Autarkic energy communities

Possibilities in the Netherlands

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Summary

The built environment, being responsible for 40% of the CO_2-emissions in the Netherlands, can contribute significantly to the success of the energy transition. Within the built environment it seems valuable to look into households specifically, being responsible for 22% of the final energy consumption in the Netherlands. When energy networks can be implemented on a small scale, it could be possible to provide small scale residential areas with locally produced energy. Energy autarky can be interpreted as a region that 'relies on its own energy resources for generating the useful energy required to sustain the society within that region'. When this kind of autonomous energy communities can be realized, less transport of energy is needed, the load on the central grid can be reduced and the balancing of energy supply and demand can be handled locally. In this research the possibilities for autarkic energy communities in the Netherlands are analyzed.

It is assumed that 500 passive houses with modelled demand profiles are a representative to-be-built community in the Netherlands. The heat demand for this kind of houses is relatively low and the demand profiles are based on a Meteonorm year representing a typical Dutch weather pattern. Based on an overview of all the possibilities for the supply side and the storage facilities in an energy community, a final selection of technologies is made. The choice was made to include PV panels, wind turbines, solar thermal collectors, heat pumps, a large-scale underground heat storage facility, a household-scale heat storage vessel and a battery installation per household. Furthermore, a digester system in combination with gas storage and a CHP engine was included as back-up capacity during critical hours. This back-up capacity is especially needed during dunkelflaute periods during which the solar irradiation and wind speed are (almost) zero.

The We-Energy Tool is used to connect the hourly demand profiles with the supply and storage technologies. In this model the balance between the demand, supply and storage facilities is determined and the aim for autarky means a shortage should never occur. Due to seasonal and hourly variations not all generated electricity and heat can be used at the same moment. Unfortunately, it is not easy to store all the overproduction until critical hours take place, because very large storage capacities would be needed for that.

Three scenarios are defined to analyze the performance of the autarkic energy community as designed in this research. In the no-energy-waste scenario, unlimited storage capacities are assumed, such that a perfect balance between energy supply and demand can be obtained. The minimum costs and minimum land use scenarios focus on a costs and land use optimization. In these scenarios the battery capacity is limited at 24 kWh per household. The desired battery capacity in the no-energy-waste scenario increased up to 460 kWh per household, which is an unrealistic capacity to be placed on a household scale. The costs in the no-energy-waste scenario corresponded to €2144,- per household per year, while the costs in the minimum costs and minimum land use scenarios are, respectively, €2415,- and €2418,- per household per year. The land use requirements for the three scenarios correspond to respectively 2.7, 11.71 and 11.68 hectares.

This research shows autarkic energy communities are technologically feasible, but further research would be needed to improve the overview of the possibilities to realize this. The system as described in this research gives a good impressions of the needed installed capacity, costs and land use, but other demand profiles and other state-of-the-art supply and storage technologies could be introduced to improve this analysis and to make a comparison between more configurations possible.

Samenvatting

De gebouwde omgeving, verantwoordelijk voor 40% van de CO_2-emissies in Nederland, kan significant bijdragen aan een succesvolle energietransitie. In the gebouwde omgeving is 22% van het finale energiegebruik afkomstig van huishoudens. Wanneer energienetwerken op een kleine schaal gerealiseerd kunnen worden, wordt het mogelijk om huishoudens ook te voorzien met lokaal geproduceerde energie. Een energetisch autarkische regio kan worden geïnterpreteerd als een regio die 'afhankelijk is van haar eigen energiebronnen voor het genereren van de bruikbare energie die nodig is om de maatschappij in die regio te onderhouden'. Wanneer dit soort autonome energiegemeenschappen gerealiseerd kunnen worden, is minder transport van energie nodig, kan de druk op het centrale net verlaagd worden en kunnen de energievraag en -aanbod lokaal gebalanceerd worden. In dit onderzoek worden de mogelijkheden voor autarkische energiegemeenschappen in Nederland geanalyseerd.

Er is aangenomen dat 500 passieve huizen met gemodelleerde vraagpatronen een realistisch beeld vormen voor een toekomstige gemeenschap in Nederland. De warmtevraag bij dit soort huizen is relatief laag en de vraagpatronen zijn gebaseerd op een Meteonorm jaar dat typisch Nederlands weer representeert. Op basis van een overzicht van alle mogelijkheden voor de energievoorziening en opslagfaciliteiten in een energiegemeenschap, is een selectie gemaakt voor de technologiëen. Er is voor gekozen om PV panelen, wind turbines, zonnecollectoren, warmtepompen, grootschalige ondergronds warmteopslag, kleinschalige warmteopslag en batterijen mee te nemen. Bovendien is een vergistersysteem meegenomen in de analyse, in combinatie met een opslagtank voor het geproduceerde biogas en een WKK motor als back-up installatie. Deze motor kan met name in "dunkelflaute" periodes gebruikt worden met lage instraling van de zon en lage windsnelheden.

De We-Energy Tool is gebruikt om de vraagpatronen te koppelen aan de energievoorziening en opslagfaciliteiten. In dit model wordt de balans tussen vraag, aanbod en opslag bepaald en bewaakt; een energietekort mag nooit optreden in dit model. Variaties in de vraag- en aanbodpatronen, zowel binnen een dag als op seizoensschaal, maken het moeilijk om alle overproductie te bewaren totdat kritieke uren optreden. Zeer grote opslagfaciliteiten zijn hiervoor nodig.

Er zijn drie scenarios gedefinieerd om te bepalen hoe goed de autarkische energiegemeenschap presteert. In het no-energy-waste scenario zijn onbeperkte opslagcapaciteiten aangenomen, zodat de vraag en aanbod van energie perfect gebalanceerd kunnen worden. De minimale kosten en minimale landgebruik scenarios focussen op de kosten- en landoptimalisaties. In deze scenarios is een capaciteit van 24 kWh per huishouden aangenomen voor de batterij. De gewenste capaciteit in het no-energy-waste scenario is 460 kWh per huishouden. Dit is een onrealistische capaciteit per huishouden. De kosten in dit scenario bedragen €2144,- per huishouden per jaar, terwijl de kosten voor de minimale kosten en minimale landgebruik scenarios respectievelijk €2415,- en €2418,- per huishouden per jaar bedragen. De benodigde grond voor deze drie scenarios bedraagt respectievelijk 2.7, 11.71 en 11.68 hectares.

Dit onderzoek laat zien dat het realiseren van autarkische energiegemeenschappen technisch mogelijk zijn, maar dat meer onderzoek nodig is om ook mogelijkheden die in dit onderzoek buiten beschouwing gelaten worden, mee te nemen. Het systeem zoals in dit onderzoek gedefinieerd geeft een goede indicatie voor het benodigde geïnstalleerd vermogen, de kosten en de benodigde grond, maar andere vraagpatronen en nieuwe of verbeterde technologiëen aan de aanbod- en opslagzijde kunnen geïntroduceerd worden om de analyse te verbeteren and om een vergelijking tussen meer configuraties mogelijk te maken.

Abbreviations

A	Surface area in squared meter
$ATES$	Aquifer thermal energy storage
$BTES$	Borehole thermal energy storage
C_p	Power coefficient
CHP	Combined heat and power
COP	Coefficient of performance
DER	Distributed energy resource
DG	Distributed generation
EMS	Energy management system
$HWTES$	Hot-water thermal energy storage
I	Irradiation in Wh per squared meter
IC	Installed capacity
P	Generated power in Watt
P_{PV}	Production by PV panels in kWh
PV	Photovoltaics
SC	Storage capacity
$STES$	Seasonal thermal energy storage
TES	Thermal Energy Storage
u	Wind speed in meters per second
$UTES$	Underground thermal energy storage
$WGPS$	Water-gravel pit storage
η	Efficiency
ρ	Density in kg per liter

1 Introduction

An energy transition is taking place. This transition is needed to achieve the climate goals that are set to prevent, as much as possible, the negative consequences of climate change. Part of this transition is already reflected in changes in the supply side of the energy market. However, the introduction of renewable energy technologies can affect the energy security, for example in the built environment, a sector responsible for 40% of the national emissions in the Netherlands. On the other hand renewable energy technologies also create opportunities. When local energy resources can be used in an efficient way, sustainable energy communities can arise. In this research the focus will be on the possibilities in the Netherlands to create autarkic energy communities in which households can provide their energy demand completely by local energy resources.

1.1 The need for an energy transition

By signing the Paris Agreement in 2015, 196 countries agreed to aim at limiting global warming to 1.5 to 2 degrees Celsius with respect to pre-industrial levels (UNFCCC, 2018). The Netherlands particularly set a goal for 2030 to reduce greenhouse gas emissions with 49 per cent or even 55 per cent with respect to the level in 1990 (Sociaal-Economische Raad, 2018). To realize this goal the use of fossil fuels has to decline, because burning these fuels cause greenhouse gas emissions, which contributes to the enhanced greenhouse effect. Another incentive to replace fossil fuels is that fossil resources are finite stocks (Okkerse and Van Bekkum, 1999). Both incentives force countries to replace fossil fuel energy sources as much as possible by renewable energy sources. This requires a shift, an energy transition, to an energy system based on energy production by renewable energy technologies like wind turbines and solar PV panels. The most significant contributions of renewable energy will probably come from these two technologies, because wind and solar irradiation are unlimited energy sources (Steinke et al., 2013). These technologies generally produce electricity, which means electricity will be an important energy carrier in the future, so significant emission reductions can be achieved by electrification of the energy sector (F. J. Rooijers and Leguijt, 2010; Sociaal-Economische Raad, 2013; Sociaal-Economische Raad, 2018).

1.2 The transition in the built environment

The built environment, being responsible for 40% of the CO_2-emissions in the Netherlands, can contribute significantly to the success of the energy transition and electrification is often mentioned as a possible solution (Van 't Veen and Keizers, 2019). Within the built environment it seems valuable to look into households specifically, being responsible for 22% of the final energy consumption in the Netherlands (ECN, 2017). While the demand for natural gas in households is expected to decrease, the electricity demand is expected to increase significantly due to the introduction of heat pumps and electric vehicles (Koirala et al., 2016; Sociaal-Economische Raad, 2018). Without any action this increase in electricity demand might cause grid congestion. Furthermore, when using solar PV and wind turbines, adjustable power generation and/or storage are needed on days without wind and solar irradiation, the Dunkelflaute (Afman and F. Rooijers, 2017). This flexibility is needed within days, but also on a seasonal time scale. For example, the supply of PV panels and the demand of heat pumps are out of phase; PV panels produce more electricity in summer than in winter, while the heat demand of households is higher in winter (Graaf de, 2018). The energy transition and the challenges that arise with it, like network congestion and the imbalance between supply and demand, require a transition in the energy system of the built environment as well.

1.3 The trias energetica

The Netherlands tries to achieve the energy transition along the lines of the trias energetica. First, the focus will be on reducing energy consumption, then on the production of renewable energy where after the focus will be on producing non-renewable energy in the most sustainable and efficient way (Sociaal-Economische Raad, 2013). Energy consumption by households can be reduced by retrofitting of existing houses with better insulation and by using more energy efficient technologies and appliances. The production of renewable energy facilitates the second step. However, due to its intermittent behavior, balancing the power in the electricity grid might become difficult and network congestion can occur (Soshinskaya et al., 2014). In that case non-renewable adjustable energy sources might be needed to stabilize the electricity production.

1.4 Introduction of microgrids

Renewable energy sources like wind and solar irradiation appear everywhere; they have a distributed nature. When these distributed energy resources (DERs) become the major energy supply, microgrids can play an important role in grid parity on a local scale. A microgrid can be defined as ‘a small scale, discrete electricity system consisting of interconnected renewable and traditional energy sources and storage with energy management systems in smart buildings’ (Soshinskaya et al., 2014). Similar small scale systems can be created for other purposes than electricity, for example heat networks for the transport of heat. Next to the distributed nature of renewable energy sources, there are other reasons in favor of decentralization of the energy system (M. O. Müller et al., 2011; Schmidt et al., 2012). First of all, transport losses can be minimized, because the locations of energy supply and demand are close to each other. Secondly, local activity in the energy sector is stimulated and local innovations can be implemented. This is a boost for the cohesion in the community as well as for economic activities in the region. Furthermore, consuming exclusively locally produced energy could even create a kind of insurance against energy prices that might rise in the future. When local microgrids are developed, this can also reduce the load on the central grid and the balancing can be handled locally. Then a local problem does not affect a larger area and the best solution can be determined for that specific region.

Microgrids can also play a role in the energy transition in the built environment in the Netherlands, especially when natural gas is going to be replaced by DERs. In the Netherlands a goal is set to realize a 75 % share of new-built houses not using natural gas between the 1st of July 2018 and the end of 2021 (Sociaal-Economische Raad, 2018). Natural gas is mainly used for heating purposes in the built environment, both for space heating as for the provision of hot water, together responsible for 70% of the primary household energy consumption (Faber et al., 2009). Possible alternatives for natural gas are electric heat pumps, green gas and heat networks (ECN, 2017). Making a choice between these options is not straightforward and the different possibilities for DERs in an energy community should be considered to find a sufficient and feasible mix of energy sources. Taking into account the spatial differences between communities, local initiatives can contribute to the energy transition towards a low-carbon energy system and also to consumer engagement and providing flexibility in the energy market (Koirala et al., 2016).

1.5 Aiming for autarky

When energy networks can be implemented on a small scale, it could be possible to provide small scale residential areas with locally produced energy. When these areas do not require any connection with the rest of the world, an autarkic energy community can be developed. Here energy autarky can be interpreted as a region that 'relies on its own energy resources for generating the useful energy required to sustain the society within that region' (M. O. Müller et al., 2011). Schmidt et al. (2012) refer to two versions of autarky, absolute and relative autarky. Relative autarky allows, for example, the balancing of energy export with energy import. For absolute autarky this balancing is not allowed and all the energy has to be produced within the system boundaries of the community. This example shows autarky is a definition issue. For this research the absolute definition is used, which means no balancing is allowed with parts outside the energy community.

When this kind of autonomous energy communities can be realized, less transport of energy is needed, the load on the central grid can be reduced and the balancing of energy supply and demand can be handled locally. Figure 1 shows a schematic of a theoretical example of an energy community (Ecker et al., 2017). In this example PV modules, solar thermal modules and CHP units are used as energy sources. Furthermore, batteries and energy managers are included to balance demand and supply. Ecker et al. (2017) mention the system presented in Figure 1 is not autarkic, because only 80 % of the energy demand is met by internal resources. The figure shows a good example of the design for an energy community, but autarky is not realized.

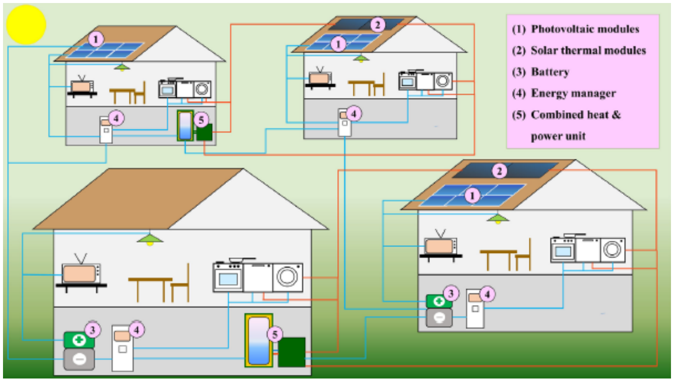


Figure 1: *Example of an energy community within a neighborhood (Ecker et al., 2017)*

Sometimes local energy initiatives are presented as being fully autonomous, implying autarky is realized. However, these initiatives often occur in very specific circumstances and in some way still depend on the outside world. For example, in the 'fully off-grid fantasy'-scenario as described in the SIDE report, the off-grid community still depends on biomass imports for heating purposes (Graaf de, 2018). The community is indeed off-grid, but not autarkic in the way aimed for in this research. In this research only indoor energy consumption will be considered, while excluding transport and the energy needed to produce food and other products being consumed within the community.

1.6 Problem definition

Although Ecker et al. do focus on autarky in their research, their system design as shown in Figure 1 does not realizes autarky. Furthermore, the off-grid scenario in the SIDE report does focus on going off-grid, but again autarky is not realized. It seems that achieving autarky is not easily managed and faces some challenges. In general three challenges arise with the desired energy transition, being the implementation of larger and better storage, network adjustments and electrification (Roelofsen and Pee de, 2015). These challenges also arise in the built environment in the Netherlands. When local energy systems are developed, these challenges should be dealt with on this local scale as well. However, every region or neighbourhood has its own characteristics, making every community a special case. An argument against autarkic energy communities is that the variety between regions cannot be optimally used when regions are going to be autarkic, because possible benefits of each region specializing on a certain part of the energy system and benefits of energy trading are lost when only internal resources within the community can be used (Schmidt et al., 2012). It would, however, be interesting to determine whether autarkic energy communities are a realistic option. The problem is that it is not clear what would be needed to realize an autarkic energy community.

When an energy system is dependent on intermittent energy sources, flexibility sources are needed to balance the increasing variability of the energy production (Koirala et al., 2016). Here flexibility can be considered the capacity of an energy system to use flexible measures to balance supply and demand of energy within the boundaries of the distribution and transmission system in place (Hers et al., 2016). Developments in demand side management and storage facilities, both on a daily basis as a seasonal basis, are desired and can contribute to this flexibility capacity (Sociaal-Economische Raad, 2013). It is clear that not energy generation, but more the balancing of supply and demand can be a challenge for an autarkic energy community.

1.7 Research aim

Based on the problem definition the aim of this research will be to determine to what is needed to realize an autarkic energy community within the built environment in the Netherlands. This boils down to looking for possibilities to overcome the flexibility and energy security challenges. The focus will be on the first two steps of the trias energetica; reducing the energy demand and the use of renewable energy sources. Fossil fuels will not be considered, because these fuels produce greenhouse gas emissions when being burned and are normally not available on a local scale within the built environment. For this research specifically the required flexibility as well as the possibilities to use DERs in an new-built residential area will be taken into account. In this residential area the energy demand for heating purposes, appliances and lighting will be taken into account.

1.8 Research questions

The research question related to the aim of this research is defined as follows:
"What is needed to realize an autarkic energy community in a residential area in the Netherlands?"

This question will be answered by considering the following sub-questions:

1. What are realistic options for energy generation and storage within an autarkic energy community?
2. What kind of particular residential area will be considered?
   (a) What kind of houses should be considered?
   (b) What will be an appropriate size for the energy community taking into account the generation and storage technologies considered for this research?
3. What are possible demand profiles for this energy community?
4. What scenarios can be used to match the demand profiles with the considered generation and storage technologies?
   (a) Which technology and what size is most appropriate for energy storage?
   (b) What role can demand side management play?
   (c) What are costs and land use indications for the considered scenarios?

1.9 Layout of this report

Based on the research questions the following section will start with an overview of all the possibilities within an autarkic energy community. In that section the energy demand, supply and storage will be discussed. In Chapter 3 the scope and system boundaries will be discussed. In that section the technologies that will be taken into account are discussed in more detail. When all the relevant aspects of the autarkic energy community have been described, the methodology will follow in Chapter 4. The results are presented in Chapter 5, followed by the discussion and conclusion in Chapters 6 and 7.

2 Possibilities within an autarkic energy community

The design of an autarkic energy community starts with considering all the possibilities for such a community. In general an autarkic energy community can be divided into three key elements:

- the demand side;
- the supply side and
- storage facilities.

Figure 2 shows a schematic representation of these elements within the energy community, including examples of parts of the elements. The demand side consists of the households and specifically all the appliances in these households that require energy when being used. The supply side is formed by the energy generation appliances, like wind turbines and PV panels. The storage facilities represent the third key element within an energy community. Within an energy community these three elements are connected by one or more energy grids, facilitating the transport of energy between these elements. Furthermore, with the help of an energy management system (EMS) these elements can exchange information, making it possible to balance supply and demand with the help of storage.

In this section some existing case studies are presented to determine what is going on in this research field. Then the demand side applications are described, subsequently the supply side is discussed and the storage facilities make the picture complete. At the end of this section the technologies included in the rest of this research are selected.

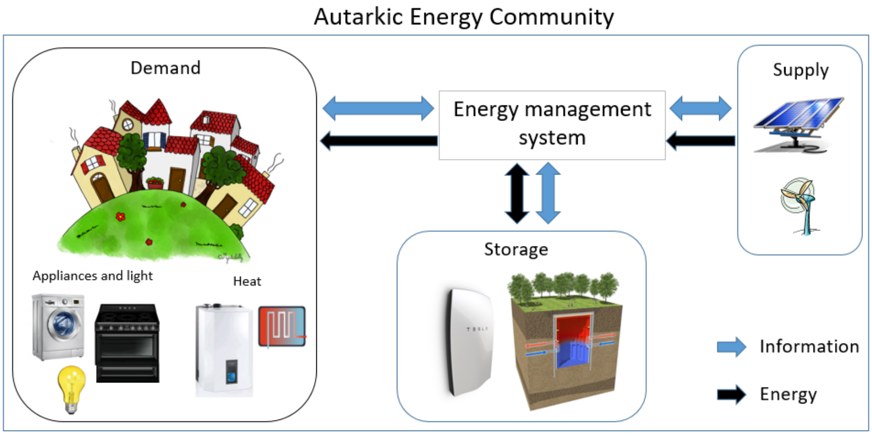


Figure 2: *Schematic representation of an autarkic energy community*

2.1 Case studies

Multiple reports about different case studies are available in which the performance of distributed generation (DG) units, energy storage facilities or combinations of both are described and discussed. Especially the combination of different energy supply sources and storage facilities is interesting, because there is not one single solution that enables the existence of an autarkic energy community. For example, the combination of PV panels and CHP engines is interesting, because these technologies together can realize a stable electricity production level during the year (Faber et al., 2009). Furthermore, the electricity supply can go hand in hand with heat supply when CHP engines are used or the electricity can be used to produce heat with the introduction of heat pumps. The case studies presented in this section show what kind of technologies are already used in local energy systems.

2.1.1 SIDE Report

In the report about Smart Integrated Decentralised Energy (SIDE) systems, multiple projects focused on decentral energy generation are listed (Graaf de, 2018). One of them is the full off-grid fantasy of Schoonschip. In this scenario a wind turbine, heat pumps, solar PV panels, micro-CHP, a fuel cell, batteries, an electrolyser, a district heating network, electric vehicles, a hydrogen tank and an energy trading system are included to realize a 100% self-consumption rate (Graaf de, 2018). This solution is quite expensive and has a payback period of 29.1 years. Furthermore, biomass in the form of woodchips is being used as energy input for the micro-CHP system. Therefore the system is not an autarkic energy system; the woodchips need to come from outside. This case study can be used as reference for the needed installed capacity of multiple technologies.

2.1.2 Smart homes Altdorf

Another interesting case study is in Altdorf, Germany. In this study Huber et al. show a supply system with solar PV, CHP, an electric heater and a battery and heat storage as storage facilities, see Figure 3 (Huber et al., 2013). Huber et al. (2013) explain how scaling up from a house to a larger community can

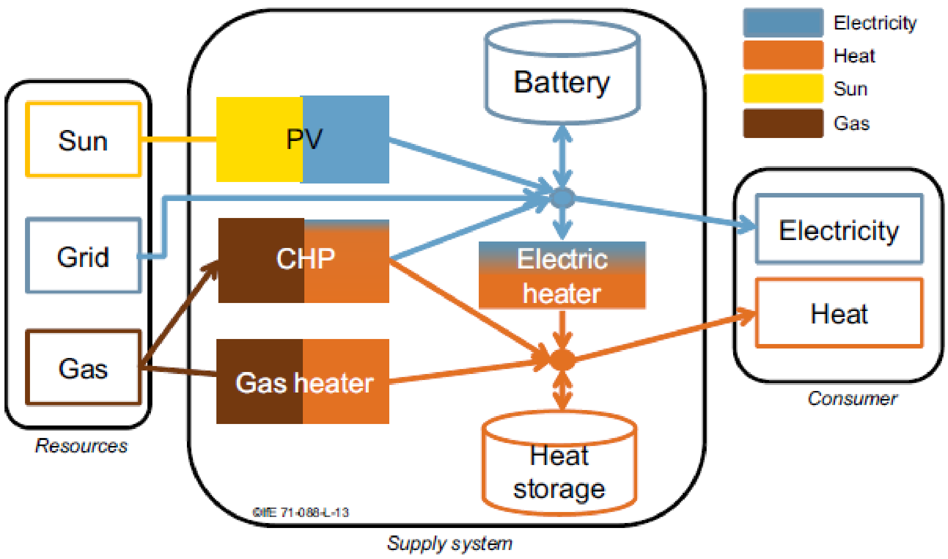


Figure 3: *Example of an energy system within a smart home (Huber et al., 2013)*

improve the self-sufficiency possibilities within this community. This is especially due to the average load pattern which in a community, on average, has a much lower peak demand than for a single household, see Figure 4 (Huber et al., 2013). Figure 4 represents a randomly chosen week by Huber et al. (2013), but the averaging effect depends on the demand profiles of these households and therefore depends on the weather conditions as well. Huber et al. (2013) also present the average peak load of the microgrid as a function of the number of houses in this microgrid as presented in Figure 5. Figure 4 clearly shows that the electric load is significantly lower for the average profile than for the individual load profiles. Figure 5 shows that the average peak load reduces significantly up to around ten homes being connected to the microgrid. From that point on, the average peak load does not decrease significantly with adding more homes to the microgrid. For the autarkic energy community it is also important that the peak load is not too high, because it can cause congestion in the electricity cables. The case study in Altdorf shows it is desired to connect multiple houses to one grid instead of focusing on realizing one single autarkic energy house.

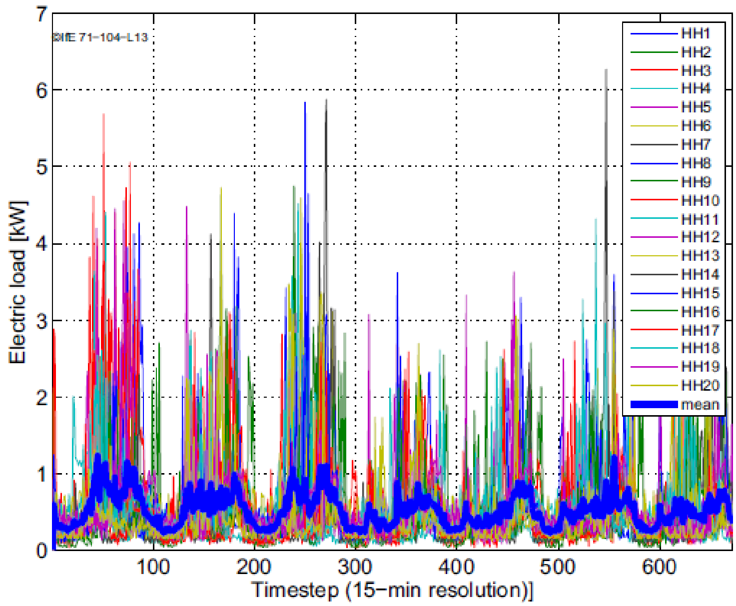


Figure 4: *The electric load profiles of 20 single homes in Altdorf (Germany) and their average for a random week (Huber et al., 2013)*

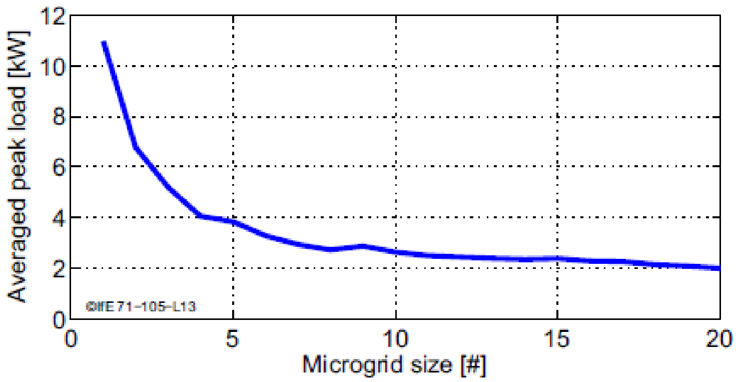


Figure 5: *The average peak load as a function of the network size (Huber et al., 2013)*

2.1.3 Hoog Dalem

The last interesting case study that will be discussed, is the Hoog Dalem energy project. In this project PV panels, batteries, heat pumps and an EMS are introduced among 42 households in the Hoog Dalem village (Stedin, 2017). Not all households have PV panels and/or a battery, but every household in this project has a heat pump and an EMS. Some important conclusions of this project are:

- the orientation of solar panels on the roofs has almost no influence on the peak load for the electricity grid;
- the heat pumps, facilitating the space heating demand for these houses, have a simultaneity factor that is almost never higher than 0.8 at low temperatures. This means the peak load for the electricity grid can be estimated based on this factor;
- the batteries used in this project had an effective capacity of 1.61 kWh, which turned out to be too small to have a relevant impact on the peak load.

The project is interesting for this research, because it shows a significant storage capacity is needed to realize peak shaving, which is desirable in an autarkic energy community.

The three case studies presented all give an example of a community energy system, although none of them being autarkic. The examples make clear that up-scaling, indeed, seems to have advantages when it comes to balancing energy demand and supply. However, the examples also show how difficult it might be to actually realize an autarkic energy system. With these examples in mind, the possibilities on the demand side, on the supply side and for storage facilities can be analyzed.

2.2 Demand side applications

It is important to determine what the energy demand of households in the energy community will be, because the goal is to meet this demand with decentral renewable energy sources. The following demand categories can be defined:

- space heating;
- hot tap water;
- electric appliances (like washing machine, coffee machine, lighting etc.);
- cooking and
- transport.

Different applications are available to provide the energy for all these kinds of demands. Table 1 gives an overview of the possible applications. As discussed in Chapter 1, the use of DERs makes electrification in the built environment desirable. Although other innovative ways of cooking might be possible, this means an assumption is made that cooking will be driven by electricity. Transport is not considered in this research. In total three demand categories are left; electricity, space heating and hot tap water demand. In Chapter 3 the particular demand profiles considered for the autarkic energy community are presented.

2.3 Energy supply

There is a lot of literature available describing the energy supply possibilities for decentral energy systems. For example both Koirala et al. (2016) and Soshinskaya et al. (2014) provide a list of DG units. Furthermore, Koirala et al. (2016) mention that locally integrated energy systems can be realized when rooftop PV, small wind turbines, district heating, and community storage or biogas and

Table 1: *Overview of household applications in an autarkic energy community*

Space heating	**Hot water**	**Cooking**
Boiler	Boiler	Stove
Heat pump	Heat pump + tank	Electric cooker
Fuel cell	Fuel cell + tank	Induction cooker
	Electric boiler	

hydrogen production systems are combined. For the purpose of this research, only renewable energy sources originating from within the community will be considered, therefore fossil fuel engines are not included and neither is hydro power, because of the very limited possibilities for this technology in the Netherlands. The following DG units remain:

- (Micro-)CHP engine;
- Biomass digester;
- Wind turbines;
- Solar PV panels;
- Solar thermal panels.

Which DG units should be included or left out for this research depends on the availability of DERs, but also on the infrastructure that is needed to transport the produced heat or electricity. For example, when making use of a relatively large heat resource on a community level, a heat network is needed to transport this heat to all the households. On the other hand, on a household scale heat pumps could be used, possibly making heat networks on a community level unnecessary. The choice for solutions on a household scale or a community scale depends on technological, but also on financial and social aspects, e.g. what are the corresponding costs of these systems and what does the community prefer? In this research the focus will be on the technological possibilities and restrictions.

2.3.1 Heat supply

The energy supply can be divided into two main categories; heat supply and electricity supply. The heat demand is significantly larger than the electricity demand in households. In 2016, 94% of the heat demand was met by fossil fuels, predominantly natural gas (Ministerie van EZK and ECN, 2017). In general there are three options to replace natural gas as energy source in the built environment: houses are connected to heat networks, houses are heated by electric heat pumps or the natural gas is replaced by green gas (ECN, 2017). A combination of these solutions is also possible when green gas is used for peak demand, while the rest of the demand is provided by electric heat pumps (ECN, 2017).

Heat networks can be part of the solution for the transition in the built environment. A small heat network might be an option for an autarkic energy community, however the energy source of the heat provided by these networks is often not a renewable source (ECN, 2017). For an autarkic energy community as aimed for in this research a heat network can only be used when the heat source is a renewable energy source and the heat is produced within the community to guarantee autarky. Solar thermal panels are an option for this.

Heat pumps are increasingly used in the built environment. These pumps are subsidized by the Dutch government, making it more attractive for households to buy one (Ministerie van EZK and ECN, 2017). Heat pumps can provide both heating and cooling demand, so the presence of a heat pump can make the need for a separate cooling installation unnecessary (Faber et al., 2009). Next to heat pumps, conventional boilers can also supply the heat needed for space heating and hot tap water in a household.

These generally need gas as energy input.

Whether gas boilers are an option, depends on the possibility to generate enough green gas within the community. However, when gas can be produced, it can also be used as input for a CHP engine as in the Waterschoon project (Graaf and Hell, 2014). In this project municipal waste is used as energy source by using a digester. The energy and material flows of this digester installation are shown in Figure 6. A digester system as in the Waterschoon project could fit perfectly in an autarkic energy system and it even brings the autarky to a next level, because it also enables the community to process their own waste, without interference from the outside world. Normally black waste water is mixed with rain and groundwater, reducing the energy content per volumetric unit of this water. Handling waste water locally can prevent this mixing and the chemical energy in black and grey water can partly be retrieved in the form of biogas. Combining this with the use of organic waste like fruit and vegetables for anaerobic digesting, the biogas production in the community can even double (Graaf and Hell, 2014).

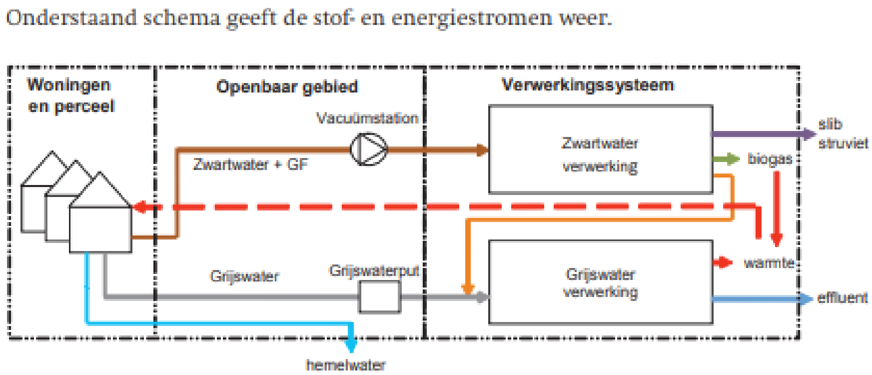


Figure 6: *Energy and material flows in the Waterschoon project (Graaf and Hell, 2014)*

The possibilities for heat production within the community are solar thermal panels, air-source and ground-source heat pumps and CHP engines running on locally produced green gas. Depending on the scale of these systems, a heat network can be implemented or the houses can have separate installations.

2.3.2 Electricity supply

For the electricity supply in the community PV panels, wind turbines and CHP engines can be used. Nowadays PV panels, being subsidized by the Dutch government, are an attractive asset to invest in for households (Ministerie van EZK and ECN, 2017). For wind turbines in the energy community, the turbines from E.A.Z. Wind are an option. These wind turbines are relatively small with a capacity of 15 kW, they are partly made of wood and have colours similar to the surroundings (E.A.Z. Wind, 2019b). This will make this kind of wind turbines more accepted to be placed within the community than much bigger wind turbines. In days when there is little solar irradiation and almost no wind, CHP engines can be used to provide the electricity needed to meet the demand.

2.4 Energy storage

Since DERs are becoming more prevalent in the energy landscape, there is a rising demand for flexibility like storage or other techniques to balance the increasing variability of energy production due to the intermittent behavior of these DERs (Koirala et al., 2016). Energy storage can be used both on a daily basis as well as on a seasonal time scale to balance energy demand and energy supply. During the day the energy supply is not the same at all times and production does not always take place at the same time as consumption is desired. This also holds for summer and winter; during the summer PV panels produce approximately six times more electricity than during winter, while the energy demand is higher in winter than in summer due to a higher heat demand (Faber et al., 2009). The daily misalignment between electricity generation by PV panels and the demand profile is shown in Figure 7 (Khalilpour and Vassallo, 2016). The figure shows that even for large PV systems the electricity demand cannot be met with only electricity generation by PV panels at each moment during the day.

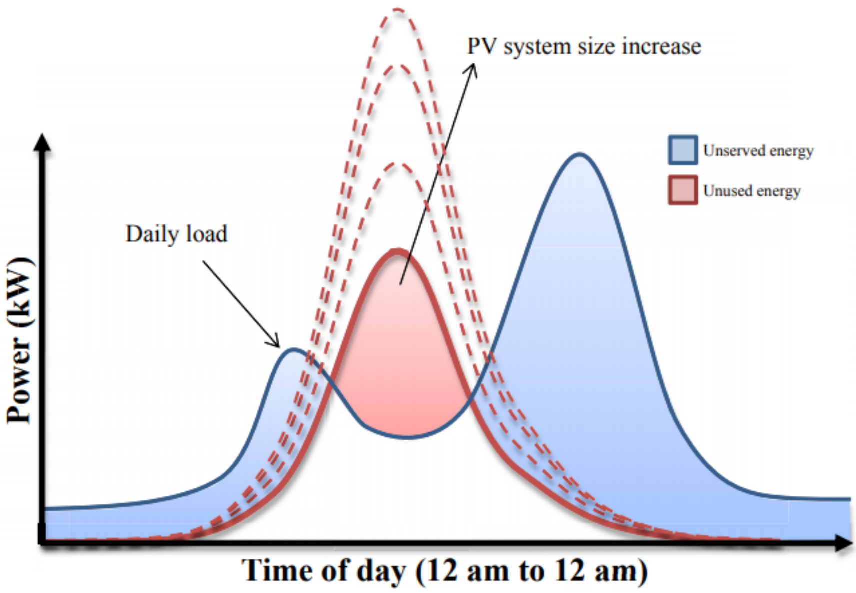


Figure 7: *The general mismatch between electricity demand and PV electricity generation, even for large PV systems (Khalilpour and Vassallo, 2016)*

To improve the match between energy supply and demand, energy storage can be used. Storage makes it possible to postpone the consumption of, for example, electricity produced by PV panels to a later moment. Next to storage facilities, curtailment methods and demand side management can contribute to facilitating a higher PV penetration, which can result in higher levels of electricity autonomy (Barbour et al., 2018).

Hull and Jones (2016) mention some possibilities for energy storage. The ones relevant for an autarkic energy community out of this list, together with home-scale and community batteries, result in the following list:

- Home-scale batteries;
- Community batteries;

- Cryogenic energy storage;
- Thermal energy storage;
- Hydrogen energy storage;
- Flywheels

Out of this list, only batteries store energy in the form of electrons. Most of the other technologies store the energy in other materials, like liquefied air or liquid nitrogen in case of cryogenic energy storage and in the form of hydrogen or hot water. Flywheels store kinetic energy in the form of rotational energy. In the energy community the energy demand consists of electricity demand and heat demand, therefore electricity storage and thermal energy storage will now be discussed in more detail.

2.4.1 Electricity storage

The home-scale and community batteries are the most straightforward options to store electricity. Home scale and community batteries might appear in different forms based on different technologies. The stationary lithium batteries, nickel-cadmium, lead-acid and NaS-batteries batteries as well as flywheels seem to be the most attractive techniques to store electricity (Faber et al., 2009; Koirala et al., 2016). The batteries in electric vehicles could also be used as a flexible storage facility (Faber et al., 2009). For (very) short time scales (super)capacitors can be an appropriate solution, but this type of energy storage is not a suitable option for longer time scales (Jenkins et al., 2008). Thermochemical batteries are also a possibility to provide flexibility in the energy supply for households. This kind of storage is still in a developing stage (TNO, 2018). An example of such an innovative battery is the Greenrock battery (Indesol, 2018). This battery is based on salt water.

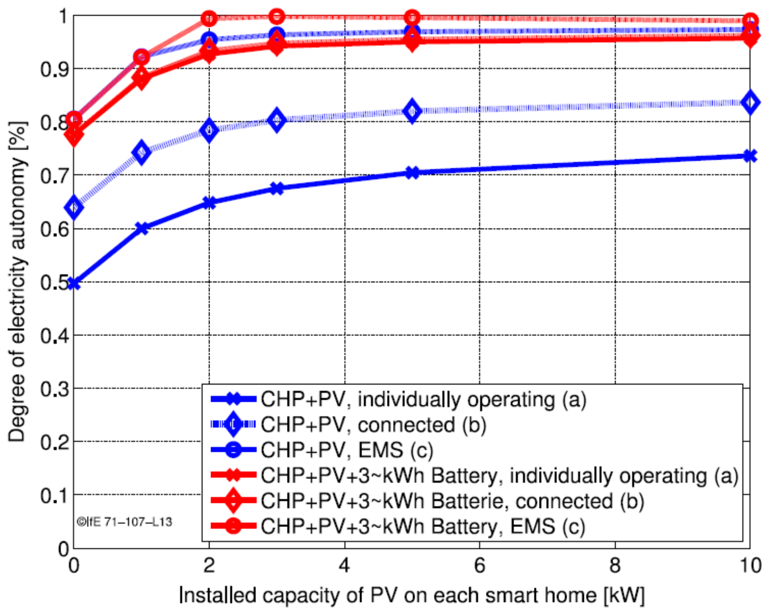


Figure 8: *Simulated degree of autonomy in three different scenarios for a community located in Altdorf (Germany); operating individually, having a connected operation system or even connected and management by an EMS (Huber et al., 2013)*

The relevance of energy storage in an autarkic energy community is clearly visible in Figure 8 (Huber et al., 2013). The figure shows that the degree of electricity autonomy of households and communities increases significantly when batteries are included in the system. Only for the system with an EMS the influence of including a battery is relatively small. The different modes of operation are represented in Figure 9.

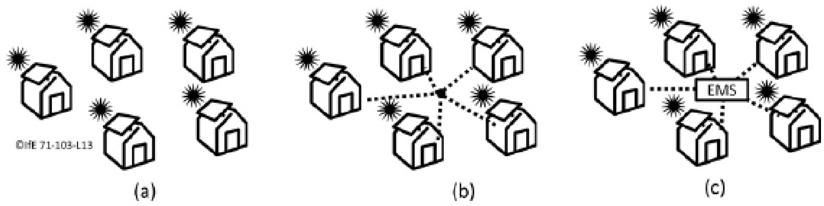


Figure 9: *Modes of operation: a) individually optimized smart homes, b) again individually optimized smart homes, but now the houses are connected, reducing consumption from the grid and c) an EMS coordinates the energy resource distribution (Huber et al., 2013)*

This comparison between the three modes of operation implies that up-scaling the community size increases the level of autonomy that can be realized. Faber et al. (2009) looked into the possible advantages of up-scaling an energy system from a system with a single household to a larger system with multiple households connected. They found out that with a high penetration of PV panels and electric vehicles, the battery size needed to realize the peak shift of energy supply increases up to 5 kWh. However, when storage is facilitated on a community level, for example for 1000 households, an equivalent of 2.5 kWh per household would be sufficient (Faber et al., 2009). This difference shows the advantage of up-scaling battery capacity. Kuhn et al. (2016a) also mention that higher levels of autonomy can be reached in a more cost-effective way, because less capacity per household is needed when homes are connected to each other. For a single household, a battery of 5 kWh can increase the degree of autonomy for a house from 42% to 65% as represented in Figure 10 (Kuhn et al., 2016).

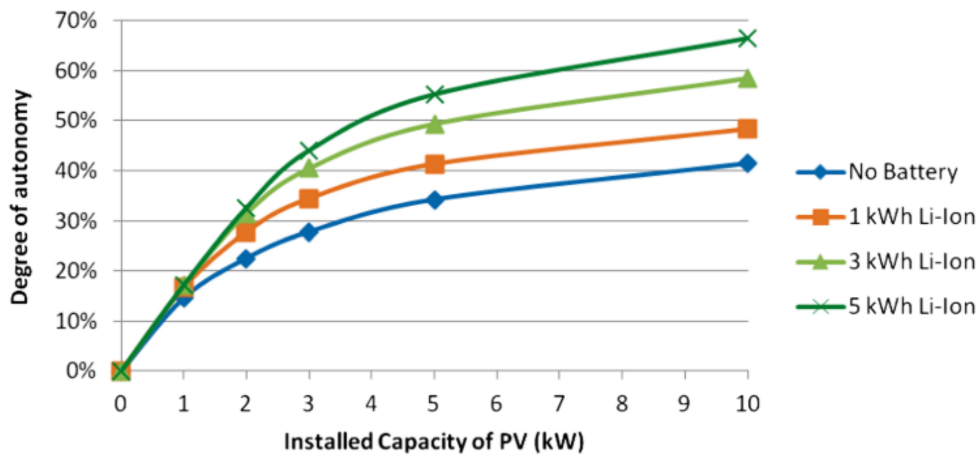
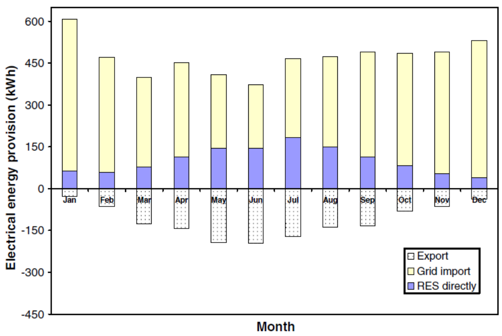
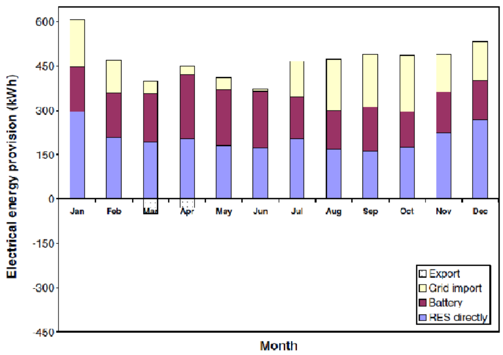


Figure 10: *Degree of autonomy for a single home with installed PV panels and batteries of different sized, located in Bavaria (Germany) (Kuhn et al., 2016)*

Comparing Figure 8 with Figure 10, it becomes clear that including CHP next to PV panels makes it possible to realize higher levels of electricity autonomy. Furthermore, based on both figures it is clear that very high levels of autonomy cannot be realized for single homes without the use of (very) large battery capacities. This finding aligns with the results of Broekema (2016). She found out a very large amount of batteries is needed to realize sufficient seasonal storage. It makes clear batteries are not suited for seasonal storage (Broekema, 2016). The effect of using storage facilities in combination with DG units is also discussed by Jenkins et al. (2008), who visualized the effect with Figures 11a and 11b. These figures show that electricity export can almost completely be prevented when storage is used in combination with PV panels and wind turbines. However, electricity import is still needed and for this study the heat demand is not even taken into account.



(a) *Electricity provision in Edinburgh with 2.5 kW PV for a dwelling without storage.*



(b) *Electricity provision in Edinburgh with 2.5 kW PV, 1.5 kW (low wind site) turbine and 1000 Ah battery storage at the dwelling location.*

Figure 11: *Visualizing the influence of storage facilities on the energy self-sufficiency of households (Jenkins et al., 2008)*

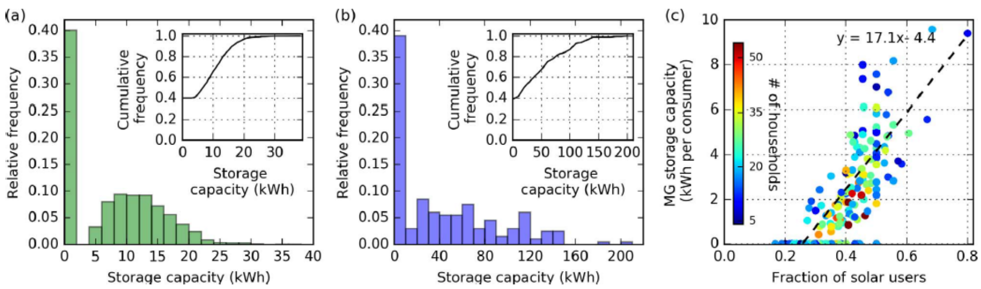


Figure 12: *Distributions for optimum capacity of batteries for (a) Individual households with PV and (b) Communities. The plot at (c) shows the optimum battery capacity against the fraction of households with PV. (Barbour et al., 2018)*

The optimum storage size is determined by Barbour et al. (2018) and the result is shown in Figure 12. The optimum daily battery capacity for households lies within the range of 5-22 kWh, with an average at 12 kWh. It should be mentioned that this is based on average solar PV production. The optimum, therefore, will be different for each season. Barbour et al. (2018) also show that community energy storage has multiple advantages with respect to household storage, including a reduction in the total optimum capacity that is needed, a reduction in the excess of PV generation that needs to be exported to the main grid and overall an increase in the self-sufficiency of the community (Barbour et al., 2018).

Whether each individual household should have a battery or a larger community battery should be shared, depends on the different advantages and disadvantages of both options. When batteries are used on a household level, these batteries can still be used to balance supply and demand on a community level when the batteries are connected to each other by a grid. The best solution will be case specific and also depends on the preferences of the people living in the community. Anyhow, it seems to be attractive to introduce a microgrid that connects the households within the energy community. In that way less storage capacity will be needed and it can bring economic advantages as well (S. C. Müller and Welpe, 2018).

2.4.2 Thermal energy storage

For seasonal storage electricity seems not to be the optimal energy carrier. Since the energy demand consists of electricity and heat demand, the other option at hand would be heat storage, or thermal energy storage. An example of thermal energy storage facilities are buffer vessels that can be filled with water (Faber et al., 2009). When these vessels are well insulated such that no significant heat losses occur, the water can be heated when there is an excess of energy production and the stored heat can be used in times of a shortage of energy. Conversion would be needed, for example, when there is an oversupply of electricity, while the desired energy storage would be in the form of heat.

There are four well-known kinds of thermal energy storage (TES): hot-water thermal energy storage (HWTES), borehole thermal energy storage (BTES), aquifer thermal energy storage (ATES) and water-gravel pit storage (WGPS) (Gao et al., 2015; Hesaraki et al., 2015). Table 2 shows the characteristics of these TES systems (Hesaraki et al., 2015). Borehole heat storage is most popular, because it does not affect the water resources (Gao et al., 2015). There are already some BTES projects developed on a community level (Lanahan and Tabares-Velasco, 2017). All these TES technologies use the subsurface as a thermal battery and, not surprisingly, these forms of TES are referred to as underground thermal energy storage (UTES) (Rapantova et al., 2016).

Table 2: *Overview of some seasonal storage techniques (Hesaraki et al., 2015)*

	HWTES	**WGPS, Artificial aquifer**	**BTES**	**ATES**
Storage medium	Water	Water-gravel	Soil/rock	Water-sand/gravel
Maximum storage capacity ($\mathbf{kWh \times m^{-3}}$)	60-80	30-50	15-30	30-40

When using an UTES system, attention should be given to the thermal stratification in these systems. In general, for domestic hot water systems, thermal stratification is important and ensures that the hot water remains at the top of the storage tank (Dickinson et al., 2013). The storage efficiency can increase with 15-20% for a stratified storage tank compared to a mixed tank (Hesaraki et al., 2015). The volume of stratification, the configuration of the tank, the size, the location and design of the inlets and outlets, the flow rates of the entering and exiting streams and the duration of the charging, storing and discharging periods determine the degree of stratification when using TES. The main factors contributing to destratification are heat losses to the surroundings, heat conduction between hot and cold regions of the stored fluid, conduction along the tank wall and mixing during charging and discharging periods (Dickinson et al., 2013).

The Ecovat storage system is an example of a state-of-the-art UTES system. It can be placed in the category of Hot Water Thermal Energy Storage. In a report of Ecovat is also mentioned that stratification is important for the performance and efficiency of the thermal storage facility (Ecovat Renewable Energie Technologies, 2014). The manufacturer of this system looks into seasonal energy storage, because this is the missing link to balance supply and demand of energy. They look into water as storage medium, because water has a high volumetric density and a high specific heat, making it one of the best media for energy storage (Ecovat Renewable Energie Technologies, 2014). The Ecovat thermal storage system is modular, consisting of multiple layers placed above each other. This modularity makes it possible to adjust the size of the system. The efficiency of this system lies between 80 and 90%. Schootstra (2018) mentions that some calculations were done for scenarios including solutions like the Ecovat system. These calculations show that thermal storage can realize reductions in both the peak demand and the amount of base load plants needed. Furthermore, lower costs and a more balanced system can be realized compared to all-electric scenarios (Schootstra, 2018). Solutions like this seem to be a promising option for an autarkic energy community.

Other ways to improve flexibility
Electricity and thermal energy storage can contribute to the flexibility of an energy system. However, these are not the only options. If a digester system is included in the energy community, the produced biogas can also be stored for moments when the energy demand can not be met by the supply at that moment. Furthermore, cryogenic energy storage, hydrogen energy storage and flywheels were mentioned as storage possibilities. Cryogenic energy storage is a relatively new technology to store energy, although it is already extensively used in the industry (Hull and Jones, 2016). For cryogenic energy storage the storage medium is kept at a very low temperature, which requires special storage tanks. Since this kind of storage as well as hydrogen storage are significantly different than electricity and thermal energy storage, it is decided to leave them out of the scope for this research. Flywheels are neither considered for this research, because this technology is mainly used for frequency regulation, which is also left out of the scope for this research (Raadschelders, 2013).

By now all key elements of an autarkic energy community came across; energy demand, supply and storage have been discussed and the possibilities for these elements have been described. Some technologies have already already been pointed out as being more promising to use for autarkic energy communities than others. A final selection of technologies to be included in the rest of this research will be formulated in the next section.

2.5 Choice of technologies

In this section all relevant technologies for the three key elements of an energy system have been discussed and case studies have been provided to indicate the opportunities and issues when implementing energy systems on a community scale. It seems reasonable to develop a microgrid on a community scale and not only on a household scale, therefore one or more microgrids (depending on the energy carriers) will be part of the energy community in this research.

Based on the analysis in this section, a few statements can be made:

- Wind and solar irradiation are infinite energy sources, which makes it reasonable to use those as good as possible;
- Seasonal energy storage should be realized by the means of thermal energy storage and not by batteries;

- Storage in general profits from up-scaling, making it reasonable to create a microgrid that connects the households within the community;
- Next to batteries for short-term energy storage and thermal energy storage for the long term, biogas can contribute to the balance of energy demand and supply;
- The heat supply can be realized by heat pumps, solar collectors and/or with biogas or a similar green molecule.

There are some success factors for a microgrid that determine whether the system will work out as intended. Based on these success factors a choice can be made which technologies would have the most potential to make the particular microgrid a success. Based on Soshinskaya et al. (2014) these succes factors are:

- Stable, reliable, and cost-effective power sources;
- Larger capacity and multiple technologies;
- Backup equipment;
- Effective power equality and EMS;
- Supportive regulatory and market framework;
- Stakeholder involvement;
- Microgrid operator training and user-friendly interfaces.

For this research the focus will be on the first four success factors mentioned in this list. A combination of supply and storage facilities will be picked and combined with demand applications to make sure the energy demand of the community can be met at all times. Stable, reliable and cost-effective power sources can be realized by choosing proven technologies that are already used in practice. Multiple technologies will be realized by including different DERs. The needed installed capacity depends on the available back-up capacity in critical hours. This back-up capacity can be provided in the form of biogas in combination with CHP engines. An EMS can realize effective power equality and this success factor is taken care of in the model representing the autarkic energy community. This model is described in Chapter 4.

Based on the statements above, wind and solar PV will definitely be taken into account. Furthermore, solar collectors and heat pumps will be considered as heat generation technologies. Since a digester system as in the Waterschoon project adds an extra dimension when it comes to autarky, such a system will also be considered for this research. The produced biogas can be used in combination with a CHP engine to generate heat and electricity. Batteries will be used on a daily time scale and for seasonal storage a TES system similar to the Ecovat system will be considered. The Ecovat project is already in the production phase and seems to be a promising solution for the long-term energy storage challenge. Furthermore, different sizes are possible, such that the size can be adjusted based on the needs of the energy community. The demand side is represented by the space heating demand, hot tap water demand and electricity demand.

In the next section the whole system will be described in more detail, where after in Chapter 4 the model for this system will be introduced and explained.

3 Scope and system description

In Chapter 2 is decided which technologies are included in this research. However, these technologies can still be used in different ways. For example, heat pumps can be used for space heating, for tap water supply as well as for charging the TES system. Furthermore different storage capacities can be used and different amounts and locations can be used for PV panels, wind turbines and solar collectors. In this section it will become clear how the technologies will be implemented in the energy community. The system design will be described and the choices on which this design is based will be explained. First, the characteristics of the community will be discussed, where after the demand, supply and storage elements will come across. At the end of this section an overview of the whole system is provided.

3.1 Characteristics community

For this research a Dutch residential area is considered. The aim is to use a system boundary that excludes everything outside this residential area when it comes to the energy supply. The area needed for the houses as well as for the installed capacity in the community are part of the system. The focus will be on a new-built area with houses meeting the latest insulation requirements. Well-insulated houses have a relatively low heat demand, making it more realistic to provide the households with enough locally produced energy. This corresponds to the first step in the trias energetica approach. If it turns out that autarky for such a community would be very difficult to realize, it will be even more difficult for less insulated houses under the same circumstances. The optimal size of the community depends on the energy sources and technologies being used. McKenna et al (2017). mention that, when the German energy-political framework is considered, it becomes economically attractive to create electrically self-sufficient districts only for 560 households or more. It was also discussed in Chapter 2 that a microgrid covering multiple houses should be considered to realize peak shaving advantages.

On the one hand, when a small microgrid is developed, it can be developed multiple times for larger scales; there can be a lot of opportunities to use these microgrids. Furthermore, on a small scale, participants might feel themselves more connected to the project and that might increase the willingness among them to cooperate. On the other hand, some technologies require a larger microgrid to become technically or economically feasible. For example, the digester system can handle the waste water and fruit and vegetables waste of 1200 citizens. Furthermore, the TES system requires a relatively large heat demand to become financially viable. The investment costs per household will rise significantly if the number of households connected to this system decreases.

The Waterschoon project and Ecovat system are used as reference for the digester and TES systems and lead to the choice to include 500 houses in the energy community, which is close to the 560 houses mentioned by McKenna et al. (2017). With this number of households, the Waterschoon and Ecovat systems can be used in an efficient way and investment costs in these projects can be spread out among a significant amount of participants. The occupancy rate of the houses is assumed to be 2.2 persons per household, based on the average household size in the Netherlands in 2018 (CBS, 2019a).

3.2 Demand pattern community

The demand pattern of an energy community consisting of well-insulated houses can be based on modelled data provided by ECN (ECN, 2018). This data set consists of the general electricity, space-heating demand and tap water demand of well-insulated houses. ECN specifically used passive houses, being extremely well-insulated, as a reference case (ECN, 2018). The insulation characteristics of the houses mainly determine the space heating demand of these houses. The space heating demand profile is shown in Figure 13. The electricity demand and tap water demand are presented in Appendix A. It is assumed that the ECN data represents an average pattern and therefore peak shaving benefits when combining demand patterns of single households are already present in the demand profiles. Especially well-insulated will also have a cooling demand, but this demand is not included the demand profiles (Mihai et al., 2017).

The total space-heating demand is 1659 kWh per household per year, while the tap water heat demand equals 1897 kWh per household per year in de ECN data set (ECN, 2018). The space-heating demand is even lower than the tap water heat demand, due to high insulation level. The total electricity demand equals 2999 kWh per household per year. The space-heating and tap water demand depend on the weather conditions. ECN used a Meteonorm year, representing typical solar irradiation and wind speed profiles in Dutch circumstances (ECN, 2018). The hourly solar irradiation profile, wind speed profile and outside temperature over the year are also presented in Appendix A. For the electricity demand provided by ECN the year 2016 is mentioned as reference (ECN, 2018).

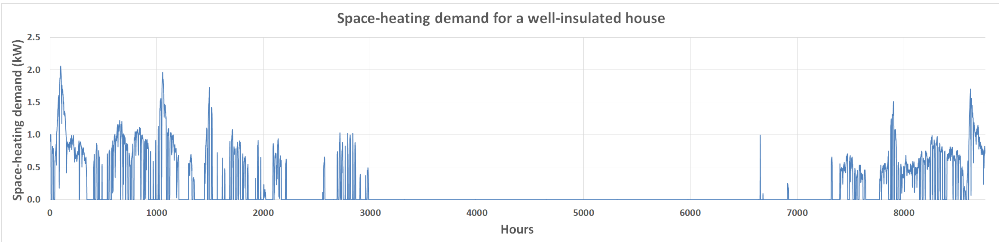


Figure 13: *Space-heating demand profile for well-insulated houses (ECN, 2018)*

Since heat pumps will be considered for space heating, these contribute to the total electricity demand and add to the general electricity demand.

3.3 Energy supply

All the supply technologies that are taken into account for this research are presented below, including relevant equations and/or conditions.

3.3.1 PV panels

First, the production of PV panels will be determined. This production is calculated based on the panel specifications and the amount of panels. The following parameters determine the electricity production by the PV panels:

- Amount of solar panels;
- Efficiency of the solar panels;
- Efficiency of the DC/AC converters;
- Tilt of the panels;
- Orientation of the panels;

- Size of one solar panel;
- External factor (shadow, snow, dust).

The electricity production by the solar panels is calculated as follows:

$$P_{PV} = \frac{I_{panel} * \eta * A}{1000} \tag{1}$$

Here P_{PV} is the electricity production by the PV panels in kWh, I_{panel} the irradiation on the panels in Wh per squared meter, η the efficiency of the PV panels and A the surface area of the panels in squared meters. The external factors are not taken into account in this research, because it is not straightforward what their influence is. There exist a lot of different panels with (slightly) different characteristics. For this research the LG NeON 2 panels are used as reference (LG Electronics, 2017). These panels have an efficiency of 18.7%, a capacity of 320 Wp and are 1.71 squared meter per panel. The space needed for the PV panels, if not placed on the roof tops of the houses, is about 30 km^2 per GW installed capacity (The National Renewable Energy Laboratory, 2003).

Orientation of the panels
The orientation of the PV panels determines the actual irradiation on these panels. The correction for the orientation of the PV panels can be determined in the model that will be further discussed in Chapter 4. In the model the position of the Sun with respect to the place on Earth where the panels are being placed is calculated for each moment in time. Furthermore, extraterrestrial radiation and refraction and diffusion of the incident radiation are taken into account. All the corrections are with respect to the ECN data that is used for the solar irradiation and wind speed (ECN, 2018). The choice is made to use 2016 as reference year for the correction for the orientation of the panels, because this year was mentioned as reference year for the electricity demand. It is assumed the panels are facing south with a tilt of 35 degrees with respect to the Earth's surface.

3.3.2 Wind turbines

For the production by wind turbines the following parameters should be taken into account:

- Amount of turbines;
- Efficiency of the turbines;
- Efficiency of the DC/AC converters;
- (Maximum) power output of one turbine;
- Cut-in speed;
- Cut-out speed;
- Rated speed of the turbine.

The power output of the wind turbine can be calculated based on the power curve for these turbines. The theoretical power generation by a turbine is given by:

$$P = 0.5 * \rho * \pi * R^2 * C_p * u^3 \tag{2}$$

In this equation, P is the generated power in Watt, ρ is the air density, R the radius of the rotor, C_p the dimensionless power coefficient and u the wind speed in meters per second. This equation holds between the start speed, or cut-in speed, of the wind turbine and the rated speed, see Figure 14. For wind speeds below the cut-in speed, the power output is zero, while between the rated speed and the cut-out speed the power output equals the rated power and above the cut-out speed the power output is zero again (Lydia et al., 2014).

For this research the E.A.Z.-twelve wind turbines will be used as reference. These wind turbines have a rated power of 8.5 meters per second, a nominal power output of 15 kW and the hub height is 15 meters (E.A.Z. Wind, 2019a). In the product specifications a nominal power output of 10 kW is mentioned, next to a maximum power output of 15 kW. Based on the specifications provided on the website, it is assumed that the power output is 15 kW for wind speeds equal or higher than 8.5 meters per second (E.A.Z. Wind, 2019b). The space needed for the wind turbines is about 100 km^2 per GW installed capacity (The National Renewable Energy Laboratory, 2003).

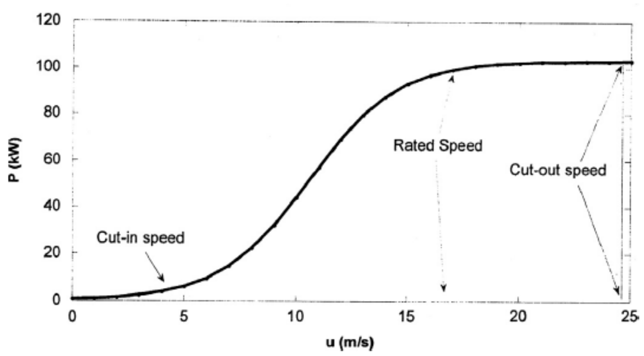


Figure 14: *Typical power curve of a wind turbine (Lydia et al., 2014)*

Corrected wind speed

The power output strongly depends on the wind speed. However, the wind speed is only measured by the KNMI at a certain height, while the wind speed varies with the height. The wind speed at the height of the turbine, H_t, can be calculated as follows:

$$U_t = U_m * \frac{\ln(\frac{H_t}{H_0})}{\ln(\frac{H_m}{H_0})} \tag{3}$$

Here U_t is the wind speed at the height of the turbine, U_m is the measured wind speed at height H_m and H_0 is the reference height, being the height of frequently present objects in the surrounding area of the turbine (Wieringa and Rijkoort, 1983). For an area with a lot of trees or houses, H_0 is approximately one meter (Wieringa and Rijkoort, 1983). Since the wind turbines will be placed close to the community, this value will also be used for this project. The weather station in Eelde is placed on top of a house in this village, which measures the wind speed at a height between 11 and 12 meter, so this height is used for H_m (Weerstation Eelde, 2019).

3.3.3 Solar thermal collectors

Solar thermal collectors can be used to supply heat to the households. To be able to calculate the production of solar thermal collectors, the following parameters are important:

- number of solar thermal collector panels;
- size per panel;
- efficiency of the panels;
- external factors (shadow, snow, dust).

Based on the solar irradiation, the produced heat by the solar collectors is calculated as follows:

$$P = A * (\eta * I - a_1 * (T_m - T_a) - a_2 * (T_m - T_a)^2) \tag{4}$$

Where,

P	: Power output of the collector	$[W]$
A	: Effective collector area	$[m^2]$
η	: Efficiency without heat loss	$[-]$
I	: Corrected irradiation on panel	$[W/m^2]$
a_1	: First order heat coefficient	$[W/(Km^2)]$
a_2	: Second order heat coefficient	$[W/(Km^2)]$
T_m	: Mean collector fluid temperature	$[°C]$
T_a	: Temperature of ambient air	$[°C]$

Equation 4 only holds if the produced heat is positive. External factors are again not included. The equation is based on Van Dorp (2018). The specifications of the HTHeatstore 35/10 collectors are used as reference (SP Technical Research Institute of Sweden, 2016). These panels have an efficiency of 74.5% when no heat losses occur. The ambient temperature is based on the ECN data and presented in Appendix A (ECN, 2018). The mean collector fluid temperature is based on the inlet and outlet temperature of the water flowing through the collectors. The inlet temperature is assumed to be 25 °C, which would be a reasonable value for the outlet temperature of the space-heating system, and the outlet temperature is assumed to be 60 °C based on the Ecovat system description and the HTHeatstore 35/10 specifications (SP Technical Research Institute of Sweden, 2016; Van de Bosch, 2018). With this outlet temperature it will (at least) be possible to charge the heat storage to 55 °C. The choice of temperatures and the thresholds for charging and discharging will be discussed in more detail in Chapter 4. It is assumed the panels are facing south with a tilt of 35 degrees with respect to the Earth's surface.

Orientation and temperature
In the report of Van Dorp (2018) the global irradiation is divided into direct and diffuse radiation. In equation 4 only the direct global irradiation is included, because this irradiation will be corrected for the position, tilt and orientation in the same way as for the PV panels.

3.3.4 Digester system

Another supply technology for the energy community is the digester system. This system does need electricity and heat as input to make the digester work, which can be provided by the PV panels, wind turbines and the TES system. The advantage of a digester system is that it produces biogas that can be used whenever a shortage of electricity or heat is expected, thereby contributing to the flexibility of the energy system in a community. A storage facility for the biogas would be needed to realize this.

The digester specifications are based on the Waterschoon report (Graaf and Hell, 2014). In the Waterschoon project a sanitation system is developed that processes both waste water and kitchen and garden waste. For the model a constant flow of waste and a constant flow of biogas production is assumed. In the report of this project a system analysis is provided and taking into account the whole system, every hour 6.37 kWh electricity and 12.56 kWh heat are needed to run the digester, which produces 18.61 kWh biogas equivalent per hour. These numbers are used as input for the energy community. The biogas is used as input for the CHP engine. The electric and thermal efficiency of the CHP engine are assumed to be 39.9% and 50% respectively, based on the CHP specifications of the engine used in the city of Deventer for processing biogas (Graaf and Hell, 2014). This CHP engine is also used as reference in the Waterschoon report. The total input power capacity of the CHP engine is 500 kW.

3.3.5 Heat pumps

Next to solar thermal collectors and CHP engines, heat pumps will be used to provide part of the heat supply in the energy community. This technology also needs electricity as input. A heat pump uses the free energy from the environment to transform one unit of electricity into multiple units of heat. The equation for calculating the coefficient of performance (COP) is:

$$COP = \frac{Energy\ output}{Electricity\ consumption} = \frac{Electricity\ consumption + extracted\ heat}{Electricity\ consumption} \tag{5}$$

Two different heat pumps will be considered for this research. First of all, a booster heat pump will be included on a household scale. This heat pump will give the final boost for the tap water heat supply. Furthermore, the TES system will be charged by heat pumps when there is an oversupply of electricity by the wind turbines or PV panels. In that way energy supply can be shifted from periods with a lot of energy production to periods with an energy shortage; e.g. electricity production in the summer can be saved for heat consumption in the winter. The COP of the heat pump generally is temperature dependent, because it depends on the difference between the source temperature and the supply temperature. This dependence is visible in Figure 15 (Melle et al., 2015).The figure clearly shows the COP of heat pumps decreases with increasing temperature difference between source and supply temperature. Tap water has to be heated to 60 °C (just) before it is delivered, otherwise Legionella bacteria can be present in the water (Gawalo, 2018). The heat pump charging the TES system will have supply temperatures ranging from 35 to 90 °C, based on the Ecovat system design (Van de Bosch, 2018). However, it is difficult to determine this supply temperature at each hour of the year, since this depends on the capacity of the heat pump, the weather conditions and the TES system temperature. Although the COP will differ over time, it is assumed the heat pumps have a constant COP.

In this research a constant ground temperature of 10 °C is assumed, although in practice this temperature will change over time (Melle et al., 2015). This means that, when the heat pumps use the ground as heat source, a temperature difference between the supply and source would be 50 °C for the booster heat pump. Based on an extrapolation of the graph in Figure 15 the average COP of the booster heat pump would be close to 2.5 for this temperature difference. The same COP will be used for the TES heat pump. The capacities of the heat pumps are assumed to be 4 kW and 415 kW for respectively the booster heat pump and the TES heat pump. These capacities are based on values mentioned in a datasheet of FactoryZero and a report about the Ecovat system (Factory Zero, 2019; Van de Bosch et al., 2017).

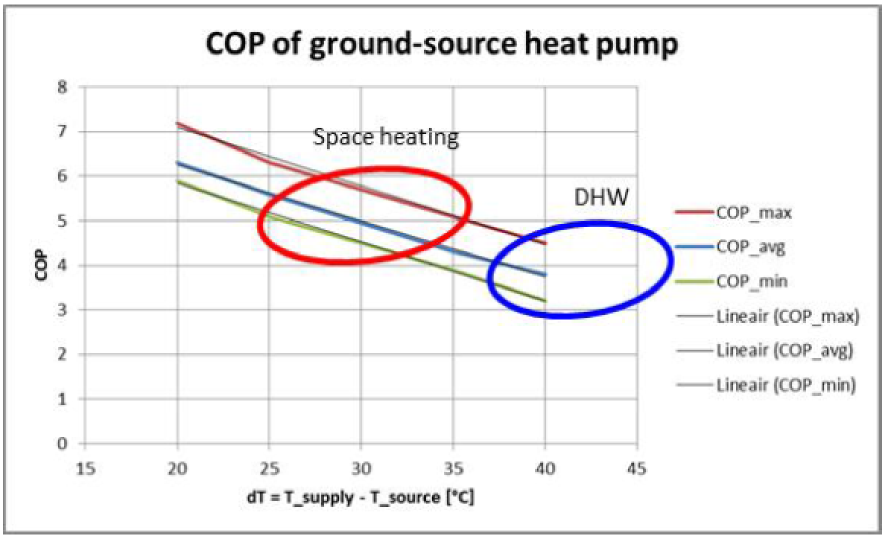


Figure 15: *The COP of a ground-source heat pump as function of the temperature difference (Melle et al., 2015)*

3.4 Storage

3.4.1 Batteries

Batteries are included in this research to facilitate the balance between electricity supply and demand. The batteries will store electricity in times of overproduction by the PV panels and wind turbines and supply electricity in times when the demand is larger than the supply by these panels and turbines. The relevant parameters for batteries are:

- the number of batteries;
- the storage capacity of one battery;
- the depth of discharge;
- the efficiency of charging and discharging;
- the self-discharge per time-unit.

The use of batteries is particularly meant for energy storage on a hourly and daily basis. How the amount of charging and discharging is calculated, can be found in Appendix B.

As discussed in Chapter 2 a wide variety of batteries do exist. There might be a promising future for electrochemical batteries, since these batteries do not require the use of heavy metals like lithium-ion batteries, while still having significant capacity and high efficiencies. An example of such a battery is the Greenrock battery. This battery is chosen as reference in this research. The overall efficiency of charging and discharging the battery is 90%, while the self-discharge of the battery equals 0.01% per hour. The space needed for the batteries is approximately 2.19 m^3 per 24 kWh battery stack and 0.73 m^3 for the DC installation box per 24 kWh (Mayer and Krausse, 2018). A capacity of 24 kWh is used as reference, because this is the largest capacity mentioned in the specifications and large batteries might be needed when significant flexible capacity is needed to realize autarky. The nowadays more commonly used Tesla powerwall has a capacity of 13.5 kWh (Tesla, 2019).

With a smart energy system the moments of charging and discharging can be determined based on the state of the battery and the amount of oversupply or shortage of electricity. When the batteries are controlled by a system that processes all the relevant information in the energy community, this system can determine how much the batteries should be charged or discharged. The model used for this research also determines when the batteries should be charged or discharged. In Chapter 4 the model is described in more detail.

3.4.2 Thermal storage

TES system
The balancing of energy demand and supply is not restricted to the electrons as energy carriers. Heat demand and supply should also be balanced to make sure the demand can be met at all times. As discussed before, the TES system is a state-of-the-art thermal storage tank, based on the specifications of the Ecovat system (Ecovat Renewable Energie Technologies, 2014). The order of magnitude for the volume of the TES system varies from a 1,000 to nearly 100,000 cubic metres (Ecovat Renewable Energie Technologies, 2014; Ecovat Renewable Energy Technologies, 2018). The height and diameter of the configuration can vary independently and the Ecovat system has a layered structure, which means the storage tank is divided into separate modules in the vertical direction. This structure prevents destratification, thereby improving the performance of this system. Furthermore, the temperature of the different layers can independently be managed. In this research such a layered structure is not included for the TES system and it is assumed that the stored water has one homogeneous temperature.

As well as for the batteries, the moment and amount of charging and discharging have to be determined for the TES system. This depends on the oversupply or shortage of heat at a particular moment and on the state of the TES system. In Chapter 4 the storage modules used in the model will be discussed and a more detailed description of the storage thresholds as well as the amount of charging or discharging can be found in Appendix B. The outlet temperature of the TES system is assumed to be 40 °C, because that would be sufficient to facilitate a low-temperature space-heating demand.

Hot water vessel storage
The supplied heat within the community is either consumed directly or stored in a thermal storage tank. This thermal storage tank can be the TES system. However, when for example the solar thermal collectors are placed on the roof of houses, it would be reasonable to introduce an extra storage tank on a household scale. In that way the heat produced by the collectors does not have to be transported to the TES system and back again when this heat is needed. In the Ecovat system solar thermal collectors are also directly connected to an extra vessel at every household (Van de Bosch, 2018). Furthermore, this vessel can be designed to store water at higher temperatures than the TES system such that it can facilitate the hot tap water supply. When there is no tap water demand, the booster heat pump present in each house can also contribute to heating up the water in this vessel. The tap water can not directly be supplied by the TES system, because it would require a significantly higher outlet temperature than 40 °C to realize a reliable tap water supply. For example, when the shower is used with a water flow of eight liters per minute, a heat pump with a capacity of approximately 11 kW would be needed to heat up such a flow of water to 60 °C when the reference temperature is 40 °C. The calculations behind this example can be found in Appendix C.

Heat losses
For the vessel storage as well as for the TES system heat losses to the environment are included. These heat losses depend on the water temperature in the storage facilities as well as on the insulation specifications. For the TES system the heat losses are based on the thermal analysis for a L-sized Ecovat tank (Ecovat Renewable Energie Technologies, 2014). The results of this cooling-down test are used to

determine the thermal resistance of the insulation. For the vessel tank a few assumptions have been made to determine a realistic thermal resistance for that system. These assumptions and the calculation of the thermal resistances of both the TES system as the vessel storage are presented in Appendix D. Furthermore, in some cases the transportation distance can be relatively large, therefore transport losses should be taken into account. For example, the heat transport to and from the TES system has to cover a significant distance. For these heat flows transport losses of 10% will be considered, which is based on an assumption in literature for similar heat transport (Schmetz, 2017). For the same reason 10% transport losses are taken into account for the transport of electricity and heat coming from the CHP engine. The choice is made to only include electric transport losses when the electricity comes from the CHP engine. However, this choice as well as the choice to use a 10 % loss factor for this electric transport are used based on simplicity reasons and not based on a literature review for this topic.

3.5 System overview

In this section all the relevant aspects of the energy community were presented. The physical system boundary would be around the community with 500 households, including the space needed for the TES storage, wind turbines, PV panels, collectors and the digester system. The roofs of the houses will also be used for the PV panels and solar collectors, but the roofs have limited space, so extra might be needed.

To summarize, all technologies included in this research are:

- PV panels;
- thermal collectors;
- wind turbines;
- a digester processing waste water and fruit and vegetables waste;
- a CHP engine using the produced biogas by the digester as input;
- home-scale batteries;
- home-scale storage vessels;
- a large-scale TES system;
- booster heat pumps at home;
- a heat pump to charge the TES system.

Two microgrids will be needed to transport electricity as well as heat within the energy community. All in all the system, including the energy flows, is visually represented in Figure 16 on the next page.

3.5.1 Costs indication

To be able to perform a costs analysis multiple costs indications are used, being summarized in Table 3 [1]. The sum of all factors listed in the table is used as indication for the total costs per year for the system.

[1] Costs retrieved from Vattenfall (2019) for the PV panels, from HR solar (2019) and Wilt (2019) for the collectors and the vessel, from Enexis Netbeheer B.V. (2019) for the wind turbine, from Ecovat Renewable Energy Technologies (2019) for the TES system, from Koppejan (2016) for the CHP engines and from De Graaf (2014) for the digester system.

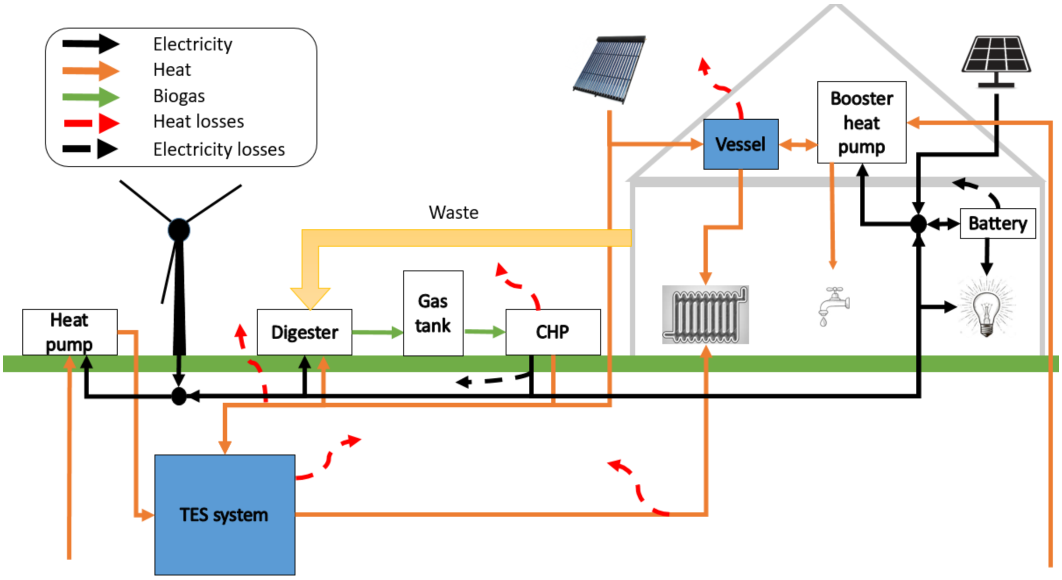


Figure 16: *Schematic representation of the energy community*

De Graaf (2014) mentioned the costs for the digester system as costs per year, so in Table 3 these costs are listed as OPEX. In practice significant CAPEX costs will be associated with the digester system, but without background information it is not possible to make a valid estimate of the division between CAPEX and OPEX. The costs for the battery are expressed per used kWh discharge, which for the Greenrock battery corresponds to €0.11 per usable kWh discharge (Indesol, 2018). Since the usage of the batteries depends on the absolute electricity supply and demand as well as on the timing of these, the used discharge can only be determined after simulating a whole year. The costs, therefore, can not be expressed in CAPEX or OPEX values.

Table 3: *Costs system components*

System component	**CAPEX (€1000)**	**Lifetime (years)**	**OPEX (€1000 per year)**	**Costs per useful discharged kWh (€)**
PV panel (320 Wp)	0.5	25	0	
Solar collector panel	0.6	25	0.01	
Wind turbine (15 kWp)	42.5	15	0	
Vessel (200 L)	1.3	25	0	
TES system	18125	50	0	
CHP engines (500 kW)	600	12	42	
Digester system			86.9	
Battery				0.11

4 Methodology

For this research the We-Energy Tool developed by the System Integration Modeling Group at the Research Center Energy of the Hanze University of Applied Sciences is used to model the autarkic energy community. This Excel tool is a modular and very transparent tool, therefore existing modules can easily be used for this project and additional modules can be created for parts of the energy community not yet processed in this tool. For the demand profiles, PV panels, wind turbines, the influence of the tilt and orientation on the production by PV panels and collectors and for batteries the modules developed by Research Center Energy of the Hanze University of Applied Sciences can be used. For the weather circumstances, solar thermal collectors, the digester and the TES system new modules are developed to complete the system as described in the previous section.

Based on hourly demand patterns the energy balance in the community can be determined for each hour. Thresholds can be used to decide whether to charge or discharge the vessel storage, the TES system and the batteries. Furthermore, based on the energy balance it can be decided to use the produced biogas by the digester system to generate extra electricity and heat supply. The goal of this section is to explain the important aspects of each module used in the tool. At the end of this section scenarios will be defined. The outcomes of different scenarios make it possible to determine the critical aspects of the energy community and the different ways in which an autarkic energy community can be realized.

4.1 Model design

For this research project the following modules are used in the We-Energy Tool:

- Demand;
- Weather;
- Tilt and orientation;
- PV;
- Wind;
- Solar thermal;
- Digester system;
- Storage;
- TES system;
- Overview energy flows.

In all modules hourly data is used, because the demand profiles are also on a hourly basis.

Demand
The energy demand is based on load profiles modelled by ECN. These hourly profiles are listed in the module. Furthermore, the electricity demand by the booster heat pumps and the digester system are added to this demand profile. The electricity demand by the TES heat pump is not included, because only electricity overproduction will be used for this heat pump. This will be explained in the description of the TES system module.

Weather
Relevant weather parameters for this research are the outside temperature, the wind speed and the solar irradiation. The yearly profiles for these parameters are presented in Appendix A.

Tilt and orientation
In this module the influences of the tilt and orientation of the panels with respect to the Earth's sur-

face as well as with respect to the position of the Sun are determined. Based on this information the effective solar irradiation on the PV panels as well as on the solar thermal panels can be determined.

PV

In the PV module the electricity generation by the PV panels is calculated. As described in Chapter 3 multiple factors determine the output of these panels. In the module the corrected solar irradiation is copied from the tilt and orientation module. With Equation 1, see Section 3.3.1, the production of the PV panels is calculated. Based on the electricity demand this module calculates how much PV production can be used directly and how much overproduction or shortage remains; an updated load profile is determined. This updated profile is the input for the next module.

Wind

With Equation 2, see Section 3.3.2, the electricity generation by wind turbines is calculated. As explained in Chapter 3 this production is based on the corrected wind speed that is determined with Equation 3. Based on the electricity generation by the wind turbines it is determined how much can be used directly and how much remains as overproduction. For the direct use of the produced electricity, the production by PV panels is considered first. When the electricity demand cannot be met by the production by PV panels, the production by the wind turbines is taken into account. It is a random choice to allocate the electricity produced by the PV panels first and this choice does not affect the results. Transport losses are not taken into account for the electricity produced by PV panels and wind turbines, so it does not really matter whether the electricity demand is met by electricity produced by PV panels or by wind turbines. The overproduction of the PV panels and wind turbines together is allocated to the battery or the TES heat pump. The destination of the overproduction is based on the state of the battery, as explained in the description of the battery module.

Solar thermal

The production by the solar thermal collectors is based on the corrected solar irradiation, similar as for the PV panels. The actual production is calculated based on Equation 4, see Section 3.3.3.

Digester system

Next to the solar collectors, CHP engines are used to produce heat. These CHP engines need the biogas produced by the digester as energy input. In the digester system module the electricity and heat use as well as the biogas production of the digester system are determined per hour. It is assumed that the digester acts as a baseload, having a constant biogas production over the year. This assumption results in the need of a storage facility that stores the biogas produced by the digester in times when the biogas will not directly be used as input for the CHP engine. In Appendix F the needed biogas storage is determined.

Storage

In this module and the following TES system module all aspects of the energy community come together. Now the energy management aspect becomes relevant, because choices have to be made when it comes to the use of the storage facilities. For the storage module the relevant inputs are the oversupply of the PV and wind turbine electricity production or the electricity shortage when not enough electricity is being produced to meet the demand. These two scenarios will now be discussed in more detail.

In case of overproduction

When the PV panels and wind turbines produce more electricity than the demand requires, the overproduction can be used to charge the battery or to charge the TES system with a heat pump. The battery is given priority and the TES heat pump is only activated when more electricity is available than the battery can be charged with.

In case of shortage

In case of electricity shortage the battery will be discharged to cover the shortage. To make sure the battery can always cover shortages, the CHP engine is activated in time to anticipate on critical hours. For example, the CHP engine can be activated when the state of the battery drops below 25%. When the state of the battery drops below this threshold, it means the battery has been discharged in the preceding hours and more discharge can be expected due to bad weather circumstances. The CHP engine will stop running when the state of the battery comes above a certain value, for example 30%. The best choice for these thresholds will be based on trial and error and should make sure the CHP engine is not turned on and off all the time; this might negatively influence the performance and lifetime of the CHP engine. The optimal values will prevent empty batteries at all times, but also make sure the CHP engine is only used when really needed. In Appendix B the mathematical equations and conditions used in the tool are presented.

TES system

In the TES system module the TES system as well as the vessel storage are included. Based on the heat production and the residual capacity of the storage systems it can be determined whether the storage facilities should be charged or discharged to balance the demand and supply. First the vessel storage will be discussed.

Vessel storage

The vessel storage is used to guarantee the supply of hot tap water. At the moments when there is a heat demand for the supply of tap water, this heat will be provided by the water stored in the vessel. However, as discussed in Section 3.4.2 the vessel stores water at a maximum temperature of 55 °C, so the booster heat pump will be used to heat this water to 60 °C before it is provided as tap water. The tap water heat demand is based on the temperature of the incoming water, because the heat demand is the amount of energy needed to heat up this water to 60 °C. It is assumed that the incoming water temperature is 15 °C, which is a reasonable temperature for the water that is delivered to the households (Vitens, 2015). The contribution of the booster heat pump to the tap water heat supply depends on the temperature of the water in the vessel. When this temperature is relatively low, the booster heat pump has to deliver more heat to heat this water up to 60 °C. The total temperature difference to cover would be 45 °C. When the water in the vessel is 55 °C, then $\frac{60-55}{60-15} * 100\% \simeq 11\%$ of the high-temperature heat demand has to be met by the booster heat pump.

The vessel storage will be discharged when it has to supply the tap water demand and it will also have heat losses to the environment. In Appendix D the heat losses are discussed in more detail. As soon as the temperature of the water in the vessel drops below 54 °C, the heat produced by the solar collectors will be used to charge the vessel. When the heat production by these collectors is low and/or the tap water demand is high, the vessel temperature might drop significantly more. It should at any time be prevented that this temperature drops too much, because the booster heat pump has a limited capacity and might not be able to provide the tap water demand when it has to cover a large temperature difference. This is also explained with an example in Appendix C. To prevent this from happening, another temperature threshold is introduced. When the vessel temperature drops below 50 °C, the booster heat pump will contribute to charging the vessel in times when there is no heat demand. In this way the heat demand can always be met.

TES system

For the space-heating supply the TES system is used. The outlet temperature of the TES system is assumed to be 40 °C, based on the system description of the Ecovat system (Van de Bosch, 2018). Assuming the space-heating demand in well-insulated houses can be met with low-temperature heating, 40 °C is high enough as input temperature. The heat losses are taken into account by increasing the total discharge of the TES system by 10 %. However, when the temperature of the water stored in this system would at any time drop below 40 °C, the vessel storage in combination with the booster heat pump at home will be used to provide the space-heating demand. Such a scenario is not preferred, because this might increase the electricity demand in critical hours. It is assumed that the heat demand of the digester system is also met by discharging the TES system.

In the TES system module different energy flows are used as input to charge the TES system. First of all, the electricity dump from the PV and wind turbine production provide inputs for the heat pump that can charge this system. Secondly, the solar collectors provide heat supply for the TES system when the heat is not needed to charge the vessel. A third heat input is provided by the CHP engine. When the CHP engine is activated in times of shortage, this heat production can be used as well to charge the TES system.

Based on the total heat demand and total heat supply for the TES system, the net load for this storage system can be determined. Similar as for the vessel storage, heat losses will occur and together with the net load that determines the change in temperature of the water stored in this system. When the TES system has reached its maximum temperature of 90 °C and a net heat supply to the TES system takes place, this heat supply is wasted. For the TES system module the mathematical equations and conditions are presented in Appendix B.

4.2 Scenario description

With the described technologies different scenarios can be formulated. All scenarios will aim for autarky, but different configurations of the technologies can be used. Three scenarios are defined, such that the results of these scenarios give an overview of the performance of the autarkic energy community. The scenarios are:

- No energy waste scenario;
- Minimum costs scenario;
- Minimum land use scenario.

The performance of the autarkic energy community can be analyzed based on these three scenarios. The amount of wasted energy reflects how efficient the community can balance the supply with their demand and the minimum costs and land use scenarios reflect how much investments and space are needed to realize an autarkic energy community.

For the three scenarios the installed capacity of wind turbines and PV panels will be changed and the storage capacities also differ between the scenarios. However, some conditions are the same for all scenarios. All relevant data came across in the system description in Chapter 3, but the following comments are specifically important for the interpretation of the results:

- 500 households are included;
- passive, well-insulated, houses with typical demand profiles modelled by ECN are considered;
- it is assumed each house has space for 12 PV panels on the roof;
- the space on the roof is not included in the land use analysis, only the extra land needed is considered;
- typical Dutch weather conditions modelled by ECN are considered;
- solar thermal collectors are not considered in the scenarios, but will be included in the sensitivity analysis;
- a battery per household is included with a different capacity in the scenarios;
- a TES system per scenario is considered with a different capacity in the scenarios;

- the COP of the heat pumps are equal to 2.5 and constant over the year in each scenario;
- the CHP capacity is 500 kW input-equivalent in all scenarios;
- the vessel storage tank can store 200 liters of water;
- energy losses are defined as transport and self-discharge losses, while wasted energy is produced electricity or heat that has no allocation;
- in all scenarios the minimum required installed capacity is used to realize autarky within the restrictions stated by the scenarios;
- a shortage in the energy supply can never occur such that autarky is guaranteed.

4.2.1 No energy waste scenario

In the no-energy-waste scenario the storage facilities will be chosen such that all the imbalances between supply and demand can be buffered; the storage facilities can not be overloaded, neither can a shortage occur at any time. This means the heat pump of the TES system has no limited capacity of 415 kW as described in Section 3.4.2. When the batteries are full, the rest of the electricity will be used to charge the TES system, no matter how large the load of this electricity oversupply is. Furthermore, the storage facilities should be filled as much at the end of the year as at the start of the year, because the demand of a fictive next year should also be met. Three different configurations will be used in this scenario to determine the influence of the ratio for installed PV capacity and wind turbines, both generating electricity for the system. The three configurations are:

- Wind, with only wind turbines and the CHP engine as back-up capacity;
- PV, with only PV panels and the CHP engine as back-up capacity;
- 12PV, with 12 PV panels per household and the rest wind turbines and the CHP engine as back-up capacity.

It is assumed that 12 PV panels can fit on the roof of each house, therefore specifically the configuration with 12 panels per household and for the rest only wind turbines as installed capacity is considered. The CHP engine is always available as back-up capacity.

4.2.2 Minimum costs scenario

In this scenario the minimum costs configuration will be determined. For this scenario the assumption is made that every household has a battery with a storage capacity of 24 kWh, which is based on the largest capacity mentioned in the data sheet for the Greenrock battery (Mayer and Krausse, 2018). With this fixed storage capacity it will be determined what configuration of PV panels and wind turbines is most cost-effective to realize autarky. The costs indications were listed in Table 3 in Section 3.5.1.

It is assumed that only the costs of PV panels and wind turbines change for different configurations, because the solar thermal collectors are left out of scope in the scenarios and the other system components are assumed to have one fixed price. In practice, for example, the costs of a TES system will depend on its volume, but this dependence is not included.

4.2.3 Minimum land use scenario

In the third scenario the minimum land use configuration will be determined. Similar as for the scenario with minimum costs, the storage capacity of the battery will be fixed at 24 kWh. The configuration of PV panels and wind turbines that results in the lowest land use requirement will be determined as well as the TES volume needed in this configuration. As mentioned in Chapter 3 the required land use for the PV panels and wind turbines is respectively 30 km^2 and 100 km^2 per GW installed capacity. The land needed for the digester system with CHP engines and storage tank is assumed to be constant in all configurations and is therefore not included in this scenario analysis. Furthermore, it is assumed that the TES system does not occupy any land, because it is placed underground and, for example, wind turbines can be placed above this system.

For both the minimum costs and minimum land use scenarios the amount of wasted energy will be determined, because the storage facilities are no longer scaled to prevent energy waste streams.

4.2.4 Overview of the scenarios

In Table 4 an overview of the scenarios and the relevant parameters that are changed within these scenarios are presented. Here IC stands for installed capacity and SC stands for storage capacity.

Table 4: *Variables per scenario*

Scenario	**No energy waste**	**Minimum costs**	**Minimum land use**
Variables	IC PV panels IC wind turbines SC TES system SC battery	IC PV panels IC wind turbines SC TES system	IC PV panels IC wind turbines SC TES system

Table 4 shows the storage capacity of the TES system can also change in the minimum costs and minimum land use scenarios, while the battery capacity is limited in these scenarios. It is assumed that the capacity of the TES system is always adjusted such that the temperature of this system is the same at the beginning of the year as at the end of the year. It is a significant operation to place such a system and the assumption is made that the size of the system does not influence any of the results; neither costs nor land use are influenced by a change in the size of the TES system.

5 Results

This section presents the results for each scenario as well as a sensitivity analysis.

5.1 No energy waste scenario

In Figure 17 the installed capacity of PV panels and wind turbines is presented for the no-energy-waste scenario.

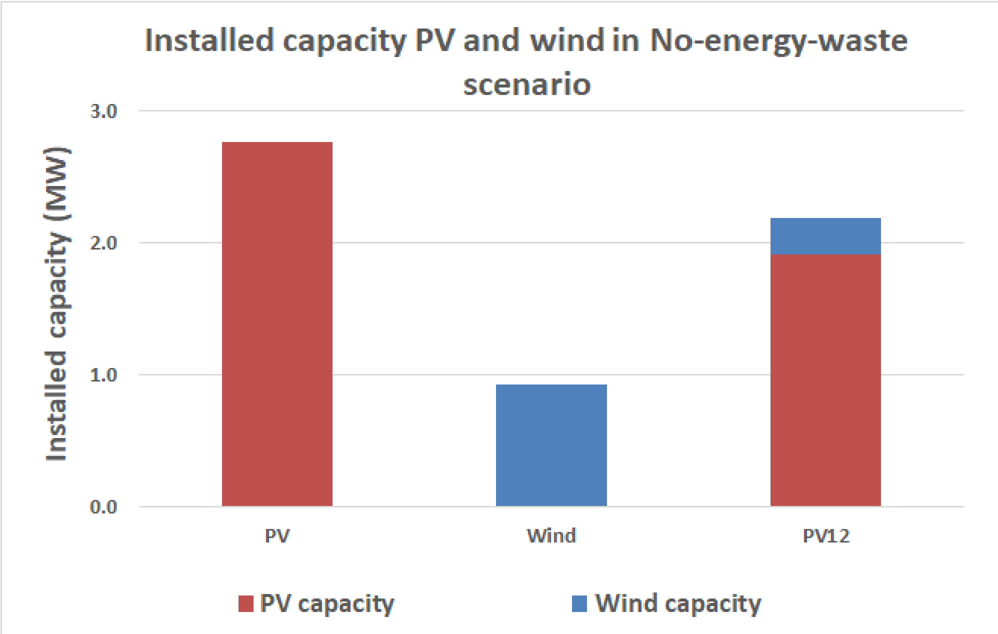


Figure 17: *Installed capacity of wind turbines and PV panels in the no-energy-waste scenario for different configurations*

Figure 17 shows much more installed capacity is needed when only PV panels are used with respect to the case in which only wind turbines are used. Furthermore, Figure 18 shows that much more storage capacity is needed when only PV panels are used with respect to the case with only wind turbines. There are three reasons for these effects, of which two are caused by the difference in the supply pattern of PV panels and wind turbines. First of all, solar irradiation has a larger seasonal variation than the wind speed. This means the production by PV panels also follows a seasonal pattern, while the production by wind turbines is more evenly distributed over the year. More storage capacity is needed to balance this seasonal variation, which explains the difference in the needed storage capacity. Furthermore, self-discharge losses take place when storing energy in batteries or in the TES system. When over the year more heat and electricity are stored, the absolute losses for these storage facilities will increase. These losses have to be compensated by extra installed capacity, which explains why the installed capacity differs. The third reason that explains part of the observed effects, is the difference in the capacity factors. The capacity factor of the modelled wind turbines is approximately 23%, while the capacity factor of the solar PV panels is close to 12%. This means for the same installed capacity, the wind turbines will produce more electricity over the year than PV panels, which enhances the observed difference in the needed installed capacity. The PV12 configuration needs an installed capacity in between of the other two configurations. The needed volume of the TES system, however, is the same as in the PV configuration.

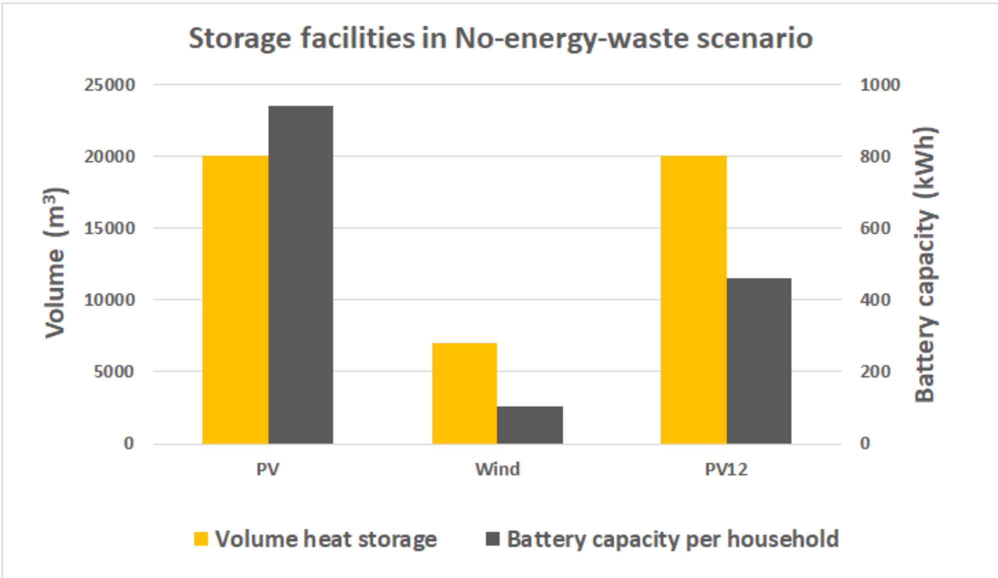


Figure 18: *Storage capacities of the Greenrock battery at a household scale and the TES system*

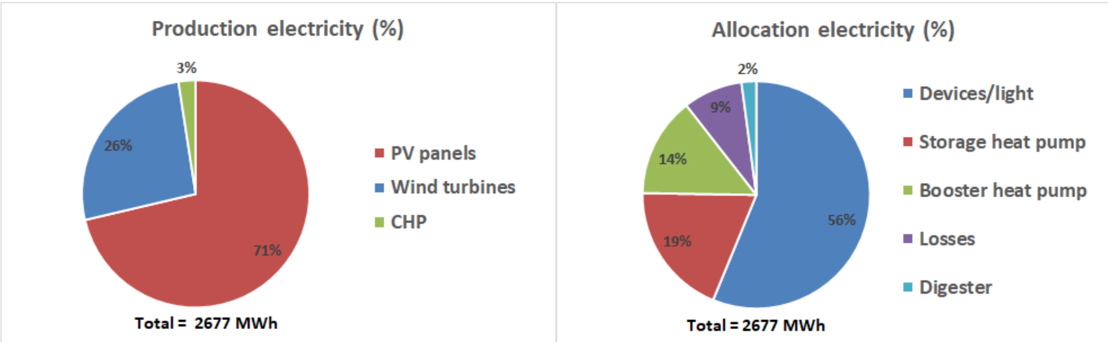
The needed heat pump capacities are 2385 kW, 813 kW and 1783 kW for respectively the PV, Wind and PV12 configurations. These capacities are based on the maximum oversupply of electricity available when the batteries are completely full. The volumes of the TES system needed are 20,000 m^3 for the PV and PV12 configurations and 7000 m^3 for the Wind configuration. These volumes respectively correspond to an useful energy content of 4.2 and 1.5 TJ, assuming a temperature range between 40 and 90 °C. These values correspond to respectively 1.2 and 0.4 GWh.

In Figures 19 and 20 the electricity and heat production and allocation are presented for the PV12 configuration. It is observed that the electricity production is dominated by the PV panels and that the CHP contribution to both the electricity and heat production is small. The storage heat pump (for the TES system) and the booster heat pump consume a significant part of the electricity and together produce all the heat needed next to the heat supplied by the CHP engine.

The losses of electricity and heat are also significant, which is caused by the relatively large storage capacities. For the batteries a constant self-discharge rate is considered, independent of the battery capacity at a household, and for the TES system a constant thermal resistance of the insulation is considered, independent of the volume. The self-discharge of the battery equals 0.01% per hour. The thermal resistance of the TES system is determined in Appendix D. When the storage capacities increase, this results in larger self-discharge losses for the batteries. Similarly, a larger TES system will have larger heat losses at a certain temperature. Transport losses also contribute to the energy losses.

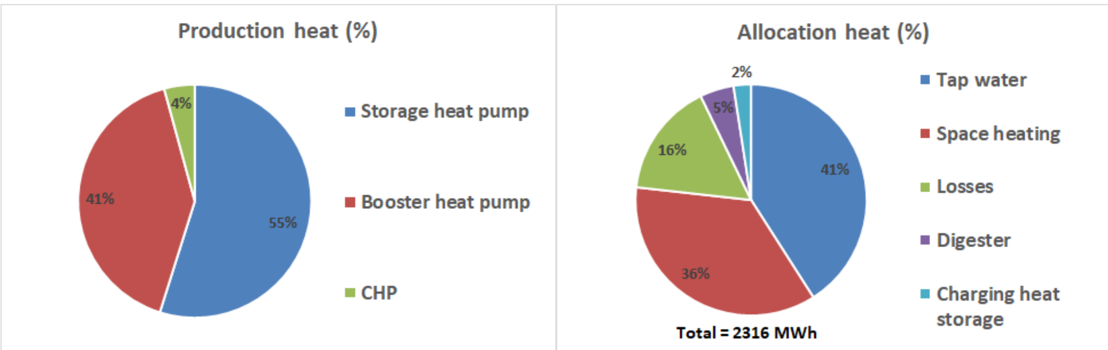
A small part of the produced heat is used to charge the TES system. This means the temperature of the TES system at the end of the year is slightly higher than at the beginning of the year. The difference between the state of the batteries at the beginning of the year and the end of the year is too small to appear in Figure 19. Of all the allocated electricity, 31% is provided by the batteries. This means 31% of the electricity consumption is realized by storing the generated electricity to be able to supply this electricity at a moment later in time.

The yearly costs per household and the land use required for the PV panels and wind turbines in this scenario are, respectively, €2144,- and 2.7 hectares.



(a) *Electricity production* (b) *Electricity allocation*

Figure 19: *The total electricity production and allocation within one year for the PV 12 configuration*



(a) *Heat production* (b) *Heat allocation*

Figure 20: *The total electricity production and allocation within one year for the PV12 configuration*

5.2 Costs optimization

In the minimum costs scenario a restricted battery capacity of 24 kWh per household is used. The results of the costs optimization analysis are shown in Figure 21. Eight different configurations of PV panels and wind turbines are presented, expressed as installed capacity on the left y-axis. On the second y-axis the yearly costs for the wind turbines and PV panels can be found. Only the costs of the PV panels and wind turbines are considered, because the other costs components are assumed to be constant. The eight configurations are based on trial and error by compensating a decreasing amount of wind capacity by an increased amount of PV capacity. Figure 21 shows there is a particular optimum with the lowest costs for configuration C3. In this configuration the costs of PV panels and wind turbines are equal to €343.2 per year, while the total costs are equal to €2415,-. The required land use equals 11.71 hectares. It should be mentioned that the costs in the eight different configurations in Figure 21 are not significantly different when these differences are put in perspective of the total costs.

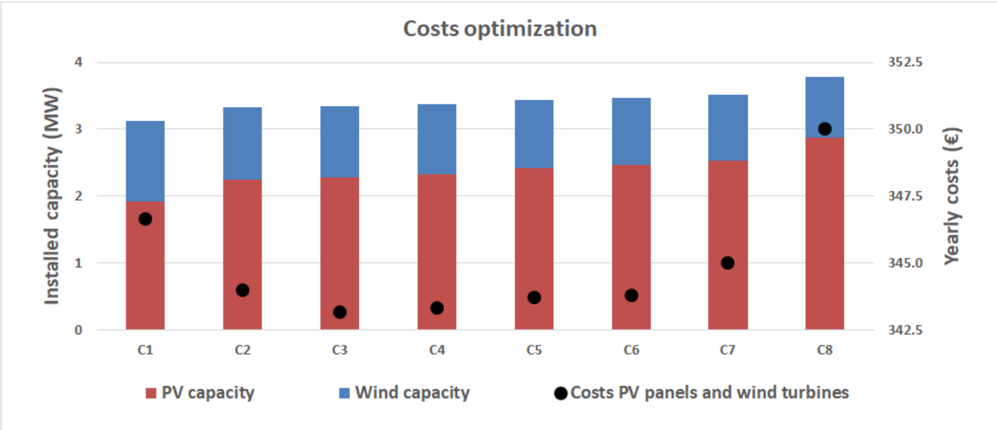
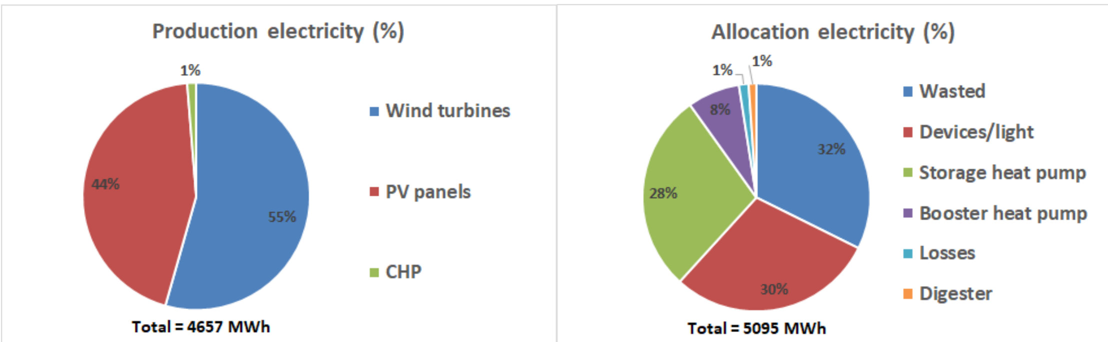


Figure 21: *Costs optimization for the autarkic energy community*

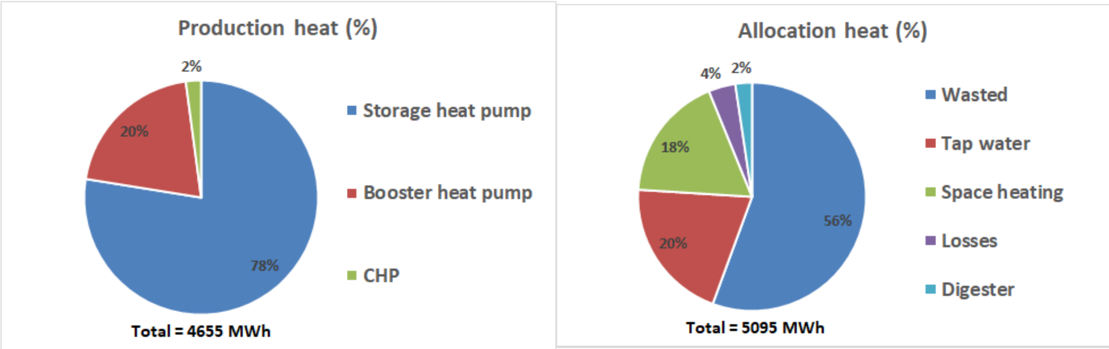
The production and allocation of electricity and heat for the C3 configuration are presented in Figures 22 and 23. The wind turbines dominate the electricity production and a significant amount of electricity as well as heat is wasted. The introduction of a limited battery capacity results in a most cost-effective situation in which a significant part of the energy production is thrown away. It can be observed that the total costs are actually higher than in the no-energy-waste scenario. However, a much larger battery capacity was needed in that scenario to balance the electricity supply and demand.

A small difference can be observed between the total produced heat and the total allocated heat. This is due to the net discharge of the vessel heat storage. This storage facility, even for all households together, is significantly smaller than the TES system and a net (dis)charge over the year is therefore not included in the heat allocation.



(a) *Electricity production* (b) *Electricity allocation*

Figure 22: *The total electricity production and allocation within one year for the C3 configuration*



(a) *Heat production* (b) *Heat allocation*

Figure 23: *The total electricity production and allocation within one year for the C3 configuration*

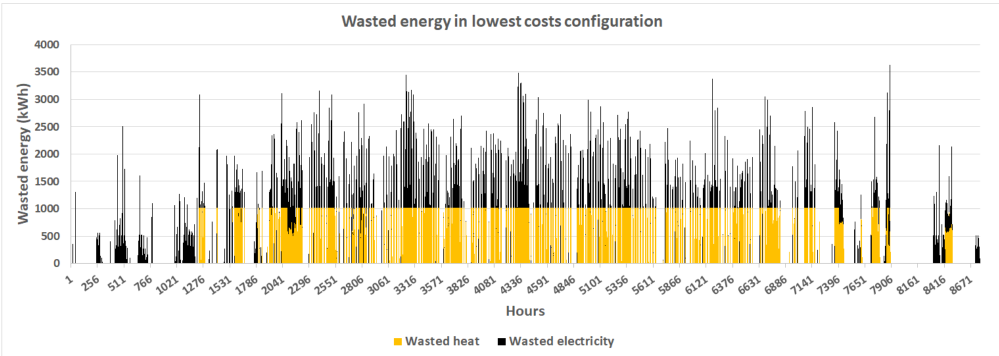


Figure 24: *Wasted energy in the lowest costs configuration*

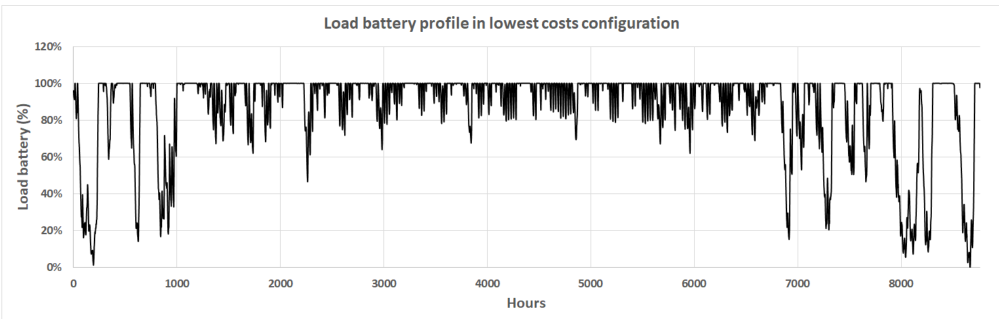


Figure 25: *Load profile battery in the lowest costs configuration*

It can be observed that a significant amount of energy is wasted in the C3 configuration. The load profiles of the battery and the TES system and the wasted energy over the year are presented in Figures 24, 25 and 26. There is a seasonal pattern with much more wasted energy in summer than in winter. Due to the restricted battery capacity of 24 kWh per battery, a significant amount of electricity is allocated to the storage heat pump. This is why the TES system only needs a volume of 3000 m^3 to end up with a temperature almost equal to the temperature at the start of the year; even in winter the TES system is charged once in a while.

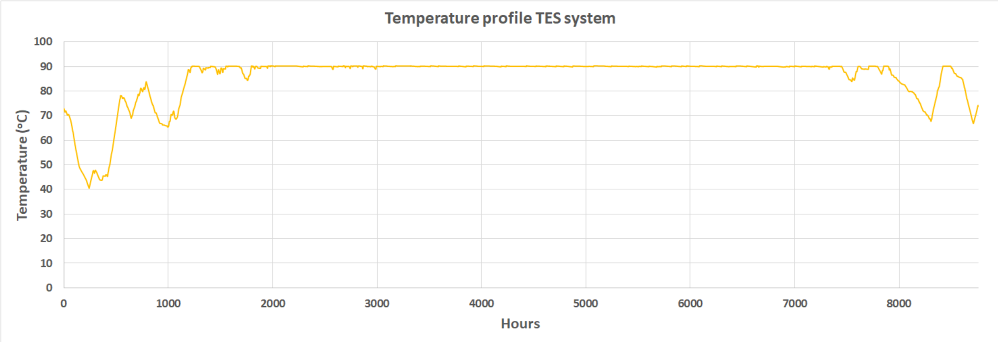


Figure 26: *Temperature profile TES system in the lowest costs configuration*

In Appendix E a Sankey diagram for the lowest costs configuration is presented. This diagram shows all the energy flows within the energy community. Furthermore, in Appendix F the needed biogas storage is determined.

5.3 Land use optimization

Figure 27 shows the same configurations as for the costs optimization, but now the land use is presented on the second y-axis. Configuration C6 has the lowest land use for the PV panels and wind turbines. The optimum for land use and the optimum for costs have almost the same ratio of wind capacity and PV capacity, which is why the same configurations could be used to determine these optima. The lowest land use is equal to 11.68 hectares. Since the minimum land use configuration is almost the same as the minimum costs configuration, the production and allocation of electricity and heat are also almost the same as in the minimum costs configuration. The costs in the configuration with the minimum land use correspond to €2418,-.

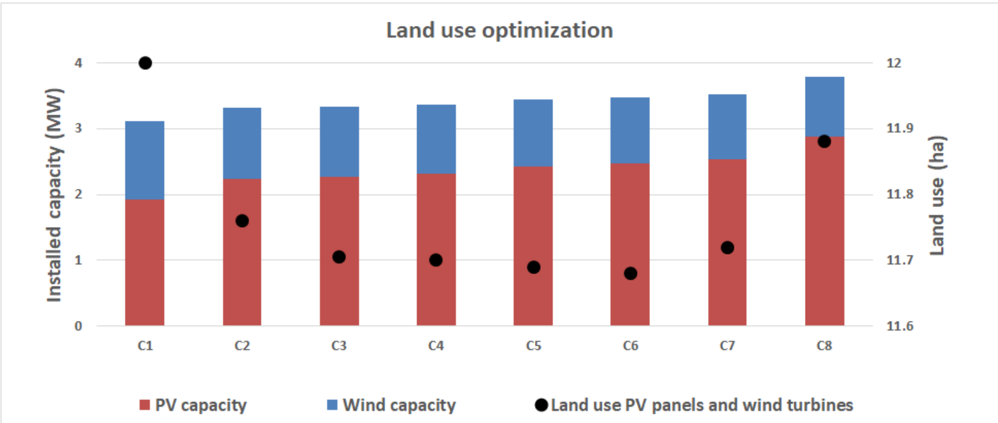


Figure 27: *Land use optimization for the autarkic energy community*

5.4 Sensitivity analysis

Next to the installed capacity of PV panels and wind turbines and the storage capacities, other parameters can be changed in the model. The values allocated to these parameters were based on assumptions and in this sensitivity analysis the influence of these assumptions will be discussed. Only the most relevant and/or the ones with the most impact on the results are discussed. For all parts in the sensitivity analysis the minimum costs configuration as described in Section 5.2 is used as reference. This means a similar trial and error process as for the minimum costs scenario in Section 5.2 is used to determine the configuration of PV panels and wind turbines that results in the lowest costs. The volume of the TES system is always chosen such that the temperatures at the beginning and the end of the year are the same.

5.4.1 Weather conditions

Until this point only the typical weather conditions provided by ECN have been used. However, different solar irradiation and wind speed profiles will result in different energy supply profiles. In an autarkic energy community even a year with relatively low electricity production by the PV panels and wind turbines should not cause any problems. It is assumed that the average solar irradiation and wind speed in a year are good indicators to compare the electricity production potential for different years. These indicators are listed in Table 5 for the period from 2009 up to and including 2018. The averages are based on the measurements in Eelde (KNMI, 2019; Weerstation Eelde, 2019). The year with the lowest production potential is used to determine the impact of using the weather conditions of that year in the model. The year with the lowest production potential is determined by allocating a score for the average solar irradiation and a score for the average wind speed in each year, on a scale from 1 to 10. The year with the highest solar irradiation gets a ten and the worst year a one. The same holds for the wind speed, where after the two scores are added to be able to compare the years on a total score. The scores are shown in Table 5. This analysis shows that 2017 has the lowest score, so the solar irradiation and wind speed profiles of this year are used in the model.

Table 5: *Allocation of scores to weather conditions in Eelde*

year	**Average wind speed (m/s)**	**Average irradiation (J/cm^2)**	**Score wind**	**Score sun**	**Total score**
2009	4.05	43.26	5	9	14
2010	3.86	42.64	2	8	10
2011	4.24	41.05	9	2	11
2012	4.12	41.17	7	3	10
2013	4.21	41.37	8	4	12
2014	4.08	42.34	6	7	13
2015	4.37	41.93	10	5	15
2016	3.85	42.06	1	6	7
2017	4.04	40.86	4	1	5
2018	3.96	45.77	3	10	14

The averages for the solar irradiation and the wind speed do not take into account the timing of production with respect to the timing of demand, neither do the averages take into account the possibility that high wind speeds result in switching off the turbines. Furthermore, the electricity generation by wind turbines does not linearly depend on the wind speed, but follows the power curve as presented in

Chapter 3. However, it is observed that the wind speed in Eelde in 2017 does not exceed the maximum of 8.5 meters per second and for simplicity the timing of the weather conditions is neglected.

With the weather conditions of 2017 as input, the lowest costs configuration is determined and compared to the lowest costs configuration of the typical ECN year in Table 6. The results show that the average solar irradiation in the typical year of ECN is even lower than this average in 2017. The average wind speed is significantly lower in 2017 than in the typical year of ECN. It is therefore not surprising that the optimum ratio of installed capacity for PV and wind in 2017 is in favour of PV. The total yearly costs increase when the weather conditions of 2017 are used instead of the typical year modelled by ECN. The difference in the needed TES volume to balance the begin and end temperature of the year shows, again, the significant impact that the ratio of installed capacities for PV and wind has on the needed storage capacity; changing this ratio in favour of the PV capacity, results in larger storage capacities needed.

It should be mentioned that the heat demand profiles, both for tap water as for space-heating, are related to the weather conditions; the heat demand increases when it is colder outside. However, these heat demand profiles are not available for the year 2017. This means only the supply side of the energy system changes due to different weather conditions, while in practice the demand side will also change.

Table 6: *The influence of different weather conditions on the performance of the autarkic energy community*

Reference year	**Average wind speed (m/s)**	**Average solar irradiation (J/m^2)**	**Installed wind capacity (MW)**	**Installed PV capacity (MW)**	**Volume TES (m^3)**	**Yearly costs per household (€)**
ECN	4.51	39.78	1.07	2.27	3000	2415
2017	4.04	40.86	0.68	3.73	9000	2499

5.4.2 Insulation characteristics

Changing the insulation conditions of households does especially influence the space-heating demand, but according to the ECN data the tap water heat demand is also different for less insulated houses (ECN, 2018). The relation between the insulation conditions and the heat demand is not provided, only the final demand profiles. To analyze the influence of a higher heat demand, the modelled demand profile for Renovated houses is used. This demand profile is also provided by ECN. The effects on the needed installed capacity, the needed TES volume and the yearly costs per households are presented in Table 7. The increased heat demand made more installed capacity, both for PV panels as for wind turbines, needed to realize autarky. Furthermore, the volume of the TES system as well as the yearly costs per household for wind turbines and PV panels increased. The wasted heat as percentage of the total produced heat decreased for renovated houses with respect to passive houses. In the lowest costs configuration for passive houses a large portion of the produced heat is wasted. Households in renovated houses have a larger heat demand, so less heat has to be wasted. Still more installed capacity is needed, because in the current model the heat is supplied by heat pumps, so the electricity demand also increases.

Table 7: *The influence of a higher heat demand on the performance of the autarkic energy community in the lowest costs configuration*

Houses characterization	**Tap water demand (MWh)**	**space-heating demand (MWh)**	**Installed wind capacity (MW)**	**Installed PV capacity (MW)**	**Volume TES (m^3)**	**Yearly costs per household (€)**	**Wasted heat (%)**
Passive	1.9	1.7	1.07	2.27	3000	2415	72
Renovated	2.5	3.0	1.25	2.30	7000	2487	52

To make sure the TES system has a similar temperature at the end of the year as in the beginning of the year, the system has to be larger to compensate for the larger heat demand. When the TES system becomes larger, more of the potential heat supply in summer can be used instead of being wasted. It is remarkable that the needed TES volume and yearly costs per household are lower when introducing renovated houses compared to changing the weather pattern as in Table 6. It shows the increase in needed installed and storage capacities when more PV is introduced in the energy mix has more impact than an increase in the heat demand when this can be compensated by introducing more wind turbines.

5.4.3 Solar thermal

Until now the focus has been on the electricity generation by PV panels and wind turbines, however solar thermal collectors have also been implemented in the model. Theoretically these collectors can replace part of the electricity generation that is meant for the heat pumps, however Table 8 shows the influence of solar thermal collectors is negligible. As much PV panels as possible have been removed by the introduction of some solar thermal collectors. The choice is made to focus on PV panels, because both solar thermal collectors as PV panels depend on solar irradiation for their production of respectively heat and electricity. Furthermore, the collectors and PV panels can both be placed on the roof that has limited space. The introduction of these collectors does not have a significant impact, because this source of heat can not effectively replace the heat production by the heat pumps. This means the collectors do not produce heat on moments when there is significant heat demand, which means the heat would mainly be used to charge the TES system, which is already overloaded during a significant part of the year. Overall, indeed some PV panels can be removed with respect to the reference case when solar thermal collectors are introduced, however the costs and wasted heat increase.

Table 8: *The influence of introducing solar thermal collectors on the performance of the autarkic energy community*

Amount of collectors	**Installed wind capacity (MW)**	**Installed PV capacity (MW)**	**Yearly costs per household (€)**	**Wasted heat (%)**
0	1.07	2.27	2415	72
1	1.25	2.18	2431	74
2	1.25	2.13	2458	76

5.4.4 Biogas and CHP thresholds

The electricity and heat production by the CHP engines are not high with respect to the other supply sources, however the CHP engines realize the supply in critical hours of electricity supply. In critical hours the electricity production by the PV panels and wind turbines is low, so it is expected that significantly more installed capacity would be needed when there is no biogas available for the CHP engine. The importance of the electricity supply by CHP engines during critical hours is clearly visible in Figure 28 and it is even more clear on a shorter time scale as in Figure 29.

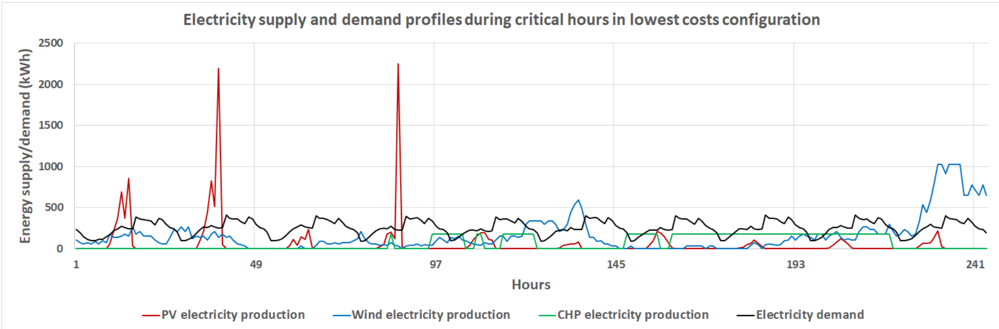


Figure 28: *Energy supply and demand profiles during critical hours in the lowest costs configuration for the first 244 hours of the year*

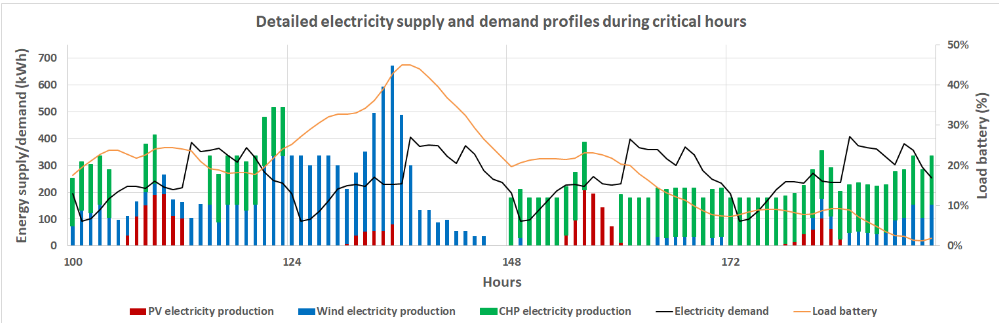


Figure 29: *Detailed energy supply and demand profiles during critical hours, with hour values corresponding to the ones in Figure 28*

The lowest costs configuration is again used as reference and it is determined how much installed capacity is needed when there is no biogas available. The results are presented in Table 9. When no biogas is used in the system, the wasted electricity and heat increase respectively to 56 and 80% of the corresponding totally generated electricity and heat. These large energy waste streams originate from the very large installed capacity needed to realize autarky without biogas. This large installed capacity is needed for the hours, days or even weeks in the year when there is almost no wind or solar irradiation at the ground level. However, during the moments when enough wind and/or solar irradiation is present a lot of electricity and heat will be generated of which only a part can be used, resulting in large energy waste streams.

Table 9: *The influence of the biogas availability on the performance of the autarkic energy community*

Biogas availability (MWh_{eq})	**Installed wind capacity (MW)**	**Installed PV capacity (MW)**	**Yearly costs per household (€)**	**Wasted heat (%)**	**Wasted electricity (%)**
163	1.07	2.27	2415	72	32
0	1.58	4.64	2886	80	56

5.4.5 Heat pumps

For the storage heat pump at the TES system and the booster heat pump at each house the capacity and the COP are of importance. Since the TES system is only charged with the heat pump when there is an oversupply of electricity and the system is still overloaded during a significant portion of the year, the specifications of the TES heat pump are less critical. However, the booster heat pump does also have a significant electricity demand, which has to be met at the exact moment of tap water demand. Furthermore, the booster heat pump charges the vessel when the temperature in this vessel drops below 50 °C. The electricity demand of the booster heat pump for five representative days in January is presented in Figure 30. In this figure the total average electricity demand for a single household is included as reference. In this total average demand the electricity demand of the digester system is also included.

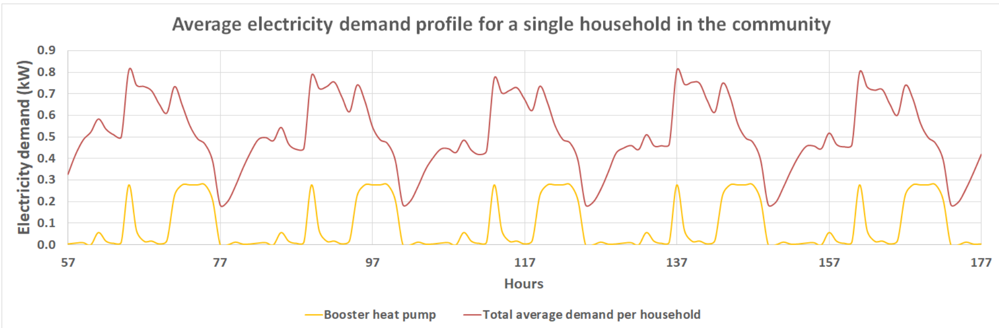


Figure 30: *Average electricity demand profile for a single household in the autarkic energy community for five days in January. The booster heat pump electricity demand and the total average demand are presented and the hour values correspond to the actual hours of the modelled year.*

The influence of the COP on the needed installed capacity to realize autarky in the lowest costs scenario is presented in Table 10. The influence of the capacity is not further analyzed, because a larger capacity would also mean larger electricity peak demands, which is not desired. Table 10 shows that significantly more installed capacity is needed when the COP of the booster heat pump is lowered, while the needed installed capacity is lower for a higher COP. A change in the COP does not significantly influence the amount of wasted heat, but does have an impact on the wasted electricity. When more installed capacity is needed to meet the electricity demand of the heat pump with a lower COP, not all the extra installed capacity can be used by the heat pump; part of it will cause extra energy waste. Vice versa does a higher COP cause a reduction in the amount of electricity waste. The installed capacity can be reduced due to a lower electricity demand during critical hours, which also causes a reduction in the wasted energy in times when this reduced installed capacity would otherwise produce unneeded electricity.

Table 10: *The influence of booster heat pump COP on the performance of the autarkic energy community*

COP	**Installed wind capacity (MW)**	**Installed PV capacity (MW)**	**Yearly costs per household (€)**	**Wasted electricity %**
2.5	1.07	2.27	2415	32
2	1.16	2.51	2484	35
3	1.04	2.03	2368	30

6 Discussion

First a general discussion of the assumptions made for this research and specifically for the model is provided. This discussion is followed by a discussion of the results per scenario as presented in Chapter 5, where after a reflection on the sensitivity analysis is included.

6.1 Assumptions in this research

Demand side of the energy system
In this research is assumed that 500 passive houses represent a realistic to-be-built community in the Netherlands. Furthermore, it is assumed that the demand profiles provided by ECN are representative for the average electricity, space-heating and tap water heat demand of an household in the community. The choice of 500 houses was based on the dimensions of the digester and TES systems, while the 2.2 persons per household reflect the average occupation rate in the Netherlands. However, the demand profiles are modelled data based on insulation characteristics of passive houses and on a Meteonorm year representing a typical Dutch weather pattern over the year. It was reasonable to use these demand and weather profiles as input, but a comparison with other weather patterns and corresponding demand profiles would make more clear what is needed to realize an autarkic energy community under different circumstances that are possible in the Netherlands. Unfortunately, other weather patterns with corresponding demand profiles were not available. The demand profiles determine how much supply and storage facilities are needed and are therefore an essential part of this research. Houses that are less-insulated will have larger heat demands. This effect is also discussed in the sensitivity analysis in Chapter 5. On the other hand, well-insulated houses will have a cooling demand which was not included in this research. Luckily, this cooling demand specifically occurs in the summer months when there is expected to be enough overproduction available for cooling purposes.

The demand side profiles can also be influenced by introducing demand side management. This would make it possible to shift some of the demand in time, which is especially desired in critical hours. Due to the limited demand profiles that were available, demand side management is not included in this research.

Supply side of the energy system
At the supply side of the energy community multiple technologies are included in this research. For the PV panels, wind turbines, solar thermal collectors and CHP engine state-of-the art products are used as reference. However, technological developments for these technologies could be considered as well as other reference products. For example, when expected future improvements in efficiencies would be included, less installed capacity and less land might be needed to realize an autarkic energy community. Furthermore, the costs of these technologies can drop in the future. Another example would be to include large wind turbines instead of the small EAZ wind turbines as reference product. This will also influence the costs and land use needed to realize an autarkic energy community. Most of these assumptions lead to an overestimation of the needed installed capacity in the future, which is therefore in favour of the realization of autarkic energy communities.

It was assumed that the water used for the tap water supply had to be heated to 60 °C every time when a demand occurred. This restriction was implemented to prevent the formation of Legionella bacteria in the water. However, the water has only to be heated once a week to at least a temperature of 60 °C for only a few minutes, depending on the temperature being reached in this moment of heating (Rijksoverheid, 2018). This means a reduction in the booster heat pump electricity demand can be realized, which could significantly influence the needed installed capacity to realize an autarkic energy community. The specifications of this booster heat pump, as well as of the TES heat pump, might also be different in practice than modelled in this research. It was assumed that both heat pumps have a COP of 2.5 and a capacity of respectively 4 and 415 kW. In the reflection of the sensitivity analysis a discussion of these specifications is provided. The assumption of 60 °C tap water supply will make autarkic energy communities in practice more feasible than modelled in this research.

It was assumed that the characteristics of the Waterschoon system were representative for a digester system that could be used in the community. The outcomes of the Waterschoon project are directly used as input in the model, but a more detailed analysis would be needed to determine the possibilities for and performance of such a system in the autarkic energy community as described in this research. It is not clear whether more or less biogas would be realistic to be produced during the year, neither is it clear whether the costs indication is realistic for such a system in an autarkic energy community. The choice to use a digester system in general also significantly influences the performance of the autarkic energy system. It is clear that back-up capacity as provided by the CHP engines in this research is essential to reduce the needed installed capacity. However, other back-up capacities could also be chosen. For example, the introduction of hydrogen production, storage and conversion back to electricity could be introduced to include flexibility in the energy system. Furthermore, a synergy with a local farmer could be assumed. Such a farmer might have manure overproduction that can be used for the production of biogas. This last option still requires a digester system, but the input for this system is different and the yearly production can probably increase when a significant amount of manure is left (Middelburg, 2019). On the other hand, to realize autarky the energy needs of the farm should also be supplied within the community. For the purpose of this research the assumption to use the Waterschoon performance as reference was reasonable.

The use of biogas could be improved when the CHP engine is only activated when the batteries are significantly discharged ánd the weather predictions are not in favour of electricity production by PV panels and wind turbines. In the current model the activation of the CHP engine does only depend on the state of the batteries, but not on the weather conditions. However, a low state of the battery will only cause a threat for shortage when the electricity production by the renewable energy technologies in place will be low as well in the hours to come.

Storage facilities in the energy system

In this research a large-scale heat storage system under the ground, a smaller heat storage vessel on a household scale and a battery installation per household have been included. The performance of the TES system and the battery were based on the Ecovat system and the Greenrock battery as references. The performance of the vessel storage was based on a thermal analysis in which PUR or PIR foam was used as insulation material and the dimensions were estimated. Using PUR foam is a realistic assumption, because this material is well-known and widely used for insulation purposes. The thickness of the insulation layer and the dimensions of the vessel are based on educated guesses, but a variation in these parameters could only affect the performance of the energy community by altering the heat losses arising from this vessel storage. However, these heat losses are quite small with respect to the other energy flows.

The Greenrock battery is a state-of-the-art battery available on the market nowadays. However, this saltwater battery requires a significant volume and the use of a lithium-ion battery as the Tesla powerwall could reduce the needed volume with almost a factor ten (Mayer and Krausse, 2018; Tesla, 2019). For analyzing the energetic performance of the energy community the Greenrock battery is still a reasonable choice.

The specifications of the TES system, however, are kind of uncertain. The thermal performance of this system is based on the thermal analysis of the Ecovat system, but the Ecovat system has a modular layered structure, which is not included in this research. The possibility to use layers with different temperatures improves the efficiency of this system and make different discharge temperature possible. Furthermore, the cool-down test of a L-sized Ecovat system is used to determine the thermal resistance of the insulation surrounding this storage system. However, a cool-down test for a smaller or larger system will have other results. Overall it seems that the assumptions made for this part of the system are pessimistic compared to the expected performance in practice.

Performance indicators
The yearly costs per household and the land use needed for the wind turbines and PV panels were used as performance indicators of the autarkic energy community. However, both analyses are indicative and do not cover all parts that could be considered.

The yearly costs per household are based on a costs indication for all supply and storage facilities in the community, except for the biogas storage tank. This biogas storage tank was left out, because of simplicity reasons. Furthermore, in the report describing the Waterschoon project nothing specifically was mentioned about biogas storage. Of course such a storage tank has a price as well. The yearly costs per household were in the order of magnitude of €2000,- to €2500,-. The costs in the minimum costs scenario had an optimum for €2415,- per household per year. Although this is only an indication for the order of magnitude of the costs associated with the realization of an autarkic energy community in practice, it is worth comparing these costs with the yearly energy bill households are on average paying nowadays for the supply of energy. The yearly energy bill in the Netherlands is estimated at €2100,- per household per year in 2019 (Milieu Centraal, 2019), which would mean that the costs of the autarkic energy community are in the same order of magnitude as the yearly energy bill. However, it is estimated that 46.7% of the yearly energy bill in 2019 is represented by taxes (Gaslicht.com, 2019). This kind of taxes are not included in the costs indication for the autarkic energy community. When comparing the actual costs for the supply of energy, the yearly costs per household would therefore be more than twice as high for the autarkic energy community than the costs households are paying per year for the supply of energy nowadays. The costs per household per year were lower in the no-energy-waste scenario than in the minimum costs scenario. This shows the very large battery capacities needed in this first scenario are cheaper than the extra installed capacity needed in the minimum costs scenario. This is an interesting difference, but the 460 kWh battery capacity per household needed in the no-energy-waste scenario is still unrealistically large. Factors like inflation were not taken into account for the costs analysis, but will have an impact on this analysis. The TES system, for example, is assumed to have a lifetime of 50 years. Over such a long time scale inflation can have a significant impact on the effective yearly costs.

When it comes to the land use required for the realization of the autarkic energy community, only the PV panels and wind turbines were included, while the digester system including a biogas storage will also require a significant amount of land. Furthermore, the TES system might also require some land to be reserved, for example for the heat pump installation. It was also assumed that each rooftop of the houses has space for 12 panels, but this is an educated guess and can differ depending on the dimensions of the houses and the orientation of the panels. The amount of space available on rooftops does influence the land use optimum, because it affects the amount of PV panels that have to be placed on land instead of rooftops. However, 12 panels per rooftop is a realistic guess and more panels might be possible, especially when the slopes on both sides of the rooftop can be used in an east-west orientation of these slopes. With an east-west orientation a different production profile by the PV panels should be taken into account. The optimum in the land use analysis will not be affected by the other facilities that require some reserved space, but it should be mentioned more land use will be needed in practice than presented in the results.

Based on the database of CBS, the average surface area needed for a house in which one household is living, would be 162 m^2 in 2019 (CBS, 2019b). It is assumed that about three times as much space is needed for the whole community, including public places as the streets. This means that close to 25 hectares would be needed for 500 houses. This is more than twice the land needed for PV panels and wind turbines in the minimum land use scenario. The needed system boundaries of the community should therefore entail significantly more than only the space needed for the households, especially when the extra land use requirements of the digester system are taken into account.

To determine the land required for PV panels on land and wind turbines, data obtained from literature has been used (The National Renewable Energy Laboratory, 2003). However, this source listed the needed squared kilometers per GW installed capacity, while the autarkic energy community is on a relatively small scale. Especially for the small wind turbines a different amount of land might be needed in practice, in favour of the larger wind turbines. The EAZ wind turbines only have a capacity of 15 kW, while large wind turbines can have a capacity up to multiple Megawatts. This means 200 EAZ wind turbines are needed to realize the same capacity as one large wind turbine of 3 MW. It depends on the preferences of the community, but it could be possible that one larger wind turbine is preferred, even when this wind turbine is much larger and with less natural materials. On the other hand, PV panels could be placed on the same land as where the wind turbines are placed, as long as the wind turbines do not significantly influence the production by these PV panels due to shadow formation. When the wind turbines are placed on the north side of the panels, this might not be a (significant) problem. The land left in between of the wind turbines could also be used for agricultural purposes.

6.2 Discussion of the results

No energy waste scenario
The no-energy-waste scenario showed that significant installed capacities and storage capacities are needed to realize an autarkic energy community in which all the energy supply and demand are balanced without causing any shortages or energy waste. This especially holds when PV panels are included; the seasonal production profile of this technology makes larger storage facilities needed to balance the energy supply and demand on seasonal time scales. The PV12 configuration still has significantly more installed PV capacity than wind capacity. This means that the intention to use all the available space on rooftops, results in the need of significantly large storage capacities.

Furthermore, large heat pumps are needed to process the peak loads of electricity that can not be stored in the batteries. It would be more reasonable to use a restricted heat pump capacity as done in the other two scenarios. The needed volumes of batteries are much larger than the conventional household-scale batteries, while the TES volume needed is in line with the available Ecovat dimensions. The volume needed for the batteries would be close to 56 m^3, which means a room of four by five meters and 2.8 meters high would be completely filled with the battery installation in case of the PV12 configuration. This is not an acceptable size on a household-scale and makes this no-energy-waste scenario an unrealistic scenario. As mentioned before, the introduction of lithium-ion batteries can reduce the needed volume with almost a factor ten, but the needed volume would still be very large. The required land use of 2.7 hectares is not unreasonable when there is some land available nearby the houses. This land has to be included in the system boundaries to guarantee autarky.

Costs optimization
The minimum costs scenario showed these minimum costs correspond to € 2415,- per household per year in case of a restricted battery capacity of 24 kWh at each household. The restricted battery capacity has a significant impact on these costs, because less flexibility is available, which also results in the significant energy waste streams in this scenario. The total costs per household per year are significantly smaller in the no-energy-waste scenario, due to the unrestricted battery capacity available

in that scenario.

The large portions of wasted electricity and heat ask for other allocations. For example, hydrogen production could be implemented such that all wasted electricity can be used in an electrolysis process. Furthermore, the wasted heat is nothing more than electricity converted into heat by the TES heat pump, so this waste stream could also be wasted as electricity before it is supplied to this heat pump. The use of an energy carrier that can efficiently store electricity during seasonal time scales would mean much less energy has to be wasted in scenarios like this.

Land use optimization
For the minimum land use scenario the required land use for an autarkic energy community is determined. The minimum land use corresponds to 11.68 hectares. The optimum for the land use analysis has almost the same ratio for the installed capacities of PV panels and wind turbines. Factors that might influence the land use analysis were described earlier in this section.

6.3 Reflection on sensitivity analysis

The sensitivity analysis shows that the weather conditions, insulation characteristics of the households, the CHP engines and the corresponding availability of biogas and possible technological developments for heat pumps have significant impacts on the results, while the introduction of solar thermal collectors does not significantly influence the results.

Weather conditions
The influence of the weather conditions on the performance of the autarkic energy community was determined by introducing the solar irradiation and wind speed profiles for 2017. However, the choice for this year was based on the average wind speed and average solar irradiation in a year, while the production by the wind turbines and PV panels and especially the timing of this production are most important. Therefore this analysis can be improved and multiple weather patterns and their influence on the wind and PV production should be included to determine the actual influence of the weather conditions on the performance of the energy community. These weather patterns, however, have to be connected to the demand profiles to give a realistic impression, which was not the case for 2017.

Renovated houses
In the sensitivity analysis a second demand profile for both space-heating as for tap water provided by ECN has been used to compare the results with those for passive houses. This second demand profile has been referred to as the demand for renovated houses, having a higher space-heating and tap water demand than passive houses. These demand profiles correspond to the Meteonorm year that was also used for passive houses, which realizes a valid comparison between the two kind of houses. The larger heat demand could theoretically be met by the oversupply, if the heat demand was not met by heat pumps. The heat pumps cause a larger electricity demand when the heat demand increases, thereby causing an increase in the needed installed capacity to realize autarky. The extra space-heating demand is especially needed on cold days, so at the moments when critical hours might occur.

Biogas and CHP engine
Figures 28 and 29 show the importance of the electricity supply by the CHP engine. During periods of low production by PV panels and wind turbines the batteries will be discharged and when these batteries are not that large or already discharged in the hours before, a shortage occurs unless the CHP engine is used. The sensitivity analysis for this part of the system showed how the CHP engine reacts on variations in the state of the batteries. The performance of the autarkic energy community could be improved when the CHP engine takes into account the expected electricity production by PV

panels and wind turbines in the hours to come, such that the biogas can be saved for the dunkelflaute periods.

Heat pump specifications
As discussed earlier for the supply side of the energy community, expected technological developments could be included in this research. The sensitivity analysis for the COP of the booster heat pump showed that indeed less installed capacity is needed when this COP would be higher.

The COP of the heat pumps was chosen to be constant over the year, being equal to 2.5. However, as discussed in Chapter 3 the COP of heat pumps depends on the source temperature and the supply temperature. This temperature difference was assumed to be constant for the TES heat pump as well as for the booster heat pump. In practice both the source temperature, being the ground temperature, as well as the supply temperature will differ over the year. The ground temperature changes due to variations in the outside temperature. Broekema (2016) looked into the temperature dependence of the COP of heat pumps and mentioned a linear dependence of the COP on the difference between the source and supply temperatures. The used equation in that study is: $COP = 6 - \frac{\Delta T}{15}$, in which ΔT represents the temperature difference. With this equation the COP would be 2.7 for a temperature difference of 50 °C and becomes higher for lower temperature differences. During summer the ground temperature will be higher than during winter and the supply temperature could also be lower during summer when the heat demand is significantly lower. The COP of 2.5 as used in this research might therefore be a bit optimistic in winter, but the COP could definitely be higher in summer when especially the TES heat pump is used a lot for charging the TES system.

The sensitivity analysis for the heat pumps explained the impact that a change in the COP and heat pump capacities might have on the performance of the energy community. In this sensitivity analysis the COP was changed to respectively 2 and 3. Based on the assumed linearly dependence of the COP on the temperature difference, these values represent respectively a realistic downgrade and upgrade of the COP. However, the seasonal variation of the COP was not included, while this would improve the quality of the analysis.

Solar thermal collectors
The sensitivity analysis for solar thermal collectors showed that the introduction of these collectors does not realize significant benefits for the energy community. However, when the tap water heat supply will be adjusted for the needed Legionella formation prevention, the temperature level in the storage vessel might be allowed to drop to lower temperatures. In that case the booster heat pump does not have to charge the vessel as soon as the temperature drops below 50 °C, which creates a larger time frame in which the solar thermal collectors can contribute to charging this vessel.

Another issue that might be in favour of the use of solar thermal collectors is that the ground heat source needed for the heat pumps might get empty. The infinite ground source of heat can still become empty locally, since a constant flow of heat is subtracted out of ground at one particular location. Solar thermal collectors can contribute to charge this source again (Miglani et al., 2017). On the other hand, heat stored in the TES system could also be used for this and the exact effect of the ground source heat pumps on the ground temperature should be further analyzed to determine the overall influence on the performance of these heat pumps over time.

7 Conclusion

Energy autarky can be interpreted as a region that 'relies on its own energy resources for generating the useful energy required to sustain the society within that region'. When this kind of autonomous energy communities can be realized, less transport of energy is needed, the load on the central grid can be reduced and the balancing of energy supply and demand can be handled locally. However, it is not clear what is needed to realize such an autarkic energy community. The research question for this research was therefore defined as "What is needed to realize an autarkic energy community in a residential area in the Netherlands?".

To answer this question the possibilities for the energy supply and storage facilities in an autarkic energy community have been determined. The demand side was formed by 500 passive houses with modelled demand profiles. The heat demand for this kind of houses is relatively low and the demand profiles are based on a Meteonorm year representing a typical Dutch weather pattern. The choice was made to include PV panels, wind turbines, solar thermal collectors, heat pumps, a large-scale underground heat storage facility, a household-scale heat storage vessel and a battery installation per household. Furthermore, a digester system in combination with gas storage and a CHP engine was included as back-up capacity during critical hours.

Aiming for autarky means a balance between demand, supply and storage has to be found. Due to seasonal and hourly variations not all generated electricity and heat can be used at the same moment. Unfortunately, it is not easy to store all the overproduction until critical hours take place, because very large storage capacities would be needed for that. The production profile of PV panels shows more seasonal variation than the production profile of wind turbines. This is why the ratio of wind and PV has a significant impact on the needed storage capacities. Demand side management could play a role in providing the needed flexibility in an autarkic energy system. However, limited data was available for the demand profiles, therefore demand side management is not included in this research.

Three scenarios are defined to analyze the performance of the autarkic energy community as designed in this research. In the first scenario, the no-energy-waste scenario, unlimited storage capacities are assumed, such that a perfect balance between energy supply and demand can be obtained. The other two scenarios are the minimum costs and minimum land use scenario and these scenarios focus, respectively, on a costs and land use optimization with a restricted battery capacity of 24 kWh per household. The results show that different configurations can be sufficient to realize an autarkic energy community. It depends on the available storage capacities how much installed capacity is needed to realize autarky and significantly more costs and land use requirements are related to an increase in installed capacity. The costs in the no-energy-waste scenario corresponded to €2144,- per household per year, while the costs in the minimum costs and minimum land use scenarios are, respectively, €2415,- and €2418,- per household per year. The land use needed for the autarkic energy community in the three scenarios is estimated to be respectively 2.7, 11.7 and 11.7 hectares for the no-energy-waste, minimum costs and minimum land use scenarios. It can be stated that the required volume needed for the storage capacity of 460 kWh per household in the no-energy-waste scenario is the limiting factor. When significantly higher storage densities would be possible, the no-energy-waste scenario would have the best overall performance.

It can be concluded that autarkic energy communities are technologically feasible and it is determined what is needed to realize such a community. However, even in the most ideal configurations, the system will have energy losses in the form of heat losses, transport losses and possibly wasted energy. Improvements in the design of the autarkic energy community might be possible when expected technological developments are taken into account and when other or more technologies are included that can provide flexibility to the balancing of energy supply and demand. In general the energetic performance of the autarkic energy community is difficult to improve since autarky does not allow any interaction with the outside world. Synergies with other energy systems could realize significant benefits. This is why Müller et al. (2011) mention that energy autarky should be used as a vision to move forwards, not as a goal on its own to isolate local regions (M. O. Müller et al., 2011).

8 Recommendations

In this research the possibilities for realizing an autarkic energy community under Dutch circumstances were analyzed. However, other system boundaries could have been chosen and other technologies could be included in this analysis to give a more complete overview of all the possibilities for autarkic energy communities in the Netherlands. Furthermore, the analyses for the performance indicators and/or other performance indicators could be used to analyze the performance of this community.

First of all, a mix of different demand profiles could be used to represent a community with different kind of houses. Furthermore, measured energy demand profiles and their corresponding weather patterns, for example in case studies at newly built houses, could be used to determine the characteristics of the demand profiles in practice. The use of heat pumps in different houses could then also be analyzed. Heat pumps have a significant contribution to the electricity demand of households, therefore the timing of the heat pump electricity demand in different households could be analyzed and included in future research. During this research FactoryZero was contacted, because they had measured demand profiles available. Unfortunately, the data sets were really big and could not be used within the time span of this research. For future research, it would be interesting to process this kind of data sets in the model. This does not only hold for the heat demand, but also for the electricity demand in communities, because there is still a lack of available data about the electricity use in energy communities (Barbour et al., 2018). Furthermore, demand side management can realize improved peak shaving in a community, such that critical hours become less critical. This can result in less installed capacity being needed to realize an autarkic energy community, therefore future research related to demand side management would be valuable as well.

Transport is not included in this research. When electric vehicles are used the electricity demand will significantly increase when these vehicles are to be charged within the community. On the other hand, these vehicles can facilitate extra storage capacity. The influence of including the transport sector in the autarkic energy community would be valuable to analyze in future research.

More flexibility facilities could be included in future research. For example, the introduction of hydrogen as energy carrier in the autarkic energy community can significantly change the needed installed capacity, because hydrogen can also be used in long-term storage facilities. When hydrogen is included in the possibilities for the autarkic energy community a more complete overview will be created. The availability of biogas that could be produced with local energy sources can also be analyzed in more detail. When more biogas is available, for example when including a farm in the community, more back-up capacity is created and less installed capacity might be needed.

The large-scale TES system used in this research is based on the Ecovat system analysis. However, significant improvements in this comparison can be made when time-dependent source and supply temperatures are taken into account for the TES heat pump. Furthermore, the Ecovat system has a modular layered system design, which prevents destratification from happening and thereby realizes high efficiencies. More research in this field can make more clear what is needed to realize an autarkic energy community in which large-scale heat storage as an Ecovat system is implemented.

Lastly, the performance of the autarkic energy community is based on a costs analysis and a land use analysis. Furthermore, a situation without waste of energy is analyzed. These analyses provided indicative values for the costs and land use needed to realize an autarkic energy community. Future research could focus on a more detailed financial or land use analysis to improve the knowledge with respect to these indicators for the performance of an autarkic energy community. For example, the possibility to place wind turbines on the same land as PV panels could be analyzed. Furthermore, other performance indicators as the willingness of people to live in such a community or the technical requirements for the electricity and heat grids needed in the autarkic energy community could be introduced. An overall energy performance could be used as performance indicator with the help of indicators as the energy returned on energy invested (EROI) or indicators related to a life cycle analysis (LCA) of all the system components included in this research.

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Appendices

A ECN demand profiles and weather data

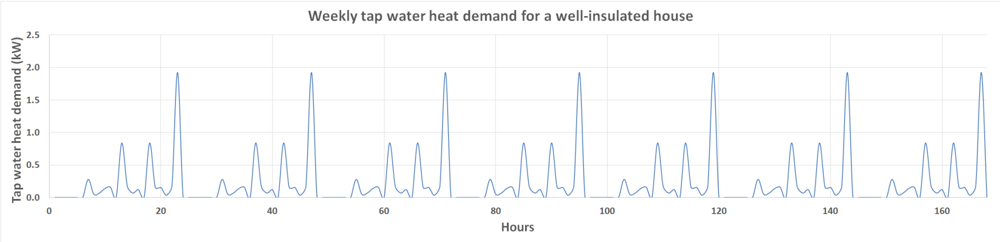

Figure 31: *Tap water heat demand profile for well-insulated houses (ECN, 2018)*

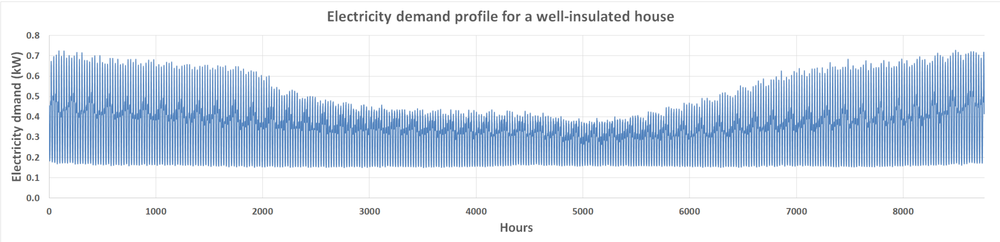

Figure 32: *Electricity demand profile for well-insulated houses (ECN, 2018)*

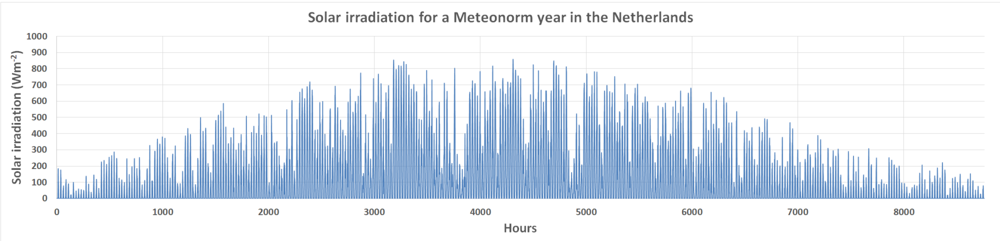

Figure 33: *Solar irradiation pattern for a Meteonorm year in the Netherlands (ECN, 2018)*

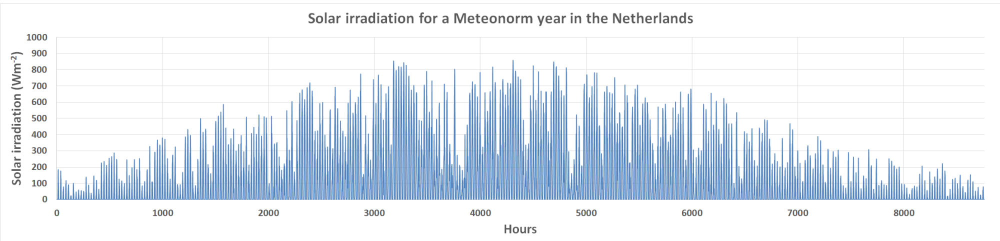

Figure 34: *Wind speed pattern for a Meteonorm year in the Netherlands (ECN, 2018)*

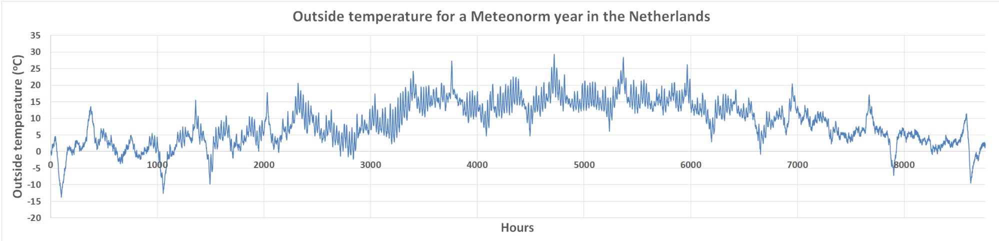

Figure 35: *Outside temperature for a Meteonorm year in the Netherlands (ECN, 2018)*

B Mathematical representation of the storage modules

Electricity storage

For the storage module, at each hour the state of the battery needs to be calculated. This state depends on the charge and (self-)discharge of the battery. In this Appendix the mathematical representation of these calculations are presented.

Oversupply wind, solar thermal and PV
As discussed in Section 4 the oversupply of wind and solar PV is initially used for charging the battery, unless the battery is already filled above the threshold level. In the storage module in the We-Energy Tool the allocation of the wind dump is determined as follows:

$$
\begin{array}{rl}
IF & State_B(T-1) < TH * Capacity_B \\
 & Charge_{w\rightarrow b} = MIN(\\
 & \quad\quad Dump_W; \\
 & \quad\quad Charge_{max}; \\
 & \quad\quad Capacity_B - (State_B(T-1) - Discharge(T-1))) \\
ELSEIF & Dump_W > Capacity_{HP} \\
 & Charge_{w\rightarrow b} = MIN(\\
 & \quad\quad Dump_W - Capacity_{HP}; \\
 & \quad\quad Charge_{max}; \\
 & \quad\quad Capacity_B - (State_B(T-1) - Discharge(T-1))) \\
ELSE & Charge_{w\rightarrow b} = 0
\end{array}
$$

Here subscript B refers to the battery, W to the electricity production by the wind turbines, HP to the TES system heat pump, $w \rightarrow b$ to the flow from the wind turbines to the battery and max refers to the maximum. Next to that, TH stand for threshold and $(T-1)$ means that quantity is determined from the previous hour in this iterative process. Important to mention; $Discharge$ refers to the total discharge of the battery, which equals the gross discharge of the battery at $T-1$ plus the self-discharge at T.

For the PV overproduction holds:

$$
\begin{array}{l}
Charge_{s\rightarrow b} = MIN(\\
\quad\quad Capacity_B - (State(T-1) - Discharge(T-1)) - Charge_{w\rightarrow b}; \\
\quad\quad Charge_{max}; \\
\quad\quad Dump_s)
\end{array}
$$

Here $s \rightarrow b$ refers to the battery charge supplied by the solar PV production. Furthermore, the PV production is especially high in summer, while the heat demand is low; the TES system will be charged anyway.

Now the battery charge has been determined. Based on the overproduction by the wind turbines and/or PV panels, there might be electricity left to charge the TES system after the battery has been charged. The amount of overproduction used to charge the TES system is determined as follows:

$$
\begin{aligned}
Charge_{w\rightarrow e} = MIN(&\\
&Dump_w - Charge_{w\rightarrow b};\\
&Capacity_{HP})
\end{aligned}
$$

Here $w \rightarrow e$ refers to the electricity production by the wind turbines that is used to charge the TES system by means of the heat pump. For the part of the PV overproduction used to charge the TES system, the following condition holds:

$$
\begin{aligned}
IF \quad & Charge_{w\rightarrow e} < Capacity_{HP}\\
& Charge_{s\rightarrow e} = MIN(\\
& \qquad Capacity_{HP} - Charge_{w\rightarrow e};\\
& \qquad Dump_s - Charge_{s\rightarrow b})\\
ELSE \quad & Charge_{s\rightarrow e} = 0
\end{aligned}
$$

The subscript $s \rightarrow e$ now refers to the overproduction by the PV panels allocated to charge the TES system.

Self-discharge of the battery

Independent of supply and demand profiles, the battery will always have a self-discharge, unless the battery is completely empty. The self-discharge at time T can be calculated with the following equation:

$$
SD(T) = \frac{State_B(T-1) - Discharge_G(T-1)}{\eta_{SD}}
$$

Here SD refers to the self-discharge of the battery and the subscript G refers to the gross discharge of the battery, while η stands for the efficiency.

Charge of the battery

The charging of the battery depends on the overproduction of renewable generation and the capacity of the battery. Furthermore, there is a maximum power for charging and it is assumed the battery starts being charged at a certain percentage of the total capacity, SC, the start condition. The amount of charging for the first hour is calculated based on the following condition:

$$
\begin{aligned}
IF \quad & P(1) - D(1) > 0\\
& Charge = MIN(\\
& \qquad CapacityB - SC;\\
& \qquad Charge_{max};\\
& \qquad P(1) - D(1))\\
ELSE \quad & Charge = 0
\end{aligned}
$$

For the following hours, at time T, the condition changes to:

$$
\begin{aligned}
IF \quad & P(T) - D(T) > 0 \;\&\; State(T-1) < Capacity_B\\
& Charge = MIN(\\
& \qquad Capacity_B - (State(T-1) - Discharge_G(T-1) - SD(T);\\
& \qquad Charge_{max};\\
& \qquad P(T) - D(T))\\
ELSE \quad & Charge = 0
\end{aligned}
$$

The last condition shows the charging depends on the state and the gross discharge of the hour before and self-discharge at the current hour. This is to prevent circular calculations. The letters P and D refer to the production and demand of electricity. For the demand the electricity supplied to the TES system heat pump is included.

State of the battery
When it comes to the state of the battery, the initial state depends on the assumption how much of the maximum capacity is occupied in the beginning, SC. The charge at the first hour is added to this, so:

$$State(1) = SC + Charge(1)$$

For the following hours, the following holds:

$$State(T) = -SD(T) + Charge(T) - Discharge_G(T-1) + State(T-1)$$

Gross discharge
The gross discharge, or the total discharge, can be calculated as follows:

$$\begin{aligned}
IF \quad & D(T) > P(T)\ \&\ State(T) > Capacity_B * (1 - DoD) \\
& Discharge_G(T) = MIN(\\
& \qquad State(T) - Capacity_B * (1 - DoD); \\
& \qquad \frac{Discharge_{max}}{\eta}; \\
& \qquad \frac{D(T) - P(T)}{\eta}); \\
ELSE \quad & Discharge_G = 0
\end{aligned}$$

Here DoD stands for the depth of discharge, so the level to which the battery can be discharged. In this case a depth of discharge equal to one, would mean the battery can be completely discharged. Then the net load of the energy system, taking into account the effect of the batteries, can be determined as follows: $Net\ load = Load\ without\ batteries + Charge - Used\ discharge$.

Here $Used\ discharge = Gross\ discharge * Efficiency$, which represents the actual useful electricity coming out of the battery; it is the amount of electricity that actually meets part of the electricity demand of the community.

Electricity shortages are prevented by using biogas as input for the CHP engine during critical hours. The electricity production by the CHP engine will start as soon as the battery reaches a certain threshold; below this threshold the electricity produced by the CHP engine will charge the battery. The produced heat by the CHP in this process is used as supply for the TES system.

$$\begin{aligned}
IF \quad & State_B(T-1) < TH_1 * Capacity_B\ OR\ (Charge_{CHP}(T-1) > 0\ \&\ State_B(T-1) < TH_2 * Capacity_B) \\
& Charge_{CHP} = MIN(\\
& \qquad BG * \eta_{CHP}; \\
& \qquad Capacity_{CHP} * \eta_{CHP}; \\
& \qquad \frac{Charge_{max}}{1 - L}) \\
ELSE \quad & Charge_{CHP} = 0
\end{aligned}$$

Here BG is the biogas stock, η_{CHP} the electric efficiency of the CHP engine and L represents the transport losses of the produced electricity. There are two thresholds included in this condition; TH_1 refers to the lower threshold, so the point at which the CHP engine should make sure the battery is charged, while TH_2 refers to the upper threshold at which the CHP engine should stop working, because more biogas than needed would be burned if the CHP engine keeps producing electricity until the battery is fully charged. The heat production by the CHP engine can simply be calculated by taking into account the electric and thermal efficiencies of the engine, η_e and η_t respectively: $P_h = P_e * \frac{\eta_t}{\eta_e}$. Here P_h refers to the heat production and P_e refers to the electricity production of the CHP engine.

Thermal energy storage

In the previous section all parts of the electricity storage module were discussed. Next to batteries, the TES system is also part of the energy buffer in the community. The electricity available for the TES heat pump, $Charge_{w\to e}$ and $Charge_{s\to e}$, are discussed above and are used as input for the thermal energy storage module. The TES system facility will also use the overproduction of the solar thermal collectors and the heat generated by the CHP engine as heat sources to be charged.

Heat supply TES system

The heat supply for charging the TES system comes from the heat pump that uses part of the overproduction of electricity, overproduction of the solar thermal collectors and heat generated by the CHP engine. The net electricity load is already calculated in the battery module. The overproduction of the collectors is calculated as follows:

$$Dump_c = Production - Charge_{c\to v}$$

In the equation above, subscript c stands for the collectors and $c \to v$ stands for the heat produced by the collectors used to charge the vessel storage.

High-temperature demand

A storage vessel with water at a temperature of 55 °C will be used at the household scale. A booster heat pump will supply the needed energy to heat the demanded tap water (HT demand) from 55 to 60 °C. The heat supply by the booster corresponds to:

$$Q_{booster} = D_{ht} * \frac{T_{ht} - T_{vessel}}{T_{ht} - Tout}$$

This gives an electricity demand of the booster heat pump of $\frac{Q_{booster}}{COP_{ht}}$. However, the booster heat pump has a maximum capacity, so a condition has to be included that accounts for this limited capacity.

$$Charge_{booster} = MIN(\frac{Q_{booster}}{COP_{ht}}; Capacity_{max})$$

The fraction of tap water heat demand supplied by the booster has now been determined. The rest of the demand is met by the heat present in the vessel storage. However, the hot water leaving the vessel has to be replaced by new water. It is assumed this water has a temperature of 15 °C, based on the information provided by the water supplier in the Netherlands, Vitens (Vitens, 2015). This means the temperature in the vessel will drop. To make sure the temperature of the vessel stays close to the desired 55 °C, the solar collectors as well as the booster heat pump can be used to charge this vessel. Priority is given to solar collectors above the booster heat pump. The amount of heat produced by the collectors per household used to charge the vessel is determined as follows, with the help of another threshold:

$$
\begin{aligned}
IF \quad & \frac{P_c}{Houses} > 0 \;\&\; (T_v(T-1) < T_{TH1} \; OR \; (Charge_c(T-1) > 0 \;\&\; T(T-1) < T_{TH2})) \\
& Charge_c = MIN(\\
& \qquad (T_{TH2} - T(T)) * V * \rho * C_{heat}; \\
& \qquad \frac{P_c}{Houses}) \\
ELSE \quad & Charge_c = 0
\end{aligned}
$$

Here P_c refers to the collectors heat production, T refers to the temperature and for this equation the small t is used for the time indication. Furthermore, $TH1$ refers to the temperature threshold of the vessel at which charging will take place. For example, when $TH1$ equals 54 °C, the collector heat will be used to charge the vessel as soon as the vessel temperature, T_v, drops below this temperature. The second threshold, $TH2$, refers the desired temperature of the vessel, so the threshold up to which charging should continue; as soon as this temperature is reached, the collectors will not charge the vessel anymore and the produced heat can be used to charge the TES system. The V, ρ and C_{heat} respectively refer to the volume, density and heat capacity of the water in the vessel.

A similar condition as for the solar collectors is used for the booster heat pump; as soon as the temperature of the vessel drops even more, below a third threshold, the booster heat pump (if not already used to supply the ht demand) will be used to charge the vessel. This third threshold is set at 50 °C.

Low-temperature demand
For the low-temperature demand, the TES system will be used. The discharge temperature of the TES system is taken to be 40 °C, corresponding to the value mentioned in the system design of TES system. This temperature is sufficient to meet the space-heating demand as long as low-temperature space-heating facilities are included in the houses. Taking into account transport losses from the TES system to the houses, the total discharge of the TES system can be determined. As long as the temperature of the TES system remains above the 40 °C all space-heating demand will be met by a supply from this storage. However, when the temperature would drop below this, the booster heat pump will take care of the space-heating demand as well. Again, this situation is not desired, because it results in a higher electricity demand, therefore the system is designed such that the temperature of the TES system does not drop too much.

Net load TES system
With the tap water and space-heating demand being discussed, the total heat demand from the TES system is known. Furthermore, the heat supply to the TES system is also determined. The net load on the TES system is calculated as follows:

$$NL_{TESsystem} = S_c * (1-L) + (Dump_w + Dump_s) * COP_{HP} + (S_{CHP} + S_{Digester}) * (1-L) - D$$

Here S refers to the supply and NL refers to net load; the other shortcuts have been explained before. The total discharge of the TES system can be determined by adding the heat loss to the net load. To be able to calculate the heat loss, the thermal resistance of the insulation surrounding the thermal energy storage has to be determined. The heat losses are discussed in Appendix D. Later on is decided to also supply the digester heat demand by a constant discharge flow out of the TES system. For this flow transport losses are also taken into account.

C Power needed for booster heat pump

In Section 3 is mentioned that a vessel storage tank is needed for the tap water supply, because the heat pump would not be able to heat water with the TES system outlet temperature in time to realize a sufficient tap water flow for, for example, a shower. The calculations behind this statement are presented in this appendix.

According to Vitens, the company that delivers the water to households in the Netherlands, a shower uses on average eight liters of water per minute. For now it is assumed this water has to be supplied by the TES system, therefore reaching the household at a temperature of 40 °C. This water has to be heated to 60 °C before it is used, because of Legionella formation issues. The amount of heat to be supplied by the heat pump can be calculated with the following equation:

$$Q = m * C * \Delta T$$

Here m represents the mass of the water, C represents the heat capacity of the water and ΔT represents the temperature difference of the particular mass. The density of water is approximately 997 kgm^{-3} and the heat capacity of water is equal to 4180 $Jkg^{-1}K^{-1}$. This results in the following needed capacity:

$$Q' = 8 * \frac{997}{1000} * 4180 * 20 \approx 7 * 10^5 \ J * min^{-1} \approx 11 \ kW$$

The $'$ makes clear the heat flow is a time derivative, because the flow is calculated per minute. From $J * min^{-1}$ to Js^{-1} can be done by dividing with the 60 seconds in a minute. This last unit is equal to the unit Watt, so dividing by 1000 gives the unit kW, in this case resulting in 11 kW. This is a very high capacity for a heat pump, especially for a booster heat pump that has to work with the high temperature of tap water. This makes clear a storage tank is needed that stores water at higher temperatures than 40 °C.

D Insulation properties

When storing heat in thermal energy storage tanks, heat losses will occur. The size of these losses determine the efficiency of the storage system and these losses depend on the thermal resistance of the insulation material on the outside of these tanks. For both the TES system as the vessel storage tank the thermal resistance of the insulation materials is determined.

TES system

The thermal resistance of the insulation material in case of the TES system is based on the cool-down test described in the thermal analysis (Ecovat Renewable Energie Technologies, 2014). With Newton's Law of Cooling the thermal resistance of the insulation configuration can be determined based on this cool-down test. This law results in the following temperature as function of time:

$$T(t) = T_a + (T_0 - T_a) * e^{ct}$$

When the initial temperature, T_0, the temperature of the ambient environment T_a and the temperature at time t are known, the constant c can be determined. This constant has the unit 'per time unit', for instance being per hour when the time is measured in hours.

$$c = \frac{ln(\frac{T(t)-T_a}{T_0-T_a})}{t}$$

Vessel storage tank

For the vessel tank the assumption will be made it is insulated by PUR or PIR foam. These foams have a thermal conductivity of approximately 0.026 $Wm^{-1}K^{-1}$. Based on the technical specifications of the Factory Zero storage vessel a volume of 200 liter will be used for the vessel storage tank (Factory Zero, 2019). Some radii are for the cylindrical vessel were tried for a realistic configuration and for a radius of 0.2 meter, the height would be:

$$H = \frac{V}{\pi * r^2} = 1.59...meter$$

The heat flows through the insulation surrounding this vessel depend on the thickness of the insulation. For simplicity, it is assumed that the top and bottom insulation parts of the vessel are also cylindrical, having the same outer radius as the cylindrical insulation on the side of the vessel. Furthermore, it is assumed that the heat flow through the top and bottom insulation parts is the same at all places of these insulation parts, while in reality this will not be true. The numbered corners in Figure 36 are not in direct contact with the vessel, therefore a smaller heat flow will occur in these corners. However, assuming a vertical heat flow similar as in the other parts of the top/bottom insulation parts will resulting in a total heat loss that is just a little bit larger than in reality.

The thermal resistance of the top and bottom insulation can be determined with the following equation (Bejan, 1993):

$$R = \frac{d}{k * A}$$

Here R is the thermal resistance in Kelvin per Watt, d is the thickness of the insulation parts and A is the surface area of the plane perpendicular to the heat flow, being $\pi * r^2$ with r being the radius of these insulation parts.

For the insulation on the side of the vessel, the thermal resistance can be calculated with the following equation (Bejan, 1993):

$$R = \frac{ln(\frac{r_2}{r_1})}{2 * \pi * k * H}$$

Here r_2 refers to the outer radius of this insulation part, r_1 refers to the inner radius of this part, k is the thermal conductivity and H represents the height of the cylinder.

Based on the dimensions of the insulation, by assuming a thickness of 5 cm, the thermal resistances of all three parts can be calculated. Assuming an initial water temperature of 55 °C and an outside temperature of 15 °C, for example in the garage, the temperature difference is known and the heat flows can be calculated with the following equation (Bejan, 1993):

$$Q = \frac{\Delta T}{R}$$

When the heat loss through each part of insulation is determined, the total heat loss can be determined as well. Based on these losses, the decrease of the water temperature in the vessel can be determined and the same steps can be executed again. With this iterative process the temperature of the water in the vessel can be determined as a function of time. This provides the same information that was also available for the TES system thermodynamic analysis, therefore the thermal resistance as used in Newton's Law of Cooling can also be determined for the vessel insulation. As a result, the temperature change for the TES system as well as for the vessel system can both be calculated based on the same Law of Cooling, only with a different value for c, the thermal resistance in this equation.

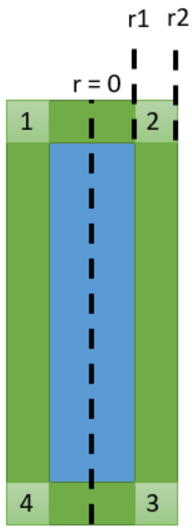

Figure 36: *Configuration of the vessel insulation*

E Sankey diagram lowest costs scenario

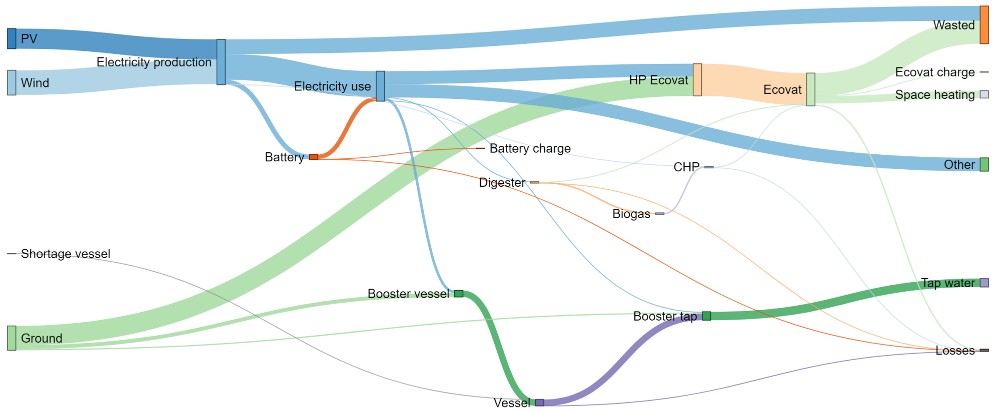

Figure 37: *Sankey diagram for the minimum costs scenario*

F Biogas storage

The needed biogas storage in the autarkic energy community depends on the biogas demand by the CHP engine and the commulative produced biogas over the year. It is assumed that the digester works as a base load and that the same amount of biogas is produced at each hour of the year. The total biogas storage needed is almost 10,000 m^3 at atmospheric pressure. The biogas stock variation over the year is presented for the minimum costs configuration in the minimum costs scenario in Figure 38.

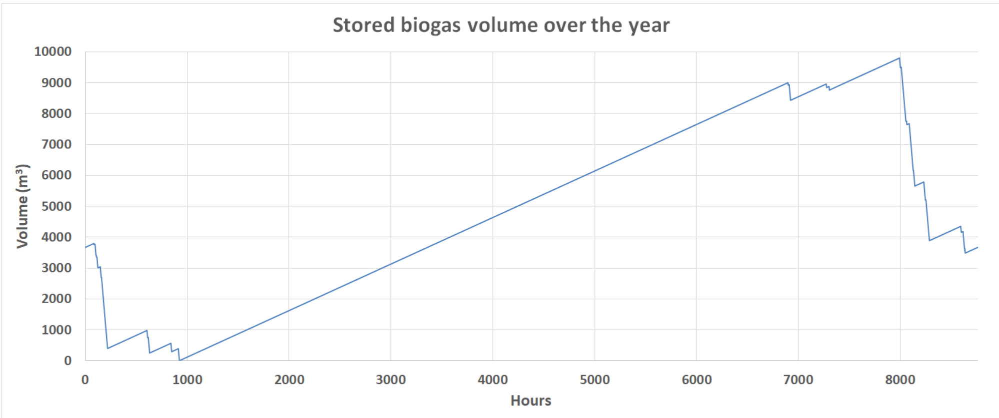

Figure 38: *Stored biogas volume over the year in the minimum costs scenario*