems to be more applicable to the Netherlands, seeing that district heating systems are not prevalent.

7.1 Heat pumps

Heat pumps use electricity to force a flow of heat against the temperature gradient by harnessing the thermal properties of expansion and compression to transfer heat energy from warm to cool space or the other way around and hence provide climate control in residential buildings all year round. Heat pumps are highly adaptable in usage and within neighborhoods and can be used for both space heating and providing warm tap water. A vapor compression heat pump is the one most commonly found in residential applications, uses compressor fueled by electricity to drive a condensing fluid known as a refrigerant through a Carnot cycle (IEA Heat Pump Centre, 2012; Harvey, 2006). Figure 7.1 shows a schematic of the compression cycle and the main parts of such a heat pump.

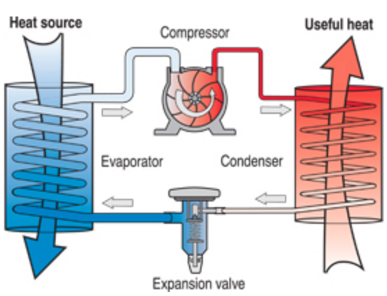


Figure 7.1: Heat pump schematic (IEA Heat Pump Centre, 2012)

Heat pumps work by drawing heat into the refrigerant within the evaporator, and compressing the refrigerant via the compressor, which is then heated and moves into the condenser where heat is radiated into the warmer space. Lastly, the refrigerant is expanded through an expansion valve and the temperature of the refrigerant decreases. The heat can either be derived from outside air, ground or surface water. The efficiency of the heat pump is determined by this medium of intake source, which is referred to as the coefficient of performance (COP) which is the ratio of heat energy delivered to energy input.

The Coefficient of Performance (COP) is dependent on the medium of intake and the temperature of that heat extracted as can be seen in table 7.1. The COP used will be 3.55, this seems a realistic assumption in which the heat pump will be able to provide the required temperatures of both space heating and the demand for warm tap water. As shown in Table 7.1, different mediums of intake can in this case be selected. This COP is realistic for residential buildings, which use radiators, as is the case in most Dutch households. Households with floor heating would see a higher COP. Although at present most Dutch households do not have heat pumps, these could easily be installed, although houses would need to be adapted (EIA Heatpump Center, 2012).

Table 7.1: COP of different intake sources at different temperatures (NEN, 2011)

COP air	3.55 – 2.8 (<30 C – 50<th<55)
COP aquifer	5.0 – 3.6 (<30C – 50<th<55)
COP surface water	4.3 – 3.3 (<30C – 50<th<55)

7.2 Comments & Critiques

-The COP of heat pumps dependents on the temperature of the intake sources, these are often variable; this variability could not be modeled

-Heat storage could not be modeled, the inclusions of heat storage, could aide tremendously in the reduction of electricity storage; seeing that heat storage technologies often are cheaper or more technologically ready.

-Heat pumps attached to for example aquifers have a higher COP a rather conservative COP was assumed.

7.3 Results

A COP of 3.55 for the heat pumps is assumed. The operation of the heat pump is dependent on the distribution and total heat demand as discussed earlier in Chapter 3 and shown in figure 3.5. Figure 7.2 depicts the consequential distribution of the additional average electricity consumption of the heat pumps throughout the year. As can be noted there is a substantial differentiation in terms of the level of consumption between the winter and summer months.

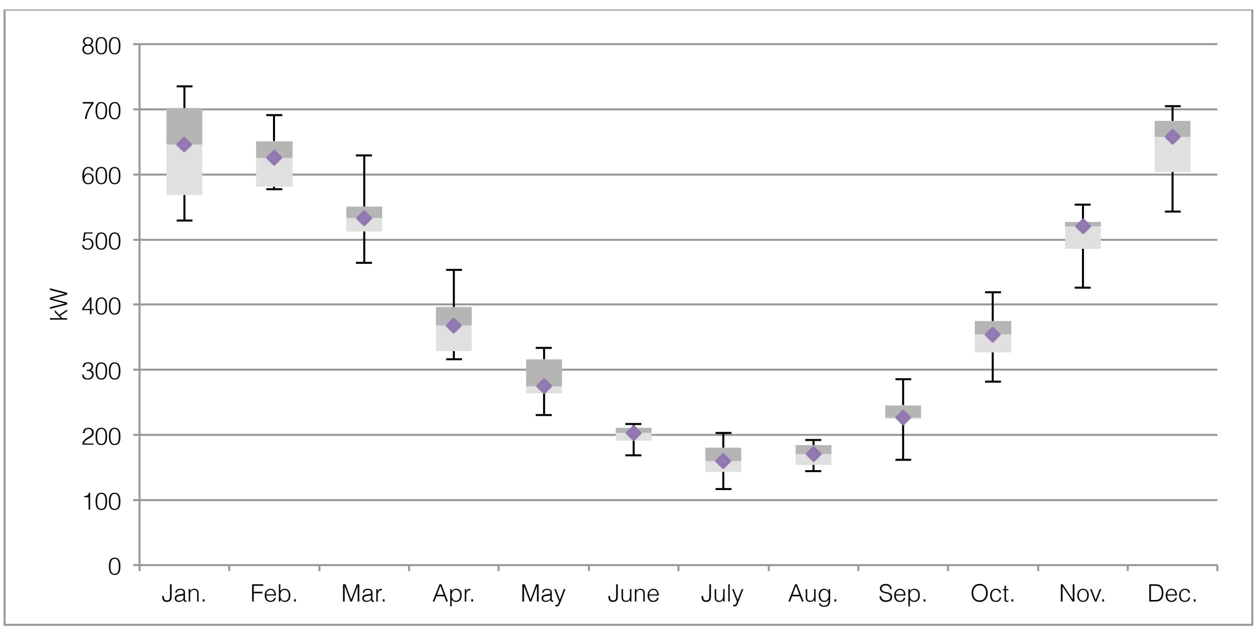


Figure 7.2: Distribution of average heat pump electricity consumption per month [period 2004-2011, De Bilt]

Section V: Dealing with Intermittencies

Chapter 8: Electricity Storage

Electricity storage is key for an energy system based on intermittent renewable energy sources. A country without energy storage is able to sustain a stable electricity system with around 20% of a single intermittent source such as wind, while most literature concurs that with large-scale storage, this figure is able to rise for a single intermittent source to around 80%. Using a mix of multiple sources allows for an even higher penetration (Barnes, 2011). Next to renewable integration storage can also have other supportive roles for the power system as a whole such as guaranteeing the power quality or congestion management.

Existing energy systems either rely on pumped-hydro systems or large-scale fossil fuel based back-up capacity. Both the profitability and technology readiness of storage options such as batteries has inhibited large-scale implementation of storage. In addition, for 100% renewable energy systems known issues and complications are the rate of deployment of storage (ramp rate) and the amount of energy that can be stored, charge and discharge capacity (capacity challenges)(Barnes, 2011).

To some extent the EnergyPlan model has been used exactly for the purpose of modeling storage capacity, especially for the usage of Compressed-air Energy storage (CAES), not only for looking at the storage capacity needed, but primarily the role of storage on the electricity market and as a tool to generate profits. Within the Energy Plan model, different types of energy storage can be modeled: non-specified electricity storage, hydrogen storage, electric vehicles as a mode of storage, and compressed air energy storage (CAES). The input parameter are the storage efficiency and the storage capacity. Of these technologies, compressed air energy storage is the only technology that could both be implemented in the Netherlands and is technological advanced enough and not too costly (Ibrahim, 2008; Barnes, 2011).

In this chapter, there first will be a discussion on the applications of storage and the types of storage, followed by a discussion of CAES and the assumptions that will be used in EnergyPlan. The concluding sections will be concerned with the question on sizing of the CAES plant, and critiques.

8.1 Applications of storage

Electricity storage can fulfill a myriad of different functions within both fossil fuel, renewable and mixed electricity systems. Storage can aid in the renewable energy integration by its ability for electric energy time shifts, hence is able in providing back-up capacity for intermittent renewable energy sources. Within the context of an independent renewable energy system, other provisions such as providing ancillary services, voltage support, spinning reserves and guaranteeing the power quality also become important. Functions which in fossil-fuel based electricity system are full-filled by power plants. An electricity storage facility thus takes over, the role of a regular power plant in fulfilling these applications. Overall storage allows for more flexibility within the system and makes a 100% renewable energy system possible (Eyer, 2010).

8.2 Different types of storage

These applications can roughly be subdivided into the following categories, UPS (uninterrupted power support), Grid support and Energy management/Bulk Power support, based on their discharge time and capacity. For each of these options, different storage technologies are available as can be seen in figure 8.1. Some of these options fall in several of these categories. These categories are also dependent on the ramp-rate, the speed at which the rated power can be reached. For the large-scale energy storage options such as CAES the ramp rate at which the level of rated power is achieved is several minutes, while for other technologies this is several seconds. The ramp-rate in completely renewable electricity systems is important, for the storage devise, needs to be able to react fast to the changing power supply (Ibrahim, 2008; Barnes, 2011).

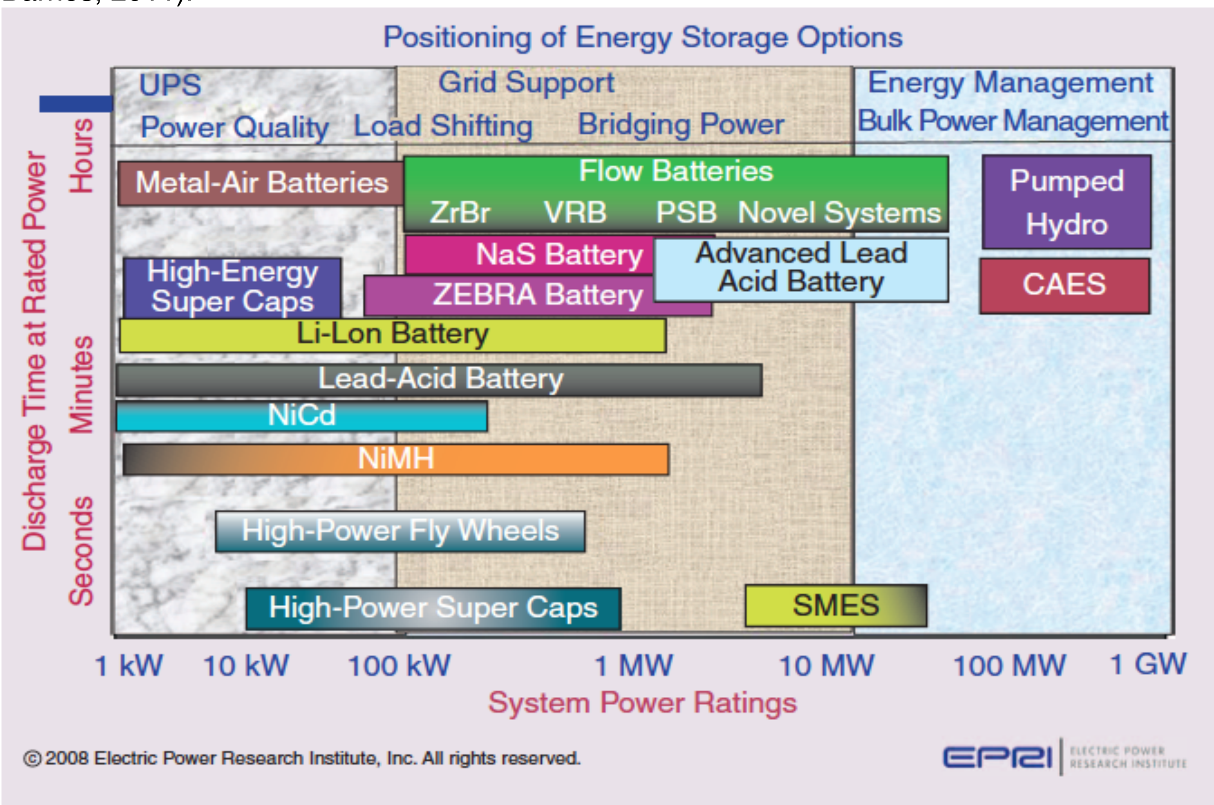


Figure 8.1: Energy storage options and their applications (Roberts, 2009)

In this research the main concern is with determining the amount of “bulk power management” that would have to occur in a renewable energy system in order to make the system stable. However, the other storage categories will also be extremely relevant and although these are not discussed in this research, will also have to fulfill an important role in a complete renewable energy system.

8.3 Bulk Power Management

There are two main technologies which can be used for large scale bulk power management which are at present technologically mature enough, namely pumped hydro-electric storage (PHS) and compressed air energy storage (CAES); the parameters of the latter technology will be used in EnergyPlan. Other storage technologies are not yet suited for filling a bulk power management as a result of factors such as technological readiness, high capital costs, high replacement rates, low efficiencies, low energy density, slow charging or discharging rates and resource intensity and coupled environmental impact (Barnes, 2011).

Pumped Hydro-electric Storage (PHS) is the most wide scale implemented energy storage method responsible for around 3% of the worldwide generation capacity (Roberts, 2009). PHS entails that "*energy is stored as the potential of water raised against gravity* (Barnes, 2011, p 51)." Water is pumped from a lower reservoir to a higher reservoir, when energy is needed, the water flows through a turbine back to the lower reservoir. This process happens at an efficiency between 70 – 80%. Next to having such installations at the Earth's surface, PHS could also be installed theoretically underground in large caverns or old mine shafts, however this system has never been build (Ibrahim, 2008; Barnes, 2011). Unfortunately, PHS cannot be implemented in the Netherlands on a large scale as a result of lack of differences in height and underground PHS is still only a theoretical option.

Although in the Netherlands there are at present no large-scale energy storage facilities present, CAES could be implemented on a large scale for the technology is mature, is not too costly, has a relatively high efficiency and has a lower environmental impact than PHS. With CAES, energy is stored in the form of high-pressure air. This high-pressured air can be stored in a wide variety of vessels, namely for smaller volumes in surface tanks, but for larger volumes in abandoned mines, saline aquifers, mined hard rock and salt domes. CAES can both be implemented on a large or small scale and thus could even be build in neighborhoods (Barnes, 2011). Figure 8.2 depicts regions in blue with average high wind speeds and the red circles depict salt dome structures where CAES installations could be build; it shows that the Netherlands is a prime candidate for CAES due to the existence of salt domes in the sub surface and that there are already solution-mined cavities in these salt domes (Calaminus, 2007).

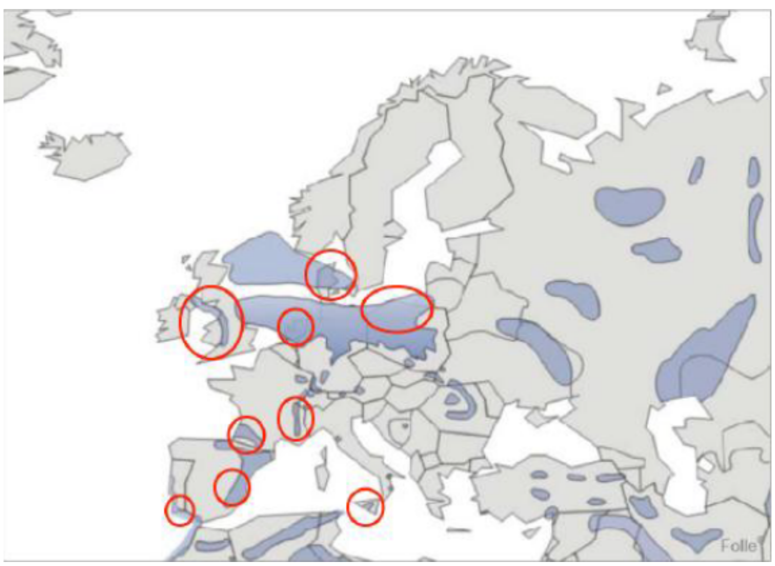


Figure 8.2: Regions with high wind & salt domes for CAES development (Calaminus, 2007)

There are two main types of CAES, namely isothermal (ICAES) and advanced adiabatic (AA-CAES). In an ICAES plant, during periods when the production of renewables is above the demand, air is compressed in an isothermal compression at which the temperature of the air is kept constant, requiring the removal of heat. This is done through a system of intercoolers and after cooler to increase the overall efficiency of the system and reduce the size of the system. The compressed air flows then into the caverns. During the storage processes exergy losses occur through the wall of the cavern. When the stored energy is needed, the air is withdrawn from the caverns and natural gas is combusted in the pressurized air; the combustion product is then expanded and used to generate electricity. The system operates in a similar fashion as a conventional gas turbine, although with CAES the compressions and expansion phases occur independently at different times (Succar, 2008).

The existing plants are isothermal CAES plants namely in Alabama (1991) and Germany (1978) have respective efficiencies of 54% and 42%. The Alabama plant has a start-up time of around 6 minutes and the pressure in the caverns fluctuates between 43 and 64 bars. This short start-up time is especially relevant for complete renewable energy systems, for the storage facility in such a system would have to be able to react fast to changes in the energy supply and demand. Newer isothermal CAES plants will have higher efficiencies between 60 -65% without a heat recuperator, but with a heat recuperator between 80 – 85%, both instances are with the usage of natural gas and thus CO_2 emissions. When the two present existing CAES plants were developed during the 70s/80s, the primarily purposes of these technologies was grid operational support such as regulation control, black start and load shifting* Barnes, 2011)

The schematic of an AA-CAES plant is shown in figure 8.3. With an AA-CAES, the system as a whole is insulated against any heat transfers with the environment. Air is compressed and the heat it is expelled, but in AA-CAES the heat is stored instead of exchanged with the environment through a system of intercoolers. The waste heat has a temperature of 600 C and is re-used for later usage. These facilities are 40m high containers with beds of stones ore ceramic molded bricks through which the air flows. The air is again stored in caverns. When the stored energy needs to be utilized, the air is re-heated and expanded through a gas turbine. With AA-CAES no natural gas is needed and the system does not emit any CO_2. At present, the first AA-CAES plant (ADELE) is under construction in Germany. The overall system will have an efficiency of approximately 70% and pressure in the cavern will be around 70 bars. The higher efficiency is the result of the usage of thermal storage (Samaniego, 2010).

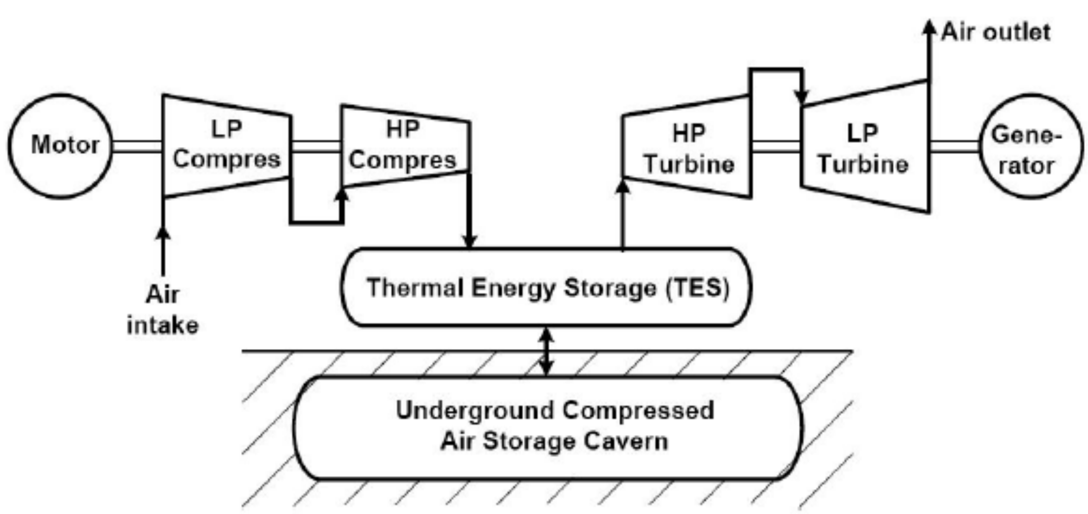


Figure 8.3: AA-CAES plant (Samaniego, 2010, p13)

Next to CAES systems in salt domes or other geological structures, which often require a bit larger scale plants, smaller "micro" CAES plants are also possible, which could in theory be set-up in neighborhoods. In the US a start-up called SustainX, claims it has developed a technology of ICAES which uses underground storage tanks/cylinders and the system as a whole would also do not require natural gas. A 1.5- 2 MW demonstration plant is currently under construction and will be completed mid-2013 (Sustain X, 2012). In addition, Kim et al. theorized about CAES systems even at a household level of a number of kWh in size (Kim, 2010).

Seeing that these more micro-technologies are still under development or theorized about, and the CO_2 emissions from a ICAES plant resulting from the burning of natural gas would undermine the principal of 100% renewable energy neighborhood, the parameters of AA-CAES will be used as input in EnergyPlan, namely an overall storage-cycle efficiency of 70%.

8.4 Sizing

Existing literature is rather inconclusive concerning the amount electricity storage that is required. Estimations tend to vary quite widely and often are not applicable for a research at neighborhood level. Often studies are done at a country-level or for mixed energy systems with quite a lot of back-up capacity in terms of CHP (Lund, 2009; Esteban, 2012). The obvious reason is that the capacity required depends on the reliability and continuity of intermittent renewable energy production. Therefore, during the initial model runs the storage capacity was not maximized.

A second sizing has to do with determining the size of the compressor and turbine. Available studies primarily see CAES as playing the economic role of arbitrager within a system and how to turn a profit with the storage facility (Denholm, 2009; Samaniego, 2010). The capacity of the compressor is primarily dependent upon the ratio between the maximum energy production and demand, seeing that the compressor will utilize excess supply. The turbine would have to be able to provide all the capacity, in case there is no production at all. The turbine thus has to have a capacity similar in size to the maximum electricity demand. Therefore, the turbine and compressor were not maximized.

The size of the cavern needed for a CAES plant is dependent on the volume that needs to be stored, but is also determined by the characteristics of the cavern for example whether it is a CAES plant with a constant pressure reservoir, variable pressure reservoir or variable pressure reservoir with constant turbine inlet pressure; but also the ratio between the lower and higher storage pressure plays a role. At an upper storage pressure limit of 70 bar (as is the case for the ADELE AA-CAES plant in Germany), the amount of energy generated per unit of stored volume differentiates between 2 kWh/m^3 and 7.5 kWh/m^3, dependent on the above-mentioned factors. In Appendix Figure V.1, a detailed figure depicts the average energy content per type of cavern under different conditions. In the results, ranges for the different types of caverns will be given in terms of size.

8.5 Critiques & Comments

-Short-term storage is not included; meaning within an hour, for a complete energy independent system, a flywheel, batteries or super capacitors need to be integrated within the system. Appendix Table V.1 show the synergies between the different applications of electricity storage, what table reveals is that the application of large intermittent renewables grid integration is overall incompatible with the other applications such as guaranteeing the power quality (Eyer, 2010). Although other sources claim that CAES would also be able to deliver ancillary services (Succar, 2008; Barnes, 2011). This difference in opinion is probably due to the fact that most sources consider CAES to be integrated into a mix renewable-fossil fuel based energy system, while in this research a 100% renewable energy system is being considered.

-AA-CAES is still under construction so the estimated efficiency of 70% might in fact be lower; it is also interesting to note that in the 100% renewable energy neighborhood the thermal storage unit of the CAES plant could be combined with additional thermal storage units, which could provide heat to a neighborhood through e.g. a district heating system. This is however only a theoretical possibility and nothing was found in existing studies to indicate the possibility of this actually being implemented.

8.6 Final figures

Advanced-Adiabatic CAES is a possible technology that could both be implemented in a neighborhood or on a larger scale in the Netherlands, and serves primarily the purpose of offering a framework technology for quantifying the storage capacity requirement of 100% renewable energy system. In EnergyPlan, an overall storage cycle-efficiency of 70% was chosen (combined efficiency of both the turbine and compressor/pump). With isothermal CAES the so-called fuel ratio has to be included, seeing that natural gas has to be used in such a system, this is not the case for AA-CAES, therefore entries were made in the EnergyPlan in electric storage and not CAES sub-section. In addition, the size of the storage equipment was not limited during the model runs, this means that all surplus production could be stored and that in case when there is no energy supply from all sources, the entire energy demand can be fulfilled by the storage devise.

In the results and discussion chapters, as a method of making the storage capacity requirement tangible in terms of sizing, a comparison is made between the storage capacity requirement and amount of batteries needed that would have the same capacity. One MWh of energy storage is roughly equal to a container filled with batteries. This comparison is strictly illustrative.

Chapter 9: Biomass fueled back-up capacity

Biomass used in back-up capacity has the potential to compensate for the intermittencies that occur in a 100% renewable energy system. The major drawback of biomass is that it has low energy intensity and is therefore extremely land intensive as will be shown in this chapter.

9.1 Biomass

Biomass is identified as a source of renewable energy; the distinction is made between three generations of biofuels. First generation biomass is derived from so-called energy crops such as sugar, starch and corn. This source of biomass is extremely land intensive as a result of the relatively low energy density of biomass crops and competes with other e.g. food production for land, thereby making its sustainability sometimes questionable. Second-generation biomass originates from woody crops or agricultural residues and waste and therefore does not require land to be set aside specifically for the biomass production. Third generation biomass are based on algae, but are still under development.

9.1.1 Biomass from energy crops

Table 9.1 shows the net energy yield, per energy crop per hectare per year, for crops which are suitable from Dutch climatic and soil conditions. The net energy yield is the total energy yield that the crops could generate minus the energy inputs used for production. These are different yields based on the number of years the crops are planted, this accounts especially for the woody crops willow and poplar, which produce more biomass over the course of a decade. In determining the total land usage for energy crops in the results section, different ranges for land usage will be shown (Faaij, 2007).

Table 9.1: Net energy yield per crop (Faaij, 2007, p 17)

Crop		**Net energy yield (GJ/ha*year)**
Rape	Short term	110
	Longer term	180
Sugar Beet	Short term	250
	Longer term	370
SRC-Willow	Short term	180
	Longer term	280
Poplar	Short term	150
	Longer term	250

9.1.2 Biomass produced by households/neighborhoods

Next to biomass from energy crops, households, through garden waste, fruit-vegetable waste and human feces, also produce biomass. This waste can be turned into biogas through anaerobic digestion. Exact production figures of the energy yield are not available, only national estimates of for example the amount of the amount of biomass produced by reed cutting, parks and household waste are available. These sources also are used for other purposes such composting or co-generation in coal fired power plants and are therefore not taken into account.

A pilot project in the neighborhood Noorderhoek in Sneek, comprising of 250 households, has shown that biogas produced from vegetable and fruit waste and human feces fulfills between 7 – 12% of the gas requirement. This is however only based on the sources provided by the company and could not be verified and therefore is not taken into account. This does show that neighborhood inherently could meet a small percentage of their own biomass requirement (Agentschap NL, 2011; Desah, 2012).

9.2 Back-up capacity

The efficiency at which the biomass is combusted is assumed to be 35%, meaning that the method of combustion would be a combustion plant. Alternatively a gas turbine could be assumed, but the biomass from the energy crops in that instance first would have to be gasified, in this instance similar efficiencies would be obtained but this technology is partially still in its infancy *(Deng et all., p 71, 2009).*

What does need to be noted is that when within a 100% renewable energy system based on intermittent sources without energy storage or grid-connection, back-up generation needs to be able to react fast to changing supply and needs to have a short black-start time, a gas turbine seems to be the most logical choice, although smaller combustion plants will probably also be able to react quickly.

Initially, a combined heat and power plant (CHP) was proposed, for these have a higher overall efficiency as can be seen in table 9.2. Unfortunately, there were some inconsistency in the results obtained in EnergyPlan and therefore this was not modeled. It should therefore be kept in mind that the results obtained for the land usage in the results section will therefore be probably higher than the actual land requirement.

Table 9.2: CHP Capacity and Efficiencies (NEN, 2011, p 47)

Capacity	η_{th}	η_e
2 kW $<P_e<$20 kW	0,57	0,28
20 kW $<P_e<$ 200 kW	0,51	0,30
200 kW $<P_e<$ 500 kW	0,52	0,32
500 kW $<P_e<$ 1000 kW	0,46	0,35
1000 kW $<P_e<$ 25 MW	0,41	0,37

9.3 Comments & Critiques

- A more exact assessment on the amount of biomass produced by households could not be made; including production of biomass by households, would lower the amount of land required
- Including CHP in the system would probably result in a lower land requirement

9.4 Results

For biomass the range that is provided will be between 110 – 370 GJ/hectare. The efficiency of the gas fired back-up generator is assumed to be a conversion efficiency of 35%. These figures primarily service an illustrative purpose.

Chapter 10: Demand Response

Demand response, also known as flexible or dynamic demand is the concept of altering levels of energy consumption (primarily electric consumption) based on the availability of renewable energy. On the one hand this can be accomplished through a top-down approach in which the energy company determines how much energy is allocated to a household during a certain time frame, while another method is through dynamic pricing. The cost of electricity changes in such a system per timeframe, the consumer can then decide whether to alter his or her consumption behavior based on the price incentives and to what extent. Both methods fall under the concept of the smart grid.

Demand response has until now primarily been used as a method for balancing electricity supply and demand in the area of large energy-intensive industrial activities, such as aluminum production; but in recent years research on demand response has been starting to focus more on households, offices and other utilities. Flexible demand with refrigerators is possible across a large number of different users, ranging from refrigerated warehouses, food retailers, butcher shops, hotels, restaurants, ice gins and off course household, in Germany the theoretical potential for flexible demand of refrigerators was estimated at around 14% of the total electricity demand. The achievable potential is between 4-6 % of the maximum electricity demand (in Germany). Demand response through refrigerator is inhibited for a number of reasons, such as strict compliance with legal cooling requirements, liability issues, lack of technical experience and other social-economic barriers (Grein, 2011, p 5598). Another demand response utility option would be indoor-swimming pools, which consume as much electricity as 400 households. The pool can also act as a heat buffer where at night the pool acts as a heat sink for excess electricity and has to consume less during the day (Woolley, 2011). Moreover, greenhouses and ice rinks can also act as thermal buffers.

However, in this chapter, the focus will only be on demand response in households. There first will be a discussion on to what extent the demand for electricity and heat within a household is flexible and how this will be modeled in EnergyPlan. Lastly, critiques on the method of modeling demand response will be discussed.

10.1 Breakdown of household electricity consumption

The breakdown of the electricity consumption in 2005 is depicted in table 10.1. Electricity usage can be subdivided in roughly the following categories: cleaning, temperature control of food, electric appliances, indoor temperature control, cooking and lighting. In the next decade it is expected that overall electricity consumption will drop but that certain categories such as electric appliances and cooling will increase, while other categories such as cleaning, fridge/freezer and lighting will show drops in consumption (VHK, 2008). The break down of consumption is important in trying to identify areas in which consumption could be shifted.

Table 10.1: Breakdown household electricity consumption (2005) (VHK, p 11, 2008)

Category	Electricity Usage (kWh/year)
Dishwasher	170
Washing machine	192
Dryer	252
Vacuum cleaner + other cleaning appliances	115
Fridge	396
Freezer	203
Television	209
Audio/video	159
ICT	167
Heating	232
Warm water	293
Cooling/Ventilation	148
Hotplate/oven/microwave	175
Kitchen appliances	121
Lighting	559
Recreational	42
Personal hygiene	28
Other	61
Total	3522

10.2 Potential for Demand Response at the household level

10.2.1 Flexible Demand: Electricity - Size

A number of studies have been done to what extent demand response can take place in households. There are two primary categories of appliances of which the energy demand could become more flexible while not significantly resulting in consumer discomfort, these are appliances or machines that convert electricity in heat or cold (A/C, heat pump, refrigerator), and appliances that can operate in a flexible timeframe (washing machines, tumble dryers, dish washers).

In the first category, thermal buffers within systems or within the house allow for more flexible demand. In the US, demand response incentive schemes for households are already implemented, these apply primarily for air-conditioning (A/C). In some states consumers are paid around 100$ annually, when electricity companies are allowed to place a small device on the A/C, that turns the A/C off for around 15 minutes during periods of peak demand (Cappers, 2010). Air-conditioning is only responsible for a small portion of total household electricity consumption in the Netherlands and is therefore less relevant.

In refrigerators and freezers "*thermal inertia provides a temporal buffer for shifting and adjusting the power consumption of cooling systems* (Grein, 2011, p 5601)." Every time your fridge heats up past a certain temperature (the baseline temperature), the electrical cooling system kicks in, to cool it down to a sub-baseline temperature (e.g. 5 and 3 Celsius). Dynamic demand device controls would regulate the bandwidth and when the fridge is cooled. For example during periods of excess electricity, the fridge or freezer could cool below its set temperature and have reduced consumption during periods of less electricity, e.g. by not cooling to the sub-baseline all the way, but leave the fridge at the baseline (Vince, 2005). It is the principal of heat/cold acting as a buffer capacity. These techniques can be both applied for small household refrigerators and fridges, but also for large scale cooling house (Grein, 2011).

The conversion from electricity in an heat energy carrier is able to provide this 'natural' buffer, for the energy content of heat/cold does not dissipate as rapidly as electricity, thereby creating a bandwidth that acts as a safety net for variations in intermittent renewable energy sources, thus negating partially the need for the back-up fossil fuel capacity or energy storage. Electrical appliances that do not have this natural buffer present, a shift in the time of use needs to occur. This is applicable to appliances such as dishwashers, washing machines and tumble dryers; which do not have to start immediately such as a TV, lighting or PC. This is dependent on the extent at which consumers receive a form of discomfort.

Hamidi et al. claimed that within the UK domestic sector as a percentage of the total demand, between 25 – 45% can be qualified as responsive demand. This estimation was made based on a an economic incentive model, this means that factual physical responsive demand can in fact be higher, but these percentages include an acceptable level of discomfort for the consumer. (Hamidi, 2009). Research in the Netherlands has shown that appliances responsible for 50% of the electricity consumption can be shifted to some degree (Leguit, 2009). Table 10.2 shows the relevant appliances that can be flexible in their demand patterns, for a Dutch household. This equates to around 43% of the total demand that could be relevant for flexible demand. The other category consists of the electric boiler, waterbed and a number of other small categories.

Table 10.2: Relevant appliances for shift in demand (Leguit, 2009; Kester 2006)

Appliance	**Usage/household (kWh/year)**
Fridge	396
Freezer	203
Washing machine	226
Tumble Dryer	252
Dishwasher	170
Other	243
Total	1490

10.2.2 Flexible Demand: Electricity – Distribution

Figure 10.1, shows the percentage of responsive demand as a percentage of the total demand during that hour over the course of the day for UK households.

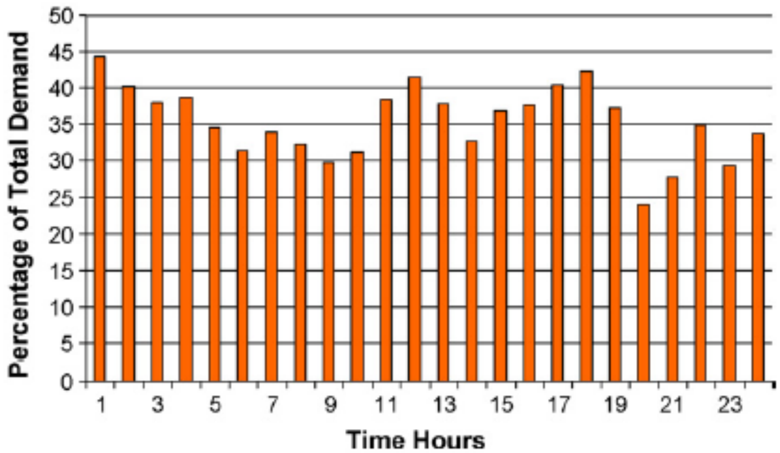


Figure 10.1: Total level of responsiveness (Hamidi, 2009, p 1726).

This percentage of the total responsive demand depends on the nature of the total demand at the time; in the early evening this percentage is considerable lower for households use their electricity primarily for tasks which have to take place during that time frame, e.g. cooking, watching TV and lighting.

In the EnergyPlan model, there are 3 time frames when demand can be shifted, within 1 day, 1 week and 1 month. For households, the bulk of possible shifts in demand will be within a day and to a much lesser extent for a week. Shifts in demand within a month will be assumed not to take place. Flexible demand that can only take place within a day are those applicable for fridges, freezers and the other category, a maximum total of 842 kWh per household or 24.6% of electricity demand. It is assumed for the washing machine, tumble dryer and dish washer that there is more flexibility; the assumption is made that 75% of the demand for these appliances has to be met within a day (486 kWh or 14.1%) and 25% within a week (162 kWh or 4.7%). In the different scenarios that will be modeled variations in flexible demand will be included, so the above mentioned figures are maximum possible flexible demand for these time frames.

Scaling these figures up to the neighborhood level would result in a annual flexible demand on the 1 day time – scale of 0.874 GWh and for flexibility of 1 week of 0.168 GWh (maximum assumed capacity respectively 148 kW and 28 kW).

10.3 Flexible Demand: Heat

Unfortunately, modeling flexible heat demand with the EnergyPlan model is not possible. Seeing that the house as a whole can act as a thermal buffer (especially for well insulated houses), this would offer additional opportunities for flexible demand.

10.4 Critiques &Comments

-Although primarily the hourly impact is modeled, demand response is often used for sub-hour activities, in order to reduce the inconvenience of the consumers, this especially applies for the case of air conditioning

-As discussed in Chapter 3 the distribution of the electricity consumption is based on the national distribution and not on actual neighborhood consumption patterns, therefore the results that are

obtained need to be treated with care; in the sensitivity analysis, other load profiles are also used
-demand response with heat pumps not possible in the energy plan model
-further research needs to be done on the size and distribution of demand response for utilities. At present, there are too many unknowns to include these in the EnergyPlan model.

10.5 Final Figures

Annual flexible demand on the 1 day time – scale of 0.874 GWh and for flexibility of 1 week of 0.168 GWh (maximum assumed capacity respectively 148 kW and 28 kW).

Section VI: Results

Chapter 11: Overview assumptions

The assumption for each individual component of the energy systems were discussed in previous chapters, but as a recap the most relevant assumptions are as followed:

- The period analyzed is 2004 – 2011 on an hour-to-hour basis per year for the locations De Bilt, Cabauw and Berkhout, with associated differentiation in wind and PV production and heat consumption. Vlieland is used only as a reference for a possible “off-shore” wind turbine.
- Energy Demand: 3.55 GWh in electricity demand and 12.20 GWh in heat demand. These figures were used for every year analyzed for they were the maximum levels of consumption; the distribution of consumption for both years is differentiated (Chapter 3)
- Heat pumps at the individual households full fill the heat requirement with COP of 3.55, the heat requirement results in an additional 3.44 GWh electricity demand, following heating degree day distribution (Chapter 7)
- Wind Energy see Chapter 5
- PV see Chapter 6
- Only electricity storage is used (not heat storage) with a cycle efficiency of 70% (Chapter 8)
- The size of the total annual flexible demand of electricity consumption is 0.874 GWh that can be shifted during a day and 0.128 GWh during a week, with a relative maximum capacity of 156 kW and 28 kW. There is no flexibility in the distribution of the heat demand (Chapter 10)
- Back-up power plants on biomass have a 35% conversion efficiency from primary energy

11.1 Context of the neighborhood

The following table summarizes the context of the predefined neighborhood of which the most relevant parameters to this research are in bold. These encompass the number of households and the amount of space that theoretically would be available for biomass production.

Table 11.1: An average Dutch neighborhood

Category	**Average**
inhabitants	2279
households	**1038**
average household size	2.2
address density	1926
average land size (ha.)	52.36
urban (ha.)	48.09
Infrastructure (ha.)	3.48
build environment (ha.)	35.49
semi-build environment (ha.)	1.60
recreational (ha.)	7.52
non-urban (size)	4.27
agriculture	**3.05**
nature	1.22

Chapter 12: Results

In this chapter, the results are presented of the modeling of the individual components in EnergyPlan, as discussed in previous chapters. The main focus of these results are on the *maximum amount of energy storage capacity* (in MWh) that is required to be able to sustain a 100% renewable energy system for the earlier defined neighborhood throughout the year.

In addition the annual *usage of storage* is quantified, meaning the amount of storage (in GWh) that had to be used in order to provide a stable backup in contrast with the overall system. This metric divided by the total energy consumption depicts the dependency of the modeled energy system on storage, and provides an insight to what extent discrepancies between production and consumption occurs, in other words the degree of intermittencies. Furthermore, the *distribution of storage usage* throughout the year is looked at; this provides an insight whether there are specific months or seasons when the storage system is either charged or discharged and to what extent figures obtained for the earlier mentioned *maximum storage capacity requirement* are primarily caused by extraordinary events or whether a more long term pattern can be spotted.

As indicated in Chapter 10, Demand Response (DR) has the potential to shift around 30% of the electricity demand over the course of a day and to a much lesser extend a week; the effect of DR on the above mentioned parameters is also discussed. Lastly, based on the parameter *usage of storage,* a rough estimate is made on the amount of land required for the growth of biomass, which could be used for back-up generations, as an alternative for energy storage.

A substantial number of different scenarios with various combinations of energy systems for different locations have been run. Firstly, scenarios with only photovoltaic will be discussed, secondly scenarios with only wind, and thirdly scenarios with a mixture of PV and wind, and in-land and coastal/offshore wind. Each type of these energy systems will be discussed based on the above named parameters: the maximum storage capacity requirement, usage of storage, the distribution of storage throughout the year, impact of demand response on storage and land requirement. The combination of the first three parameters give a thorough indication of the degree of necessity for storage, the operational context of storage and the extent storage could be replaced by back-up capacity based on biomass within the context of the neighborhood.

On a side note, in a number of the graphs abbreviations have been used that describe the variables of that particular energy system, for example "DB**W**3MW+VL**W**1.5MW+PV1MWp", means a 3 MW Wind turbine at De Bilt + a 1.5 MW Windturbine at Vlieland + a 1 MWp PV installation. The location that is named first, in this case De Bilt, is also the location for which the distribution of the heat demand is used. The abbreviations are explained in Appendix VI.

12.1 Overview Key Results

The most important findings are shown in Table 12.1. This table shows the composition of the different energy systems, the mean maximum storage capacity requirement, mean storage usage, the storage dependency (storage usage/total energy demand), the surplus in production as a percentage of the combined general electricity heat demand and heat pumps, and the minimum and maximum land use requirement for biomass.

Table 12.1: Overview main results

	# wind turbines	*PV roof m^2 per house-hold*	*Max Storage Cap. Req. (MWh)*	*Storage Usage (GWh)*	*Storage Dependency (%)*	*Mean surplus as % consumption*	*Biomass land usage min. (hectare)*	*Biomass land usage max. (hectare)*
DBPV8MWp	0.00	55 m^2	2504	4.4	63%	14.7%	126	419
DBW6MW	2.0	0	404	2.8	40.1%	38.3%	80	267
VLW1.5MW+PV1MWp	0.5	6.87 m^2	270	2.5	35.7%	39.8%	71	238
VLW3MW	1.0	0	94	0.7	10%	152.6%	20	67

- An energy system solely based on PV is not feasible, for a large amount of storage (+/- 2500 MWh or 2500 containers filled with batteries) is required. This is the results of seasonal differences in both demand and production. In addition the amount of roof space required is extremely high (55m^2 per household) and most likely would not fit. If instead of storage, back-generation based on biomass would be used this would require an area between 2.5 to 8 times the size of the entire neighborhood itself.
- A 100% wind system in De Bilt requires around 5 times less storage capacity than a 100% PV system, while a 100% wind system on Vlieland requires between 1-10% of the PV storage capacity; resulting from differences in the height and reliability of the wind speeds.
- A neighborhood with one 'off-shore'/Vlieland wind turbine, with around 25 MWh of storage and a couple of hectares of land allocated for biomass would be able to be completely renewable and self-sustaining. A neighborhood realistically can therefore only truly be renewable and self-sustaining with off-shore wind.
- Within mixed wind/PV energy systems in which most of the energy is delivered by wind, an additional 1000 kWp PV reduces the required storage capacity by around 10% and storage usage by 10-15%; but the benefits in terms of storage usage reduction of each additional 1000 kWp shows diminishing returns.
- Demand response has a limited effect on the maximum storage capacity requirement and usage, especially for mixed energy systems.
- There is not enough available space within a Category-II neighborhood to produce sufficient biomass production to act as back-up generation in all scenarios.

In the rest of this chapter these results are discussed in more detail.

12.2 Photovoltaics

A 5000 kWp PV system would be able to provide all the energy needed to meet the annual energy demand of an average residential neighborhood. However, a PV system requires a substantial amount of energy storage, as a result of the need to store energy on both a 24-hour and seasonal basis. Seeing that the modeled storage device has a 70% cycle-efficiency, additional capacity is required in order to compensate for this storage inefficiency. Moreover, additional capacity needs to be included to compensate for the differences in production between years, which are in the range of about 10% between the extremes. Therefore, a 8000 kWp PV system would be able to guarantee enough production to meet the demand for the period that was researched. It needs to be noted that this system has on average a surplus production of 14%, based on the combined electricity consumption of the heat pumps and households.

Figures 12.1, shows an example of the output from EnergyPlan for the 8000 kWp system for a week in April in 2005. The figure on the left represents the production of PV in blue, which differentiates during and between the day based on the amount of solar irradiation. At night storage is used in order to meet the demand. The energy demand is shown on the right, depicting the consumption patterns of electricity and heat pumps, but also shows in orange the consumption of the storage devise during the day, when the PV installation produces more than is needed at that moment, which in terms can be consumed at night or during another season.

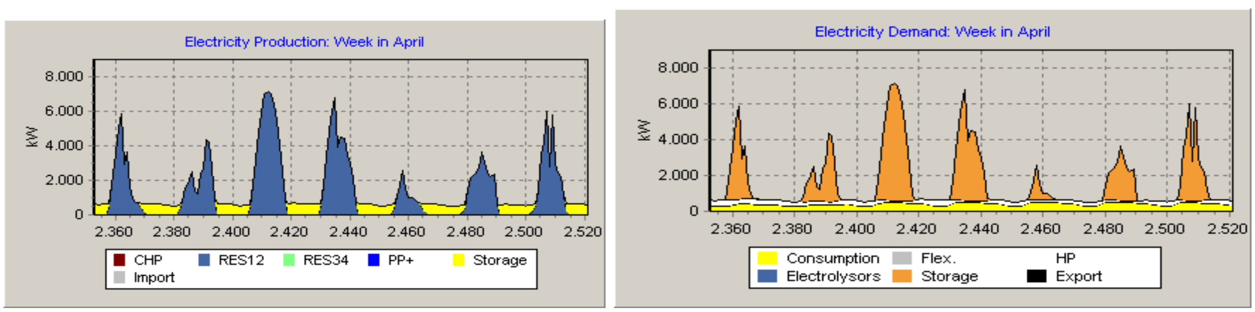


Figure 12.1: Example of EnergyPlan Output for a 100% PV system [larger figure in Appendix VI]

As shown in Chapter 6, PV production between the selected locations within the Netherlands only shows a less that 10% difference in production between the different locations, therefore in this section only the results for de Bilt will be discussed.

12.2.1 Maximum storage capacity requirement

A 8000 kWp PV system requires between 2350 – 2650 MWh of storage capacity in order to guarantee a stable energy system throughout the year for the modeled neighborhood. Detailed results for the maximum storage capacity requirement are shown in figure 12.2. The MWh size of this storage system could be compared to roughly 2500 containers filled with batteries. A quadrupling of the PV capacity would result in a storage reduction in the maximum storage capacity requirement of about 40%; which on the one hand would still mean that a substantial amount of storage is required but also that there is a surplus in production of about three times the total energy requirement for this system.

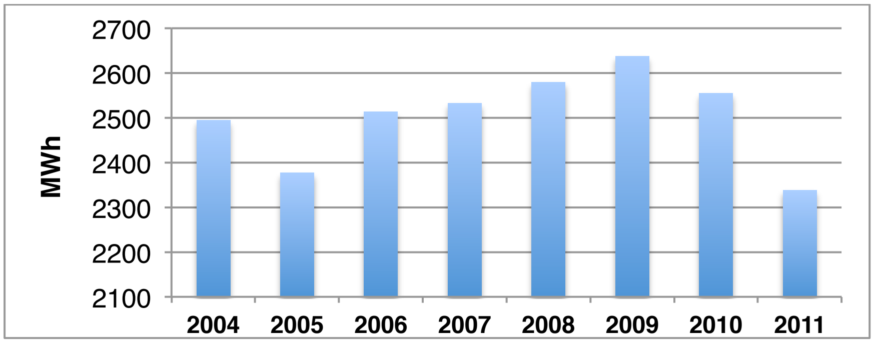


Figure 12.2: Maximum storage capacity requirement 8000 kWp PV system

12.2.2 Storage usage

This large storage requirement is for an important part explained by the high reliance on storage production of around 4.4 GWh/year, as shown in figure 12.3. This means that 63% of the energy demand is delivered by storage and 37% directly by PV. In contrast with the maximum storage requirement, there is little differentiation between the years, namely at maximum just 0.07 GWh.

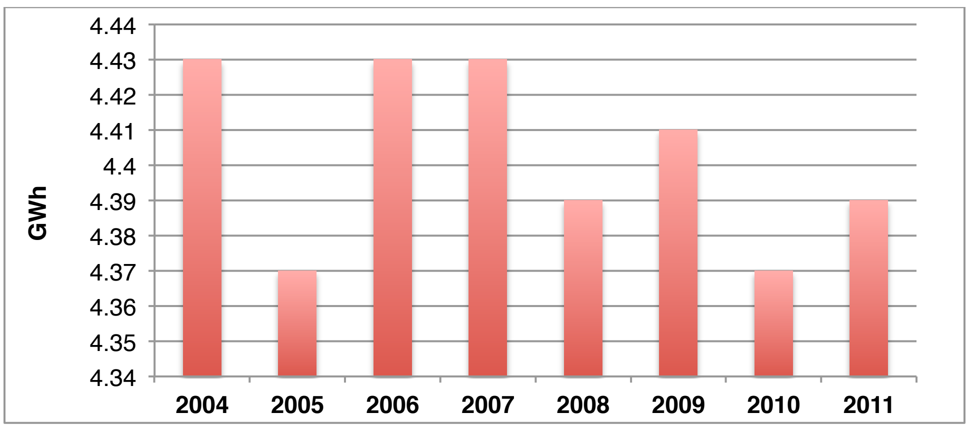


Figure 12.3: Storage Usage in GWh/year

12.2.3 Distribution of storage use

Figure 12.4 shows the energy content of the storage facility throughout the year of an all PV energy system. In this figure, the maximum storage capacity is set 3000 MWh per year, which allows for easy in comparison between the different years. At 3000 MWh, the storage reservoir is completely filled. As earlier noted, the maximum storage capacity requirement is around 2500 MWh, which can be spotted as the difference between the lowest point of the individual curves and the 3000 MWh maximum storage content line. The curve for each year has a sinusoid shape, which is deducible from the almost sinusoid distribution of annual PV production as presented in Chapter 6. Based on this production curve, it can be deduced that the storage usage distribution curve has this shape, for there is a surplus in production basically in the period April – September, while during the other months there is a shortage in production. What this comes down to is that during the ‘shortage’ months, during the daylight period not enough energy is produced to meet the full energy requirement of that day – night cycle. This effect is enhanced by the higher demand than average during the ‘shortage’ months.

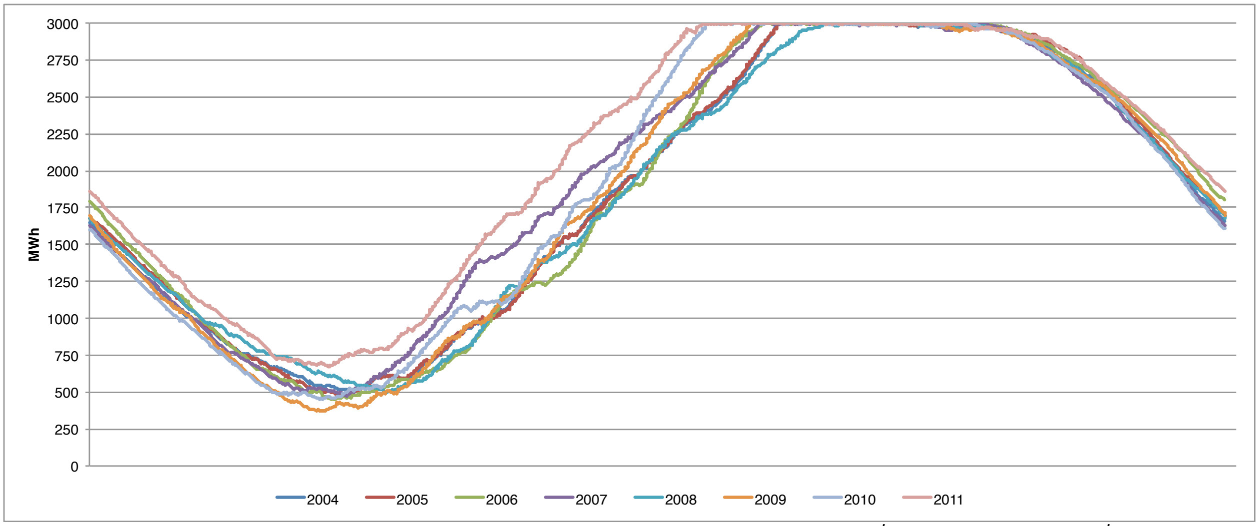
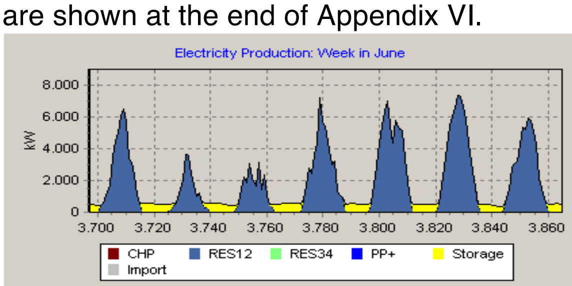


Figure 12.4: Distribution storage in MWh through a year [January 1st - December 31st]

At the end of March - early April the minimal storage content of the year is reached. This marks the end of period in which energy demand is high (as a result of lower outside temperatures) and solar irradiation is low. From that period onwards, enough energy is produced during the day, to both cover the energy demand at night, as well as store energy for seasonal purposes.

What becomes evident in all years is that during the period June – September the following occurs: the storage content hits needed maximum to full fill the energy requirement for the rest of the year, and electricity is only stored for short-term use for fulfilling the demand for a 1 day period, as can be seen in figure 12.5. Additional production are seen as surpluses and in EnergyPlan this is marked as 'export'. Larger versions of all Energy Plan figures in this chapter are shown at the end of Appendix VI.



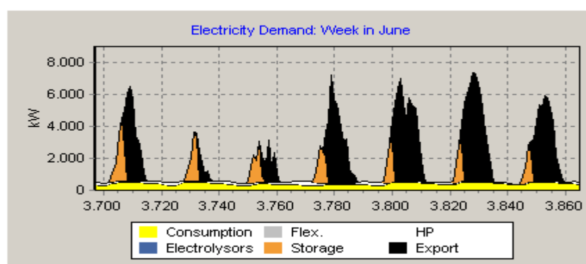


Figure 12.5: Example week in June in which maximum storage content is reached

The points when storage content is at its minimum and maximum differs per year, which is the result of the amount of irradiation during the winter/spring months and distribution of energy requirement. This can be explained by the fact that the amount of PV production differed most substantially on a year-to-year basis in March and April as shown in Chapter 6.

Reducing the size of the PV system would reduce these surpluses/exports, but this would also results in an increased maximum storage requirement and storage usage, for the already low production during the winter months would decrease even further and more energy needs to be stored during the summer months. As will be shown in the rest of this chapter, sizing and often the oversizing of the energy supply components play an integral effect in the amount of storage required.

The maximum storage requirement is the aggregate of all the individual days when PV production was too low to meet the energy requirement of the full 24-hour cycle. In addition because of the inefficiency of storage cycle, the need for additional storage is aggravated even further. What is extremely noteworthy is that because of these seasonal discrepancies, the actual usage of the maximum capacity is actually extremely low. When dividing storage usage by the maximum storage requirement shows that each MWh of installed storage capacity would only be used around 1.7 times per year, which is extremely marginal. This is again explained by the seasonal dsicreptancies in production and consumption.

12.2.4 Impact of Demand response

Demand Response is often seen as a method of successfully integrating PV within the energy system. It is reasoned that demand could be shifted from night to day, and thereby decreasing the need for storage, an example of this is shown in figure 12.6. The figure on the left is without DR and on the right is with DR, consumption indeed shifts partially from night to day, this can best be spotted by looking at the difference in the white area in both graphs or in Appendix VI, figure VI.9.

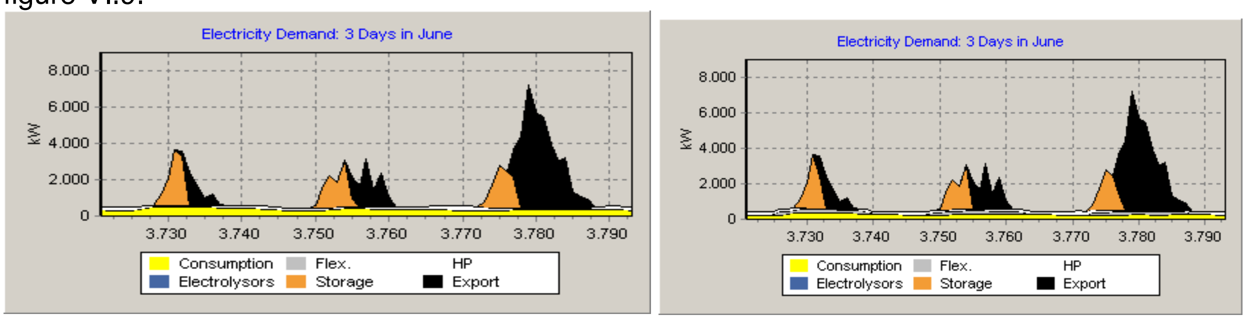


Figure 12.6: Example 100% PV, without DR (left) and with DR (right)

However, the impact of DR on the overall maximum storage capacity requirement and usage is minimal at best; resulting from the fact that with a 100% PV energy system the bulk of the storage is required for seasonal differences and not for over the course of day regulation, for which DR is used.

Around 0.15 GWh per year is the reduction in storage usage, while the maximum storage requirement drops between 22 and 45 MWh, with one outlier of 105 MWh. In percentages DR would reduce the maximum storage requirement between < 1 % to 4%; the storage usage drops by 3 – 3.5%. The dependency of the energy system as a whole on storage drops from 63 % to 60.8%.

As a result of DR the surplus production of the system rises between 3.5 -7.5 % (around 0.06 GWh). This rise in surplus is the result of a reduction in storage requirement and the efficiency losses that come with storage are negated.

The period with the most noticeable impact of DR is during the months June-August, when the storage facility hits its maximum and the amount of energy that is stored only is used to make sure that the storage facilities stays at its maximum capacity. Demand response is able to increase the length of this period in which this occurs, by shifting all the flexible demand to the daytime period. This effect is still limited, for the primary problem with PV is the discrepancy in production between the periods of high production and low consumption (summer) and the period of low production and high consumption (winter) periods

12.2.5 Land usage

- Roof space requirement: 55 m^2 per household or 5.7 hectares
- If no roof space would be available and all PV panels have to be located on land, a land factor is included which was assumed to be 3, thereby 171,360 m2 is required or 17 hectares.
- Storage size requirement CAES in m^3: between 1,325,000 m^3 – 353,333 m^3 of storage CAES volume; (or roughly 2600 containers filled with batteries)
- Land requirement for biomass production: between 126 - 419 hectares, between 2.4 – 8 times the size of the total neighborhood, or between 42 – 140 times the size of the agricultural lands available in a Category-II neighborhood.

12.3 Wind Energy

Wind energy is less predictable than PV and differentiates more substantial per location; thereby the size of the wind system per location differs. For De Bilt an installed wind capacity of 6000 kW (2 turbines) was required to meet the demand in a non-grid connected system; while less than 4.5 MW (1.5 turbine) is required in a grid-connected system. For Cabauw and Berkhout less than 3000 kW (1 turbine) suffice, while for Vlieland this is around 1500 kW (0.5 turbine). The reason for this is shown in figures 12.4 and 12.5, showing an example of the production of wind for the same month for both de Bilt and Vlieland. Production in De Bilt is not able to meet the demand for a substantial number of consecutive periods of time, despite its considerable higher installed capacity than on Vlieland, which can be explained by low and irregular wind speeds in De Bilts. This is because the cut-in wind speed, when the wind turbine starts to produce, is often not reached in this location. Vlieland on the other hand, hits its installed capacity of 1500 kW very often and only a few periods of time would require energy storage as backup. The cut-in wind speed is almost always reached. The only real worry in this system is that on a regular basis, wind speeds are too high and the cut-out wind speed is reached, which results in a shut-down of the wind turbine. However, this happens only a few hours per year.

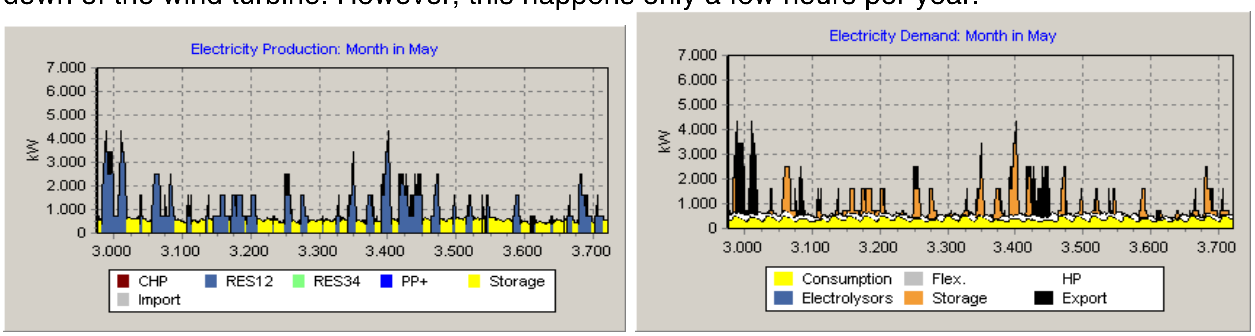


Figure 12.4: Example 6000 kW Wind – De Bilt

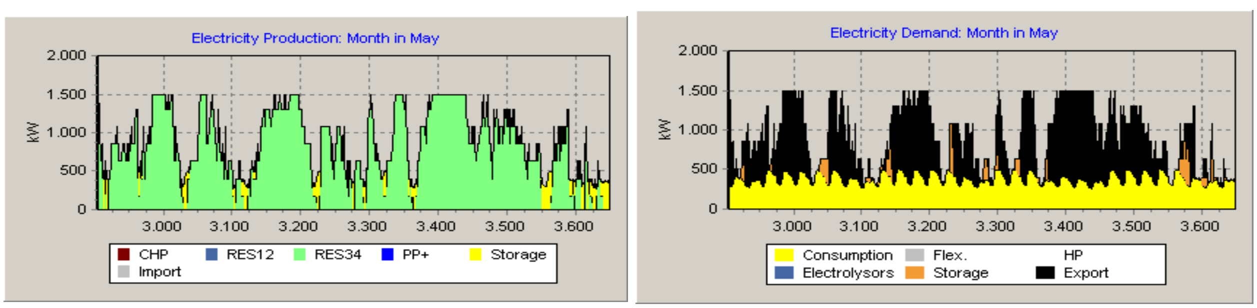


Figure 12.5: Example 1500 kW Wind - Vlieland

12.3.1 Maximum Storage Capacity Requirement

These differences in wind speeds and wind reliability have a substantial impact on the maximum storage capacity requirement as can be seen in Figure 12.6. The capacity requirement for a 6 MW system in De Bilt requires 4-5 times as much as Vlieland. Indicating that near-shore or off-shore wind results in a substantial reduction in the storage requirement, a conclusion supported by the results for Cabauw and Berkhout which are also more windy locations. Just as in the case of PV, sizing plays again an important role in reducing the storage requirement; increasing the size of the production facilities results in a drop in storage requirement. The trade-off is that these systems start to produce surpluses. In fact, all these systems have surpluses in production, some of which are above 100 – 200% of the energy demand. The extend of these surpluses are detailed in Appendix VI.

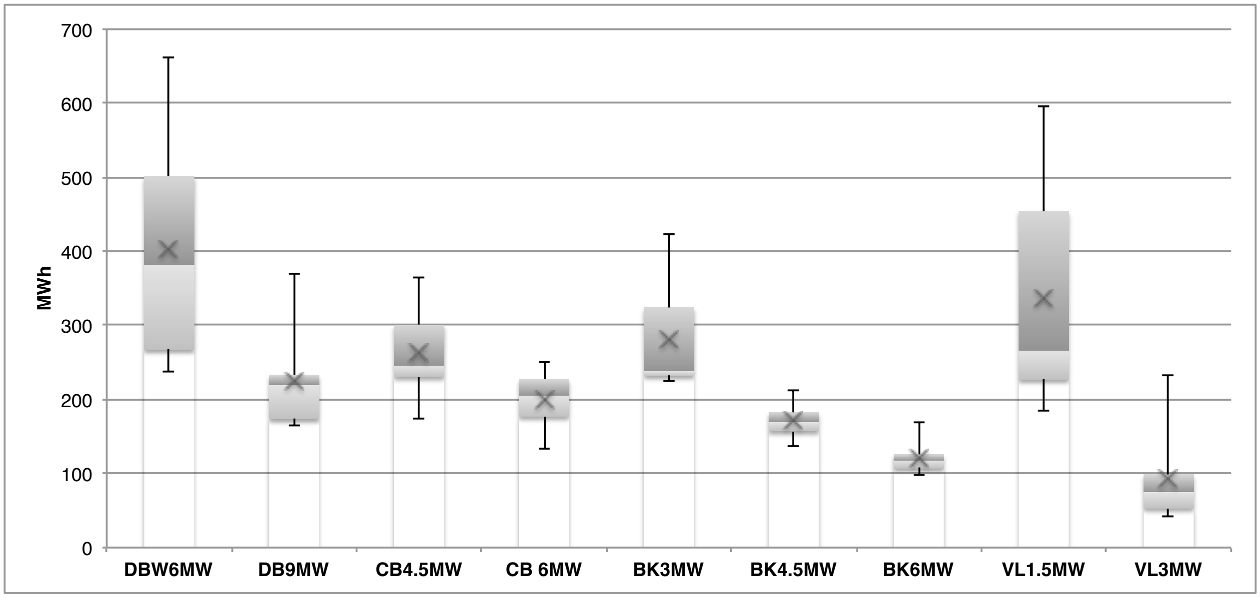


Figure 12.6: Maximum Storage requirement 100% wind systems in MWh

12.3.2 Storage Usage

The total storage usage also differs quite substantially between different locations; the range between the extremes is a factor of five. Storage dependency ranges from 10 – 40% for the total energy supply. This large range can again be explained by the height, but more importantly, the continuity or reliability of the wind speeds.

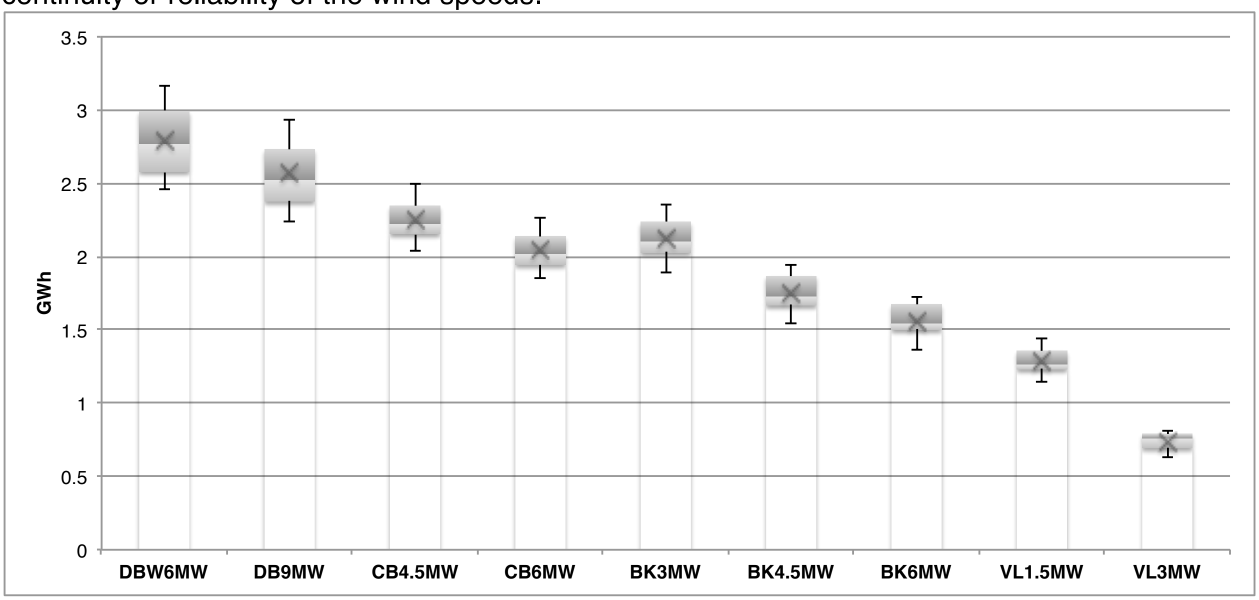


Figure 12.7: Total storage usage per year in GWh

12.3.3 Distribution Storage

Looking more closely at the distribution of storage usage throughout the year for a number of locations, reveals a substantially more chaotic pattern than the sinusoid distribution of storage content for PV (figure 12.8 – 12.11). The only real pattern that can be observed is that storage content is highest during the summer, even though wind speeds are often lowest then, as was discussed in Chapter 5. This was especially apparent for the examples of de Bilt. This would then mean that not the absolute wind production matters, but the ration between production and demand, Because of the much lower heat demand during the summer the actual wind capacity is more sufficient during this period, and the system is less reliant on storage. Increasing the capacity in de Bilt from 2 to 3 turbines results in a much less chaotic storage content pattern. With 9000 kW capacity, it seems that a maximum storage requirement between 100 – 150 MWh would suffice, for the content primarily moves within this bandwidth, with the exception of some outliers. The earlier reported average maximum storage requirement for a 9000 kW is 224 MWh, this figure is thus higher as a result of outliers (figure 12.9).

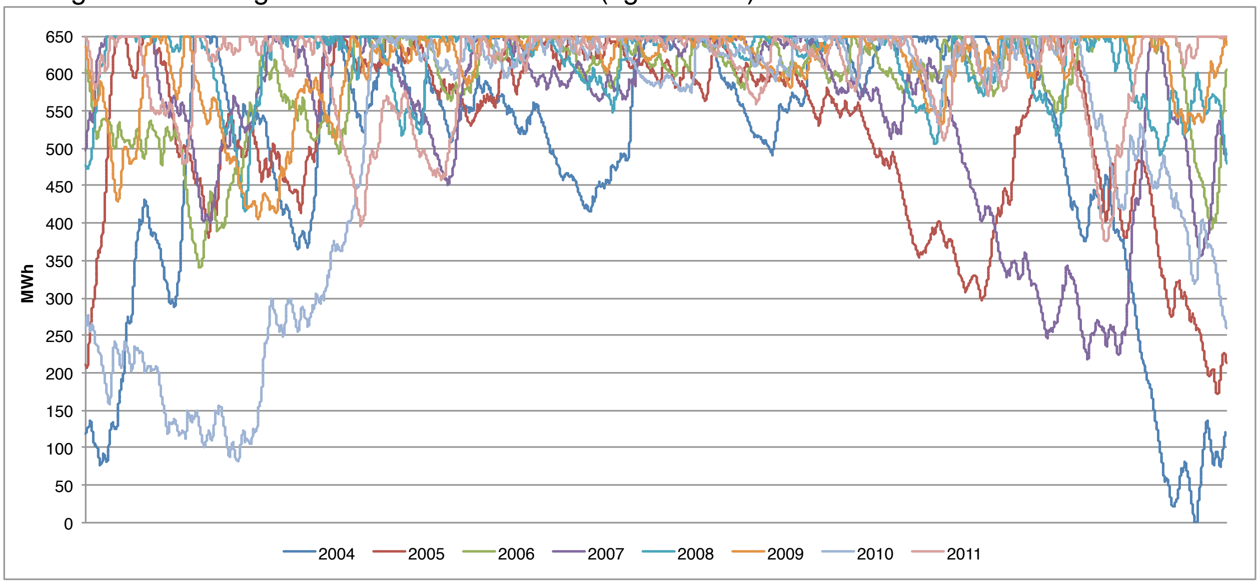


Figure 12.8: Storage Content 6000 kW – De Bilt [January 1st - December 31st]

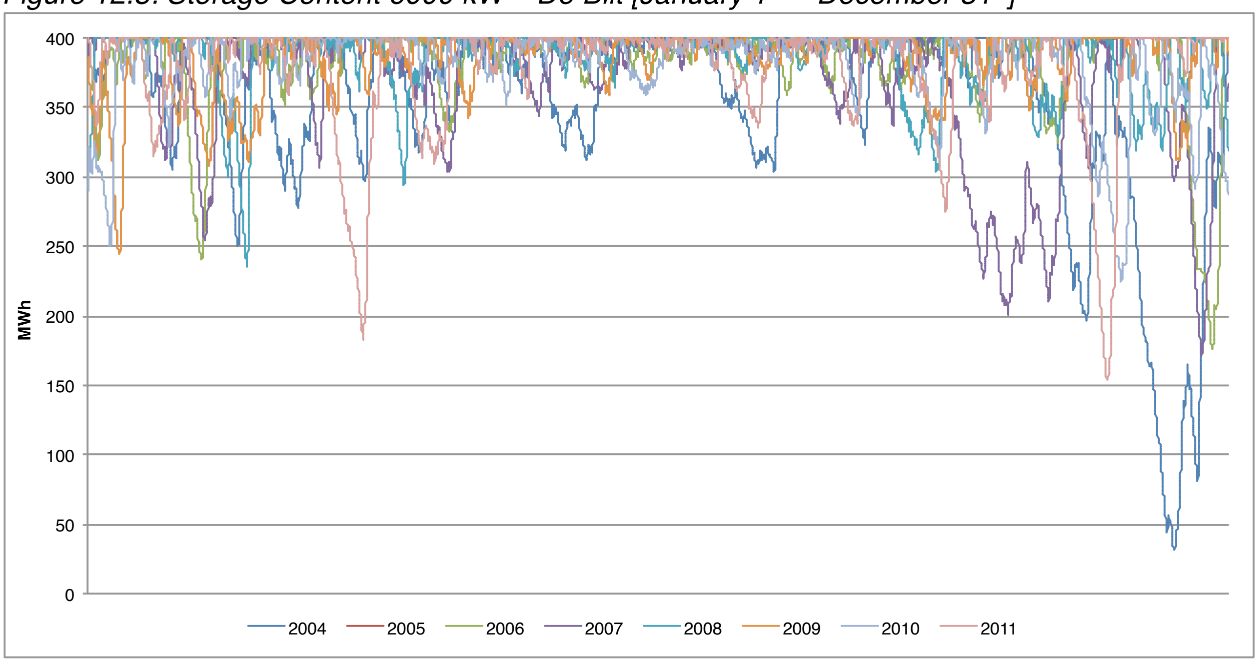


Figure 12.9: Storage Content 9000 kW – De Bilt [January 1st - December 31st]

In the case of Vlieland, similar patterns are evident, storage content is higher during the summer, as a result of lower demand. What is most interesting is figure 12.11 of 3 MW on Vlieland. With the exception of a few outliers, a maximum storage requirement of 25 MWh would seem to suffice, which is three to four times lower than the earlier mentioned requirement, for most of the storage usage falls within this range. This shows that these figures were influenced by these outlier events. The question therefore should be raised whether in this particular case, back-up capacity either on biomass or fossil fuels should be used for these events, but also whether a neighborhood could become completely energy independent only when offshore or near-shore wind is in play. For this figure clearly shows the advantage of off-shore wind farms, namely the vast reduction in storage usage and requirement.

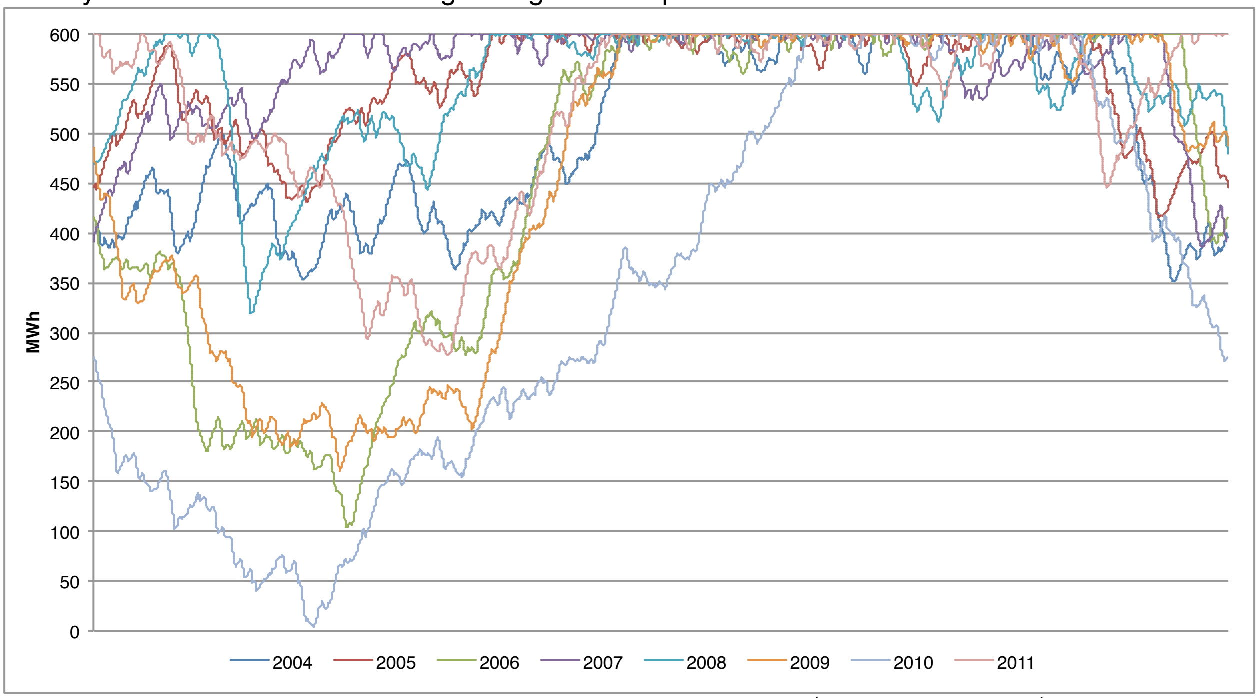


Figure 12.10: Storage Content 1500 kW – Vlieland [January 1st - December 31st]

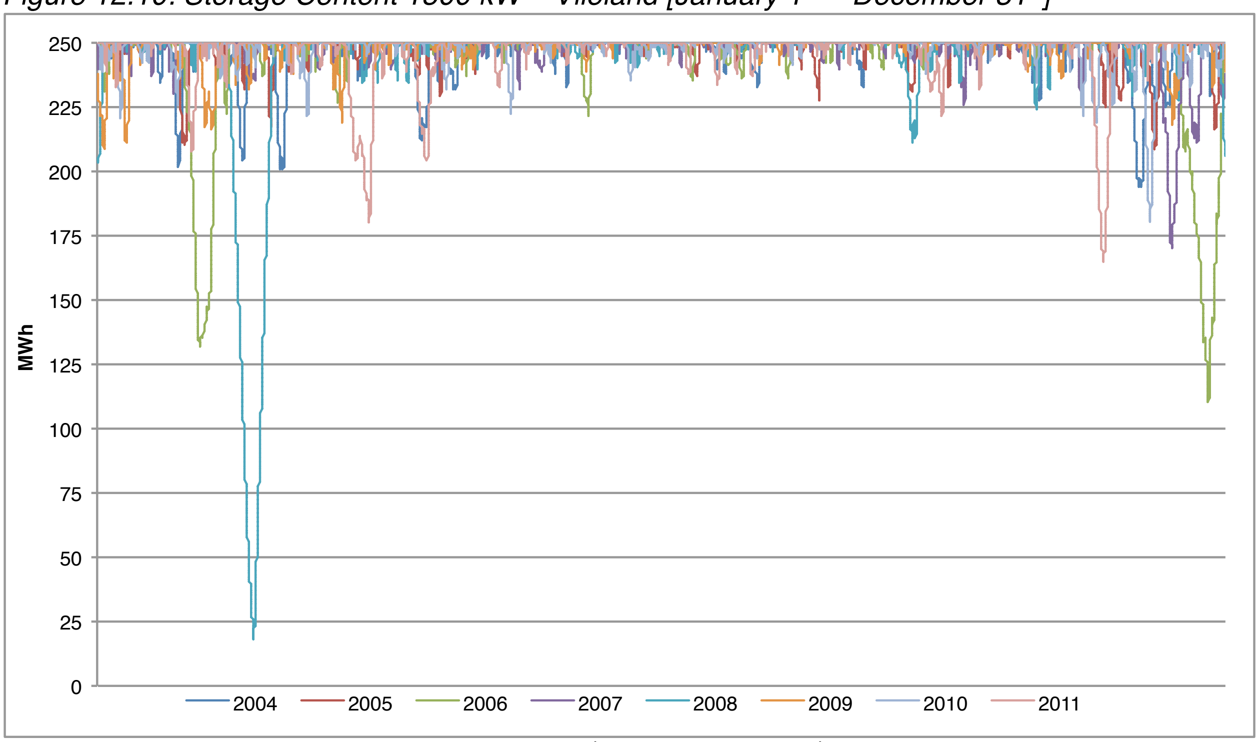


Figure 12.11: 3000 kW – Vlieland [January 1st - December 31st]

12.3.4 Effect of Demand Response

The impact of DR on the storage requirement and usage for complete wind systems is slightly larger than complete PV systems, most likely the result of larger day-to-day variations in wind-speeds, as can be seen in figures 12.12 and 12.13. The mean % impact on the maximum storage capacity requirement is between 3 – 6%, while the mean impact on storage usage ranges between a 5 – 13% reduction. Demand response consequently reduces the system's storage dependency only by a couple of percent.

A smaller effect for De Bilt can be noted. This is the result of consecutive days often being without wind, and therefore DR has a negligible effect. While for Vlieland the effect is substantially higher as a result of wind production being much more continuous and shortfalls in production occur more for a couple of hours instead of days, in contrast with De Bilt, which can be deduced from the stark effect in storage usage. While looking at these figures, one should remember that perfect information is assumed; therefore the effects in practice might be even lower.

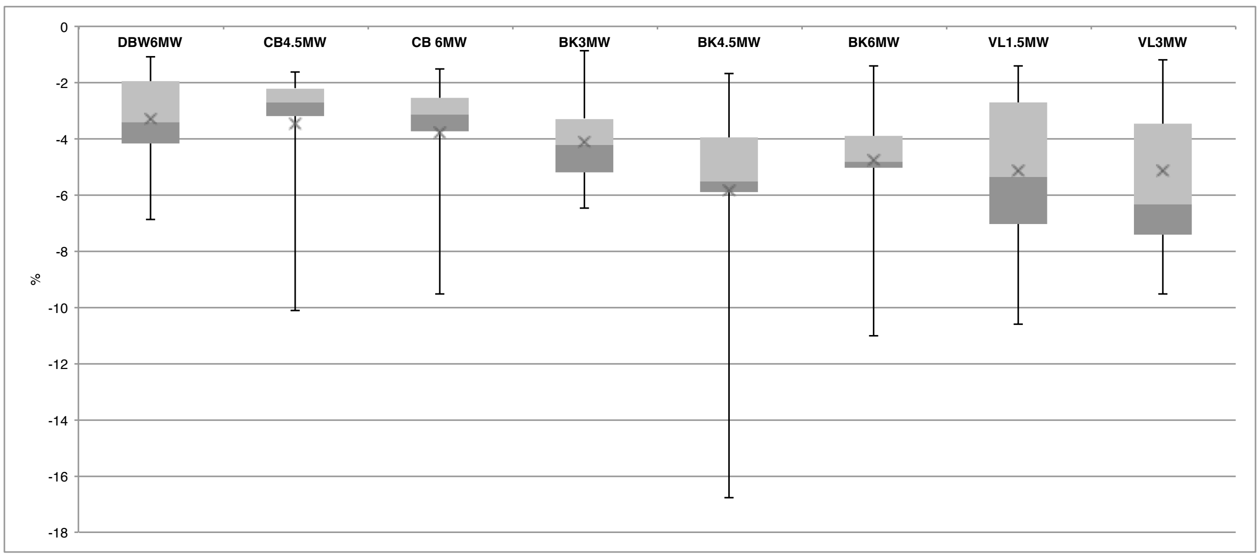


Figure 12.12: Effect of Demand Response on Maximum Storage Requirement

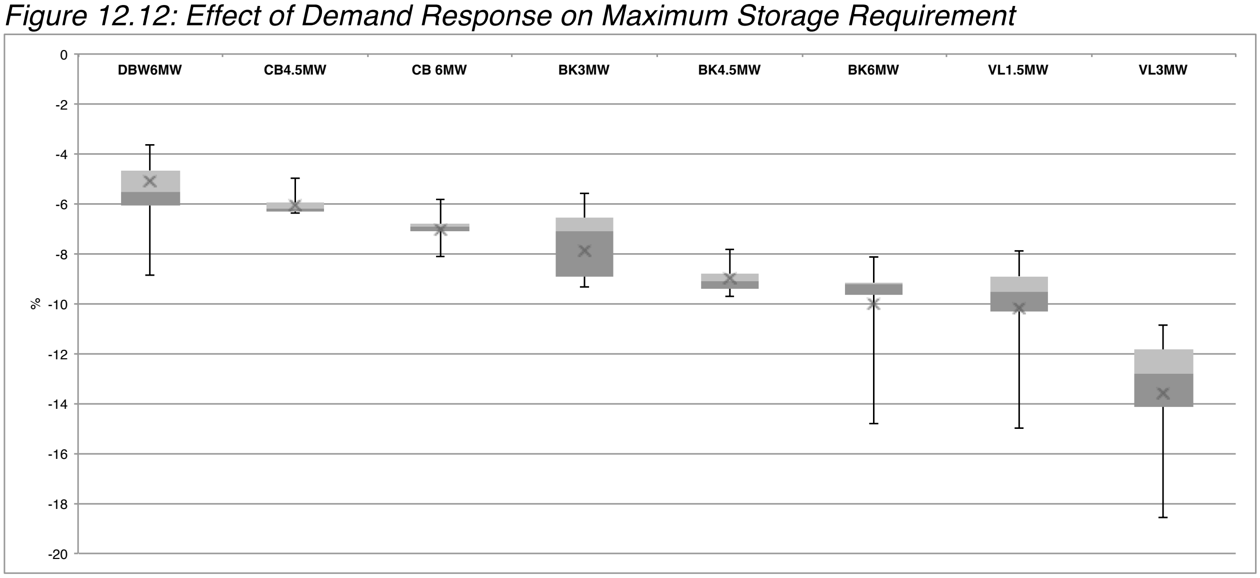


Figure 12.13: Effect Demand Response on storage usage

12.3.5 Land usage

Table 12.2 shows the land usage requirement and volume of CAES for the different wind scenarios. In all scenarios under the most optimal growing conditions, there would not be enough space within the neighborhood in order to produce all the necessary biomass for a back-up power plant. Seeing that it was deemed that there was only around 3 – 4 hectares of land available for agriculture and nature. However, in a scenario with a combination of one turbine on Vlieland in combination with a small 25 MWh storage facility, and a couple of hectares of biomass, a 100% stable renewable energy system would be possible.

Table 12.2: Overview Space Requirement

	# 3MW -wind turbine	Mean Max Storage Req. (MWh)	Mean Storage Usage (GWh)	Storage Dependency (%)	Mean Surplus as % consumption	CAES min volume (m^3)	CAES max volume (m^3)	Biomass land usage min. (hectare)	Biomass land usage max. (hectare)
DB6MW	2	404	2.79	39.91	39	201875	53833	80	266
DB9MW	3	224	2.57	36.77	116	111938	29850	73	245
CB4.5MW	1.5	263	2.25	32.19	64	131375	35033	64	214
CB6WMW	2	201	2.04	29.18	124	100375	26767	58	194
BK3MW	1	280	2.12	30.33	37	140000	37333	61	202
BK4.5MW	1.5	172	1.75	25.04	113	85750	22867	50	167
BK6MW	2	122	1.56	22.32	189	60875	16233	45	149
VL1.5MW	0.5	337	1.29	18.45	21	168563	44950	37	123
VL3MW	1	94	0.74	10.59	153	46750	12467	21	70

12.4 Hybrid Energy Systems

In terms of mixed energy systems, the following three options have been modeled: an energy system predominantly focused on solar with additional wind capacity, a system heavily focused on wind with some PV and mixed in-land and 'off-shore' wind energy system.

12.4.1 Predominantly Solar

An energy system with heavy reliance on solar and some wind as shown in figures 12.14 and 12.15, in which a 8000 kWp system is combined with both 500 kW and 1000 kW in off-shore wind capacity and 6000 kWp PV system with 1000 kW indicates substantial reductions in the maximum storage capacity requirement and storage usage in comparison to a 8000 kWp system only. However, these systems still require substantial amount of storage in comparison to larger wind capacities systems and also have substantial surpluses. The distribution of storage usage shows to a large extent a similar sinusoid shape, as a 100% PV system, although the curve is considerably more compressed, and the period at which the maximum storage content is hit takes much longer. This is because wind energy aids partially in bridging the seasonal discrepancies, which were encountered in 100% PV systems.

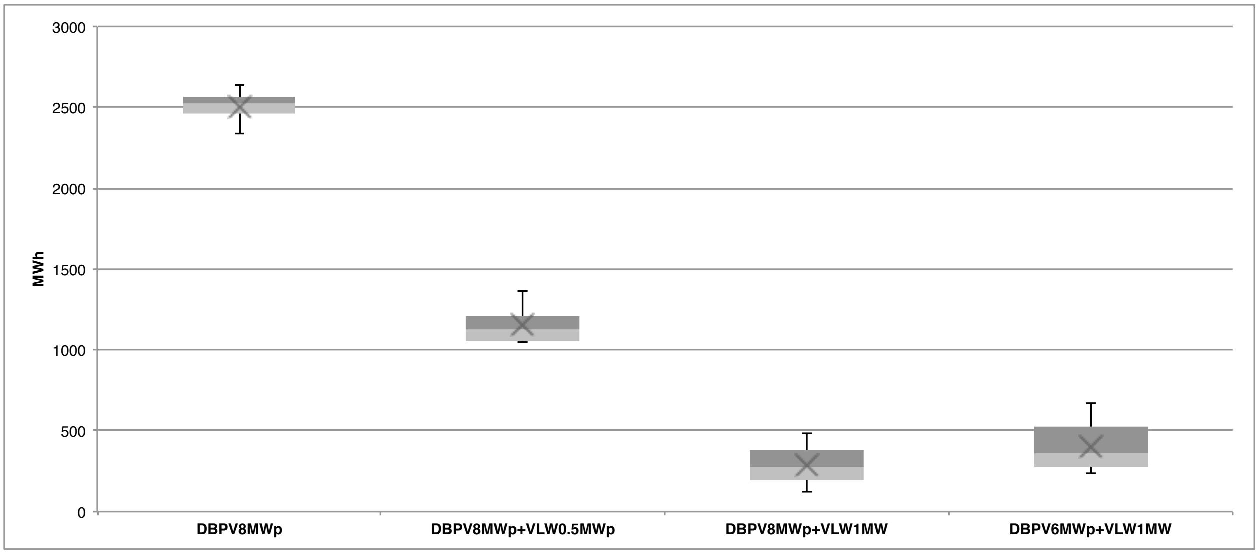


Figure 12.14: Maximum storage capacity requirement predominantly PV energy system

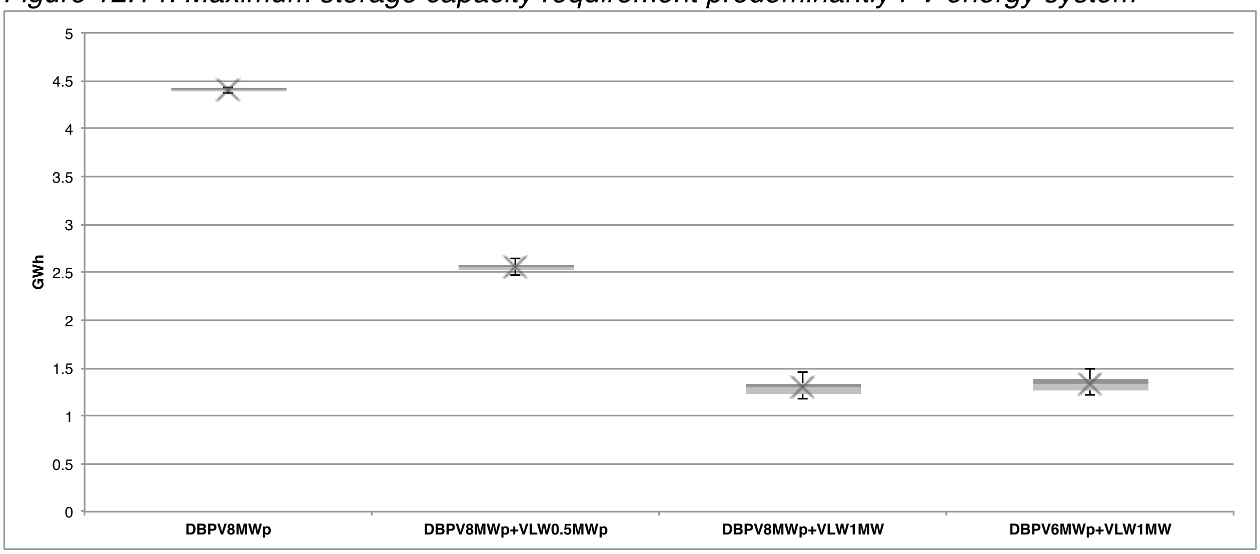


Figure 12.15: Storage usage predominantly PV energy system

12.4.2 Predominantly Wind

Figure 12.16 and 12.17 show the maximum storage requirement and usage for predominant wind systems with between 1000 – 3000 kWp in PV capacity. These figures primarily follow the earlier discussed patterns for 100% wind systems, although PV has the benefit of reducing the need for storage. On average for every additional 1000 kWp capacity results in a 10% drop maximum storage capacity requirement in comparison to a 100% wind system. The storage usage drops for the first 1000 kWp PV by 10 -15%, for the second 1000 kWp an additional 5- 8 % reduction and the third 1000 kWp this drops to an additional 3-5 % reduction. Thus, there are diminishing returns on integrating additional PV in heavily tilted wind systems. The just slight decreases in storage capacity requirement by including PV in a wind energy mix can be explained by the fact that when storage is needed in wind energy systems, this is during the winter, the same period when PV production is at its lowest.

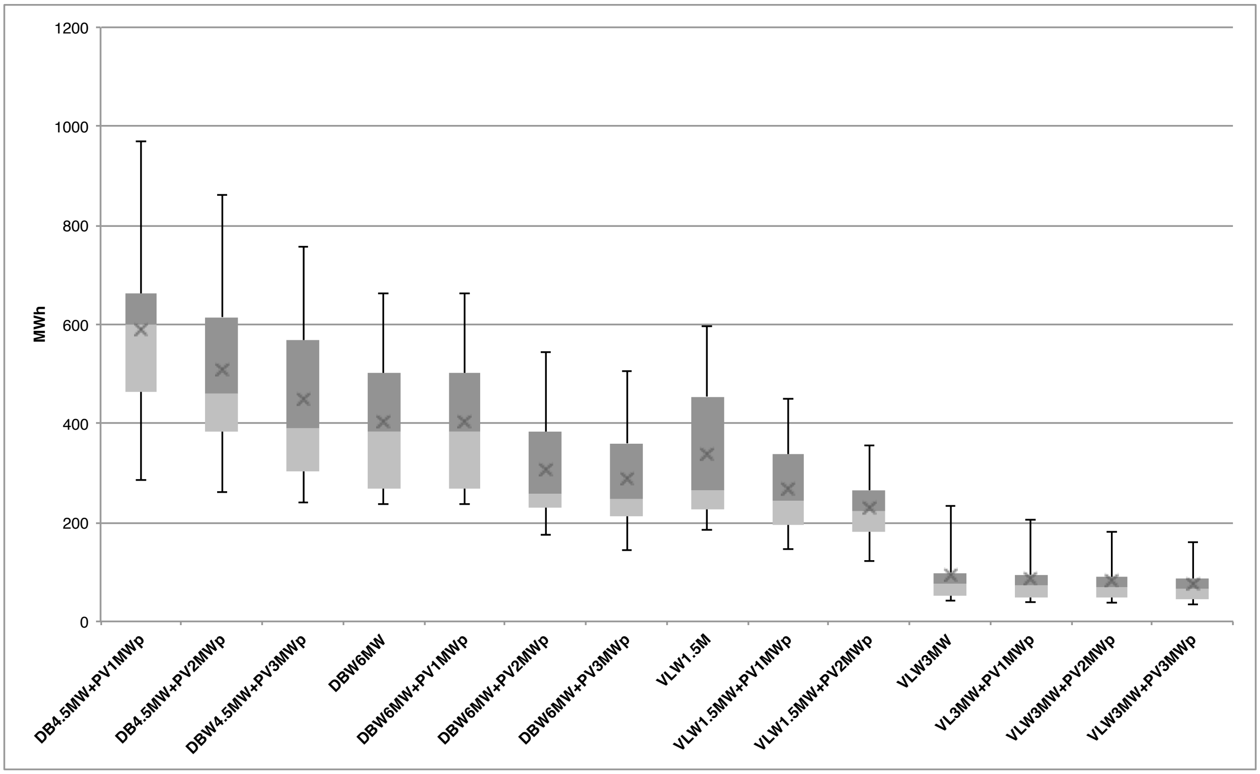


Figure 12.16: Maximum Storage Capacity Requirement – Mixed Wind/PV systems

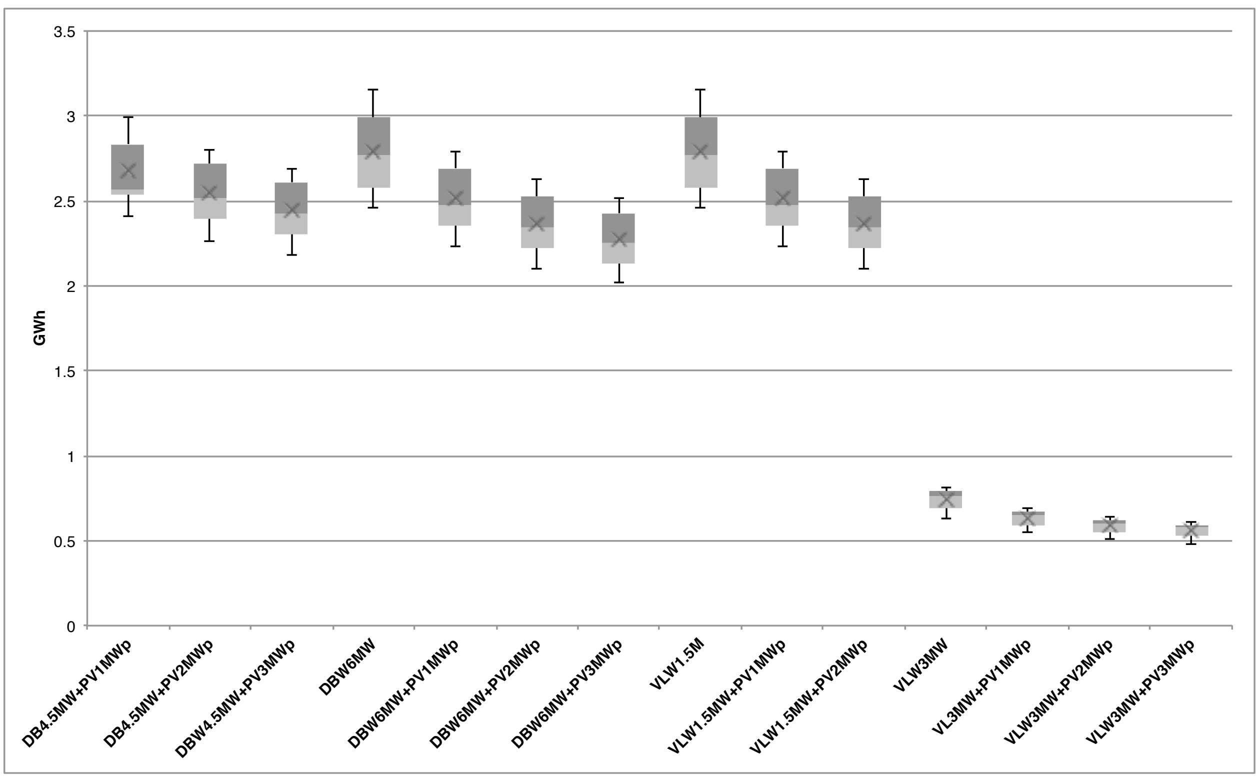


Figure 12.17: Storage Usage throughout the year

12.4.3 Onshore/Offshore Wind

Figures 12.18 and 12.19 show mixed wind systems between both "onshore (De Bilt, Cabauw, Berkhout) and "offshore" (Vlieland). Mixed systems require a reduced maximum storage capacity, but even more a reduction in storage usage in contrast with wind systems of which wind energy is derived from one location. Adding 1 MWp PV installation also reduces the need for storage. Still a 3 MW turbine on Vlieland has the lowest storage requirement. This reduction in storage capacity and usage is accompanied by an increase in energy surpluses, as can be seen in Appendix VI.

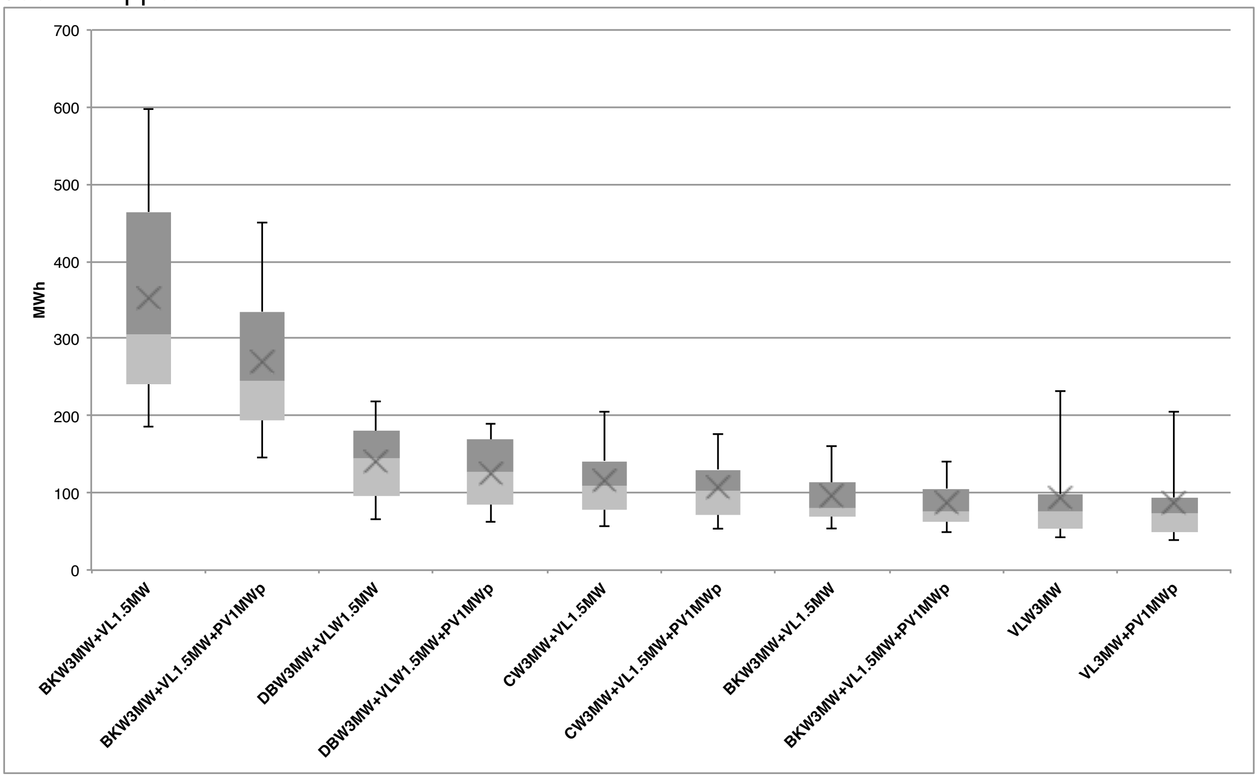


Figure 12.18: Maximum Storage Requirement per year in MWh (Onshore/Offshore Wind)

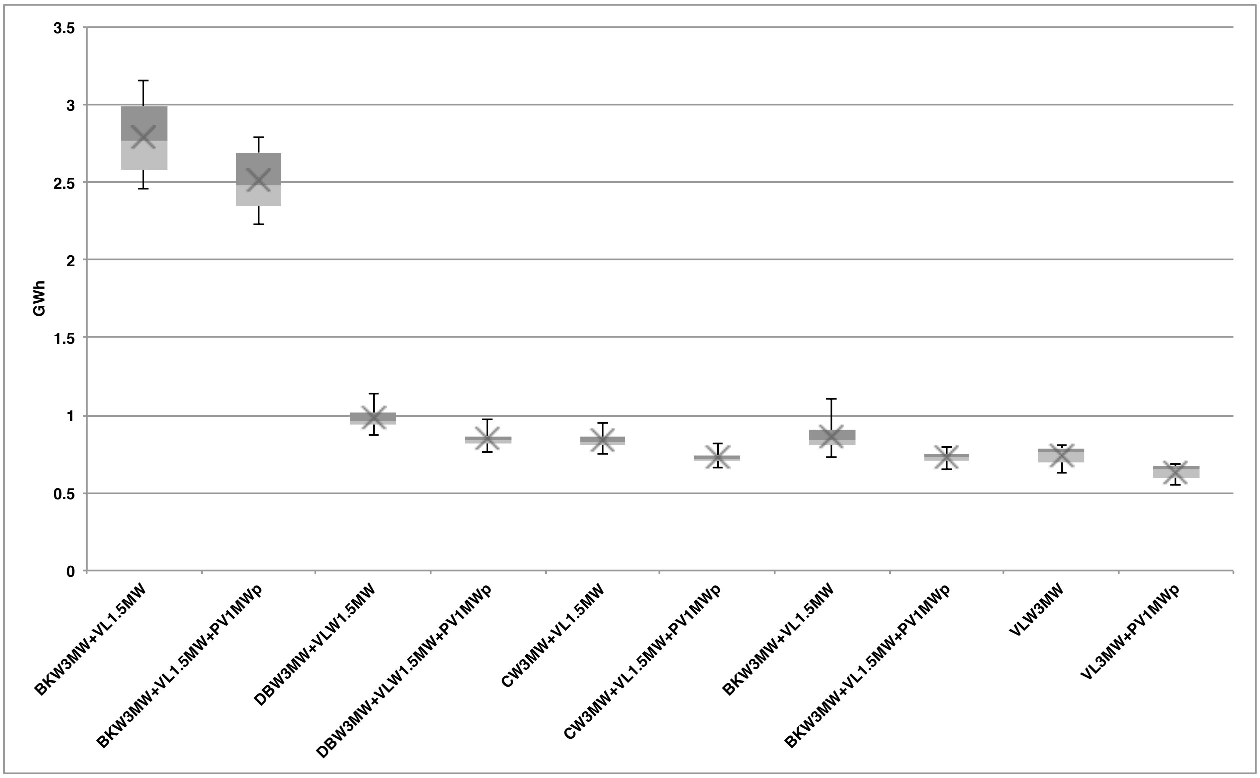


Figure 12.19: Storage Usage per year in GWh (Onshore/Offshore Wind)

12.4.4 Demand Response

Looking at the effect of DR and mixed energy systems indicates that the impact of DR becomes smaller than in complete PV or Wind energy systems, often only resulting in a 1 to 2 percent point additional reduction for the storage usage and often below 1 percent point additional reduction in maximum storage requirement.

12.4.5 Land usage

In table 12.3, an overview is presented of all the results for the mixed energy systems. Again it can be concluded that there is not enough space within a neighborhood to produce sufficient biomass for back-up generation.

Table 12.3: Overview land usage & other parameters - Mixed Systems [orange = predominantly PV; green = predominantly wind; blue onshore/offshore wind]

	# wind turbines	Total PV space m2	PV per household (m2)	Mean Max Storage Req. (MWh)	Mean Storage Usage (GWh)	Storage Dependency (%)	Surplus as % consumption	CAES min volume (m^3)	CAES max volume (m^3)	Biomass land usage min. (hectare)	Biomass land usage max. (hectare)
DBPV8MWp	0	57120	55.0	2504	4.4	62.95	14.7	1001,400	333,800	126	419
DBPV8MWp+VLW0.5MWp	0.17	57120	55.0	1156	2.5	35.77	68.6	462,350	154117	71	238

DBPV8MWp+VLW1MW	0.33	57120	55.0	290	1.3	18.60	119.4	116,050	38683	37	124
DBPV6MWp+VLW1MW	0.33	42840	41.3	403	1.3	18.60	83.4	161,300	53767	37	124
DB4.5MW+PV1MWp	1.5	7140	6.9	590	2.7	38.63	17.7	236,150	78717	77	257
DB4.5MW+PV2MWp	1.5	14280	13.8	510	2.5	35.77	35.8	204,100	68033	71	238
DBW4.5MW+PV3MWp	1.5	21420	20.6	449	2.4	34.33	54	179,550	59850	69	229
DBW6MW	2	0	0.0	404	2.8	40.06	38.3	161,500	53833	80	267
DBW6MW+PV1MWp	2	7140	6.9	404	2.5	35.77	57.6	161,500	53833	71	238
DBW6MW+PV2MWp	2	14280	13.8	306	2.4	34.33	76.2	122,300	40767	69	229
DBW6MW+PV3MWp	2	21420	20.6	290	2.3	32.90	94.3	116,050	38683	66	219
VLW1.5M	0.5	0	0.0	337	2.8	40.06	21	134,850	44950	80	267
VLW1.5MW+PV1MWp	0.5	7140	6.9	270	2.5	35.77	39.8	107,900	35967	71	238
VLW1.5MW+PV2MWp	0.5	14280	13.8	230	2.4	34.33	57.9	92,150	30717	69	229
VLW3MW	1	0	0.0	94	0.7	10.01	152.6	37400	12467	20	67
VL3MW+PV1MWp	1	7140	6.9	88	0.6	8.58	170.8	35100	11700	17	57
VLW3MW+PV2MWp	1	14280	13.8	82	0.6	8.58	188.7	32650	10883	17	57
VLW3MW+PV3MWp	1	21420	20.6	76	0.6	8.58	206.5	30500	10167	17	57
						0.00					
BKW3MW+VL1.5	1.5	0	0.0	352	2.8	40.06	21	140700	46900	80	267

MW											
BKW3MW+VL1.5MW+PV1MWp	1.5	7140	6.9	269	2.5	35.77	15.5	107550	35850	71	238
DBW3MW+VLW1.5MW	1.5	0	0.0	140	1	14.31	99.6	55950	18650	29	95

Chapter 13: Sensitivity Analysis

The validity of the earlier found results are to a large extent dependent on the reliability of the used variables and the extent to which altering a number of these different elements alters the overall results in a sensitivity analysis. In the results annual variability in solar irradiation, wind and distribution of heat demand throughout the year as a result of different outside temperatures were already taken into account. In addition, for wind the results for different locations were shown. Most results indicated that there is indeed a considerable variation between years and locations, but the interplay between the variability of the different components of the energy system does indicate certain bandwidths in which the results fall.

In this sensitivity analysis the effect of electricity load profiles, the storage efficiency and the level of energy consumption on the overall results are discussed. For each of these components four cases have been analyzed: 8000 kWp PV (De Bilt), 6000 kW wind (De Bilt), 1500 kW wind (Vlieland) and 1000 kWp PV, and 3000 kW wind (Vlieland), on the basis of the parameters maximum storage requirement, storage usage and surplus production. In the paragraphs concerning the effect of the electricity load profiles, changes in the effect of demand response are also discussed. In this sensitivity analysis, the effect of altering these variables on land usage is not discussed for the overall conclusion that there is not enough land available within a Category-II neighborhood remained valid.

13.1 Different load profiles

The electricity load profile used in the results section is the national Tennet distribution; for there is a lack of data concerning specific load profiles for Dutch neighborhoods. In this sensitivity analysis two load profiles were constructed based on available literature on non-Dutch households, primarily for the purpose of at least giving an indication of what the effect of a more neighborhood-like load profile would be and trying to bridge to most important differences between the national distribution and neighborhood load profile.

These load profiles were constructed in a database program, by assigning comparative values to each hour of the day and assigning comparative values to days of the week, for the latter making the distinction between weekdays and the weekend. Due to the way in which this database program was constructed, the total monthly and weekly electricity consumption remains the same as was seen in the Tennet distribution (with a <0.5% variance), hence trying to retain the seasonal variability as well as possible. A higher consumption during the winter months is still seen in comparison to the summer.

As indicated in Chapter 3, a neighborhood has a lower base load in comparison to the national output for the load of industry has to be subtracted, this means that in a neighborhood consumption is lower at night than in comparison to the national distribution. The consequence of this is that when the total electricity demand remains similar when both these different distributions are used, demand during the day becomes higher. In addition, during the day the consumption patterns shift as well; the national distribution shows a peak around mid-day, while in a neighborhood this is not the case for most people are at work or school. Instead the day-time peak in neighborhoods occurs in the early evening, when people return to their homes. Especially in the case of an all PV system this would result in a higher storage requirement for a large part of the consumption is during the period when there is little to no solar irradiation.

On the scale of a week, the national distribution has the highest consumption Monday – Thursday, with Friday having a slightly lower consumption, for in the Netherlands a large number of people work on that day either from home, leave early for the weekend or work not at all. Consumption during the weekend is even lower on a national scale for most people are off work. In a neighborhood, consumption is higher as a result of people being at home for a longer period of time during the day.

When constructing the load profiles these considerations were taken into account different, figure 13.1 shows the constructed load profiles in comparison to each other and the national load profile. The first load profile is based on a mean household consumption curve based on a paper from Paatero and Lund from 2005. In their paper, they constructed a mean load profile for around 1000 households, devoid of seasonal variability and in which electrical heating is absent. The main distinction was made between a weekday and weekend. In the weekend, consumption is higher during the day (Paatero, 2005). In constructed load profile 1, an additional distinction was made between the height of the overall curve for a Saturday and Sunday, in contrast with each other and a weekday, seeing that demand on Saturday are 25% higher and 50% higher on a Sunday during the day, based on UK load profiles (Hamidi, 2009).

Constructed load profile (CLP) 1 depicts the mean of a number of apartment blocks, in which the behavior and lifestyle of consumers cancel each other to some extent out, such as would happen in a neighborhood with a mixed age/income demographic. Therefor a more ‘extreme’ load profile was constructed, in which the same loadprofile for the weekend was used as in CLP 1, in which the distinction was not made between Saturday and Sunday, but with a different pattern during the week. A pattern more suited for a household/neighborhoods in which its inhabitants are not at home during the day. This load profile was constructed much more arbitrarily and without being backed up by existing data, but based on general assumptions.

As figure 13.1, shows these load profiles differ quite substantially from the national distribution, especially concerning the moment of their peaks, at night and during the weekend. In the next sections the impact of these different load profiles will be discussed, which as it turns out is insignificant. The detailed results can be found in Appendix VII.

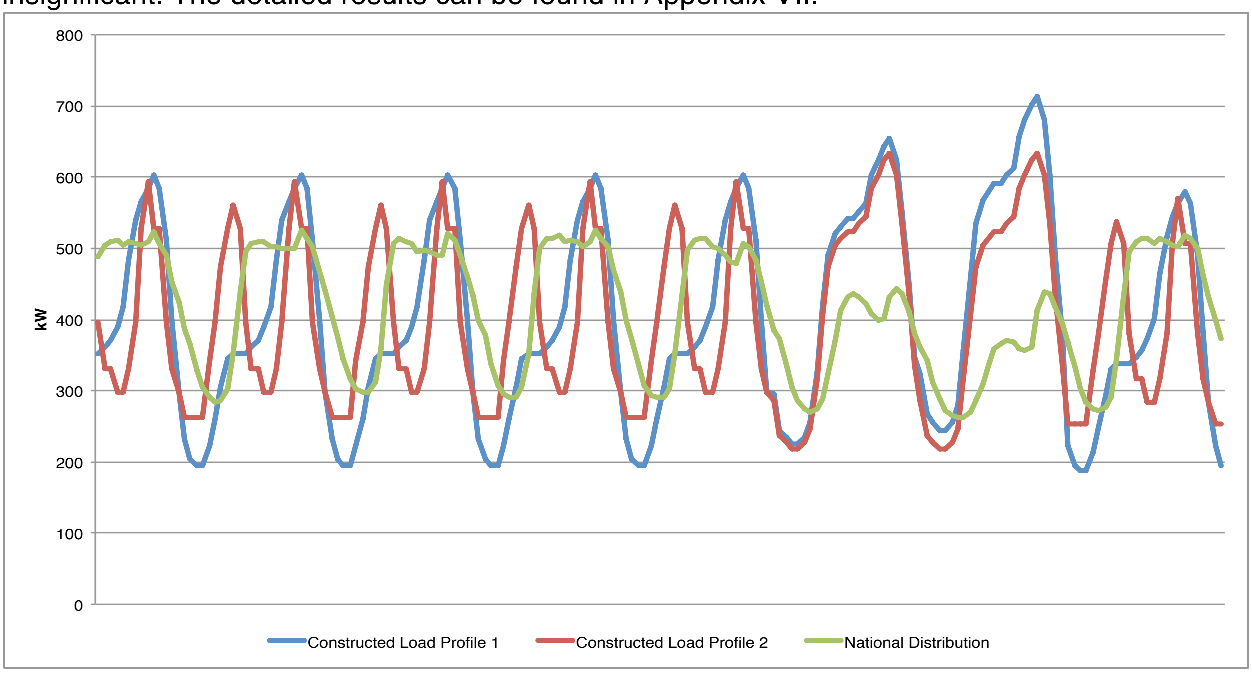


Figure 13.1: Comparison load profiles: Monday – Monday, week in 2004

13.1.1 Constructed Load Profile – 1

Table 13.1 shows the results for this sensitivity analysis, with CLP 1, between the usage of this profile and national distribution both in mean real terms and % changes. What becomes evident is that there is a small increase in the maximum storage requirement and a slightly bigger increase in the storage usage. As a result of the higher storage usage, the surplus production drops. The variance in the found results was a couple of percent points.

The increase in storage requirement, can be explained by the higher maximum consumption during the day, thereby a larger percentage of the installed capacity of either the wind turbine or PV needs to be reached in order the fulfill the production at that moment in time, if not the storage installation will deliver the power. This effect is partially compensated by the lower demand at night, seeing that the total electricity consumption remains the same.

However, the overall changes in these results are very small and can be considered to be almost insignificant on an annual scale and barely influencing the earlier obtained results. The actual time of use of storage on a daily or weekly scale differs however greatly, but has a minute impact on the overall results. What these results especially confirm is the hypothesis that in the case of in-land wind production and a complete PV system, the bulk of the maximum storage capacity requirement is required to compensate the seasonal differentiation both in production and demand. This can be deduced from the fact that the results remain in the same bandwidth of storage requirement.

Table 13.1: Sensitivity Analysis – Constructed Load Profile 1 (without Demand Response)

	Real Term			**% Change**		
	Maximum Storage Requiremen t (MWh)	*Storage Usage (GWh)*	*Surplus Producti on (GWh)*	*Maximum Storage Requiremen t (%)*	*Storage Usage (%)*	*Surplus producti on(%)*
DBPV8MWp	4	0.06	-0.05	0.17	1.46	-3.62
DBW6MW	10	0.09	-0.19	2.98	3.57	-5.21
VLW1.5MW+PV1MWp	10.88	0.06	-0.04	4.53	5.38	-1.69
VLW3MW	2.25	0.03	-0.02	2.51	3.54	-0.18

The results of the sensitivity analysis shown above does not include demand response. Initially it was hypothesized that the effect of a different load profile, especially a load profile which has higher peaks and deeper troughs would result in a higher impact on the maximum storage requirement and especially storage usage. To some extend this is indeed true when comparing table 13.1 and 13.2, however the differences in all cases are only a small positive reduction in the requirement and usage between 0.5 – 1.5 percent point. These results confirm that the overall effect of demand response remains limited and that again in the case of 100% PV systems and on-land wind the issue is not on a day or week scale but on a seasonal scale. There should be some caution in the interpretation of these results, partially resulting from the fact that consumers have a lower willingness to shift their consumption during the peak in the early evening as shown in figure 10.1 in Chapter 10, therefore these results might in fact be slightly overstating this positive effect (Hamidi, 2009), as well as the fact that this still is a constructed load profile and not real measured data.

Table 13.2: Sensitivity Analysis – Constructed Load Profile 1 (with Demand Response)

	Real Term			% Change		
	Maximum Storage Requirement (MWh)	*Storage Usage (GWh)*	*Surplus Production (GWh)*	*Maximum Storage Requirement (%)*	*Storage Usage (%)*	*Surplus production(%)*
DBPV8MWp	8.5	0.04	-0.03	0.34	0.98	-2.41
DBW6MW	7.625	0.06	-0.07	2.10	2.47	-3.72
VLW1.5MW+PV1MWp	8.5	0.04	-0.03	3.65	4.04	-1.22
VLW3MW	1.375	0.02	-0.02	1.82	3.69	-0.16

13.1.2 Constructed Load Profile – 2

The sensitivity analysis of load profile 2 shows similar results as the analysis of CLP 1, although in this instance the storage usage does increase a bit more. This can be explained through the existence of two large day peaks, both in the morning and evening, and a trough in consumption during the day. These results reaffirm the earlier found results, that storage for technologies such as solar and more on-land wind is more of a seasonal problem. While for 'off-shore' wind the higher differences can be explained by the fact that the storage is requirement primarily as bridging power for a number of hours in which the pattern of the wind speeds and the consumption no longer coincide as well as with the national distribution. Storage for off-shore in is required for longer periods of time only in rare events.

Table 13.3: Sensitivity Analysis – Constructed Load Profile 2 (without Demand Response)

	Real Term			% Change		
	Maximum Storage Requirement (MWh)	*Storage Usage (GWh)*	*Surplus Production (GWh))*	*Maximum Storage Requirement (%)*	*Storage Usage (%)*	*Surplus production(%)*
DBPV8MWp	8.63	0.12	-0.07	0.35	2.79	-7.18
DBW6MW	9.63	0.10	-0.20	2.63	3.89	-6.03
VLW1.5MW+PV1MWp	9.75	0.07	-0.05	3.85	5.98	-1.79
VLW3MW	1.13	0.02	-0.02	1.28	3.21	-0.15

The effect of demand response is also of a similar effect as in CLP1, for similar reasons, as shown in table 13.4.

Table 13.4: Sensitivity Analysis – Constructed Load Profile 2 (with Demand Response)

	Real Term			**% Change**		
	Maximum Storage Requirement (MWh)	*Storage Usage (GWh)*	*Surplus Production (GWh)*	*Maximum Storage Requirement (%)*	*Storage Usage (%)*	*Surplus production(%)*
DBPV8MWp	13.5	0.09	-0.05	0.54	2.03	-5.02
DBW6MW	8	0.07	-0.08	2.25	2.66	-4.26
VLW1.5MW+PV1MWp	7.88	0.04	-0.03	3.23	4.44	-1.30
VLW3MW	0.88	0.02	-0.02	1.17	2.96	-0.18

The overall results of these two constructed load profiles were considered to be rather surprising, for initially it was thought that the actual load profiles would have a considerable larger effect on the overall results than was in fact found. This does however not take away the need for real load profiles of neighborhoods to be measured. While the effects on an overall annual scale remains small, differentiation in the time of use of the storage device and the actual sizing of the storage equipment will indicate larger differentiation, if such 100% renewable energy systems would actually be implemented.

13.2. Storage efficiency

In the results section, an overall storage cycle-efficiency of 70% was assumed, in which the compressor had an efficiency of 89% and the turbine and efficiency of 79%. When the overall efficiency of the storage devise is lowered and hence both components with a similar ratio, a drop in surplus production was noticed, and surplus production increased with a higher efficiency. Alternating the increased and lower efficiencies for both components, showed that the efficiency of the turbine played a role in the maximum storage requirement. A lower efficiency of about 20% the turbine would result in an increased maximum storage requirement, of around 5% and increased consumption of the compressor. This indicates that when interpreting the results, the efficiency of the individual components should be kept in mind, instead of the overall efficiency.

What is important to note is during the runs of the model the capacity size of both the turbine and compressor were initially not maximized, and hence it was assumed that there was enough capacity to store all surplus energy production. If the capacity size of the compressor is below the maximum production capacity of the system, a smaller portion of the surplus production could be captured, which would influence the results in a negative manner. Overall in the in the most extreme 100% PV case, the size requirement for the compressor of the CAES installation, has to be around 7.5 MW. A lower capacity of the compressor results in a higher maximum storage requirement or higher installed PV capacity, for the compressor needs to be capable to capture basically all PV production that is not consumed in that instance. In contrast, the turbine only needs to have a capacity of 1.5 MW.

13.3. Energy Savings

Within the result section, the total electricity consumption and heat requirement where kept constant for each year, at the level of the highest consumption during the period that was research. This was done, for this research is concerned with the question to what extent a 100% renewable energy system is possible in an *existing* neighborhood. At the current level of technology however, quite substantial reductions in residential energy consumption can be achieved. Therefore, in this section the effect of reductions on the gathered results will be analyzed. As all results in this research, the results in this sensitivity analysis need to be treated with extreme care; while the energy consumption was cut, the distribution of the consumption was not altered and this in fact will happen when energy savings measures are applied, these results do give a clear indication of the positive benefits energy savings have on the storage requirement and usage.

13.3.1 Reduction in Electricity Consumption

In this first analysis, annual electricity consumption is reduced by 30% to 2.485 GWh/year (or a 15.2% reduction in the total energy consumption). In a best practice scenario for households, this would be a likely reduction by the year 2020 (VHK, 2008). What needs to be noted is that with altered overall consumption patterns, a change in electricity usage patterns will also occur, it is guess work at best to determine what the consumption patterns would be and therefore were kept similar to the distribution pattern of the national Tennet load profile.

What can be seen in table 13.5, is that the maximum storage requirement and usage both drop considerably and that the surplus production rises with the same actual level as the consumption drops, or even slightly more, seeing that less energy is lost in the inefficiency of the storage device.

Table 13.5: Sensitivity Analysis – Electricity consumption reduced by 30 %

	Real Term			**% Change**		
	Maximum Storage Requirement (MWh)	*Storage Usage (GWh)*	*Surplus Production (GWh))*	*Maximum Storage Requirement (%)*	*Storage Usage (%)*	*Surplus production(%)*
DBPV8MWp	-514.38	-0.64	1.31	-20.55	-14.45	153.92
DBW6MW	-120.63	-0.44	1.10	-27.55	-15.62	62.75
VLW1.5MW+PV1MWp	-113.50	-0.25	1.15	-38.90	-22.62	41.82
VLW3MW	-16.13	-0.16	1.12	-17.40	-21.05	10.57

13.3.2 Reduction in Heat Requirement

The total heat demand is reduced by 30%, which means total heat demand drops to 8.54 GWh/year. As a results of the COP of 3.55 of the heat pumps, electricity demand from heat pumps drops from 3.44 GWh/year to 2.41 GWh/year. The total energy demand in terms of electricity drops by 14.8%, this is almost similar to the drop seen in the previous paragraph. For this reason this figure was chosen, though in practice these reductions can be higher.

In all heat reduction cases, a bigger reduction in the maximum storage requirement and usage in comparison to the scenario with the electricity reduction can be noted. This means that the maximum storage requirement is more dependent on the fluctuations and time of occurrence of the heat requirement than on electricity consumption.

Table 13.6: Sensitivity Analysis – Heat Requirement reduced by 30 %

	Real Term			**% Change**		
	Maximum Storage Requirement (MWh)	*Storage Usage (GWh)*	*Surplus Production (GWh)*	*Maximum Storage Requirement (%)*	*Storage Usage (%)*	*Surplus Production (%)*
DBPV8MWp	-697	-0.76	1.34	-27.85	-17.35	156.69
DBW6MW	-160	-0.51	1.09	-37.33	-18.06	62.24
VLW1.5MW+PV1MWp	-147.13	-0.31	1.14	-51.30	-28.51	41.51
VLW3MW	-25.75	-0.18	1.10	-28.21	-23.78	10.36

13.3.3 Combined Reduction in Electricity consumption & Heat Requirement

Combining the reductions in both electricity consumption and heat requirement from previous paragraphs, results in most instances in a drop in the storage requirement of 40% or more and a reduction in usage of 30% or more. The reductions are very substantial and in comparison to the effect of demand response on these same variables, lowering consumption has far higher reductions. It needs to be noted that the storage usage reduction in percentages would be equal to the reduction in land usage.

Table 13.7: Sensitivity Analysis – Electricity consumption & Heat Requirement reduced by 30 %

	Real Term			**% Change**		
	Maximum Storage Requirement (MWh)	*Storage Usage (GWh)*	*Surplus Production (GWh)*	*Maximum Storage Requirement (%)*	*Storage Usage (%)*	*Surplus Production (%)*
DBPV8MWp	-1164	-1.41	2.67	-46.49	-32.11	312.74
DBW6MW	-237	-0.96	2.35	-55.51	-34.31	129.09
VLW1.5MW+PV1MWp	-187.25	-0.53	2.30	-66.68	-48.86	83.52
VLW3MW	-40.25	-0.30	2.23	-43.53	-40.22	20.93

Section VII: Discussion & Conclusion

Chapter 14:Discussion & Conclusion

In the introduction the following research question was proposed:
"To what degree could a self-sufficient and stable decentralized renewable energy system without a grid connection be created today within the context of a Dutch residential neighborhood, and what form and quantity of energy storage would be required?"

As can be concluded from the previous results, the answer to this question is quite clear: it is, in given adequate resources and appropriate constraints, indeed possible to create a neighborhood that runs entirely on intermittent renewable energy sources. However, under certain circumstances, the definitions of the words local and decentralized have to be stretched. Realistically, a neighborhood could only have a self-sufficient and stable energy system when near-shore or off-shore wind is included within the energy mix, otherwise the amount of storage required is too massive to be placed inside the neighborhood. Whithout a grid connection to regulate intermittencies, neighborhoods entirely dependent on solar energy in the Netherlands are completely unrealistic given the tremendous amount of required seasonal storage. In scenarios where only on-shore wind is included, the storage capacity requirement is about five times as small as in a PV only system.

In the problem definition it was discussed that in existing literature and practices, 100% renewable energy systems often are possible only because of beneficial climatic conditions such as high wind speeds or high solar irradiation. In the case of a minimization of the storage requirement and usage, these beneficial circumstances are required for independent operation of the system, as shown in the results section. In instances without these beneficial conditions, the confines of the neighborhood seem to be too small, either for the production of enough biomass, roof space for PV or size of the storage installation. While some parts of the system will be located within the neighborhood, other parts will have to be situated elsewhere, especially energy producing technologies. This undermines the notion of the decentralized energy paradigm in which everything is produced and consumed locally.

In addition to main research question, 4 sub-questions were posed concerning the topics of the size of the intermittencies, the effect of demand response on the need for storage, the feasibility of biomass based back-up generation as an alternative to storage and the extent to which energy systems should or could be local. These sub-questions will be answered in the following paragraphs, followed by the discussion of a number of opportunities for improvement and further research, and a final conclusion.

14.1 Size of the intermittencies – Storage Dependency

"What is the size of the intermittencies or discrepancy between the energy production of technologies such as wind and PV in contrast with the energy demand, comprising of the electricity and heat demand?"

The level of intermittency, here assumed as the % of the total energy demand that had to be derived from energy storages, ranges from 63% for all PV system, to 34% for wind in De Bilt, to 22% for near-shore wind (Berkhout) and around 10% for off-shore wind (Vlieland). The intermittencies decrease when energy systems consist of a mix of sources; in a hybrid wind-PV systems, there is a notable drop of around 10% in the maximum storage requirement and 10-15% in the storage usage for each additional 1 MWp in PV capacity. This effect, however, decreases as PV capacity is increased. The need for storage, for technologies such as PV and onshore wind are primarily required for seasonal differences in both demand and production. With 'off-shore' wind these intermittencies primarily occur on the basis a number of hours, and not days or seasons.

Another important variable, which determines the degree of intermittency, is the capacity sizing of the renewable energy technologies. Oversizing of the system reduces the amount of storage needed, but increases surplus production. As was shown in the results, all of the energy systems display a surplus production of 20% and more than 100%. This therefore primarily becomes a matter of economics, with the cost of building additional storage capacity weighed against the cost of increasing the energy supply capacity. The question then becomes whether the system is production or storage biased. In the future, when the penetration of electrical vehicles increases, these surpluses will indeed be required in order to meet the increasing electricity consumption; however, a rise in seasonal storage will also be required, for electrical vehicles, similar to demand response, will only help in regulating the grid on the sub-day scale, while demanding at the same time generating additional load on the system during peak consumption seasons.

As became evident in examining the intermittency of renewable power generation, three different time scales of intermittency can be seen, namely the day scale, week/month scale and seasonal scale. For these different types of intermittencies, different types of storage technologies should be considered. However, the sizing of these different types of intermittencies and their associated storage technologies is work for further research.

14.2 The effect of Demand Response

"What is the effect of demand response or flexible demand on the need for energy storage?"

The effects of demand response on the storage capacity requirement and usage are in most instances relatively small even though around 30% of the electricity demand is considered to be flexible. To a certain extent this is the result of the fact that the national electricity distribution was used, instead of the specific load profile of a neighborhood. The distribution of the load profile of a neighborhood tends to be more extreme, with nighttime base load around a third smaller than the national distribution and peaks in consumption later in the day. The peaks and troughs in electricity consumption are considerably higher and deeper for a neighborhood and it is therefore more likely that consumption would need to be shifted from one period to the next in order to reduce the reliance on storage.

However, as shown in the sensitivity analysis, the impact of more neighborhood-like load profiles on the effect that demand response has on the storage capacity requirement and usage, is still limited. For example, in the case of a pure PV system, the problem still is that the maximum storage requirement is primarily dependent on the seasonal differences in terms of production and consumption. Demand response only has an impact on the daily results and therefore a different distribution primarily impacts the usage of storage. In the case of wind for a location such as de Bilt, the problem is also less on a daily basis but more on a weekly basis, for there is often little to no wind production in de Bilt for a number of consecutive days. Again demand response has little effect as a result of the different time frame in which the primarily problems are occurring on a longer seasonal timeframe. Where DR had percentagewise a quite large effect was for the ‘offshore’ wind cases, this can be explained by the fact that wind at the Vlieland location often only dies down for a number of hours and picks up again. This is exactly the purpose for which DR can be used. It is also noteworthy that the impact of DR on mixed systems was often in the range of only a few percent, while the mixing of power generation technologies produced a considerable larger effect. In addition, energy savings measures produced a much larger impact. This raises the possibility that the focus of policy measures should not be household demand response, but instead energy savings demands response in large-scale energy users such as industrial facilities or refrigerated warehouses. In such contexts the effects on the wear and tear on equipment can be better monitored and less consumer discomfort is experienced. It is possible that DR has a very positive effect on the storage usage and maximum requirement on a sub-hour level, but due to the hourly time scale of EnergyPlan, it was not possible to check this.

Electrical vehicles are seen as an additional demand response option and solution that will become more widely available in the near future, and will help in reducing energy storage requirements. What can tentatively be concluded is that electrical vehicles will not provide an all-encompassing solution, and in some renewable energy systems could potentially be an additional burden on the system. Electrical vehicles would, similarly to demand response, only be able shift demand on the scale of a day. Seeing that for the delivery of energy of most technologies, with the exception of offshore wind, the imbalance is not on a daily basis but on a weekly or seasonal basis, the impact of electrical vehicles will be limited. Further research, however, is required in order to confirm this hypothesis.

14.3 Back-up generation on biomass

“As an alternative to energy storage, how much land would be required to produce the biomass for back-up capacity?”

In general, the amount of land required to act as back-up capacity by far exceeds the possible production of biomass that could occur in a Category-II neighborhood. The energy production capacity or footprint of the neighborhood is far bigger than the amount of space available within the neighborhood. Keeping in mind that the amount of agricultural land available in the Category II neighborhood is around 3 hectares (and the total size of the neighborhood being 52 hectares), even in the most positive scenarios with the highest caloric content of biomass crops per hectare, several times this area would still be required. In the most pessimistic calculations almost fifty times that amount of land is required. (Table: 11.3)

In chapter 2, concerning the provision of a framework, a number of sensitivity analyses were conducted for different types of neighborhoods, with higher and lower population densities and hence more available space for either energy supply technologies or biomass production. Reexamining these figures, and in light of the above presented findings, it can be concluded that for a neighborhood with a higher address density (Category I), the available space would be even less sufficient, and even in a neighborhood with lower address density (Category III), and in which on all agricultural lands are used for biomass crops, only scenarios with off-shore wind would are feasible. This is despite the fact that the amount of available agricultural lands in these types of neighborhoods is around five times that of a Category-II neighborhood.

Second generation biomass sources such as household and garden waste could potentially reduce the land-usage requirement. Unfortunately, there was too little data available on how much biomass a neighborhood inherently produces. Furthermore, by not using a CHP plant, but a combustion plant as back-up generation, a lower efficiency was used for the conversion of biomass into energy. Thereby overestimating the land usage values. What can be concluded is that there is not enough available land to produce the necessary biomass for back-up generation, and energy storage is therefore a necessary alternative to guarantee that the energy system is CO_2-neutral.

14.4 Decentralized renewable energy paradigm

"To what extent can, or should, energy supply technologies and storage facilities be located within the confines of the neighborhood?"

In recent times the decentralized renewable energy paradigm has been gaining momentum in different news outlets, in contrast with a decreasing interest in the centralized energy paradigm. The results of this study indicate that, at least in the light of 100% renewable energy systems, this move is only partially sensible. From an intermittency perspective, investing primarily in offshore wind makes the most sense; however, this hardly can be classified as local decentralized energy production. Although, in theory, a neighborhood could produce in some scenarios all its energy within the confines of its borders, this does not mean that it should. The land intensity of onshore wind and PV, and the associated need for storage, is so much greater than for offshore wind, that it means that it often is not realistic. Although CAES can be implemented on a small scale, the technical and economic efficiency is limited when compared to more centralized scale, large scale installations. Overall, the idea of a decentralized energy paradigm is romantic, but often not realistic.

14.5 Points of further research and improvements

A large number of assumptions had to be made in this study, as often empirical data was lacking or certain technologies, such as heat storage or geothermal, could not be taken into account. Therefore, there is quite some room for further research and improvements as indicated in the list below:

- Modeled PV and wind energy production was used in this research; actual measured production would be preferable.
- The national electricity distribution instead of neighborhood electricity distribution was used as a result of lack in data; more measured data in this area should be gathered; the same is true for the heat demand.
- Modeling was done on an hour-to-hour basis. The next step would be research on sub-hour scale; however in many instances existing data is only on an hourly level.
- Demand response with heat pumps was not modeled, but this could be a major additional source of flexible demand.
- Heat storage was not modeled, but offers tremendous opportunities for fulfilling a part of the (seasonal) storage function
- Additional research on energy efficiency and storage should be done
- A constant COP for the heat pumps was assumed, but this often not the case
- CHP instead of a combustion plant as back-up, this would result in a drop in the required land for biomass
- Quantified differentiation between seasonal and daily/weekly storage usage; this would provide
- Impact of electrical vehicles on the amount of storage required

- Additional research on the question to what extent oversizing of energy supply technologies should occur in order to reduce the storage capacity requirement and storage usage. Here the next step would be economic optimizations.

14.6 Conclusion: the effect on Energy Policy

The transition to a renewable energy system is ongoing, but on the road to a renewable energy future, one major obstacle remains: the amount of energy storage necessary in order to maintain a stable, 100% renewable energy system.

Based on the results and discussions mentioned above, this study would tentatively suggest in order to minimize this storage roadblock in a 100% renewable energy systems under the used assumptions, that Dutch energy policy should focus primarily on financially backing energy savings and offshore wind, as both options minimize the need for energy storage, and leave PV and onshore wind to civil and market initiatives. Government funds allocated for the research and implementation of demand response at a household level should be reexamined, and the degree to which these technologies will yield the desired effects drawn into question.

If the energy system of a neighborhood is to be turned into a pure renewable energy system, this transition will have to commence in phases following the principles of the 'trias energetica'. First the energy demand will have to be reduced, while at the same time investments in offshore wind and limited PV installations are made. In the initial phases, efficient natural-gas turbines could be run as back-up, in order to gather more data concerning the desired capacity for an energy storage device and the optimal balance between back-up generation and storage.

Many questions about intricate details are still left unanswered, but the primary conclusion and societal objective is clear: in the end, energy storage helps us pave the way to a renewable energy future, and here in the Netherlands it is possible to make our neighborhoods completely based on renewable energy through reduced energy consumption and investment in offshore wind.

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Appendices

Appendix I: Chapter 2 Neighborhood

Sensitivity Analysis – Category I & III neighborhoods

Table I.1: Category I Neighborhood – overview

Category	**Average**
inhabitants	3164
households	1712
average household size	1.85
address density	3741
average land size (ha.)	42.20
urban (ha.)	41.29
infrastructure (ha.)	3.48
build environment (ha.)	31.54
semi-build environment (ha.)	1.14
recreational (ha.)	5.12
non-urban (size)	0.81
agriculture	0.45
nature	0.36

Table I.2: Category III Neighborhood – overview

Category	**Average**
inhabitants	2382
households	992
average household size	2.4
address density	1239
average land size (ha.)	82.76
urban (ha.)	63.45
infrastructure (ha.)	4.71
build environment (ha.)	45.86
semi-build environment (ha.)	3.23
recreational (ha.)	9.62
non-urban (size)	19.17
agriculture	14.64
nature	4.53

Appendix II: Chapter 3 Energy Demand

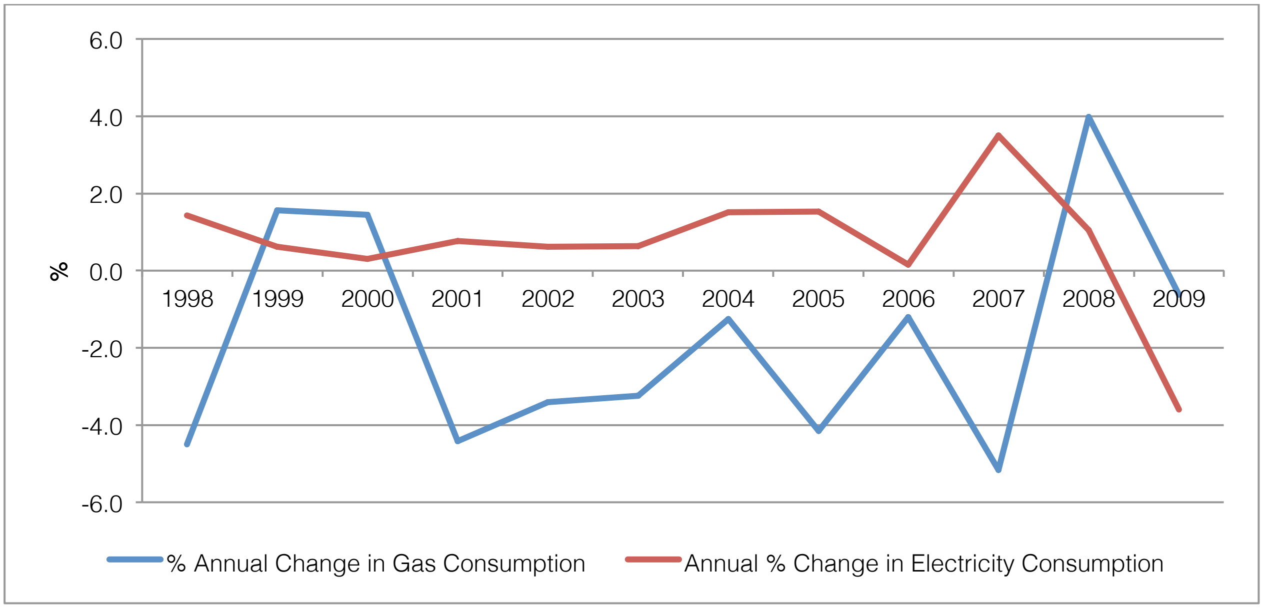


Figure II.1: annual percentage change in gas & electricity consumption (VROM, 2012)

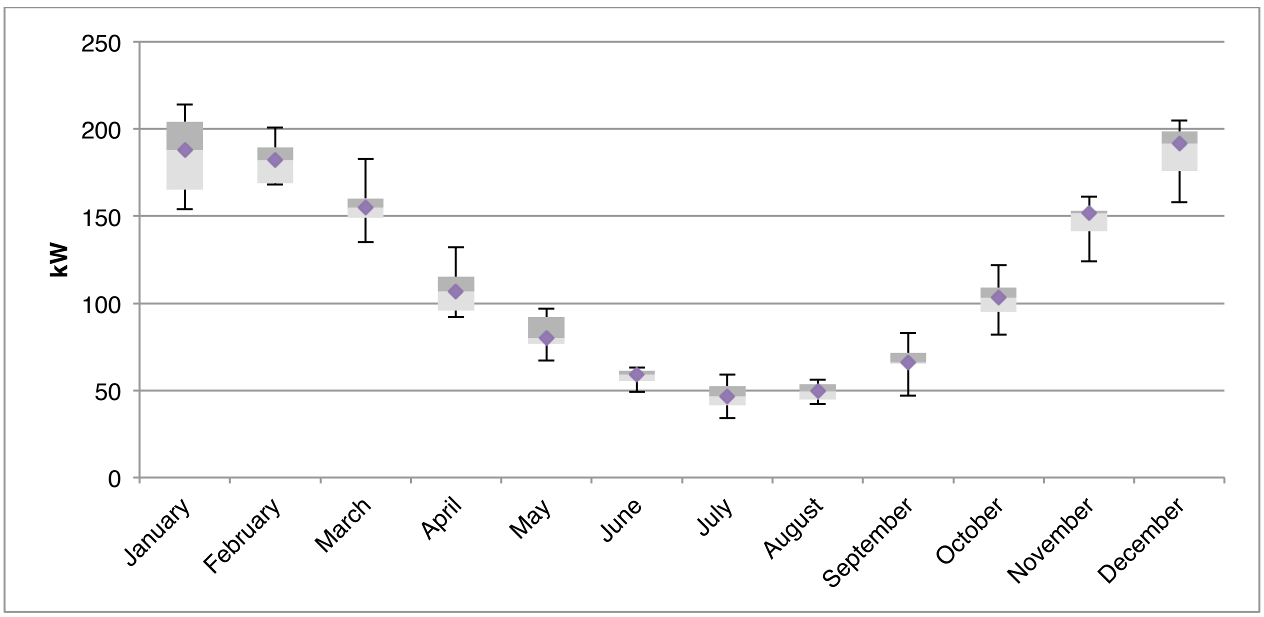


Figure II.2: De Bilt – Heat Demand Distribution at Total Heat Demand of 1 GWh/year

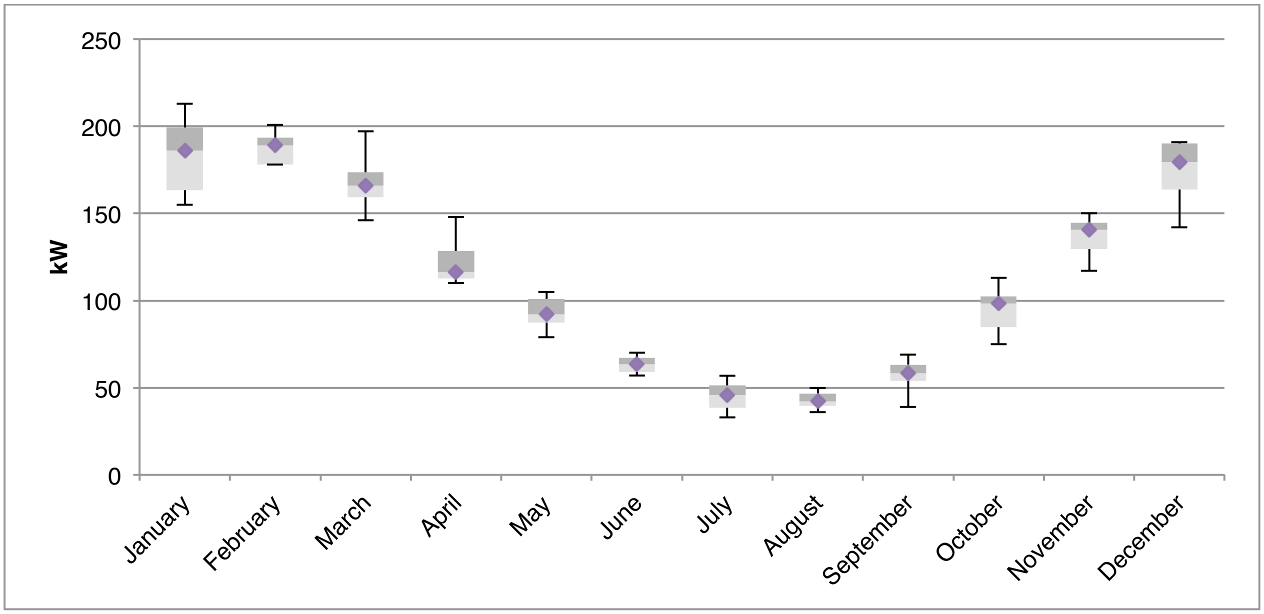


Figure II.3 :Twenthe– Heat Demand Distribution at Total Heat Demand of 1 GWh/year

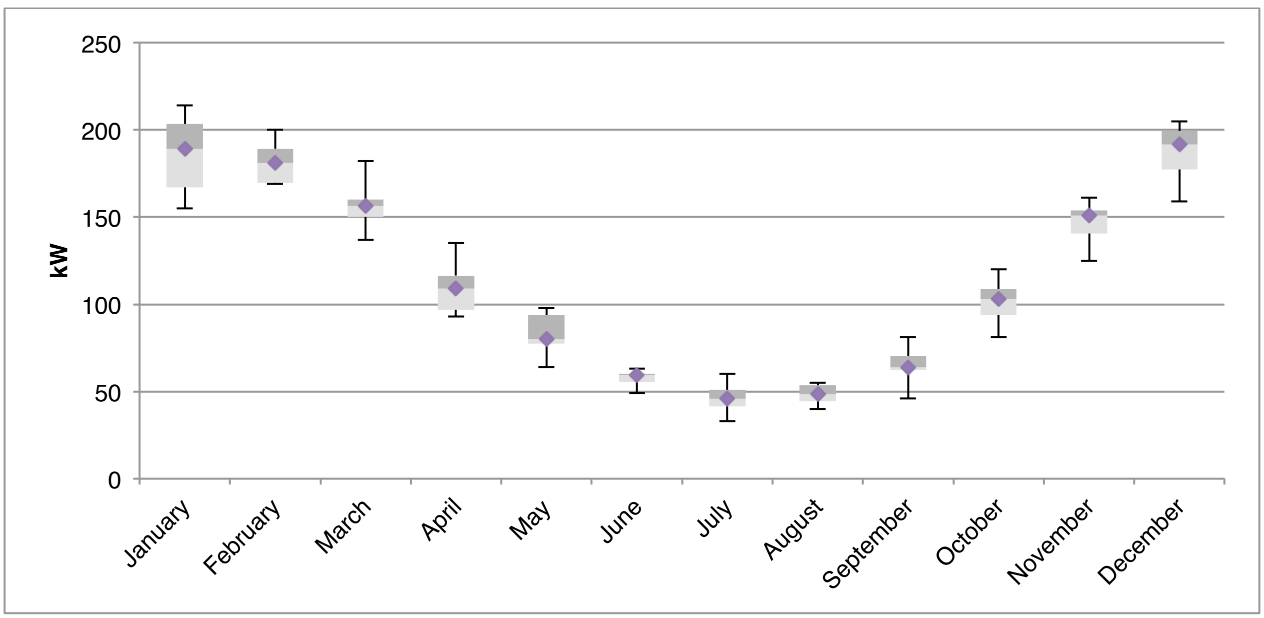


Figure II.4: Vlieland– Heat Demand Distribution at Total Heat Demand of 1 GWh/year

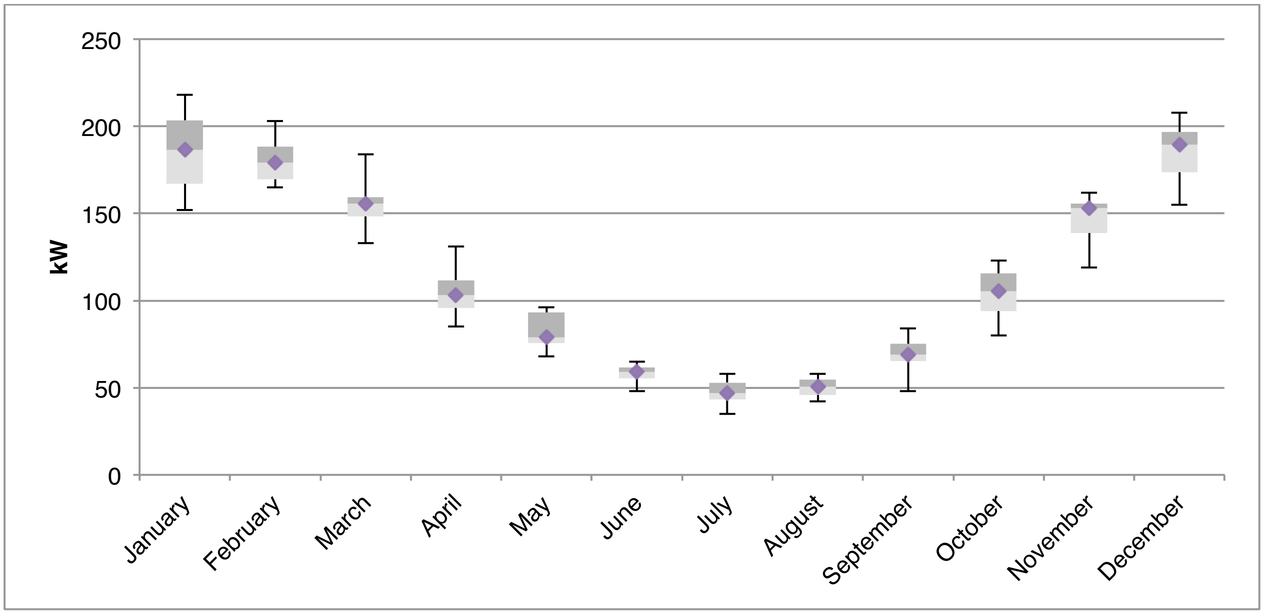


Figure II.5: Cabauw– Heat Demand Distribution at Total Heat Demand of 1 GWh/year

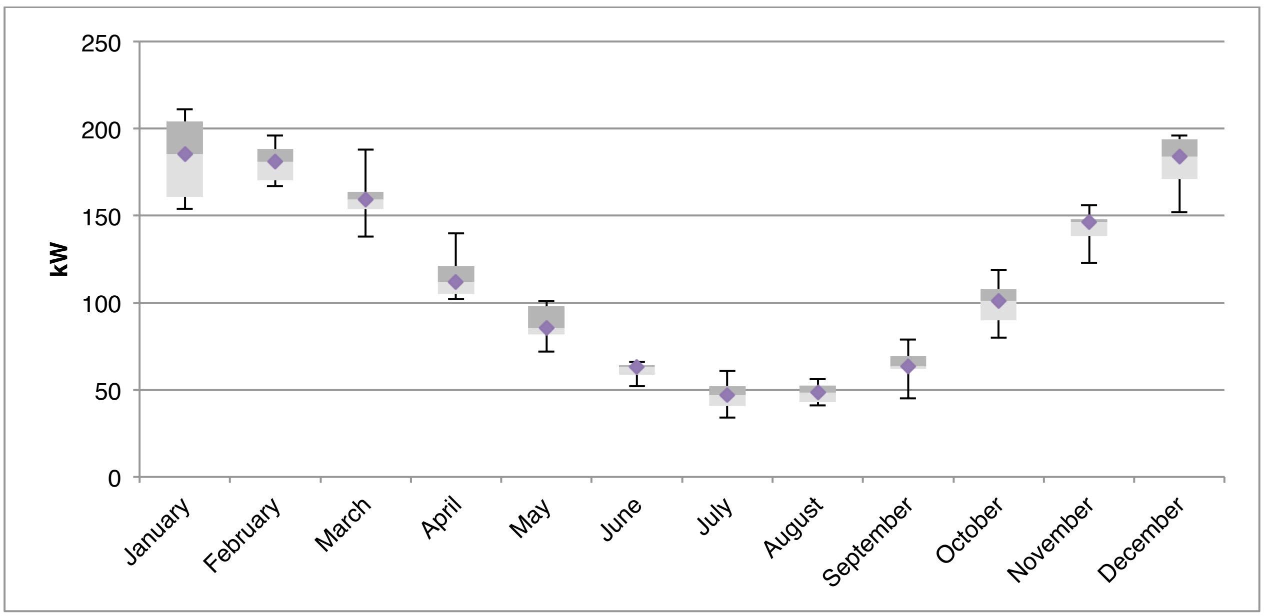


Figure II.6: Berkhout– Heat Demand Distribution at Total Heat Demand of 1 GWh/year

Descriptive Statistics[a]

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
Gas Consumptie Totaal	1637	0	5250	1575.63	523.157	273693.449
Gas Consumptie Appartement	1420	0	3750	1105.81	372.788	138970.802
Gas consumptie Tussenwoning	1563	0	3050	1527.48	419.432	175923.347
Gas consumptie Hoekwoning	1527	0	3600	1795.35	484.648	234883.347
Gas consumptie 2-onder-1-kap	1228	0	3950	2173.57	570.159	325081.505
Gas consumptie vrijstaand	1072	0	5300	2849.95	771.437	595114.377
Gas consumptie onbekend type huis	249	0	8300	2307.03	1325.464	1756855.65
Stadsverwarming	1712	0	100	4.21	18.460	340.754
Electriciteit Totaal	1641	1700	7350	3165.48	612.149	374726.737
Electriciteit Appartement	1446	1350	4550	2241.87	398.142	158516.970
Electriciteit Tussenwoning	1569	1200	6150	3308.06	547.041	299254.152
Electriciteit Hoekwoning	1526	1850	6000	3531.95	576.462	332308.275
Electriciteit 2-onder-1-kap	1230	1550	6550	4054.11	734.236	539102.332
Electriciteit Vrijstaande Woning	1056	2000	8150	4613.21	784.886	616045.704
Electriciteit Woning Type onbekend	173	200	8750	3276.01	1367.018	1868738.07
Valid N (listwise)	129					

a. Regio aanduiding = Buurt, Stedelijkheid = 2

Table II.7: Breakdown of gas & electricity consumption per dwelling type in a Category-II neighborhood

Appendix III: Chapter 5 Wind

De Bilt

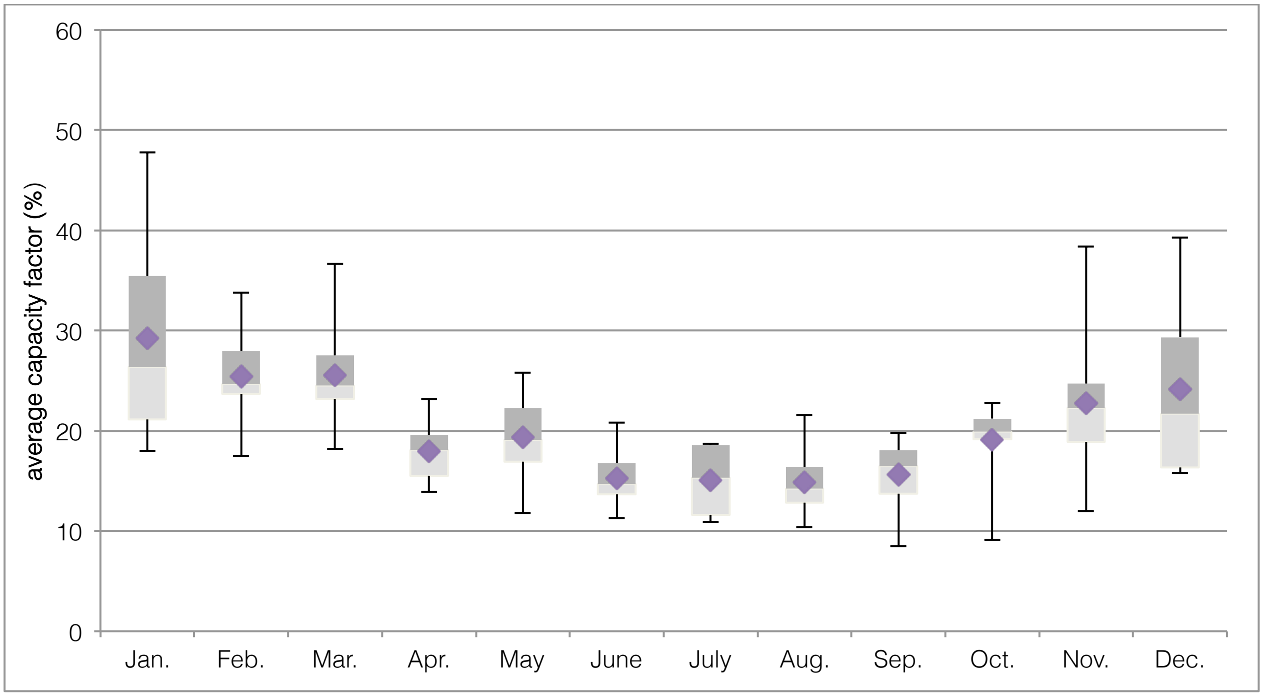


Figure III.1: Average simulated wind capacity factor [2004 – 2011, De Bilt]

De Bilt	**1,000 kW Capacity**	**3,000 kW Capacity**
2004	1.66	4.99
2005	1.49	4.48
2006	1.77	5.31
2007	1.79	5.37
2008	2.12	6.37
2009	1.87	5.61
2010	1.64	4.91
2011	1.96	5.89

Table III.1: Annual Production in GWh [De Bilt]

Wind Vlieland

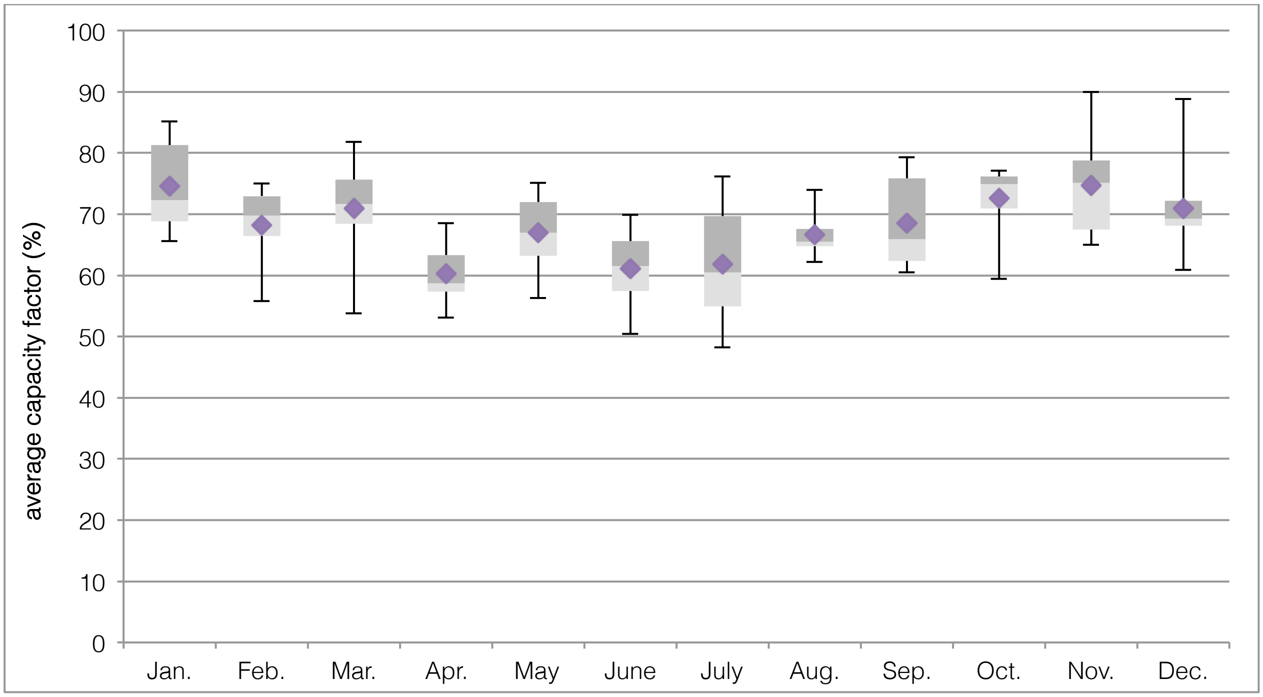


Figure III.2: Average simulated wind capacity factor [2004 – 2011, Vlieland]

Vlieland	**1,000 kW Capacity**	**3,000 kW Capacity**
2004	5.87	17.62
2005	5.99	17.97
2006	6.02	18.06
2007	6.22	18.65
2008	6.22	18.66
2009	6.04	18.22
2010	5.6	16.81
2011	5.92	17.76

Table III.2: Annual Production in GWh [Vlieland]

Wind Twenthe

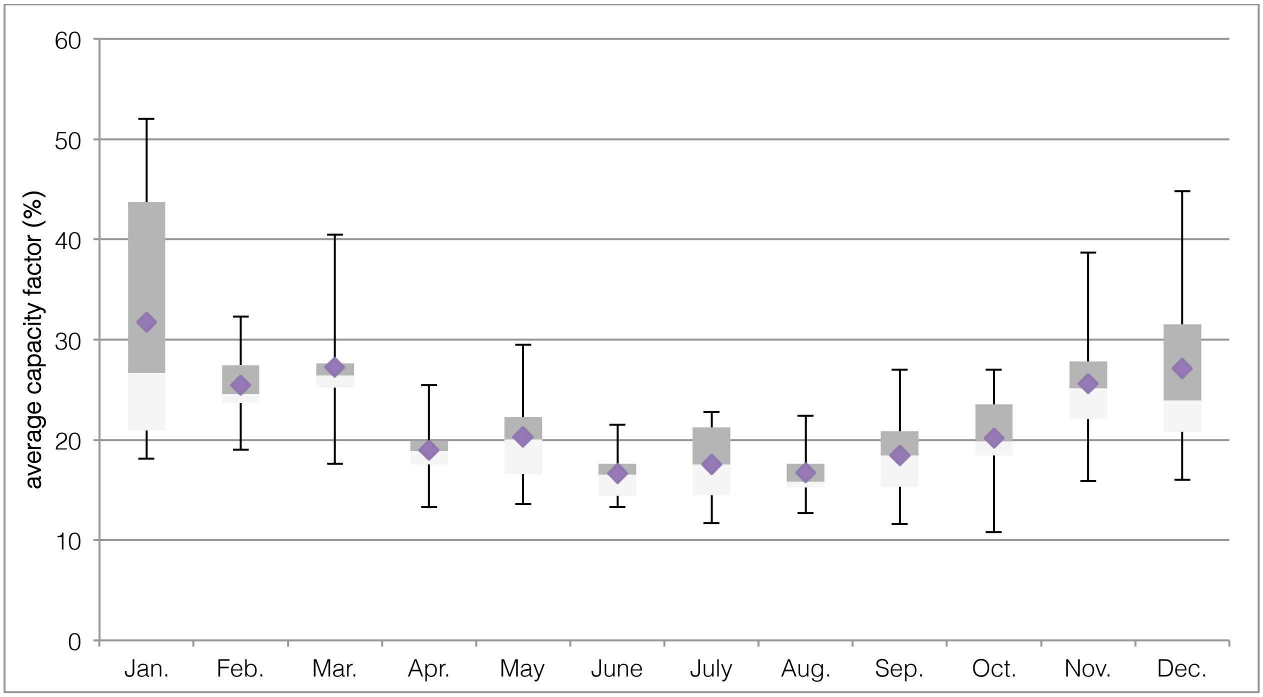


Figure III.3: Average simulated wind capacity factor [2004 – 2011, Twenthe]

Twenthe	**1,000 kW Capacity**	**3,000 kW Capacity**
2004	2	6.01
2005	1.84	5.51
2006	2.04	6.12
2007	2.11	6.33
2008	2.12	6.36
2009	1.88	5.63
2010	1.62	4.85
2011	1.97	5.97

Table III.3: Annual Production in GWh [Twenthe]

Wind: Cabauw

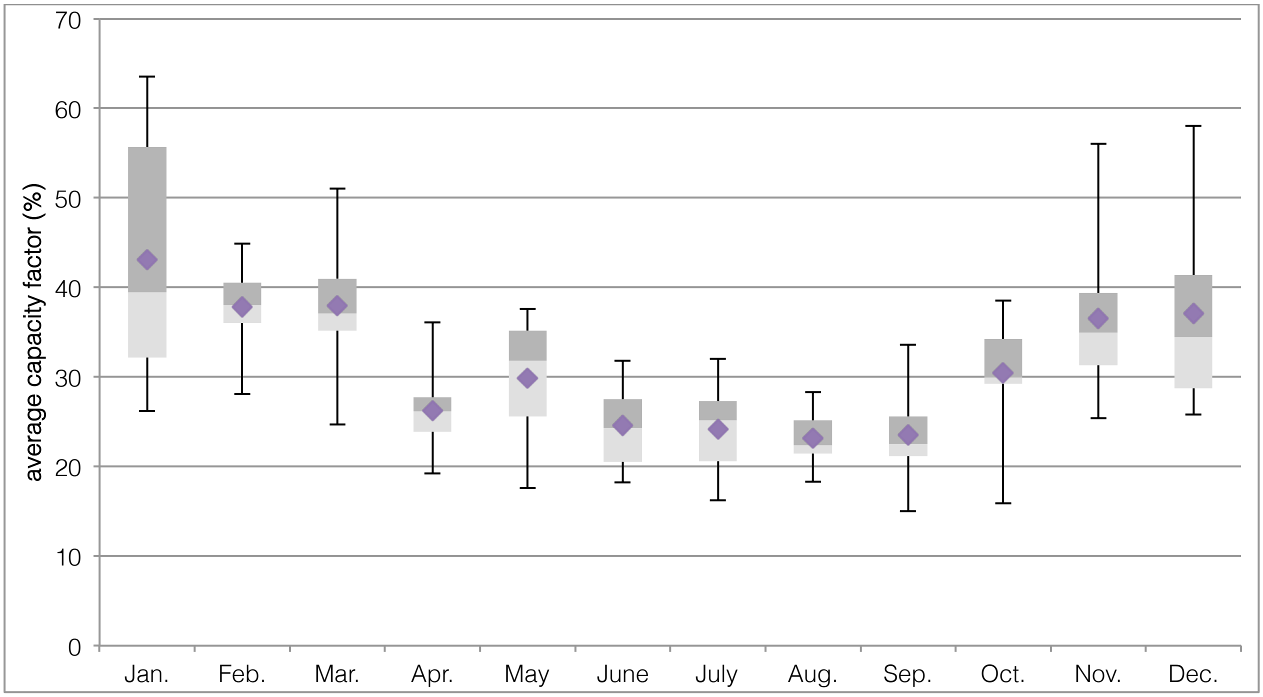


Figure III.4: Average simulated wind capacity factor [2004 – 2011, Cabauw]

Cabauw	1,000 kW Capacity	3,000 kW Capacity
2004	2.82	8.45
2005	2.62	7.87
2006	2.89	8.68
2007	2.87	8.61
2008	2.87	8.61
2009	2.69	8.08
2010	2.35	7.05
2011	2.82	8.46

Table III.4: Annual Production in GWh [Cabauw]

Wind – Berkhout

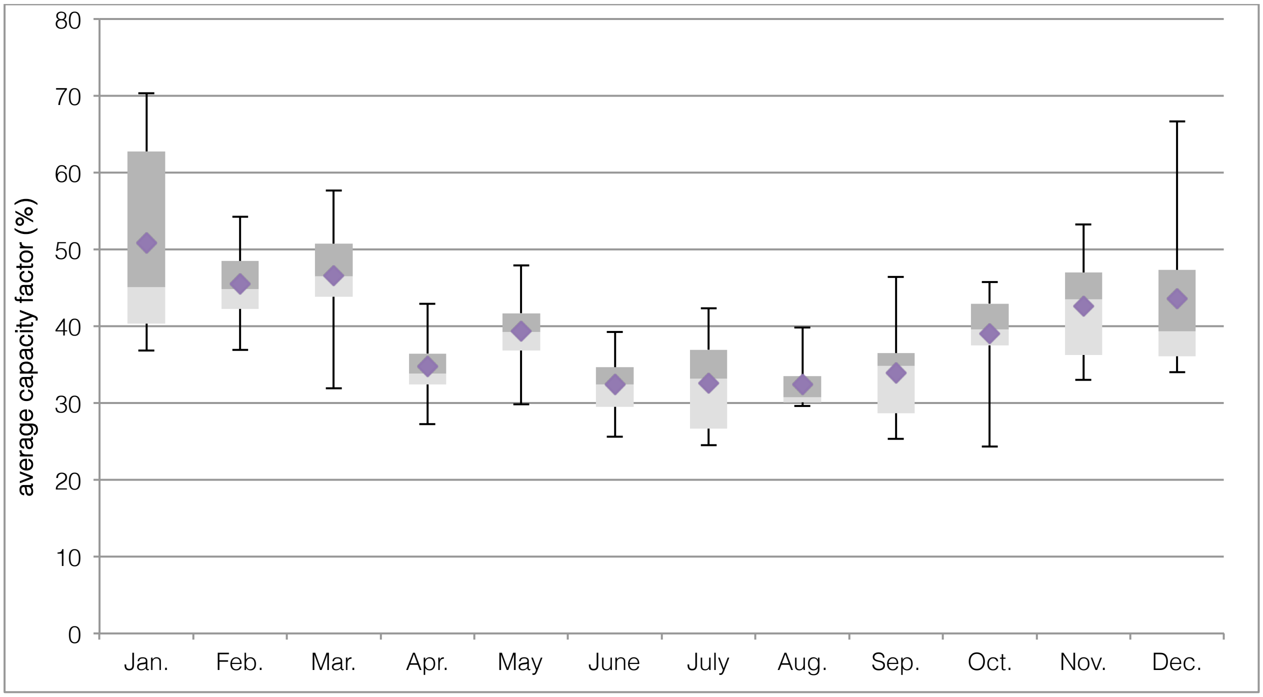


Figure III.5: Average simulated wind capacity factor [2004 – 2011, Berkhout]

Berkhout	**1,000 kW Capacity**	**3,000 kW Capacity**
2004	3.46	10.38
2005	3.27	9.8
2006	3.55	10.65
2007	3.59	10.78
2008	3.74	11.21
2009	3.44	10.32
2010	3.09	9.27
2011	3.58	10.73

Table III.6: Annual Production in GWh [Berkhout]

Appendix IV: Chapter 6 Photovoltaic

Figure IV.1: De Bilt – Measured Solar Irradiation (2004 – 2011)

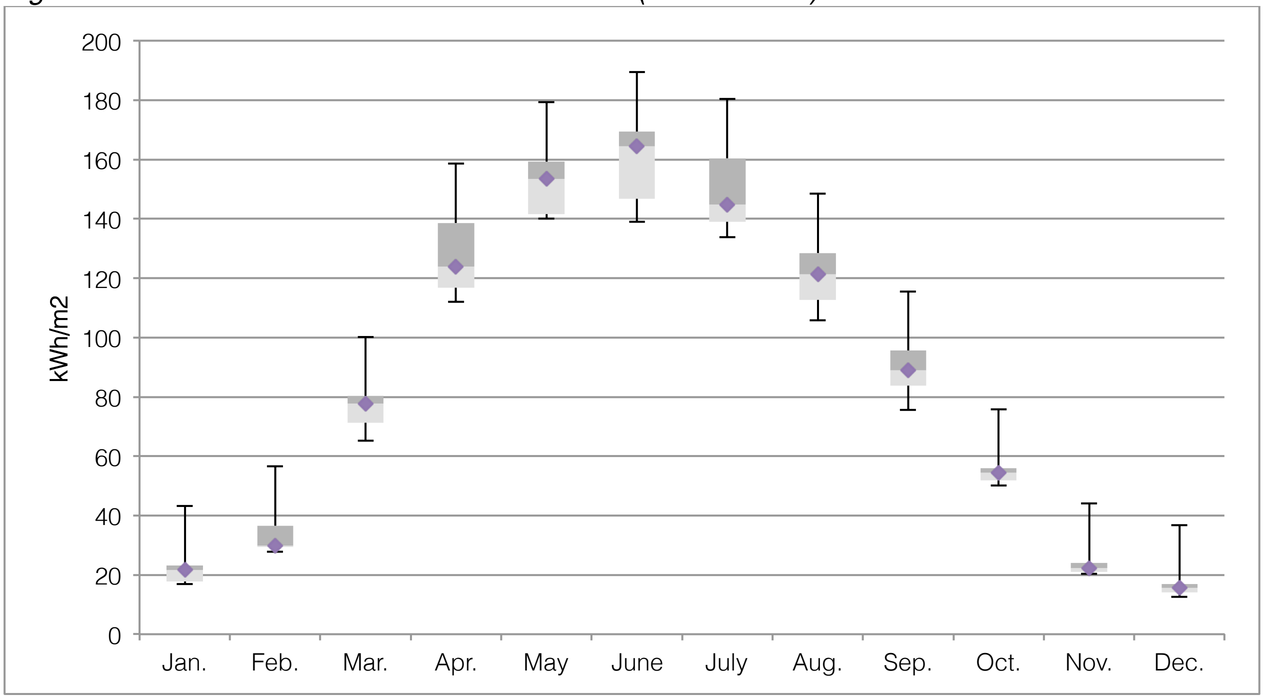


Figure IV.2: De Bilt –Simulated PV production (2004 – 2011) for a 1.5 kWp per month

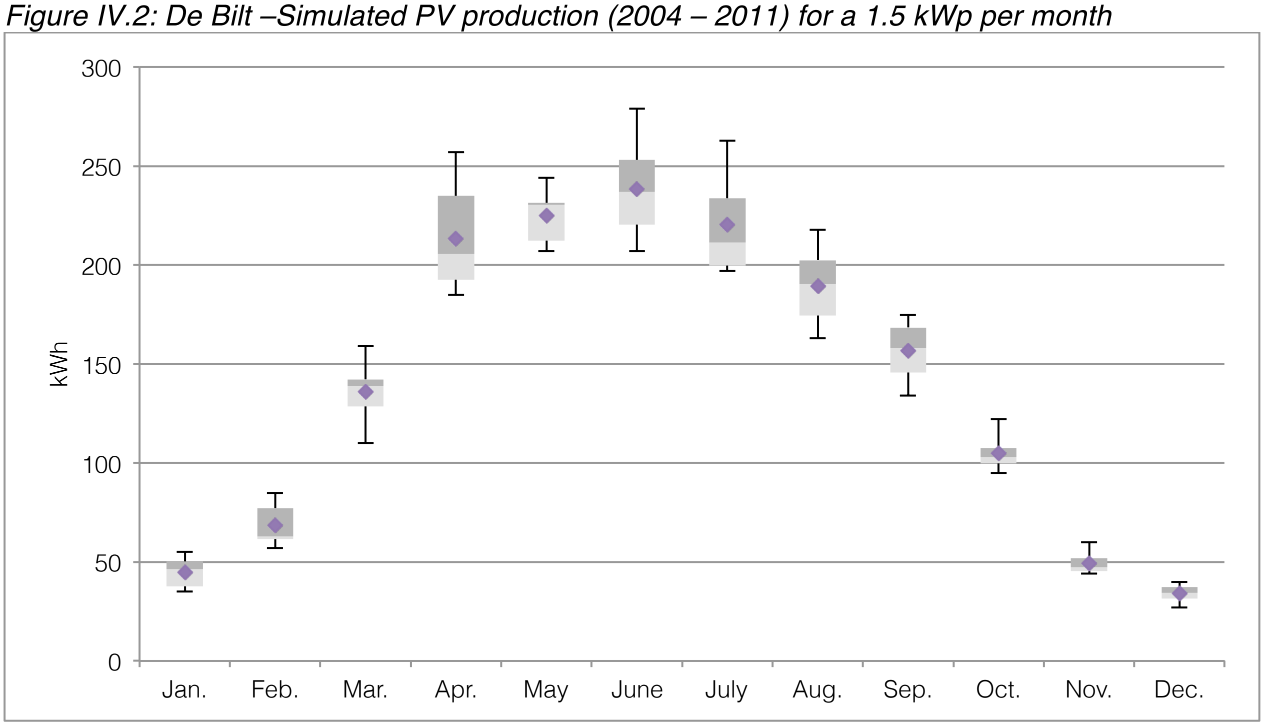


Figure IV.3: Twenthe – Measured Solar Irradiation (2004 – 2011)

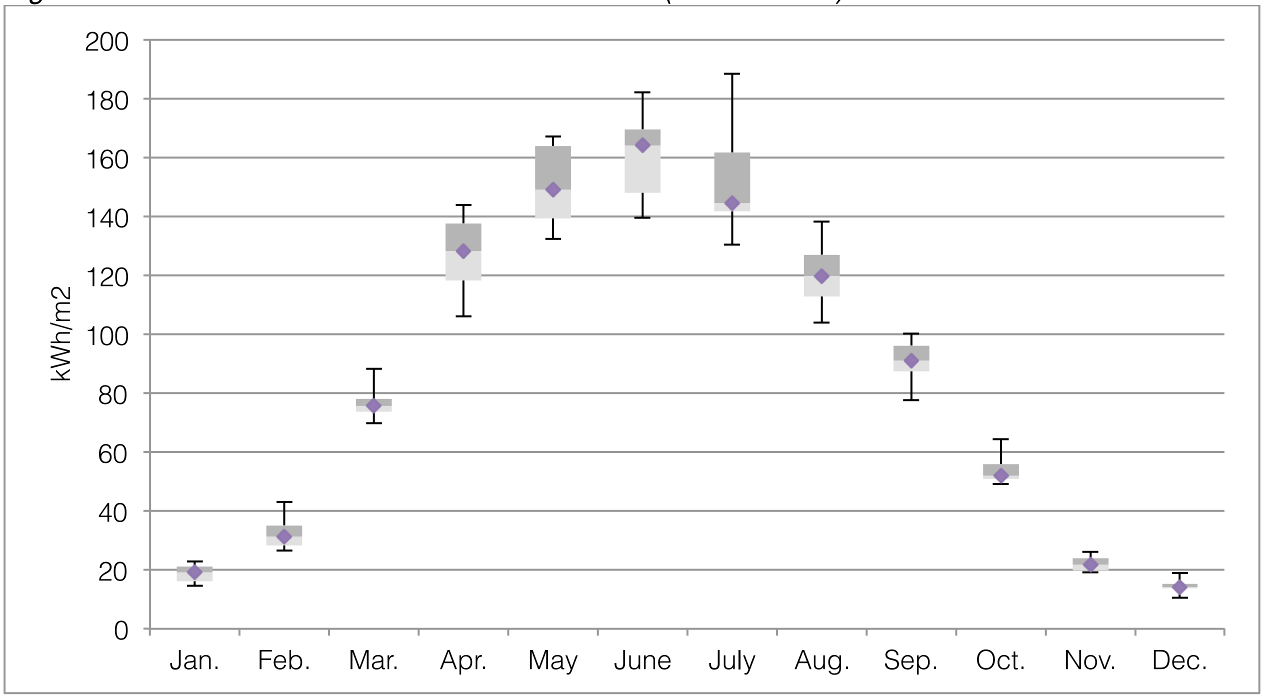


Figure IV.4: Twenthe – Simulated PV production (2004 – 2011) for a 1.5 kWp per month

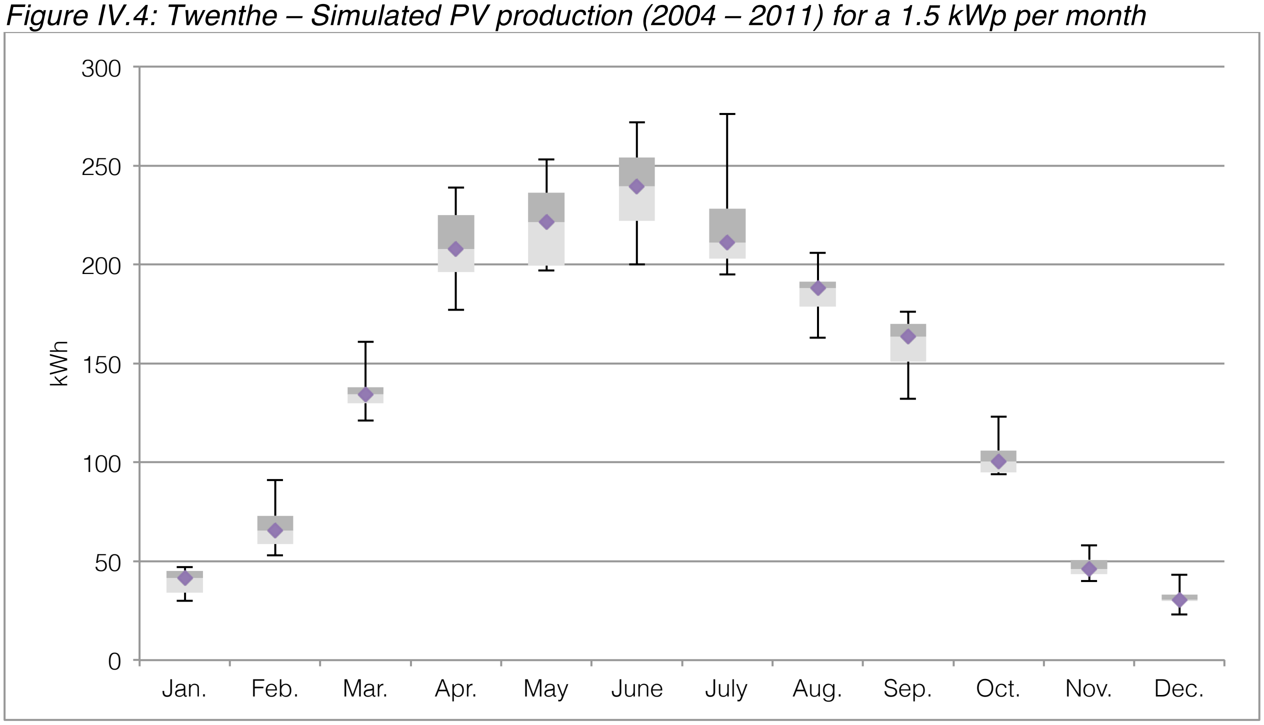


Figure IV.5: Berkhout – Measured Solar Irradiation (2004 – 2011)

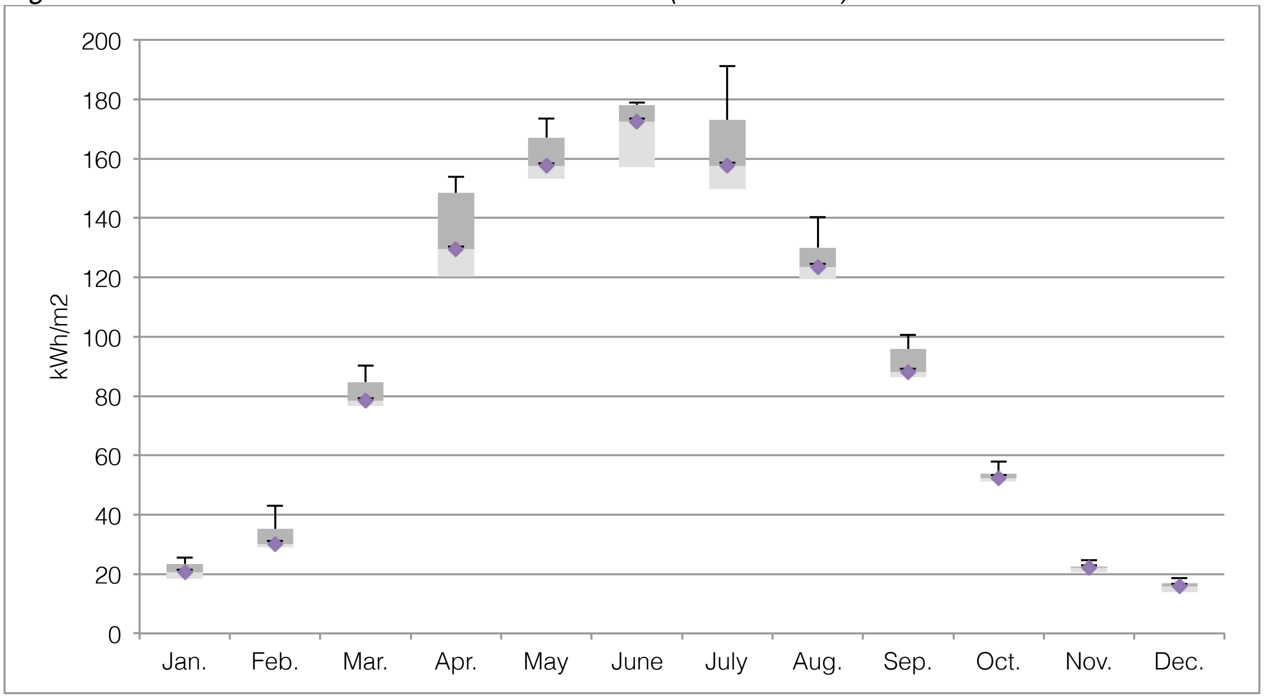


Figure IV.6: Berkhout – Simulated PV production (2004 – 2011) for a 1.5 kWp per month

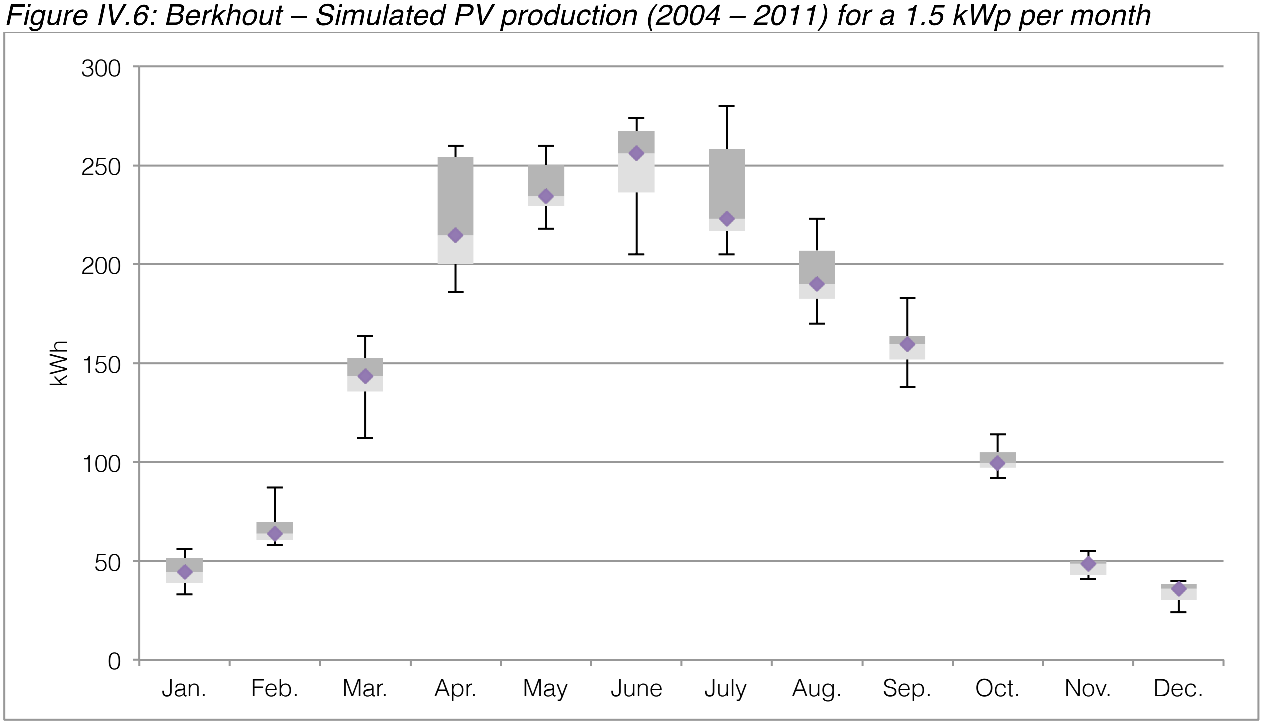


Figure IV.7: Cabauw – Measured Solar Irradiation (2004 – 2011)

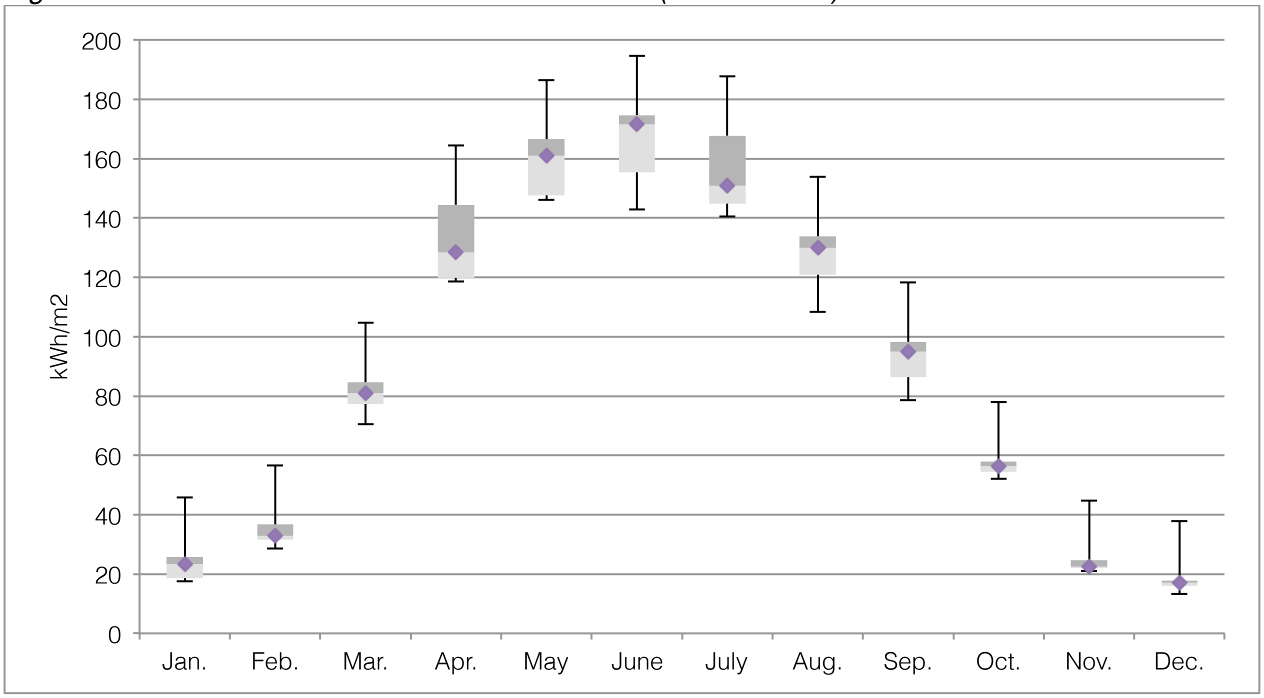


Figure IV.8: Cabauw - Simulated PV production (2004 – 2011) for a 1.5 kWp per month

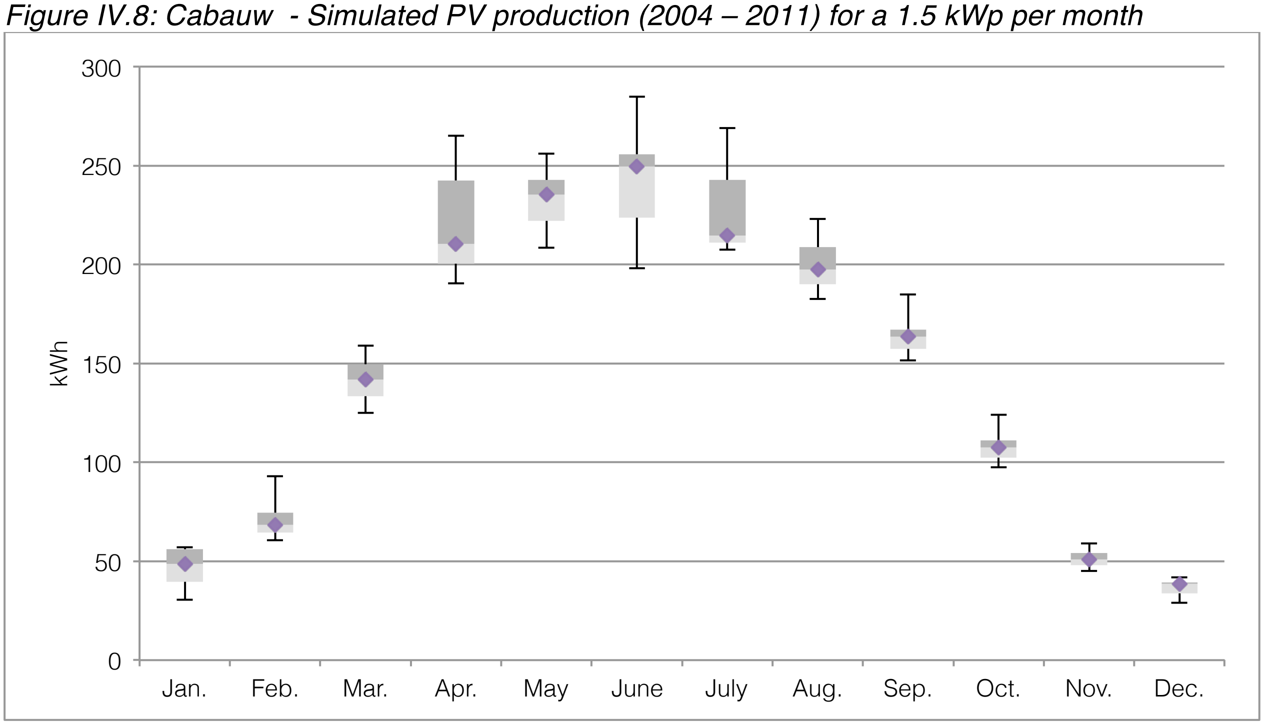


Figure IV.9: Vlieland- De Kooy: Measured Solar Irradiation (2004 – 2011)

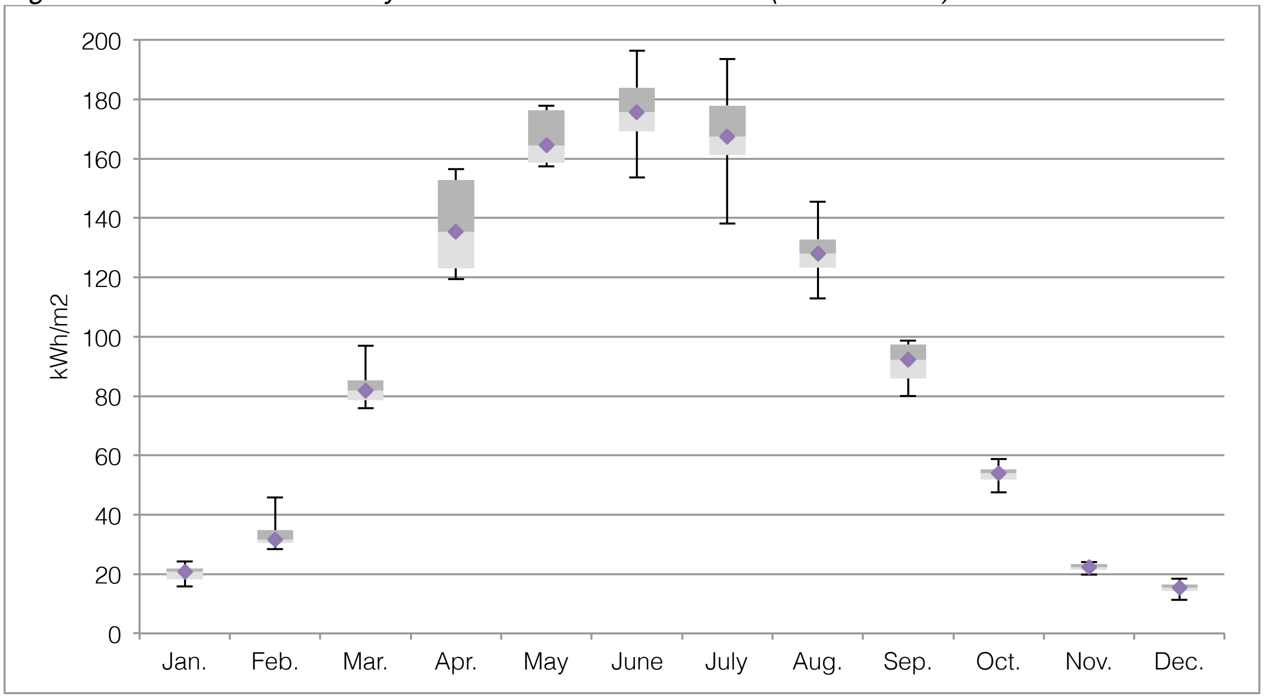
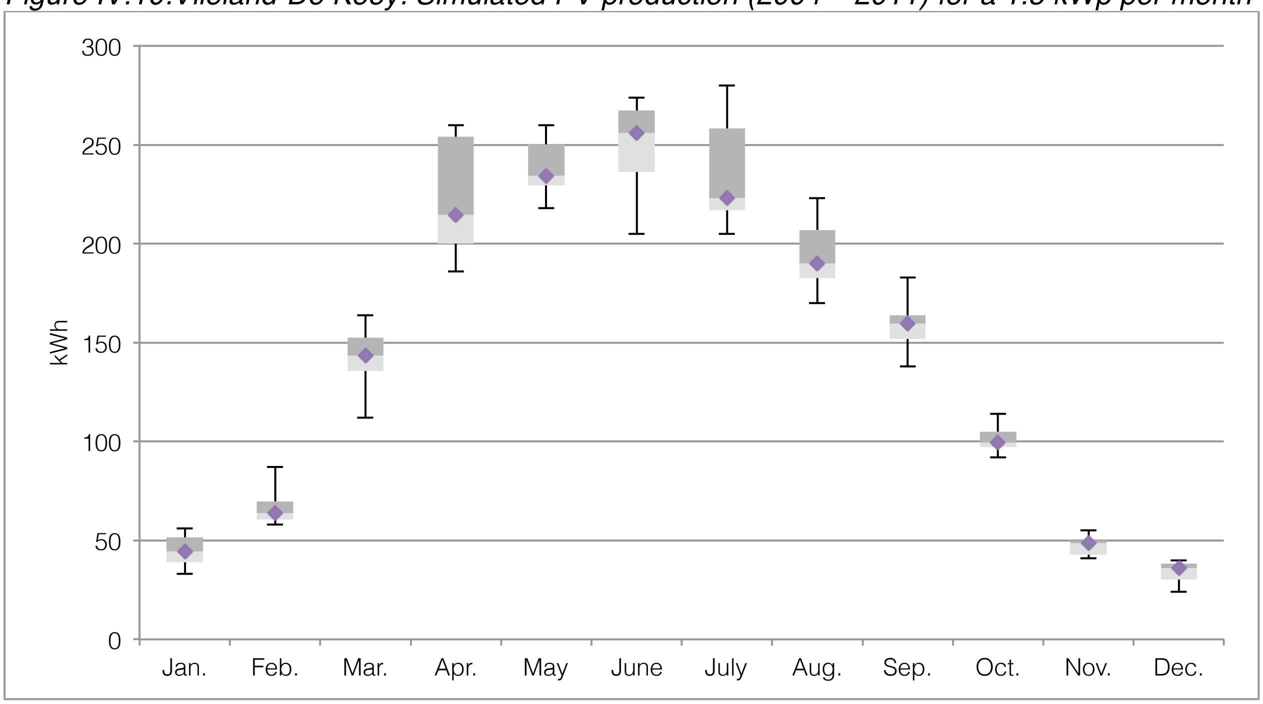


Figure IV.10:Vlieland-De Kooy: Simulated PV production (2004 – 2011) for a 1.5 kWp per month



Appendix V: Chapter 8 Energy Storage

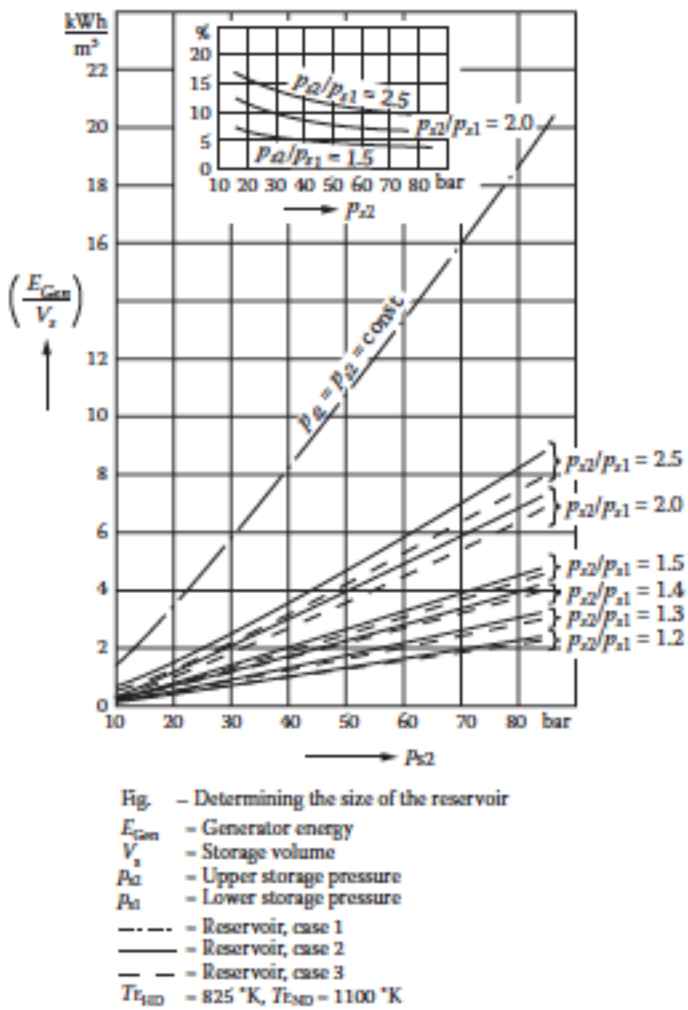


Figure V.1: amount of energy produced per unit volume for CAES with constant pressure reservoir (case 1), variable pressure reservoir (case 2), and variable pressure reservoir with constant turbine inlet pressure (case 3)

Table V.1: Applications Synergies Matrix of Electricity Storage (Eyer, 2010, p 121)

● Excellent ◉ Good O Fair ○ Poor ⊗ Incompatible

Application	Electric Energy Time-shift	Electric Supply Capacity	Load Following	Area Regulation	Electric Supply Reserve Capacity	Voltage Support[1]	Transmission Congestion Relief[1]	T&D Upgrade Deferral[1]	Time-of-Use Energy Cost Management[1]	Demand Charge Management[1]	Electric Service Reliability[1]	Electric Service Power Quality[1]	Renewables Energy Time-shift	Renewables Capacity Firming	Wind Generation Grid Integration
Electric Energy Time-shift		●	◉	O[*]	◉	●	●[†]	●[†]	⊗	⊗	⊗	⊗	◉	◉	O
Electric Supply Capacity	●		◉[*]	O[*]	◉[*]	●	◉[†]	●[†]	⊗	⊗	⊗	⊗	O[X*]	O[X*]	⊗
Load Following	◉	◉[*]		O[*]	◉[*]	◉	O[X]	◉[X*]	O[*‡]	O[*‡]	⊗	⊗	O	⊗	⊗
Area Regulation	O[*]	O[*]	O[*]		O[*]	⊗	O[X*]	⊗	⊗	⊗	⊗	⊗	○	○	⊗
Electric Supply Reserve Capacity	◉	◉[*]	◉[*]	O[*]		●	O[*]	◉[*]	◉[*‡]	◉[*‡]	⊗	⊗	O[*]	O[*]	○[*]
Voltage Support[1]	●	●	◉	⊗	●		◉	●	◉[‡]	◉[‡]	◉[‡]	◉[‡]	◉[#‡]	◉[#‡]	⊗
Transmission Congestion Relief[1]	●[†]	◉[†]	O[X]	O[X*]	O[*]	◉		◉[X†]	◉[†]	◉[†]	○	⊗	◉[#]	◉[†]	⊗
T&D Upgrade Deferral[1]	●[†]	●[†]	◉[X*]	⊗	◉[*]	●	◉[X†]		◉[†]	◉[†]	○	⊗	◉[#]	◉[†]	⊗
Time-of-Use Energy Cost Management[1]	⊗	⊗	O[*‡]	⊗	◉[*‡]	◉[‡]	◉[†]	◉[†]		●[†]	●	●	◉[#]	◉[†#]	⊗
Demand Charge Management[1]	⊗	⊗	O[*‡]	⊗	◉[*‡]	◉[‡]	◉[†]	◉[†]	●[†]		●	●	◉[#]	●[†#]	⊗
Electric Service Reliability[1]	⊗	⊗	⊗	⊗	⊗	◉[‡]	○	○	●	●		●	◉[#]	◉[#]	⊗
Electric Service Power Quality[1]	⊗	⊗	⊗	⊗	⊗	◉[‡]	⊗	⊗	●	●	●		⊗	⊗	⊗
Renewables Energy Time-shift	◉	O[X*]	O	○	O[*]	◉[#‡]	◉[#]	◉[#]	◉[#]	◉[#]	◉[#]	⊗		●	O[X]
Renewables Capacity Firming	◉	O[X*]	⊗	○	O[*]	◉[#‡]	◉[†]	◉[†]	◉[†#]	●[†#]	◉[#]	⊗	●		O[X]
Wind Generation Grid Integration	O	⊗	⊗	⊗	○[*]	⊗	⊗	⊗	⊗	⊗	⊗	⊗	O[X]	O[X]	

Appendix VI: Chapter 11 Results

Table VI.1: Abbreviations used in Results section

Abbrevation	Meaning
DB	De Bilt
VL	Vlieland
CB	Cabauw
BK	Berkhout
W	Wind
PV	Photovoltaic
MW	Megawatt

The following Graphs depict the surpluses in production for the different scenarios that have been run:

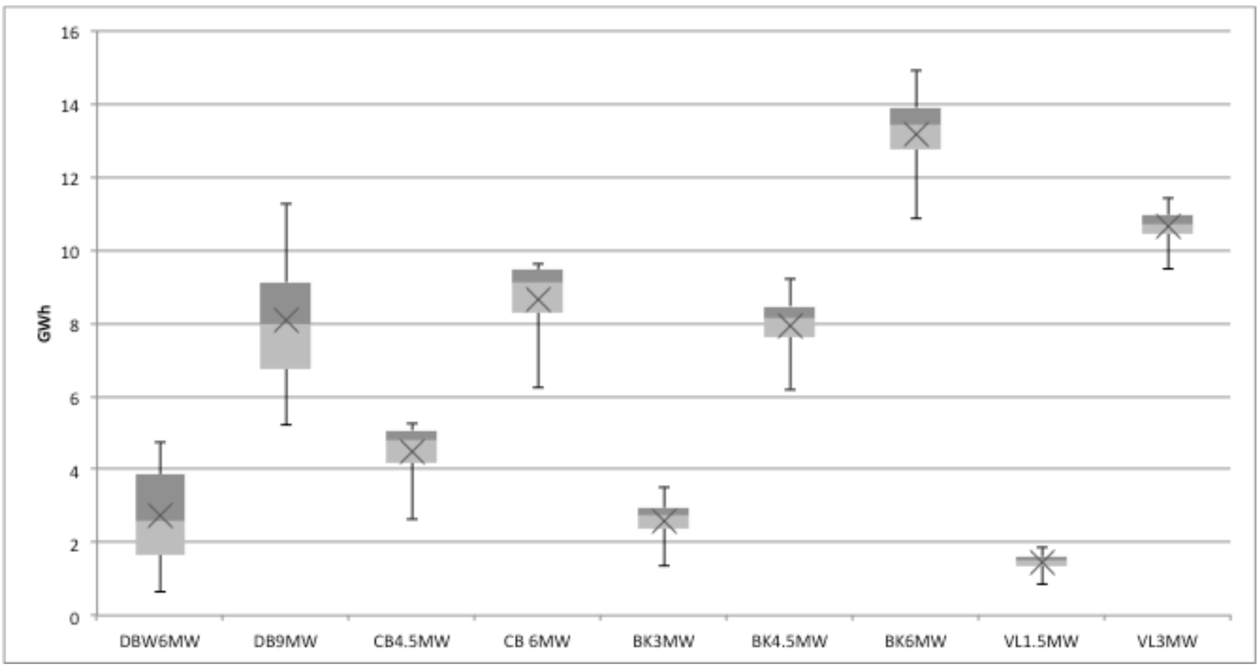


Figure V.1: Surplus production in GWh/year- Wind systems

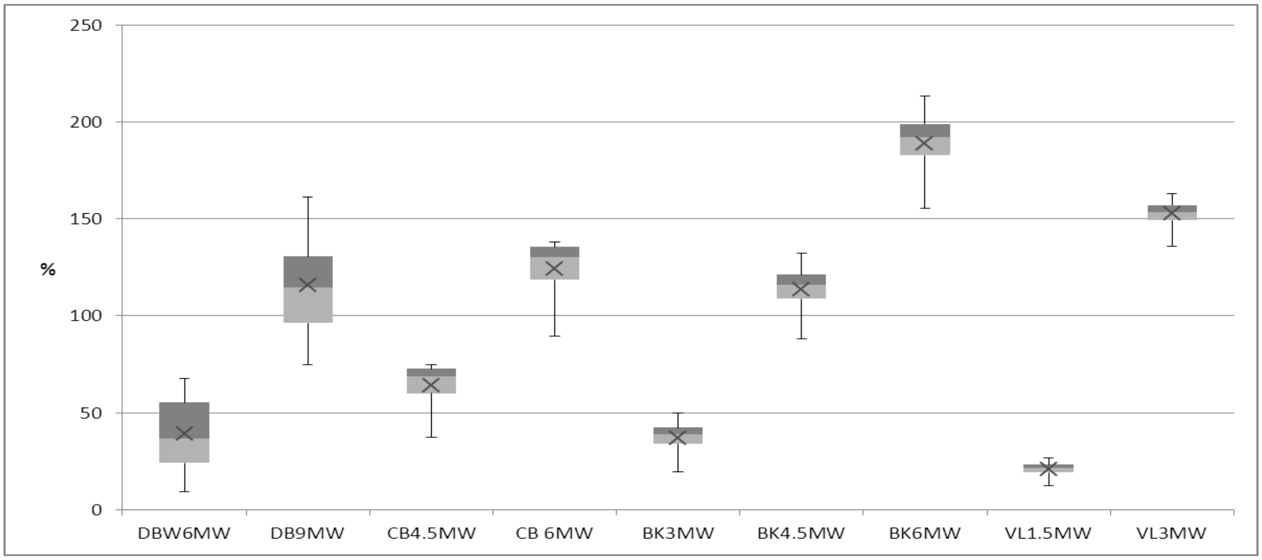


Figure VI.2: Surplus production wind systems as % of total energy demand

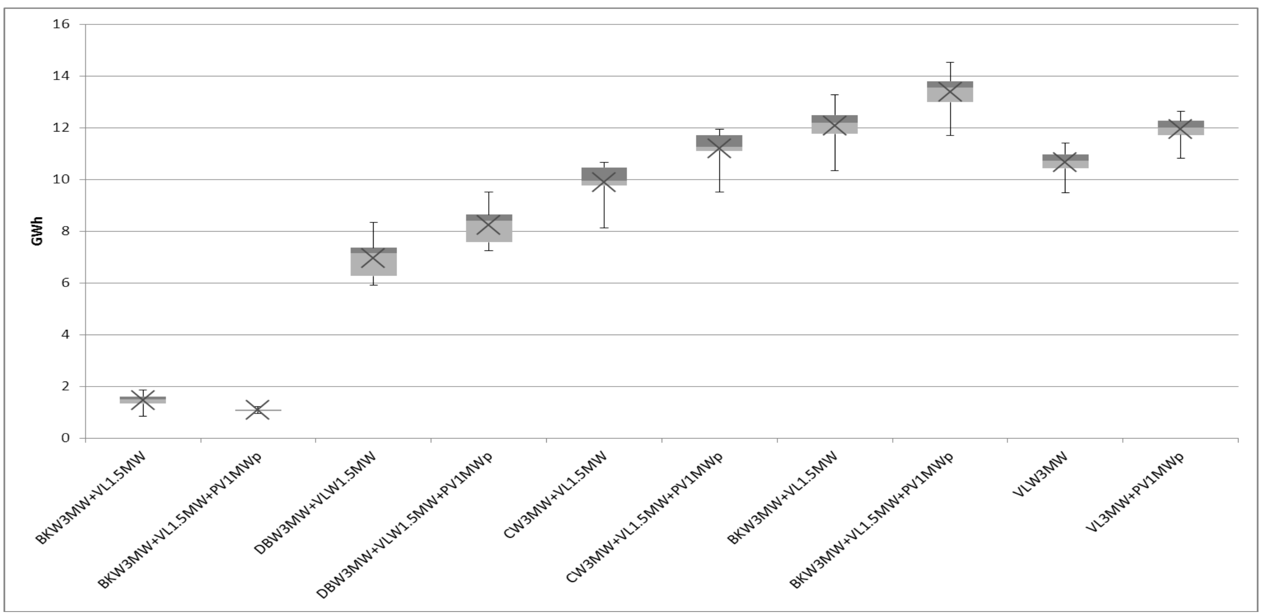


Figure VI.3: Surplus production in GWh – Onshore/Vlieland wind

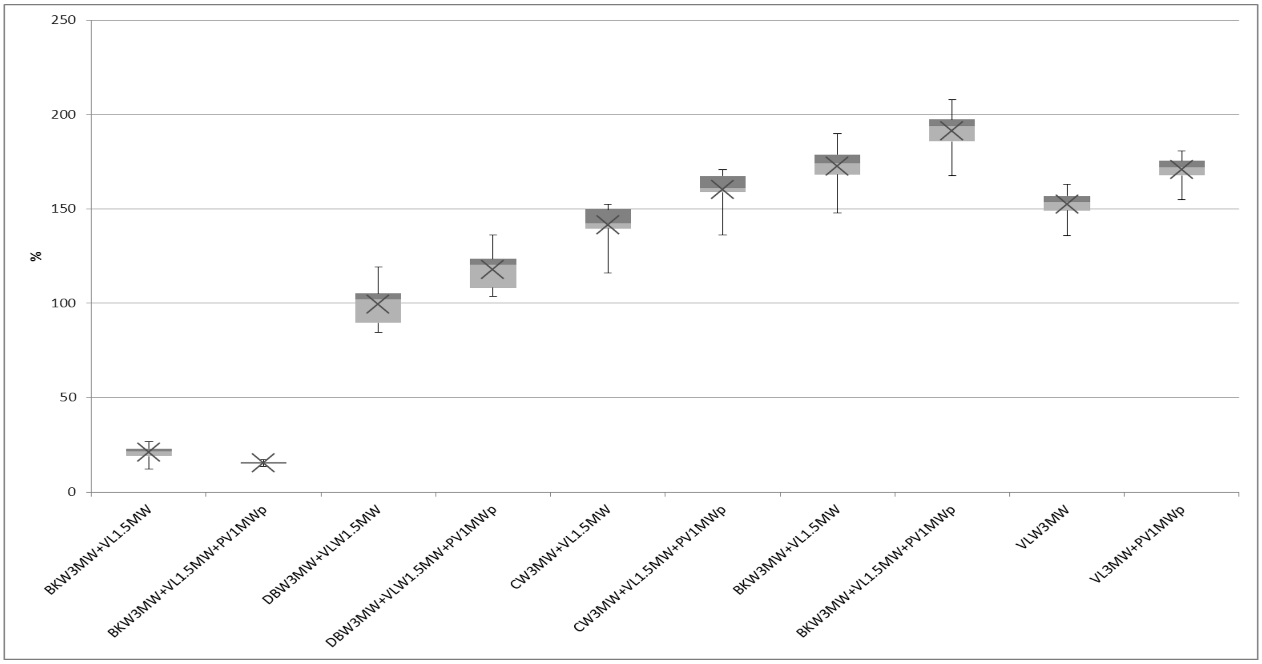


Figure VI.4: Surplus product as % of total energy production - Onshore/Vlieland Wind

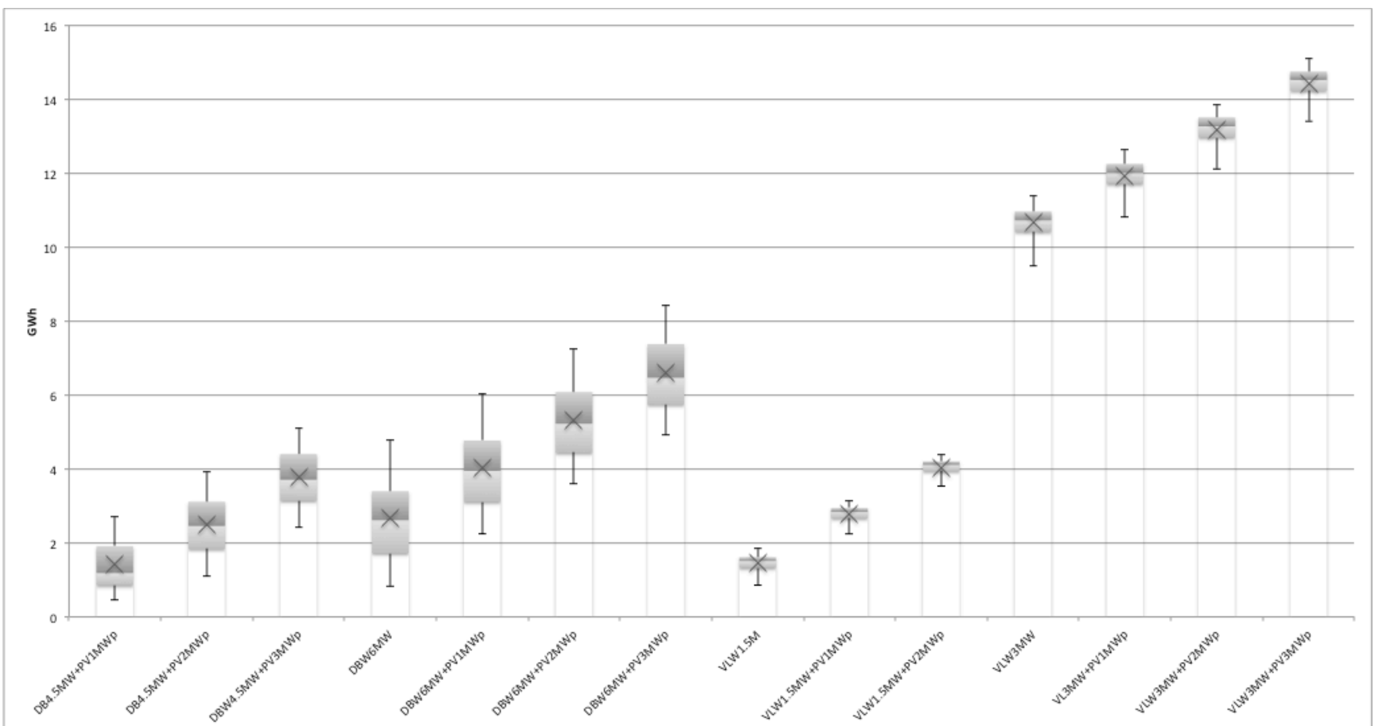


Figure VI.5: Surplus production in GWh – Mixed PV/Wind systems

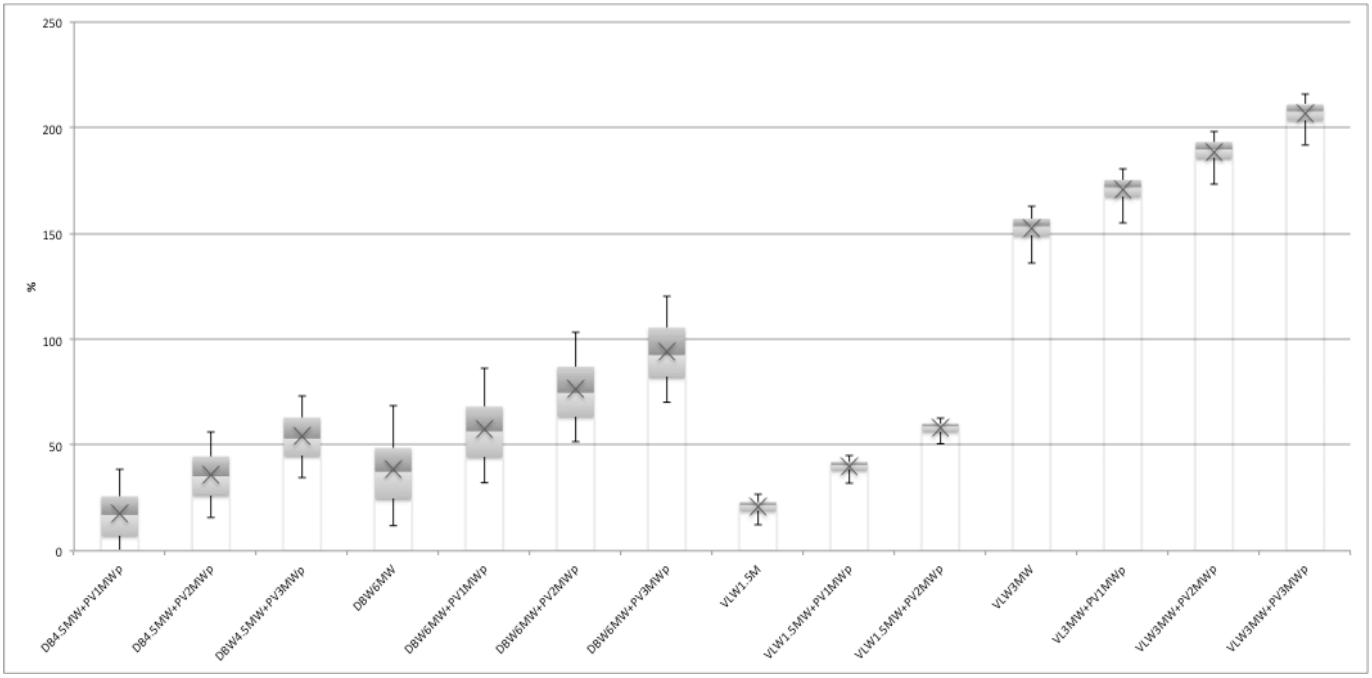


Figure VI.6: Surplus product as % of total energy production – Mixed Wind/PV systems

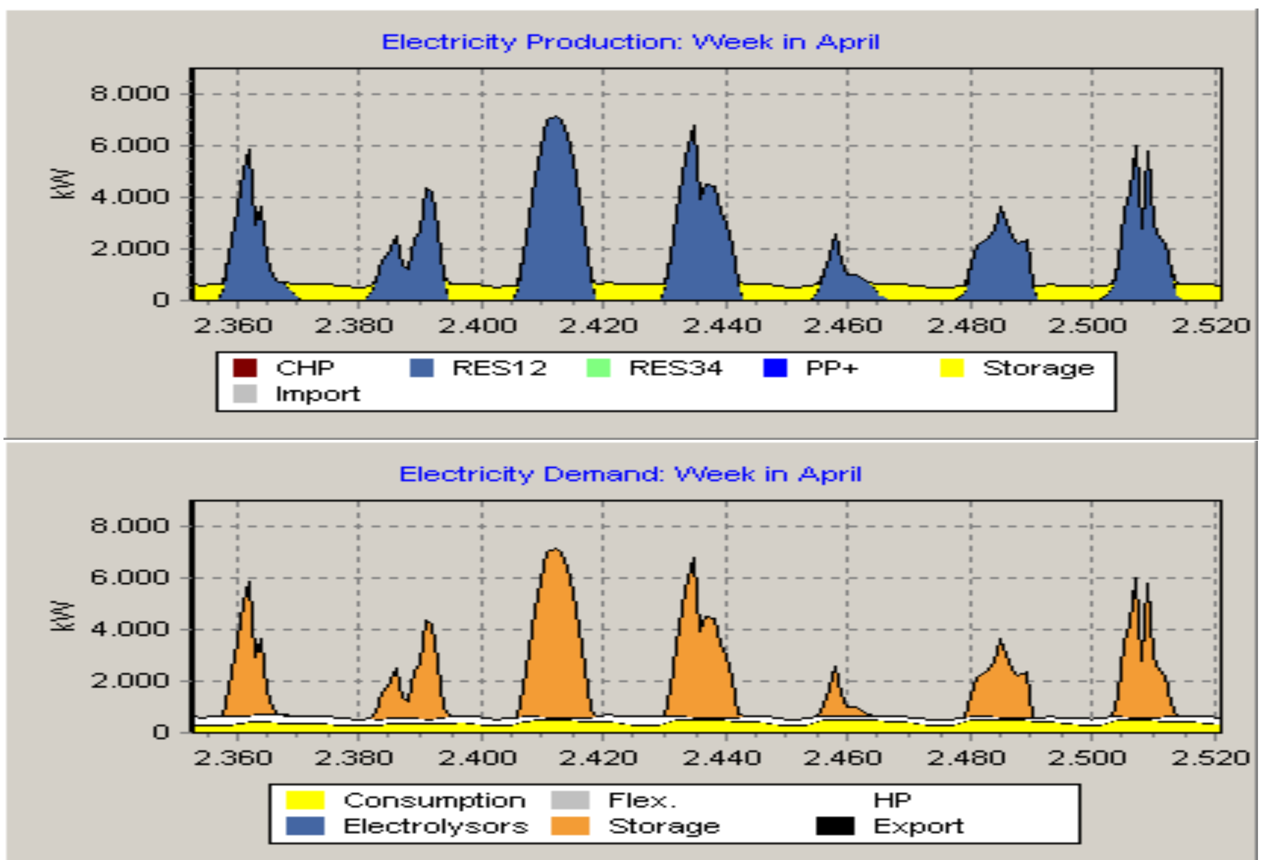


Figure VI.7 : Example of EnergyPlan Output for a 100% PV system (Larger version figure 12.1)

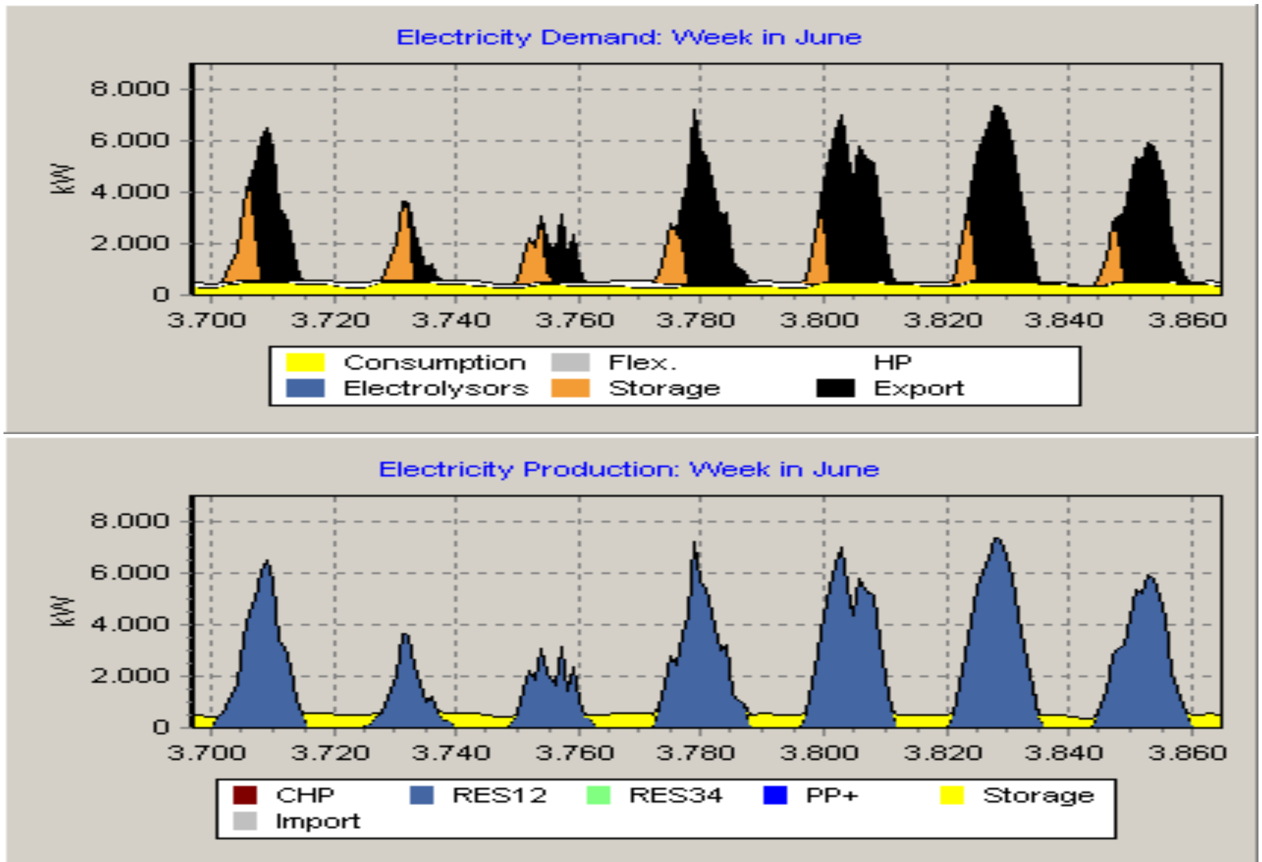


Figure VI.8 : Example week in June in which maximum storage content is reached (Larger version of figure 12.5)

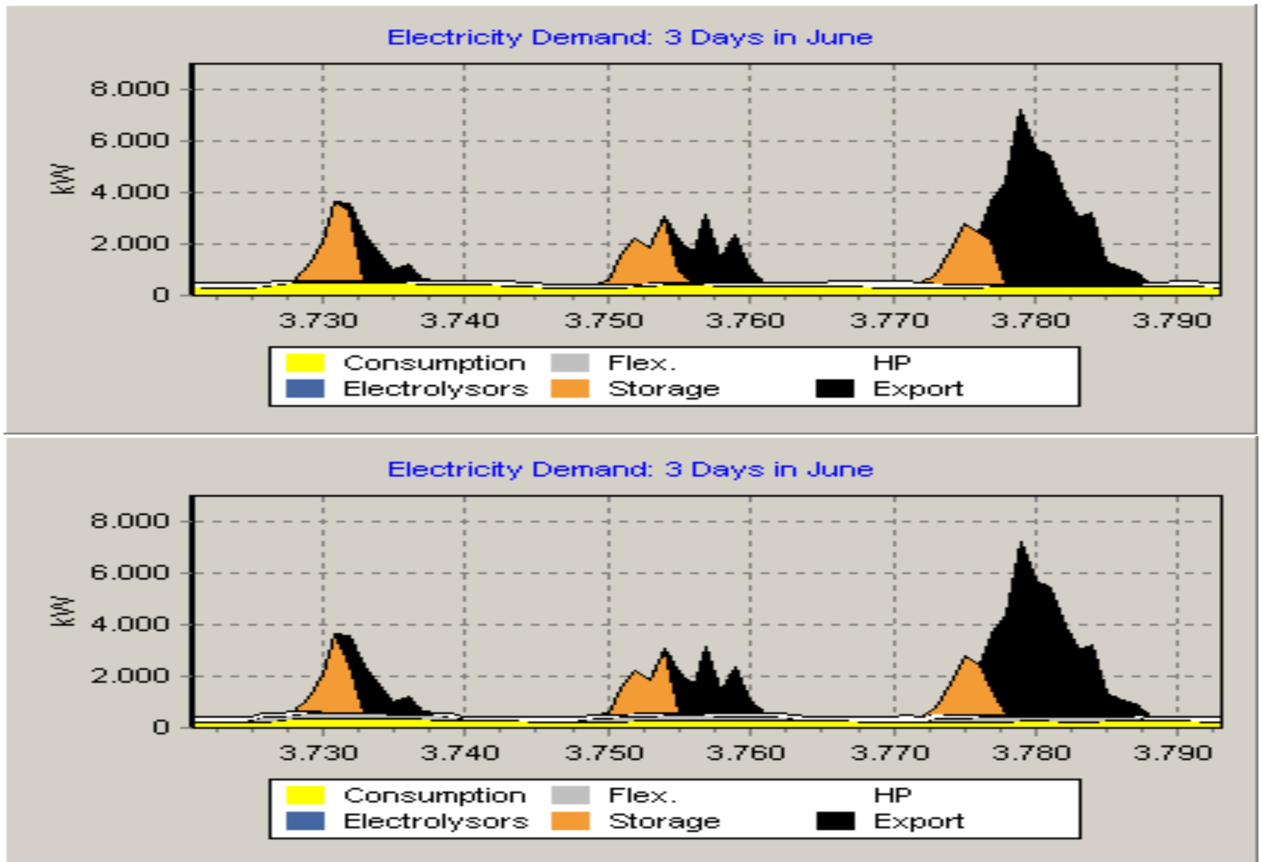


Figure VI. 9 : Example 100% PV, without DR (above) and with DR (below)