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MSc thesis Energy Science

Who is going to pay?

On the utility death spiral and grid defection in the Netherlands

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1. Abstract

Recent years have shown a rapid decline in the costs of solar photovoltaics (PV) and similar cost reductions for battery energy storage systems (BESS) are expected. This has led to social and academic discussions on the possibility of installing PV + battery systems to be fully self-sufficient in energy supply and to defect from the grid, to avoid high grid fees. Concerns arise that if grid defection occurs, the electricity price increases significantly, pushing more consumers to defect from the grid. This feedback loop has been termed 'the utility death spiral'.

Previous grid defection studies were conducted in regions with high solar irradiance throughout the year. In this study, the technical feasibility and economic viability of electricity grid defection was researched for individual households in the Netherlands, where solar radiation is significantly lower. In order to cover electricity supply in longer periods of little solar irradiance, a PV+BESS system alone would require a battery that is too large to be technical feasible, let alone be economically viable. Therefore, a micro combined heat and power (µCHP) unit is added to supply electricity (and heat) during the darker seasons.

By developing a Matlab model, the levelized costs of electricity (LCOE) of optimally sized PV+BESS+µCHP systems have been calculated for 16 dwelling types in 12 provinces, for the years 2017 to 2050. These LCOE's were compared to the electricity prices to find the economic viability of grid defection per household type. Various scenario- and sensitivity -analyses were carried out over critical parameters such as technology costs and decision criteria, to find their influence on the possible grid defection rate and its impact on society.

The results show that disconnecting from the grid is not the most favorable option yet, but off-grid systems can reach grid parity in 2037 and onwards, depending on the household type. The household types that have the most attractive business case to go off-grid are flats and apartments, even though there is less rooftop surface available for PV.

The policy implication of this study is that from both economic and socially desirable perspectives, widespread disconnection might not be a realistic projection of the future. Given the plans of the Dutch government to phase out natural gas consumption in the built environment, the adoption of µCHP units is not likely to be stimulated. Other future possibilities that can trigger massive defection from the electricity grid include joint grid defection of multiple households and developments in new forms of distributed generation at household level.

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3. Introduction

3.1. Background

The utility death spiral was already introduced during the 1970's, but only first framed as such in the 1980's. In the global energy sector, these two decades are marked by a surge in fossil fuel prices due to the 1973 and 1979 oil crises. Secondly, growing environmental concerns led to stricter policies on water and air emissions from power plants. These factors led to large utility construction projects such as investments in expensive nuclear reactors and safer and cleaner fossil fuel power plants. As a result, these construction programs caused higher electricity prices, which were needed to cover the increased fixed costs for utilities (Joskow, Bohi, & Gollop, 1989). At the same time, electricity consumption did not grow as expected, but actually declined due to energy efficiency investments in households and industries. Concerns rose that due to this decrease in power demand, the expected revenues from electricity sales would not be realized. This in turn would then force the utilities to further increase the electricity prices to pay off their investments or to find another way to avoid structural financial problems. The scenario in which electricity prices would keep rising and electricity consumption from utilities would keep falling was coined the utility death spiral.

Although this scenario of a wide-spread utility death spiral did not take place, utilities did face economically tough times in the years after the large power supply construction projects. However, regulatory changes created a more competitive environment for utilities by giving consumers the option to choose their preferred utility. In the US and later also in Europe, utilities had to split themselves in two entities, divided between generation and distribution of electricity. A free market system of electricity supply shifted the risks of high costs of capacity from consumers to investors. Secondly, the electricity demand started rising again, since the cheapest energy efficiency improvements were implemented and the number of electricity consuming appliances per household kept increasing (de Almeda, Fonseca, Schlomann, & Feilberg, 2011).

3.2. Research problem – Grid defection

Recently, the utility death spiral has made its return amongst politicians, reporters and researchers. This time around, the threat does not come from utility investments in large and costly central generation capacity, but instead from the growth of decentralized generation capacity. Over the last years, the amount of distributed generation (DG) capacity has increased rapidly, with (rooftop) solar photovoltaics (PV) as its most prevalent technology among households. The costs of solar PV installations have been declining and are expected to keep falling in the future (Fraunhofer Institute for Solar Energy Systems, 2016). Currently, the excess energy that is produced during sunny hours is sent back to the grid, but battery energy storage systems (BESS) are becoming more economically viable. With a combination of PV and BESS, solar power can be stored in the battery to be consumed during the nights and during cloudy days. Such a combined system helps households to reduce a significant part of their consumption from the electricity grid.

Although a lower energy consumption from the grids ensures a lower energy bill for the consumers, there is a part of the energy costs that is fixed and does not vary with consumption. These fixed costs consist of grid fees and fixed supply costs. This means that reducing the energy consumption entails relatively higher fixed costs in proportion to the wholesale price and taxes for energy, which are variable. Following research of Khalilpour & Vassallo (2015) and Kantamneni et al (2016), this study examines the possibilities for home owners to completely eliminate energy costs including their grid fees and other fixed costs, by defecting from the grid. The grid fees or network costs are paid to the distribution system operators (DSOs). These operators are in charge of maintaining the quality of the electricity grid. The current increasing penetration of distributed PV on the grid can create higher risks of reverse power flow, overvoltage and voltage unbalance (Haque & Wolfs, 2016). Combined with an increased adoption of electric vehicles, this increases the need for investments in the grid either to reinforce the network to support higher peak flows or to implement more smart grid components.

Currently, the network costs are socialized, which means that they are borne by all the connected consumers. In the case of grid defection, when consumers would choose to disconnect from the electricity grid, the DSO will be dependent on a smaller group of ratepayers. Initially, the overall network costs do not decrease with the amount of grid-leavers, since the same maintenance and upgrades are required for neighborhoods with a few disconnected households as with neighborhoods that are fully connected. A predictable measure for the DSOs would be to raise the grid fees for consumers, in order to socialize the investments that are needed to ensure a stable and reliable grid. The rising grid fees can induce a positive feedback loop between the net electricity price and the rate of households reducing their consumption from the grid. Eventually, the high fixed costs can cause consumers to leave the grid. In this scenario of massive grid defection, consumers that are not able or willing to disconnect themselves from the grid can be left with higher and higher energy costs, far exceeding their current energy bills. This can introduce a collapse of the DSO's and their grids, thereby destabilizing the electricity supply.

3.3. Previous research

Multiple studies have researched the topic of grid defection (Bronski et al., 2014; Graffy & Kihm, 2014; Kantamneni et al., 2016; Khalilpour & Vassallo, 2015; Laws, Epps, Peterson, Laser, & Wanjiru, 2017; Mundada, Shah, & Pearce, 2016; Zinaman et al., 2015). One of the main conclusions that can be derived from literature regarding the subject is that massive grid defection is unlikely to happen within a few years. However, studies also state that there already is a technical potential for households to be fully self-sufficient in their electricity supply. These studies have been conducted in regions with more solar irradiance than in the Netherlands, such as Australia, California and Hawaii. There, a combination of solar photovoltaics (PV) and battery energy storage systems (BESS) can be used to generate electricity during the day and to store the excess electricity to be consumed during the night or on cloudy days.

In the Netherlands, the subject of grid defection has not been researched yet, since less solar irradiance reduces the potential of households defecting from the electricity grid in a similar manner. However, in the near future, economic barriers are expected to be lowered due to decreasing PV and BESS costs and the possible removal of net metering. This gives reason to explore the possibilities of grid defection in the Netherlands. Secondly, in the reviewed literature, there is a distinction between different types of households and their annual income (Kantamneni et al., 2016), but less distinction on how the potential of grid defection varies with different types of dwellings. Finally, a massive grid defection scenario is often associated with high electricity costs for the remaining connections on the grid and losses of revenue for electricity suppliers and DSO's. However, less has been written on impact on other segments of society, such as the emissions of CO_2, for example.

3.4. Research question

Given these gaps in the literature, this thesis would have preferably researched the expected rate at which households in the Netherlands will leave the electricity grid, separated per region and per dwelling type. This would give policymakers insights in how to prevent an underprivileged minority of the population to be saddled with the network costs of the grid. However, to make such a prediction, there would be a need for current grid defection rates and the criteria for households to disconnect their electricity connections. Since no publicly available data can be found on the current defection rates in the Netherlands, an accurate prediction seems unrealistic. From interviews with 2 of the 3 largest DSO's it seems that the grid defection rate in the Netherlands is not actively measured or monitored by the DSO's. Furthermore, the decision for a household to disconnect from the grid is influenced by factors besides cost savings, such as a desire for convenience and reliability. Furthermore, the available knowledge and affection for technology also play a role. Still, information on the economic feasibility of households to defect from the grid can help policymakers by showing what the potential rate of grid defection could be. With adapted scenarios, this rate can then be converted to more accurate and realistic predictions of the actual grid defection rate. Therefore, the research question of this master thesis was:

"What is the feasibility of massive household defection from the electricity grid in the Netherlands and what would be its impact?"

To answer this research question, the following sub-questions will be answered:

1. What are drivers for the technical feasibility and economic viability of grid defection for a household?

2. Which types of households can be determined in the Netherlands, and how can they be categorized in terms of potential for grid defection?

3. Which performance indicators are relevant to assess the impact of grid defection?

4. How can the results from sub-questions 1, 2 and 3 be simulated in a workable model to estimate the overall feasibility of massive household grid defection in the Netherlands and the threat of a utility death spiral?

5. What is the impact of massive grid defection, based on performance indicators derived in sub-question 3?

3.5. Reading guide

The next chapter of this report contains the background theory that is used to form the research questions and construct the conceptual framework. This is followed by the methods chapter in which the application of the conceptual framework is explained. Then, the results chapter shows the answers to the research questions, to be followed by the conclusion and discussion, in which the implications of the research and options for further research are discussed. Figure 3.1 shows a visualization of this reading guide.

Subject	**Chapter**
Literature study on grid defection and utility death spiral	Introduction
Research questions	
Concepts from literature + specific concepts for this research	Theory
Conceptual framework	
Application of conceptual framework to answer research questions	Methods
Answers to research questions	Results / Conclusion / Discussion
Implications of answers to the research questions	

Figure 3.1. Framework of this research paper

4. Theory

This chapter of the report expands on the concepts that were introduced in the sub questions. It elaborates on the technical feasibility and economic viability of households to defect from the grid, the difference in the Dutch households and the impacts of (massive grid) defection. For these four concepts, an exploratory literature study was conducted to build a research framework. The methodology chapter describes in more detail how this research framework was applied.

4.1. Technical feasibility of grid defection

The first sub question concerns the technical feasibility of grid defection on a household level. An exploratory literature study was conducted to identify the options that are available for a Dutch household to disconnect from the electricity network, while keeping the amount of electricity consumption at least equal to its current consumption. To do so, the household must use a certain technology or combination of technologies to provide in its own electricity consumption. Therefore, the amount of consumed electricity is used to assess the feasibility of household grid defection. Another criterion that an off-grid system must meet, is a stored amount of electricity that can satisfy the household's electricity demand of several days. This is required to compensate for periods in which no electricity can be generated.

Although no studies have been found researching household grid defection in the Netherlands, there is a growing body of research in this field globally. (Bronski et al., 2014; Jonas, Flannery, & Radcliff, 2014; Kantamneni et al., 2016; Khalilpour & Vassallo, 2015; Laws et al., 2017; Mundada et al., 2016; Shah, Mundada, & Pearce, 2015; Speidel & Bräunl, 2016). In the reviewed literature, a distinction can be made in two fields. The first is the combination of technologies that is assessed, and the second is the region in which the study is conducted. Table 4.1 shows an overview of the reviewed studies, with the applied technology for a household grid defection system and the regions in which the (case) studies were conducted.

Authors	Technology	Region
Laws et al. (2017)	PV+BESS	Los Angeles, California; Sydney, Australia; Boulder, Colorado
Alyousef et al. (2016)	PV+BESS	Germany
Kantamneni et al. (2016)	PV+BESS+µCHP	Upper Peninsula, Michigan
Mason & Miller (2016)	PV+BESS	Christchurch, New Zealand
Mundada et al. (2016)	PV+BESS+µCHP	Houghton, Michigan
Speidel & Bräunl (2016)	PV+BESS	Ridgefield, Australia
Khalilpour & Vassallo (2015)	PV+BESS	Sydney, Australia
Shah et al. (2015)	PV+BESS+µCHP	Prescott, Arizona; Sacramento, California; Houghton, Michigan
Jonas et al. (2014)	PV+BESS	US
Graffy & Kihm (2014)	PV+BESS	US
Bronski et al. (2014)	PV+BESS	New York, Kentucky, Texas, California, Hawaii

Table 4.1. Overview of the reviewed studies on the topic of grid defection

From literature, it can be concluded that there are two combinations of technologies that are used in the research on grid defection. The first is a combination of solar photovoltaics (PV) and a battery energy storage system (BESS). A mix of PV and BESS is used to generate electricity during the day and to store the excess electricity to be consumed during the night or on cloudy days. The second combination includes a micro combined heat and power (µCHP) unit. In a PV + BESS + µCHP system, the solar energy is harnessed and excess electricity is stored in the battery. The µCHP component is used as a backup to generate electricity in the darker season when the battery is low on capacity and no solar energy can be transformed into electricity.

The regions in which the study is conducted and the technologies that are applied are related. . shows that the studies that researched the feasibility of grid defection in a northern area like Michigan, are all using a PV+BESS+µCHP system, except for Alyousef et al. (2016). That research states that grid defection with PV+BESS only is not feasible in Germany. The first conclusion of the authors of the articles with a PV+BESS+µCHP is also that a PV+BESS combination in colder climates with longer periods of little solar irradiance would require a battery that is too large to be technically feasible, given the limits of available space in most households (Kantamneni et al., 2016; Mundada et al., 2016; Shah et al., 2015). As the name implies, the µCHP also produces heat. This is extra beneficial in colder areas, since periods with less solar irradiance correlate with a higher heat demand.

The following paragraphs elaborate on PV, BESS and µCHP technologies and their influence on the feasibility of grid defection for a Dutch household.

4.1.1. Solar photovoltaics

The recent years have known a global surge in the installed capacity of solar photovoltaics. In the Netherlands, this has not been different. While the installed capacity of residential rooftop PV was 65-90 MW in 2010, by the end of 2015 this figure reached higher than 1 GW (CBS, 2016c, 2016e). This is by far the most prevalent technology that is applied to distributed electricity generation on household level.

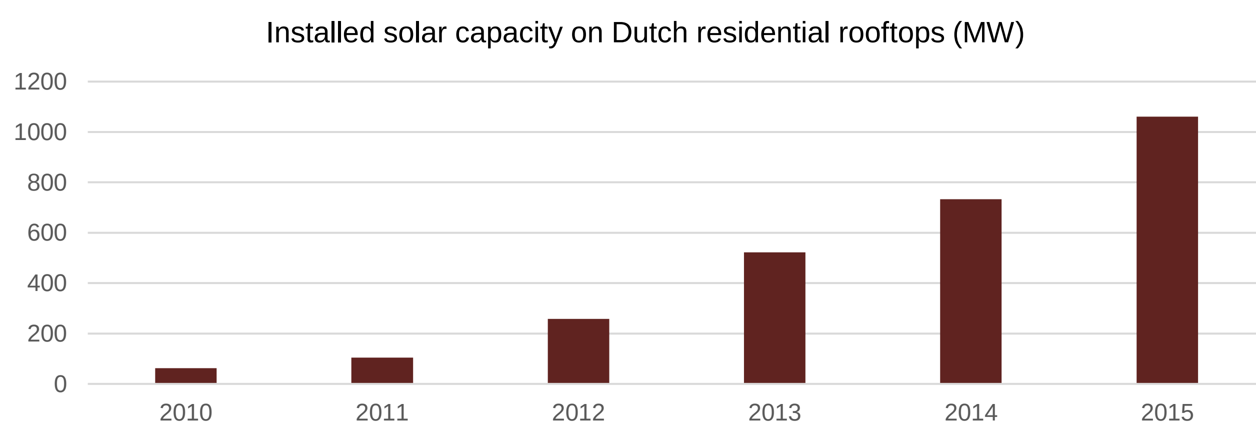

Figure 4.1. Installed capacity of residential rooftop solar power in the Netherlands

There are various solar module technologies, which in turn have different types of solar cells. The most common technologies in the Netherlands are monocrystalline silicon, polycrystalline silicon and thin-film silicon modules. The efficiency of the solar modules also influences the feasibility of solar photovoltaics for grid defection. This efficiency represents the amount of power that can be generated from the solar irradiance and has also increased vastly over the years. Research from the American national center for photovoltaics shows this increase in efficiency for a wide variety in solar cell module technologies (NCPV, 2017), as depicted in Figure 4.2. Expectations are that solar cell efficiency will continue to improve, which increases the potential of households to use this technology to go off-grid.

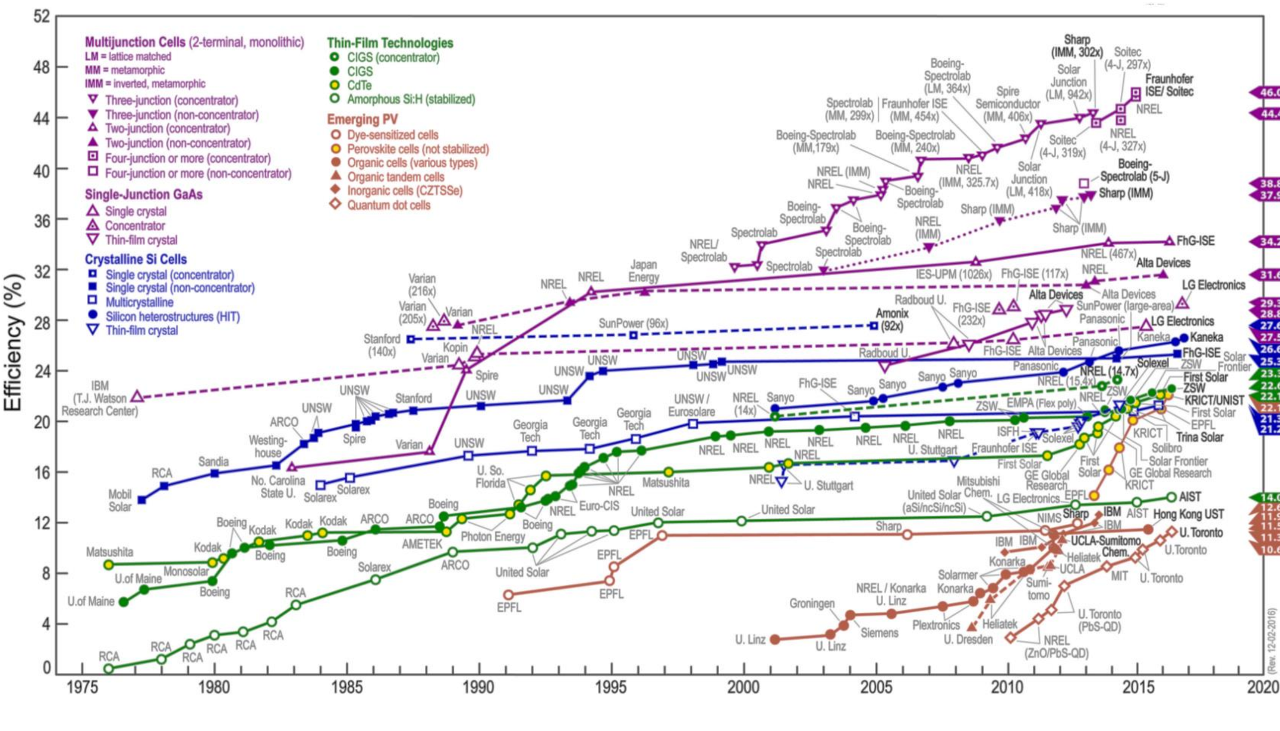

Figure 4.2. The efficiency of solar modules, separated per technology and type of cell (NCPV, 2017)

4.1.2. Battery energy storage systems

Similar to PV, there is a wide variety of different battery technologies that are suitable for residential electricity storage. Examples are lead-acid, lithium-ion (Li-ion), Nickel–cadmium (NiCd), sodium-sulphur (NaS) and Nickel metal hydride (NiMH). Currently, lead-acid batteries are seen as the most mature storage technique, but lithium-ion batteries are expected to have the greatest potential for future development and optimization (Naumann, Karl, Truong, Jossen, & Hesse, 2015). The Li-ion technology is characterized by high storage efficiency as well as high energy density (Divya & Østergaard, 2009; Gallo, Simões-moreira, Costa, Santos, & Moutinho, 2016). Moreover, developments in the electric automotive industry are rapidly increasing the cumulative production of Li-ion batteries. Although the potential for battery energy storage systems is high, the technology has not seen the same explosive growth as PV in the residential sector.

For the technical feasibility of BESS for grid defection, the depth of discharge (DoD) is also an important metric. This is the maximum percentage of a battery capacity that can be used. If a battery is discharged below this threshold, an irreversible capacity decrease can occur. Currently a safe DoD for Li-ion batteries is 80% (Ghiassi-farrokhfal, Keshav, & Rosenberg, 2015). Furthermore, in a fully self-sufficient electricity system, the battery has to provide for the whole power consumption of a household when there is no solar energy available. Therefore, to be technical feasible for an off-grid system, the BESS has to be able to output the maximum power load of the household. Finally, the battery charge and discharge efficiencies have to be taken into account while determining this technology's potential to be feasible in an off-grid situation. For a Li-ion battery, these values are around 85% and 100%, respectively (Wang, Ren, Sivasubramaniam, Urgaonkar, & Fathy, 2012).

4.1.3. Micro combined heat and power systems

Micro combined heat and power (μCHP) systems for homes or small commercial buildings are fueled by natural gas to produce electricity and heat. Generally, there are two types of μCHP technologies, fuel cells and heat engines. In the fuel cell technology, the natural gas is first reformed to hydrogen, which then chemically reacts with an oxidant such as liquid oxygen, to convert directly and continuously into electricity and heat. In the heat engine CHP technology, a Stirling engine is used to combust the natural gas to generate heat, while also driving a dynamo to generate electricity.

In the Netherlands, the Stirling engine μCHP is the most applied technology (ECN, 2008). In the Dutch power sector, CHP represents 38% of the total installed electricity generating capacity (CBS, 2016a). In households however, the adoption rate of μCHP technology is not similar. A study by the Intelligent Energy Europe Program of the European Union (CODE2, 2014) calculated a minimal potential in the Dutch market of 2.250.000 household μCHP units.

A μCHP may primarily follow heat demand, delivering electricity as the by-product, or it may follow electrical demand to generate electricity, so that heat is the by-product. A μCHP unit has an electrical and a thermal efficiency. To determine the feasibility of an off-grid system that uses μCHP, the electrical efficiency parameter is the most important, since this determines what size the μCHP unit must be to supply the dwelling's maximum power load.

4.2. Economic viability of grid defection

Although the general consensus of the reviewed literature is that it is technically feasible for households to defect from the grid, most studies state that it is not (yet) economically viable. To be economically viable, the off-grid system (PV+BESS or PV+BESS+μCHP) must at least reach grid parity. Grid parity means that a system can generate power at a cost that is less or equal to the price of power from the grid (Breyer & Gerlach, 2013). For the cost of power, the LCOE is often used. This is the total cost to build and operate a power-generating unit over its lifetime, divided by its total energy output over that lifetime (Mundada et al., 2016). Included in the LCOE calculation are the investment costs, replacement costs and operation & maintenance costs, which include fuel costs, if applicable. These costs are discounted to their present value by using a discount rate, after which the total levelized sum is divided by the total energy output of the system over its lifetime. This results in a unit that can be compared to the electricity price (€ / kWh) to see whether or not grid parity has been reached. In general, the equation to calculate the LCOE is formulized as follows:

$$LCOE = \frac{I + \sum_{n=1}^{L} \frac{O_n + R_n}{(1+r)^n}}{\sum_{n=1}^{L} \frac{E}{(1+r)^n}}$$

Equation 1. General calculation of the LCOE

I = Investment costs of technology (PV, BESS and μCHP)
L = Lifetime over which the LCOE is calculated
O_n = Annual operation and maintenance costs in year n
R_n = Replacement costs in year n
r = Discount rate
E_n = Energy generation in year n

4.2.1. Investment costs

The first economic barrier that currently impedes a household's disconnection from the electricity grid is the required high investment costs that are involved. However, both the PV and BESS technologies are undergoing significant price drops, as can be seen from their learning curves, or experience curves. A learning curve represents a fixed percentage cost decrease for each doubling of the total quantity of items produced (Breyer & Gerlach, 2013).

4.2.1.1. Solar photovoltaics

The global increase in solar panel production has decreased the costs for solar power tremendously through economies of scale and technological improvements. Over the last 35 years, the solar panel module price decreased by 23% with each doubling of the cumulative module production (Fraunhofer Institute for Solar Energy Systems, 2016). On average, this resulted in an annual cost reduction of 9%. In the Netherlands, the prices of PV modules vary per type and quantity of modules. Besides the costs of the solar module, there are also costs for the required inverter, which converts the AC power from the modules to DC power that can be used in homes. Furthermore, soft costs that cover labor costs for the installation and potential permit fees must be included. In general the PV price is stated in € / kWp, which stands for kilowatt-peak, the nominal power of PV modules under standard test conditions. On average, the total costs per installed kWp in the Netherlands in 2016 was € 1.860 per kWp, which include the required inverter and soft costs (Van Sark & Schoen, 2016). From the learning curves, these costs are expected to continue to decrease.

4.2.1.2. Battery energy storage systems

Although many households have already adopted solar PV modules (see Figure 4.1), adding a battery system is a costly undertaking. The costs of BESS are most often expressed in € / kWh of storage capacity. In 2010, a battery unit costed roughly € 2.000 per kWh (Bronski et al., 2014). A typical Dutch household consumes 3300 kWh of electricity per year, which can be translated to roughly 10 kWh per day for a high-demand day. If the off-grid system would be required to supply this household's power for two days, a unit of at least € 40.000 would be required. Similar to solar power, there are hardware costs as well as soft costs involved in the purchasing of battery system. The costs of an inverter that is also needed for the battery system, were not included in the aforementioned price figure, just as the installation costs. However, most residential batteries that are combined with PV are using the PV inverter instead.

In 2015, Tesla Motors Inc. announced the Powerwall, a lithium-ion BESS developed for residential PV systems, available in 2016/2017 at about € 500 per kWh, a much lower cost than anticipated. In the Netherlands, in early 2017, a Tesla Powerwall costs € 7.500 for a 14 kWh residential battery, including inverter and installation costs (Tesla, 2017). This comes down to approximately € 535 per kWh. Other Li-ion batteries show similar prices. Although no extensive research has been found on the learning curves of residential battery technologies, a study on Li-ion battery packs for electric vehicles shows an annual price decrease of 8% for this battery technology (Nykvist & Nilsson, 2015).

4.2.1.3. Micro combined heat and power systems

In the studies to grid defection that use a PV+BESS+µCHP system, the investment costs of µCHP are given in € / kWe, which stands for the maximum electric power that µCHP can supply. Currently, there are little options of µCHP on the market in the Netherlands, as several brands have stated to be starting in 2017 (MTT, 2017). Therefore, little information is available for Dutch investment costs per kWe. A German market study stated a minimum of € 2.630 / kWe in 2007. In the research of Mundada et al. (2016) and Kantamneni et al. (2016), a price of $ 1.400 / kWe is used for 2016. Little research has been found on future costs of µCHP, and Mundada et al. (2016) assume that the investment costs remain constant.

4.2.2. Replacement costs

Besides the initial investment costs, the replacement costs of system components are also important to take into account to assess the economic viability of grid defection. For the PV technologies, a lifetime of 30 years is often used in research (Branker, Pathak, & Pearce, 2011). The required inverter has a shorter lifetime of 10 years, which means that at year 10 and year 20 of the system, a new inverter must be purchased.

The relatively low estimated lifetime BESS currently a disadvantage for the potential of grid defection. The lifetime of Li-ion BESS is on average 10 years with 100% capacity (Alyousef et al., 2016). This means that similar to the PV inverter, there is a need for re-investing in battery capacity every 10 years.

The µCHP has a lifetime of approximately 15 years (EA Technology, 2001), which means it should be replaced 1 time during a 30-year lifetime of the whole system.

4.2.3. Operation & maintenance costs

The operation and maintenance costs of a PV+BESS+µCHP system are also to be taken into account, when determining the LCOE. For the PV system, a study from 2005 found that annual O&M costs of off-grid residential PV systems were equal to 5% of the investment costs of those systems, but that O&M costs were declining (Canada, Moore, Post, & Strachan, 2005). More recent studies use annual O&M costs of 1% of the investment costs of PV systems (Ameli & Kammen, 2014).

For BESS, little maintenance is required, and there are also no operation costs. An annual cost figure of 0.5% of the investment costs can be found in literature (Electric Power Research Institute, 2010; Obi, Jensen, Ferris, & Bass, 2017).

µCHP systems also require moderate maintenance costs in the range of 1% of the investment costs annually (González-pino, Campos-celador, Pérez-iribarren, Terés-zubiaga, & Sala, 2014; Mundada et al., 2016). However, the operation costs are higher, since the µCHP is consuming fuel, natural gas. The costs of natural gas consumed are variable and scale with the electricity output of the µCHP unit.

4.2.4. Discount rate

The choice of discount rate can vary depending on the location, the lifetime of the project and the technologies being used based on investors' perception of financial risk (Mundada et al., 2016). From literature, a wide range of discount rates exists for consumers that invest in energy efficiency home improvements. These discount rates range from 3% to 70% (Hanstad, Blumstein, & Stoft, 1995; Train, 1985). In their research to the LCOE of a PV+BESS+µCHP system, Mundada et al. (2016) used a discount rate of 3%.

4.2.5. Electricity price

To compare the LCOE of a grid defection system to the electricity price, it is important to know the electricity pricing structure. Since the LCOE takes all costs of electricity into account, a fair comparison to the electricity price would require all costs involved in electricity from the grid as well. The Dutch prices of electricity for households are made up of multiple components, which can be summarized as 1) the wholesale price, 2) an energy tax, 3) a levy for renewable energy, 4) fixed supply costs (vastrecht in Dutch), 5) grid fees and 6), a fixed annual reduction of the energy tax. Table 4.2 shows the breakdown of the total annual costs of electricity. Components 4, 5 and 6 are fixed costs that are not influenced by the amount of consumption, while the other price components are variable costs. Besides the energy tax and the levy for renewable energy, the value added tax is charged on all of the six components.

Price component	Fixed/variable?
1. Wholesale price	Variable
2. Energy tax	Variable
3. Levy for renewable energy	Variable
Retail price (inc. VAT)	**Variable**
4. Fixed supply costs	Fixed
5. Grid fees	Fixed
6. Energy tax reduction	Fixed
Total Fixed costs (inc. VAT)	**Fixed**

Table 4.2. Breakdown of the costs of electricity from the Dutch electricity grid

The electricity wholesale price and the fixed supply costs are determined by the electricity suppliers, of which there are over 30 in the Netherlands (Energieleveranciers, 2017). These suppliers base their wholesale prices on their costs of electricity production. Changes in fuel prices or the carbon tax have an impact on the wholesale price that is charged on consumers.

The energy tax is an environmental tax, charged by the Dutch government to incentivize the reduction of energy consumption. The levy for renewable energy which is also charged by the Dutch government, is used to encourage and subsidize generation of renewable energy.

The grid fees are charged by the distribution system operators (DSO's). There are 7 DSO's on the Dutch electricity grid, which all have a regional monopoly. The DSO's are government owned and regulated by the ACM (Authority Consumer and Market), so that grid fees are always below a maximum.

The energy tax reduction is supplied by the government, since energy is considered an essential good that has to be available for all consumers (Belastingdienst, 2017). This reduction is supplied to compensate both the energy tax on electricity consumption and the energy tax on natural gas consumption. Finally, the value added tax of 21% is charged over all aforementioned cost components.

As there are variable costs involved, the final costs per kWh depend on the amount of electricity (in kWh) consumed per year. The example in Figure 4.3 shows the breakdown of the electricity costs for a typical household with an annual electricity consumption of 3300 kWh. In this case, half of the energy tax reduction is subtracted from the energy tax costs. The largest contributers to the electricity bill are the wholesale price, the energy tax, the grid fees and value added taxes.

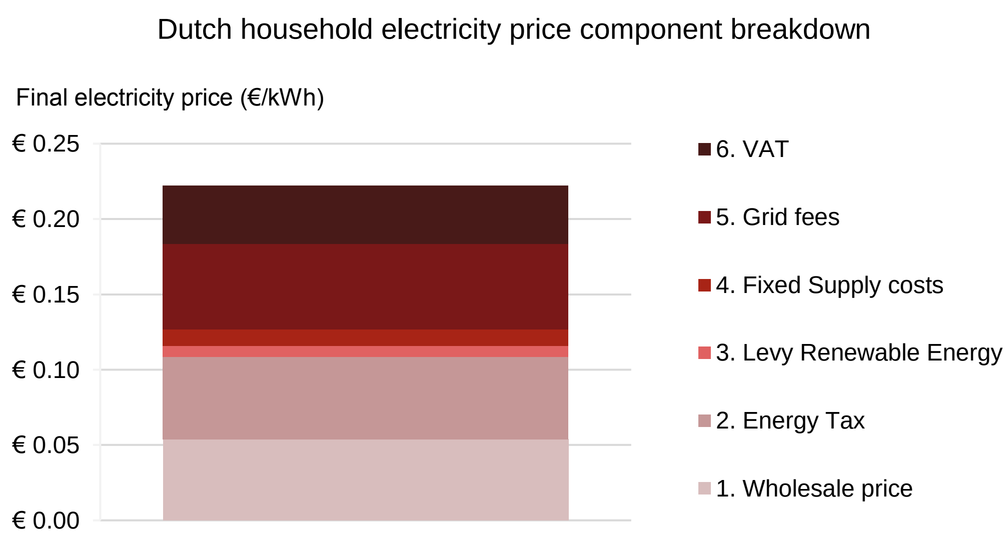

Figure 4.3. Breakdown of the cost components of electricity from the Dutch electricity grid

4.3. Household types

The technical feasibility and economic viability to defect from the grid do not only differ per combination of technologies that is applied or the region in which the household is located. The type of the household in question also influences these factors greatly. There are two main distinctions that can be made in the household type. The first is the dwelling type in which the household lives and the second are the socio-demographic properties of the household itself.

Different types of dwellings can have different potential for grid defection. Especially for the amount of roof surface available for PV, the type and age of the dwelling play an important role. In the Netherlands, in general a distinction can be made between a multi-family residential (35% of households) dwelling and a single-family residential dwelling (65% of households) (CBS, 2016d). The first category typically consists of flats and apartment buildings, while the second category can be subdivided into detached houses, semi-detached houses and terraced houses. Additionally, for the age of the dwelling, the report 'example dwellings of the current building stock 2011' uses 4 building periods; building years until 1964, 1965-1974, 1975-1991 and building years after 1991 (RVO, 2011).

Furthermore, as can be seen from the reviewed literature, the region in which the dwelling is located is also important. Even within a small country as the Netherlands, different regions have different solar radiation profiles during the year (Stichting Montitoring Zonnestroom, 2014).

From the household socio-demographic properties, the most important variables are the household composition, the household income, and the home-ownership status of the household. The household composition plays a significant role in the electricity consumption (Huebner, Shipworth, Hamilton, Chalabi, & Oreszczyn, 2016). The household income partly determines the economic viability of the household to disconnect from the grid, since investment costs can easier be overcome with a higher income. Finally, the distinction between renters and home owners is important, since renters are generally less inclined to invest in a dwelling they do not own (John & Booth, 2014).

4.4. Impact of grid defection

The various studies that have researched the potential of massive grid defection were mainly concerned with the fall of utilities and the dangers of soaring electricity prices for consumers. However, this research is also focused on other factors that impact society. The European Union's energy policies are driven by three main objectives: to secure affordable, reliable, and sustainable energy supply. In this research, these parameters are used to assess the quality of the energy supply and serve as performance indicators to measure the impact of grid defection.

4.4.1. Affordability

The impact of grid defection on the affordability of electricity supply is a key societal concern, according to Khalilpour & Vassallo (2015) and it is the most mentioned impact factor of grid defection in the reviewed literature. The general consensus is that if massive grid defection would occur, the electricity price of power from the grid would rise, thereby losing its affordability for more and more consumers. Besides the electricity price, the affordability of electricity for households depends on the household income.

4.4.2. Reliability

In the study by Bronski et al. (2014), the reliability of supply is researched as one of the motivations for grid defection in the US. Concerns on the reliability of the electricity network rose due to aging grid infrastructure, weather storms and potential physical attacks on grid infrastructure. In the Netherlands, the reliability of electricity supply from the grid is generally high compared to other countries (Frontier Economics, 2015). However, in a scenario of massive grid defection, it is unknown if distribution system operators can maintain a stable and reliable network. Due to decreasing income for electricity suppliers and DSO's, the reliability of electricity supply could also be in danger. At the side of the households that disconnect from the grid, reliability of electricity supply is also an important factor. Since there is no grid to be used as backup, failures in the PV, BESS or μCHP of the off-grid system must be resolved immediately.

4.4.3. Sustainability

The third societal impact factor is the sustainability of electricity supply. As sustainability is a broad term, the scope in this context is focused on the environmental sustainability. The most commonly used parameter to measure sustainability is the amount of emission of carbon dioxide (CO_2) equivalents. On the Dutch electricity grid, most electricity is generated through coal and natural gas combustion. Burning thermal coal emits twice as much (CO_2) as burning natural gas for electricity production (Jaramillo, Griffin, & Matthews, 2007). A highly sustainable electricity supply uses renewable resources such as solar, wind and water power, were no CO_2 is emitted during the electricity production. This minimizes the strain on the environment that is associated with the emissions of greenhouse gasses. Therefore, the fuel mix of electricity from the grid is important to take into consideration while assessing the impact of grid defection on the environmental sustainability of electricity supply (Ang & Su, 2016).

5. Methods

This chapter describes the approach that was taken to answer the sub-questions and the main research question. It starts with a broad overview of the steps that were taken, followed by a more detailed explanation of the data and tools that were used.

The nature of the research question is both technical and economic. It tries to find if it is technically feasible for households to defect from the electricity grid, while taking into consideration that households are not likely to defect if it is not economically viable to do so. Additionally, the scope of the research is set on a micro and macro level. On the micro level, the aforementioned feasibility and viability of grid defection are determined on a household basis. On the macro level, the grid defection percentage of the total Dutch housing stock is examined, along with its effects on the affordability, reliability and sustainability of electricity supply. For these reasons, a techno-economic model was built to compute the amount of households in the Netherlands that defect from the grid, with given values for a set of input parameters. The research framework on which this model is built, is shown in Figure 5.1.

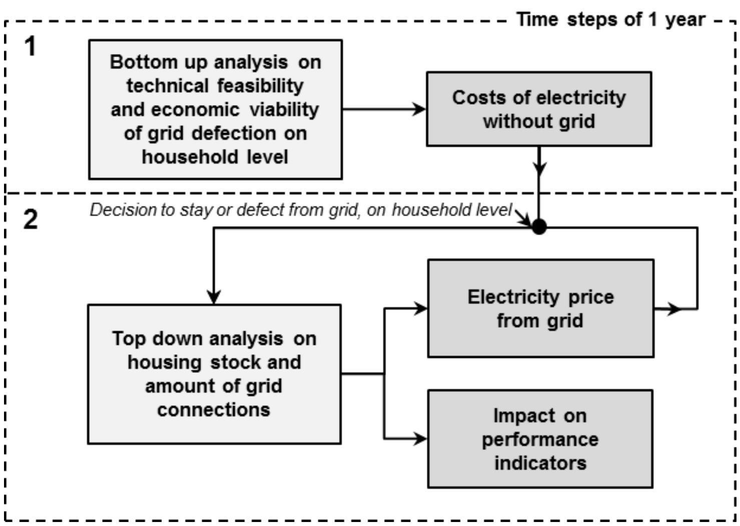

Figure 5.1 Schematic overview of the research framework

5.1. Grid defection modelling and suitability of the methods

To calculate the rate of grid defection, multiple methods were found in the reviewed literature. The study by Shah et al. (2015) uses the HOMER software (HOMER Energy, 2017) to simulate different combinations of system components. This software then generates a list of feasible configurations sorted by net present cost along with outputs to compare configurations and evaluates them on both economic and technical grounds. Kantamneni et al. (2016) use a Matlab simulation model to calculate the LCOE of going off-grid, for a set of predefined system configurations. Both of these studies researched the economic viability of grid defection, but did not fully research the likeliness of the so called 'death spiral'.

In this thesis, a simulation model was built that uses both approaches of the aforementioned studies, and uses the results to calculate the potential of grid defection and the utility death spiral over time. This model consists of two parts. The first part uses a bottom up approach similar to methods of Kantamneni et al. (2016) to research the economic viability of a household to defect from the electricity grid, with the LCOE of this off-grid system as the main output. However, since the assessment was done for multiple households, the off-grid systems were optimized in size for each household type, by minimizing the output LCOE. The LCOE's of these off-grid systems were calculated through a simulation model. Since the HOMER software was not freely available, a new Matlab script was developed to simulate grid defection for these LCOE's of various off-grid system configurations, for different household types, over 34 years (2017 to 2050). In this way, both the optimization of the HOMER method and the LCOE calculation method of a PV+BESS+µCHP unit were used. For each household type, the optimal LCOE and associated outputs were exported to a Microsoft Excel model.

The second part of the grid defection model was built in this Excel model and compared the LCOE's for off-grid households to the electricity price from the grid. If the option of grid defection in a given year has a lower costs of electricity than the electricity price from the grid, a household chooses to disconnect from the grid, based on decision assumptions. As a result, the fixed costs in the electricity price increase, since a lower amount of households has to bear the same fixed costs. This improves the viability of grid defection for other households that have not defected yet. The output of the second part is the amount of households that are connected to the grid and the impact this has on the performance indicators affordability, reliability, and sustainability of electricity supply in the Netherlands.

Sections 5.2 and 5.3 elaborate on the approaches that were taken for the Matlab model and the Excel model, respectively.

5.2. Bottom up analysis on technical feasibility and economic viability of grid defection on household level

Following the results from the exploratory literature study in the theory chapter, the two combinations of technologies that are used in an off-grid residential system are PV+BESS and PV+BESS+μCHP. In this research, the assumption was made that for defection from the electricity grid, a system consisting of PV, BESS and μCHP will be used to facilitate household grid defection. The reason for this is that the Netherlands knows longer periods of little solar radiation, comparable to the regions studied by (Kantamneni et al., 2016; Mundada et al., 2016; Shah et al., 2015). A similar approach to these studies was used to assess the technical feasibility and economic viability of a Dutch household to disconnect from the electricity grid. In this first part of the research, five steps were taken:

1. The total housing stock was categorized in smaller groups of households, as different types of households have a different potential for grid defection.

2. The electricity consumption per type of household was determined, in order to know how much electricity must be generated by the off-grid system.

3. The annual solar radiation per type of household was determined, to be compared to the electricity consumption. This data depends on the dwelling location for the regional solar irradiance.

4. Data on technical and economic parameters of the PV, BESS and μCHP technologies was obtained. This consisted of the costs per kWp for PV, the costs per kWh for BESS and, the costs per kWe and costs per m^3 of natural gas for the μCHP. For these cost figures, also the future estimates were researched, since this required for the forward-looking model. Finally, the lifetimes and efficiencies of all three technologies were researched.

5. Per household, an off-grid PV+BESS+μCHP system with a minimal LCOE was designed. This system combines the electricity demand data, the solar radiation data and the economic parameters of PV, BESS and μCHP.

5.2.1. Household types

A primary distinction was made between 16 types of dwellings. These 16 categories were composed by separating the four dwelling types: flats and apartments, detached houses, semi-detached houses and terraced houses, and then separate them again by building years until 1964, 1965-1974, 1975-1991 and building years after 1991. This approach follows the report 'example dwellings of the current building stock 2011' (RVO, 2011). Besides the dwelling type, a second distinction in households was made, based on regional differences. As the solar irradiance differs even on a regional level in the Netherlands, each household was categorized into one of the twelve Dutch provinces. In total, this gives 192 different types of households. Figure 5.2 shows an overview of the used household types.

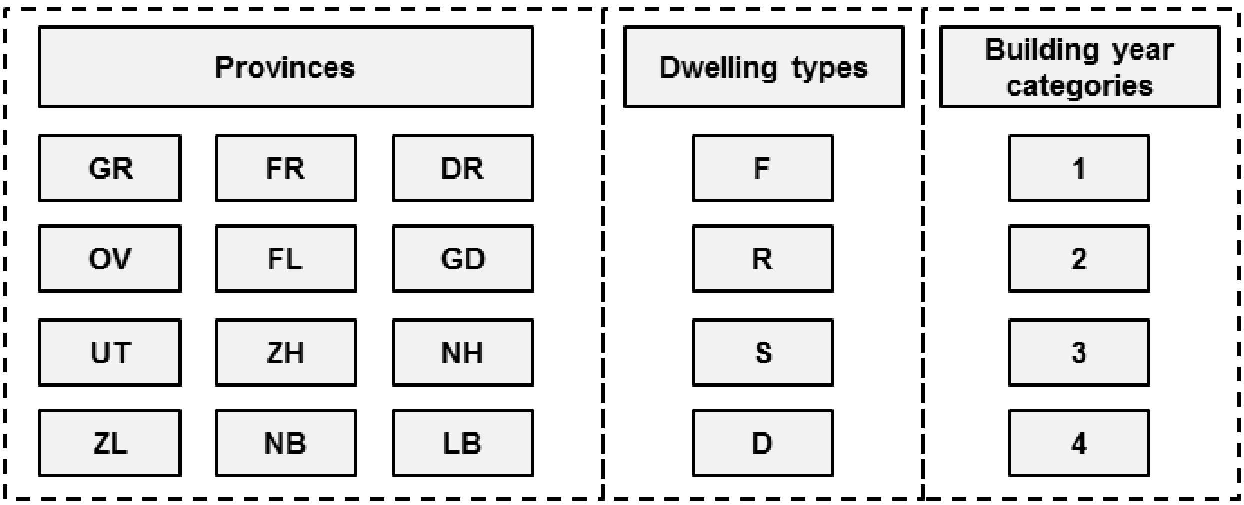

Figure 5.2. Overview of the possible combinations of the 192 household types.
Province labels: GR=Groningen, FR=Friesland, DR= Drenthe, OV=Overijssel, FL=Flevoland, GD=Gelderland, UT=Utrecht, NH=Noord-Holland, ZH=Zuid-Holland, ZL=Zeeland, NB=Noord-Brabant, LB=Limburg.
Dwelling codes: F=Flat/Apartment, R=Row house, S=Semi-detached, D=Detached.
Building year periods: 1= pre 1965, 2=1965-1974, 3=1975-1991 and 4=after 1991

One of the main sources of information on the household types was the WoonOnderzoek (WoON) database. The WoonOnderzoek Nederland is a triennial survey research that involves approximately 60.000 respondents who answer questions regarding their current housing conditions. Topics of the research that are relevant for this research include the respondent's current dwelling type, household composition, household income, home-ownership status, annual electricity consumption and annual electricity costs. The size of the WoON gives basis for reliable statements on national and regional (provinces) level (WoonOnderzoek, 2016). This is done by applying weighting factors that represent an amount of households. The weighting factor per respondent differs and is based on the Bascula software, using the Huang-Fuller algorithm (Vondenhoff, 2016).

The WoOn dataset was obtained through Rijksoverheid (2016) and with this dataset, the household weighting factors were supplied. The SPSS data file was filtered for the variables that were relevant for this part of the research. These were the variables 'dwelling type', 'province' and 'building year of dwelling'. The last variable was categorized into the four building year categories.

Then, the weighting factors were applied on each answer of the respondents. For example, a respondent with a weighting factor of 5.76 states that he or she lives in a detached house in Utrecht built in 1971. This will add 5.76 households to the total amount of household type GR-D2, following the coding of Figure 5.2. Farms and dwellings that accommodate a store besides a household were excluded from the WoOn dataset, as the assumption was made that owners and renters of these dwelling types have businesses that rely on reliable electricity supply. Finally, the amount of households in the Netherlands were summed for each of the 192 household types, separated by home owners and renters. This data was exported to a Microsoft Excel file to be used for further analysis. Table 12.2 and Table 12.3 in Appendix III depict the total amounts of households per household type for renters and owners, respectively.

5.2.2. Electricity consumption per household type

The annual electricity consumption was determined through a similar method, using an SPSS analysis on the WoOn 2015 data set. For each respondent, the annual electricity consumption in kWh is given in the data set in variable 'electricity consumption'. Through the 'aggregate' function in SPSS, a weighted average for each household type was calculated by summing the annual electricity consumption on break variables 'building year category', 'dwelling type' and 'province'. Then using the weighting factors, the weighted average was calculated per household type. Table 10.1 in Appendix I shows the annual electricity consumption per household type.

The electricity consumption of a household differs through the day, is at a minimum during the night and can also be different through various seasons. Therefore, the annual electricity consumption values were disaggregated to hourly values. This was done by using a load profile, obtained through NEDU, the Dutch energy data exchange organization (NEDU, 2016). A load profile consists of 8760 values that represent the hours in a year. Since the sum of these values is 1, they all represent a proportional hourly electricity consumption of a household in a given year. For each household type, the total annual electricity consumption was multiplied with the 8760 values to obtain the hourly electricity load values. From interviews with DSO's it was concluded that no separate load profiles are used for the different dwelling or household types. Therefore, the electricity consumption of all Dutch households was disaggregated to hourly values by using the E1A profile. This profile is based on households with a 3x25 Ampere grid connection, which is the most prevalent connection type for Dutch households (NEDU, 2016).

The annual consumption figures were determined for 2017, but are unlikely to remain constant in the future. The Netherlands has known a long period of increasing household electricity consumption, coupled to the growth of GDP (Frontier Economics, 2015). The consumption stabilized around 2010, after which a decrease in household electricity consumption started (CBS, 2016b). This decrease is expected to continue, with an average annual reduction of 0.5% until 2030, according to the National Energy Outlook (ECN, 2016). The decrease can be explained by energy-saving measures and overall energy efficiency improvements of electrical household appliances. After 2030, the average annual electricity consumption is assumed to remain constant.

5.2.3. *Solar radiation per household type*

Solar irradiance varies highly during the day and during different seasons. Fortunately, the solar irradiance data is generally given in hourly values. Hourly solar irradiance data of the past 15 years from 40 weather stations was obtained through the Dutch meteorological institute (KNMI, 2017). For each of the 12 Dutch provinces, average hourly solar irradiance values were constructed by averaging the data of the weather stations of that province. The data was obtained in $J/cm^2/hour$. This was translated to $kWh/m^2/hour$ by multiplying the values by 10^4 for the cm^2 to m^2 conversion, and then dividing them by 3.6×10^6 for the J to kWh conversion. For each dwelling type in a province, the solar irradiance was assumed to be the same.

However, the maximum solar radiation does differ per dwelling type, since this depends on the available rooftop surface of the various dwellings. For this data, a study by PBL & DNV-GL (2014) was consulted. From their study, Table 10.2 in Appendix I was derived, containing the available rooftop surfaces for Dutch households in m^2, separated by dwelling type and age category of the dwelling. From the m^2 of available rooftop surface, spacing surface around roof edges and obstacles on the roof are excluded. This is done through the obstacle indication method described by Vreugdenhil (2014).

The data Table 10.2 from was recalculated to the dwelling types of this research, which led to the data presented in Table 5.1. These values of available rooftop surface per dwelling type are assumed to be similar for all provinces, since no data was found on regional differences.

Average available rooftop surface for PV (m^2)

Dwelling Type	Building year category			
	Pre 1965	1965-1974	1975-1991	After 1991
Flat/Apartment	21.7	18.0	16.9	18.8
Row house	30.9	35.3	35.2	31.8
Semi-detached	39.7	46.2	47.0	52.1
Detached	54.1	66.6	69.2	55.2

Table 5.1. Average available rooftop surface for PV per dwelling type, in m^2

5.2.4. Technical and economic parameters of the PV, BESS and µCHP technologies

To determine the minimal LCOE (levelized cost of electricity) of the PV+BESS+µCHP system, the technical and economic parameters of the three technologies were researched. For all household types, these technical and economic parameters were assumed to be equal, which means no regional or municipal subsidies have been taken into account.

5.2.4.1. Solar photovoltaics

For the PV investment costs, the average current costs per installed kWp are used, according to the report 'monitor PV Netherlands' (Van Sark & Schoen, 2016). In this report, 1249 unique solar PV module types and 741 unique inverters were analyzed on price and efficiency. The weighted average price of PV in the Netherlands is € 1.860 per kWp for a residential scaled system of approximately 2.5 kWp. This price consists of € 1.460 per kWp for the hardware and €400 per kWp for the installation. To estimate the future values, an annual module cost reduction of 9% was used, following the Fraunhofer Institute for Solar Energy Systems (2016). The installation costs for residential solar photovoltaic systems were assumed to reduce by 2% annually.

The lifetime of the PV system is assumed to remain 30 years and the average efficiency is 14.3% (Van Sark & Schoen, 2016). The annual efficiency improvements are already incorporated in the annual cost reduction of solar modules. In Table 5.2, a summary of the data of technical and economic parameters of solar photovoltaics can be found.

Parameter	Current value	Future values
Investment costs	€1.460/kWp system costs €400/kWp installation costs	9% reduction per year for the system costs, 2% for installation costs
O&M costs	Annually .5% of investment costs	Constant
Lifetime	30 years	Constant
Efficiency (from 1 kWh of solar radiation to 1kWh of electricity)	14.3%	Constant

Table 5.2. Technical and economic parameters of solar PV

5.2.4.2. Battery energy storage system

Similar to PV, the investment costs of batteries are expected to decrease. The current investment costs were assumed to be equal to Tesla's Powerwall 2, at € 530 per kWh of installed battery capacity. These costs are composed of hardware costs of € 430 per kWh and installation costs of € 100 per kWh (Tesla, 2017). For future costs, the hardware costs were assumed to reduce by 8% annually (Nykvist & Nilsson, 2015), while the installation costs were assumed to reduce by 2% annually.

For the lifetime, 10 years with 100% capacity was assumed, following research of Alyousef et al., (2016). The charge and discharge efficiencies were assumed to be 85% and 100% respectively, following research of Wang et al., (2012). Finally, the maximum depth of discharge was set to 80%, according to research by Ghiassi-farrokhfal et al., (2015). For these four technical parameters, the conservative assumption was made that they did not increase in future years, since no clear research has been found to make substantiated statements on this. Table 5.3 summarizes the economic and technical parameters of BESS, along with their current and future values.

Parameter	Current value	Future values
Investment costs	€430/kWh system costs €100/kWh installation costs	8% reduction per year for the system costs, 2% for installation costs
O&M costs	Annually .5% of investment costs	Constant
Lifetime	10 years	Constant
Charge efficiency	85%	Constant
Discharge efficiency	100%	Constant
Maximum depth of discharge (DoD)	80%	Constant

Table 5.3. Economic and technical parameters of BESS

5.2.4.3. Micro combined heat and power system

For the µCHP system, the specific investment costs in the Netherlands are difficult to find per kWe. In their study, Mundada et al. (2016), assumed a price of $ 1.400 per kWe which remains constant in their research. Converted to euros, this is € 1.320 per kWe. The electrical efficiency is assumed to be 15% (Kantamneni et al., 2016; Mundada et al., 2016), which was also remains constant, given the maturity of the technology. Regarding the O&M costs, the operation costs of a µCHP consist mostly of the fuel costs of the natural gas that is required. The 2017 natural gas price for households was taken. This € 0.65 per m^3 of natural gas was divided by the calorific value of Dutch natural gas: 9.769 kWh/m^3. This resulted in a price of € 0.067 per kWh of natural gas. The fuel costs were assumed to increase 1% per year, following inflation the rate. Table 5.4 displays the assumptions on the technical and economic of the µCHP system.

Parameter	Current value	Future values
Investment costs	€ 1.230 / kWe installed system costs	Constant
Operation costs	€ 0.067 / kWh natural gas	1% increase per year
Maintenance costs	Annually 1% of investment costs	Constant
Lifetime	15 years	Constant
Electric efficiency (from 1 kWh of natural gas to 1 kWh of electricity)	15%	1% increase per year, until 20%

Table 5.4. Technical and economic parameters of µCHP

5.2.5. Optimal PV+BESS+µCHP system design per household type

An optimal PV+BESS+µCHP combination uses as much power from the sun as possible to harness the free energy from the sun, while taking into account not to over-invest in solar panels. Furthermore, the battery pack must be large enough to last for multiple days, but not so large that there is always a surplus of capacity. On the other hand, if the PV and BESS are not large enough, the µCHP system must be scaled up, which also requires extra investment and fuel costs. For each household type, there are many feasible options of an off-grid system, with nearly endless combinations of PV sizes, BESS sizes and µCHP sizes. The optimal system satisfies the electricity load of the household at every hour of the year, at the lowest levelized cost of electricity.

To determine the optimal system size for each household type, a Matlab script was written. First, the data obtained in sections 5.2.2 to 5.2.4 was stored in Matlab data format. The annual electricity load of each household type was stored in a 1×192 vector. The load profile was stored in an 8760×1 vector, representing the 8760 hours in a year. For each of the 12 provinces, the solar radiation in kWh per m^2 per hour was stored in an 8760×12 matrix. The maximum rooftop surface available for PV of each of the 16 dwelling types was stored a 1×16 vector. The investment costs and O&M costs of PV, BESS and µCHP were also stored as vectors.

The Matlab script follows the structure as depicted in Figure 5.3

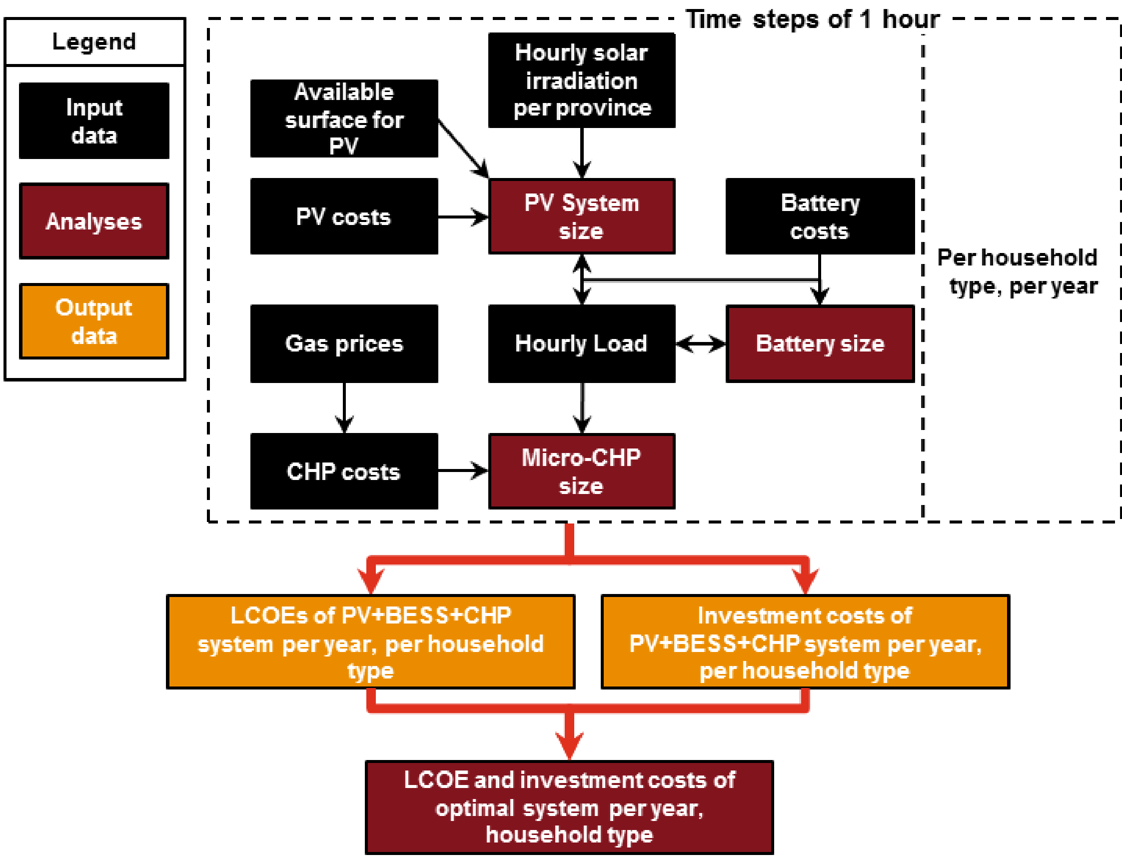

Figure 5.3. Structure of the bottom up analysis of off-grid PV+BESS+µCHP systems for households

The Matlab script is included in Appendix II. First the hourly load values for each household type are generated by multiplying the annual consumption vector with the load profile vector. Then, the script iterates over the 16 dwelling types, located in 12 provinces, who each have separate set of hourly load values. For each of these 192 household types, the script iterates over 34 years, from 2017 to 2050. Each year has different investment costs and corresponding O&M costs for the next 30 years. For each year, the script iterates over 11 PV system sizes, from 0% of the available roof surface of that household, to 100% of the available roof surface, with steps of 10%. Finally, for each of the PV system sizes, the script iterates over 11 BESS sizes, from 0-20kWh, with steps of 2kWh of battery capacity. In total, this means that there are 16×12×34×11×11 = 789.888 iterations to go over.

Each iteration follows module 3 in Appendix II, which can be summarized in the following steps:

1. Check hourly value of electricity load, compare it to hourly value of solar power
2. If solar power > load, then store 85% of excess solar power to battery (85% charging efficiency)
3. If load > solar power, extract required amount from battery
    a. If extracting the required amount from the battery would cause the battery to reach below the maximum depth of discharge (20% of capacity), then only extract until maximum DoD
    b. If load > (solar power + available battery capacity), then generate remaining amount with μCHP
4. Update new state of charge of the battery and continue to next hourly value

After this series of calculations has run for 8760 times, several equations are calculated to obtain the final LCOE of this iteration. To calculate the PV investment costs, the used roof surface of the iteration is multiplied with the PV efficiency, to obtain the power of the system in kW. This figure is multiplied with the price of PV per kW of the year of the iteration. Similarly, for the investment costs of the BESS, the used capacity of the iteration is multiplied with the price of BESS per kWh of the year of the iteration. The maximum μCHP power supply of the 8760 hourly values determines what size the μCHP has to be in kWe. This in turn is used to calculate the investment costs of the μCHP unit, by multiplying the kWe power with the €/kWe price of that year. The equations used to calculate the investment costs are summarized in Equation 2, 3 and 4.

$$Investment\ costs\ (PV) = S * Eff * P_y$$

Equation 2. Investment costs of solar photovoltaics

S = Used surface for solar pv modules, in m^2
Eff = Solar module efficiency, in kWp per m^2
P_y = Price of solar module in year y, in € per kWp

$$Investment\ costs\ (Battery) = C * P_y$$

Equation 3. Investment costs of battery energy storage systems

C = Battery capacity in kWh
P_y = Price of batteries in year y, in € per kWh

$$Investment\ costs\ (CHP) = \frac{\max(D_h)}{Eff} * P_y$$

Equation 4. Investment costs of micro combined heat and power

D_h = µCHP demand in hour h, in kWe output
Eff = µCHP efficiency, in kWe input per kWe output
P_y = Price of µCHP unit in year y, in € per kWe

For the total annual maintenance costs, 1% of investment costs of the µCHP and 0.5% of the investment costs of PV and BESS are summed, as shown in Equation 5.

$$Maintenance\ costs_n = \sum_{x=1}^{3} \left(I_{x,y} * F_x\right)$$

Equation 5. Maintenance costs of PV, BESS and µCHP

$I_{x,y}$ = Investment costs of technology x in year y, in €
F_x = Maintenance factor of technology x

The PV and BESS are assumed not to have annual operation costs. For the annual operation costs of the µCHP unit, the total kWh of hourly electricity supplied by the µCHP is summed and divided by the electrical efficiency of the µCHP, to obtain the amount of natural gas required for a full year. The natural gas costs for the 30 year lifetime of the system are then calculated by multiplying the coming 30 year's gas prices by the obtained annual gas demand, as is shown in Equation 6.

$$Operation\ costs_n = \frac{\sum_{h=1}^{8760} D_h}{Eff} * G_n$$

Equation 6. Operation costs of an optimized µCHP unit

D_h = µCHP demand in hour h, in kWe output
Eff = µCHP efficiency, in kWe input per kWe output
G_n = Price of natural gas in year n, in € per kWh

The replacement of the battery and inverter at year 10 and 20 of the lifetime and the replacement of the µCHP system at year 15 of the lifetime are also levelized. As shown in Equation 7, this is done by multiplying the investment costs of these components by their annual cost reduction factor to the power of the lifetime of the component that is replaced. The replacement costs are then summed per year, to obtain an overall replacement cost per year, for 30 years.

$$Replacement\ costs_n = \sum_{x=1}^{3} \left(I_{x,y} * (1 - R_x)^{L_x} \right)$$

Equation 7. Replacement costs of an optimized PV, BESS and µCHP

$I_{x,y}$ = Investment costs of technology x in year y, in €
R_x = Annual cost reduction of technology x
L_x = Lifetime of technology x, in years

The LCOE is calculated by first summing the 30 annual O&M and replacement costs. This figure is levelized with a discount rate of 3% and added to the investment costs. Together they are divided by the sum of the levelized electricity outputs of the 30 years lifetime of the system. This is shown in Equation 8:

$$LCOE_y = \frac{I + \sum_{n=1}^{30} \left(\frac{O_n + M_n + R_n}{(1+d)^n} \right)}{\sum_{n=1}^{30} \frac{E_n}{(1+d)^n}}$$

Equation 8. LCOE of an optimized PV+BESS+µCHP system

I_y = Investment in year y, in €
O_n = Annual operation costs, in €/year
M_n = Annual maintenance costs, in €/year
R_n = Annual replacement costs, in €/year
d = Discount rate
E_n = Annual electricity generation in kWh/year

After the LCOE and the required investment costs are stored in a new array, the next iteration starts. In total, for each of the 192 household types, there are 121 PV+BESS+μCHP system size combinations for each year, which are all stored in an array. For each household type, each year's combination with the minimum LCOE is selected. The corresponding LCOE and investment costs were stored in a new array. Besides the LCOE of each optimized system, the annual gas consumption values are also stored in an array. These values were used later to calculate the CO_2 emissions of off-grid households. The gas consumption is calculated through Equation 9. Annual gas consumption of an optimized μCHP unit

$$Annual\ gas\ consumption(CHP) = \frac{\text{sum}(D_h)}{Eff}$$

Equation 9. Annual gas consumption of an optimized μCHP unit

D_h = μCHP demand in hour h, in kWe output
Eff = μCHP efficiency, in kWe input per kWe output

Finally, the amount of hours per year in which the power load on the μCHP is more than 95% of the maximum power load of the household are summed for each optimized system. These values were later used to measure the reliability of electricity supply of off-grid households.

$$Amount\ of\ hours\ near\ max\ load\ (CHP) = \text{sum}(D_h > .95 * \text{max}(D_h)$$

Equation 10. Annual amount of hours in which μCHP supplies more than 95% of the maximum load

D_h = μCHP demand in hour h, in kWe output

The LCOE's, investment costs, annual gas consumptions and amount of hours near maximum load were stored in four separate arrays. These were exported to different tabs of the Excel model, to be used in the top down analysis.

5.3. Top down analysis on housing stock and amount of grid connections

For each year, all household type's minimum LCOE's of an off-grid PV+BESS+μCHP system were exported to an excel model, together with corresponding annual gas consumption and amount of hours per year near the maximum power load. In this model, the total amounts of current households are stored, per household type (see 5.1.1 and Appendix I). These amounts are separated by owners and renters. The schematic overview of the Excel model structure can be seen in Figure 5.4.

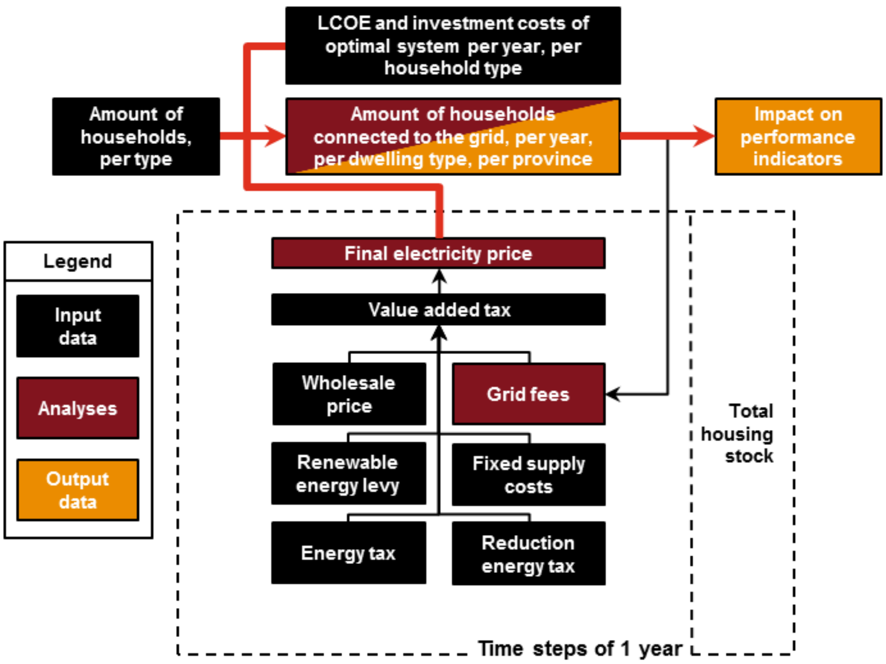

Figure 5.4. Structure of the top down analysis on the amount of grid connections from 2017-2050

The top down analysis on the amount of grid connections consists of four steps:

1. The initial final electricity price per household type was determined, in order to be compared to the LCOE of an off-grid system for each household.
2. The components of the final electricity price were researched and estimations were made on their future values.
3. Per household type, the LCOE of an off-grid system was compared to the final electricity price in that year. If the household type's LCOE is lower than its final electricity price, it defects from the grid, depending on the difference, the annual income and the ownership status of the household.
4. The amount of households connected to the electricity grid are calculated on an annual basis, which is used to state the impact of grid defection on the performance indicators: reliability, affordability and sustainability of the electricity supply in the Netherlands.

5.3.1. Initial final electricity price and electricity price components

As discussed in the theory chapter, the electricity price consists of multiple components. As some components are variable, the final electricity price in €/kWh is dependent on the annual electricity consumption. Table 5.5 shows an overview of the electricity price components, on which the next section elaborates.

Price component	Fixed/variable?
1. Wholesale price	Variable
2. Energy tax	Variable
3. Levy for renewable energy	Variable
Retail price (inc. VAT)	**Variable**
4. Fixed supply costs	Fixed
5. Grid fees	Fixed
6. Energy tax reduction	Fixed
Total Fixed costs (inc. VAT)	**Fixed**

Table 5.5. Breakdown of the price components of electricity from the Dutch electricity grid

Even in a small country as the Netherlands, there are over 30 different electricity suppliers with different electricity tariffs (Energieleveranciers, 2017). Some use a relatively low wholesale price and high fixed supply costs, while others charge higher variable prices and lower fixed fees. The largest three suppliers in the Netherlands are Essent, Eneco and Nuon, which have a combined market share of over 90%, together with their subsidiaries. Table 5.6 shows the amount of customers, the wholesale price and the fixed supply costs for households of these three electricity suppliers, excluding VAT. The weighted average of the wholesale price and fixed supply costs excluding VAT amount to 5.39 cents per kWh and € 35.99 per year, respectively.

Energy supplier	Customer base	Wholesale price	Fixed supply costs
Essent	3100000	€ 0.04901 / kWh	€ 39.57 / year
Eneco	2100000	€ 0.05610 / kWh	€ 34.30 / year
Nuon	2000000	€ 0.05905 / kWh	€ 32.23 / year
Weighted average		**€ 0.05387 / kWh**	**€ 35.99 / year**

Table 5.6. Variable and fixed electricity tariffs of the three largest Dutch electricity suppliers, exc. VAT.

Sources: (Eneco, 2017; Energieportal, 2017; Essent, 2017; Nuon, 2017)

Besides the electricity suppliers, there are 7 distribution system operators (DSO's), of which 3 have the majority of the market share (94%). The weighted average of the household grid fee that these DSO's charge, is € 188.08 per year, excluding VAT.

Distribution system operator	Amount of connections	Grid fees
Liander	2960000	€ 196.51 / year
Enexis	2600000	€ 179.80 / year
Stedin	1975000	€ 186.35 / year
Weighted average		**€ 188.08 / year**

Table 5.7. The grid fees of the three largest DSO's in the Netherlands.

Sources: (Energiegids, 2017; Enexis, 2017; Liander, 2017; Stedin, 2017)

Finally, the government taxes and levies consist of the variable energy tax, the fixed energy tax reduction, the variable renewable energy levy and the value added tax. The energy tax (exc. VAT) on electricity for Dutch households amounts to € 0,1013 per kWh, while the levy for renewable energy (exc. VAT) amounts to € 0,0074 per kWh. The energy tax reduction (exc. VAT) amounts to -€ 308.54 / year. However, this reduction is also compensating the energy tax that is charged over gas consumption. Therefore, only half of the reduction is used to calculate the final electricity price per kWh.

Tax component	Fixed or variable	Value
Energy tax	Variable	€ 0.1013 / kWh
Renewable energy levy	Variable	€ 0.0074 / kWh
Energy tax reduction	Fixed	-€ 154.27 / year
Value added tax	Variable	21% over all components

Table 5.8. Tax components charged over household electricity consumption from the Dutch grid.

Source: (Belastingdienst, 2017)

Table 5.9 shows the aggregated data from Table 5.6 to Table 5.8.

Price component	Fixed or variable	Value
1. Wholesale price	Variable	€ 0.0539 / kWh
2. Energy tax	Variable	€ 0.1013 / kWh
3. Levy for renewable energy	Variable	€ 0.0074 / kWh
Retail price (inc. VAT)	**Variable**	**€ 0.1967 / kWh**
4. Fixed supply costs	Fixed	€ 35.99 / year
5. Grid fees	Fixed	€ 188.08 / year
6. Energy tax reduction	Fixed	-€ 154.27 / year
Total Fixed costs (inc. VAT)	**Fixed**	**€ 84.47 / year**

Table 5.9. Breakdown of electricity price components and their values for 2017

As there are variable costs involved, the final costs per kWh depend on the amount of electricity (in kWh) consumed per year, as is shown in Equation 11:

$$P_h = \frac{C_h * (W + T + L) * VAT + F + G - R}{C_h}$$

Equation 11. Final electricity price of a Dutch household

P_h = Final electricity price of household h, in €/kWh
C_h = Annual electricity consumption of household h, in kWh per year
W = Wholesale costs in year y, in €/kWh
T = Energy tax in year y, in €/kWh
L = Levy for renewable energy in year y, in €/kWh
VAT = Value added taxes (21%)
F = Fixed supply costs, in €/year
G = Grid fees, in €/year
R = Reduction on energy tax, in €/year

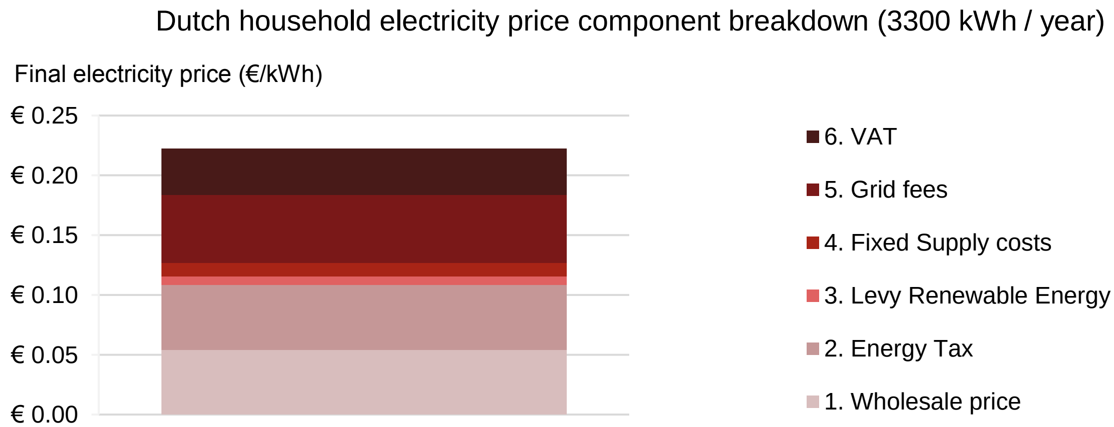

Figure 5.5. Breakdown of the final electricity price of a Dutch household (3300 kWh per year)

For a typical household electricity consumption of 3300 kWh, Figure 5.5 shows the breakdown of the final electricity price (€ 22.2 cents per kWh). However, the final electricity price rises as the annual electricity consumption decreases, as can be seen in Table 5.10. Appendix III shows the final electricity prices in 2017 per household type.

Annual consumption	Final electricity price
1500 kWh	€ 0.25302 / kWh
2000 kWh	€ 0.23894 / kWh
2500 kWh	€ 0.23049 / kWh
3000 kWh	€ 0.22486 / kWh
3500 kWh	€ 0.22084 / kWh
4000 kWh	€ 0.21782 / kWh
4500 kWh	€ 0.21548 / kWh

Table 5.10. Relation between final electricity price and annual electricity consumption

5.3.2. Future electricity prices

In the previous section, the electricity price components were introduced, with their values in 2017. These were used as initial values in the Excel model to compare with the LCOE's of off-grid systems of households in 2017. To compare the future electricity prices to the future LCOE's, assumptions were made on future changes to the price components.

5.3.2.1. Wholesale price

The initial used wholesale price is a weighted average of the three largest electricity suppliers. The largest impact on the wholesale price is caused by the generation portfolio of these suppliers, since different electricity generation units have different cost structures. For example, renewable energy generation units have no fuel costs, but higher investment costs that need to be earned back (Felder, 2011). Although it is not possible to precisely predict the future electricity generation portfolio in the Netherlands, researchers have conducted studies on the future electricity price and the impact of increased renewable energy on these prices (ECN, 2016; Frontier Economics, 2015; Mulder & Scholtens, 2013). The consensus is that the wholesale electricity prices will rise. Frontier Economics (2015) states an increase of 25% from 2015 to 2035, while ECN (2016) finds an increase of 100% from 2015 to 2035, starting from 2020. These percentage increases come down to annual growth rates of 1.25% and 4%, respectively. Given the uncertainty involved in these trends, this research uses an average annual increase in the wholesale price of 2.5%. Furthermore, the assumption was made that grid defection has no impact on the wholesale price of suppliers, since the electricity market is competitive and increased wholesale prices would only steer consumers away to competitors or away from the grid.

5.3.2.2. Energy tax

No forecasts have been found on the energy tax and the levy for renewable energy in the Netherlands. However, a study by CE Delft (2015) has conducted research on these taxes on both electricity and natural gas consumption. Currently, per unit of energy content, the energy tax that is raised on natural gas is approximately 6 times lower than the tax that is raised on electricity. Therefore, the study researches the effects of an increased gas tax so that it will reach the same level of €/GJ taxed as the electricity tax, which remains constant. Therefore, in this research, the energy tax on electricity consumption will remain constant as well until 2050.

If grid defection occurs, there is a lower amount of electricity consumption from the grid, which entails a lower government income from the energy tax. However, the main goal of the tax is also to reduce consumption so that less greenhouse gasses are emitted. Thus, the assumption was made that grid defection has no impact on the energy tax.

5.3.2.3. Levy for renewable energy

Similar to the energy tax, no forecasts have been found for future values of the levy for renewable energy. However, in a note from the Dutch Ministry of Economic Affairs, the preliminary prognosis of the levy was announced (EZ, 2017). In this prognosis, the levy will raise from € 0.0074 per kWh in 2017 to € 0.0270 in 2023. In this thesis, the assumption was made that after 2023, the levy will remain constant, since no other data or forecasts have been found. Furthermore, grid defection is assumed not to have an impact on the levy for renewable energy, since grid defection in itself already induces an increased electricity consumption from renewable energy technologies.

5.3.2.4. Fixed supply costs

The annual fixed supply costs are determined by the electricity suppliers and do not vary with the amount of electricity consumption. Some suppliers use higher fixed tariffs and lower variable tariffs to ensure revenue when consumption is low due to increased distributed generation. However, competition amongst the suppliers exerts a pressure on the fixed tariffs, as consumers would switch suppliers if fixed tariffs would become too high. Therefore, the fixed supply costs are assumed to be constant in this model. For the same reason, it is assumed that grid defection has no effect on the fixed supply costs.

5.3.2.5. Grid fees

The grid fees consist of annual fixed fees that are set by the DSO's and regulated by the Dutch Authority on Consumers and Markets (ACM). The household grid fees in 2017 were calculated by using a weighted average of the three largest DSO's. Then, the grid fees for all household connections were summed to calculate the total Dutch DSO income. Due to increasing PV and EV (electric vehicles) penetration on the network, this total income is likely to be insufficient for the future electricity grid. Besides the ongoing maintenance and reinforcement of the grid, adaptions and smart grid applications require investments (El-hawary, 2014; Mwasilu, Justo, Kim, Do, & Jung, 2014). Therefore, for future years, the assumption is made that the DSO's require a 2% higher income per year.

This total income for the DSO's is the sum of the grid fees of the individual household connections. In the case of grid defection, the amount of households connected to the electricity grid decreases. Still, the assumption is made that the same total sum is required for the DSO's, as maintenance and new investments on the grid are performed at the level of neighborhood and higher. Therefore, the grid fees increase with grid defection, as the total income has now to be provided by a lower amount of households. This was also validated through interviews with Stedin and Enexis.

5.3.2.6. Energy tax reduction

For the future energy tax reduction values, the same assumptions are made as with the future energy tax tariffs. The tax reduction remains constant and grid defection has no direct impact on the height of the reduction.

5.3.2.7. Annual electricity consumption

Besides the various price components, the annual electricity consumption per household type is also a factor that determines the final electricity price of a household. As mentioned in 5.2.2, an annual 0.5% decrease of household electricity consumption is assumed until 2030, following the national energy outlook of 2016 (ECN, 2016). After 2030, the electricity consumption is assumed to stabilize.

5.3.2.8. Future final electricity price

When all the aforementioned changes to the final electricity price are taken into account, the future final electricity price per household was calculated through equation 10:

$$P_{h,y} = \frac{C_{h,y} * \left(W_y + T_y + L_y\right) * VAT + F_y + \frac{G_y}{A_y} - R_y}{C_{h,y}}$$

Equation 12. Final electricity price of a Dutch household, based on the amount of grid connections

$P_{h,y}$ = Final electricity price of household h in year y, in €/kWh
$C_{h,y}$ = Annual electricity consumption of household h in year y, in kWh/year
W_y = Wholesale costs in year y, in €/kWh
T_y = Energy tax in year y, in €/kWh
L_y = Levy for renewable energy in year y, in €/kWh
VAT = Value added taxes (21%)
F_y = Fixed supply costs in year y, in €/year
G_y = Total DSO income needed in year y, in €/year
A_y = Total amount of grid-connected households in year y
R_y = Reduction on energy tax in year y, in €/year

5.3.3. Off-grid LCOE comparison to the final electricity price and the choice of grid defection

The LCOE's of optimal off-grid PV+BESs+µCHP systems per household type and per year from 2017 to 2050 were compared to the final electricity prices of each household type. Through the methods described in 5.3.1 and 5.3.2, the final electricity prices were calculated for 2017. The amount of households on the grid in 2017 was determined per household type and divided by ownership status, through the methods described in 5.2.1. Appendix III shows these final electricity prices and the amount of households on the grid per household type in 2017.

In the Excel model, the following steps were taken, per household type:

1. Compare LCOE of off-grid system in this year to the final electricity price in this year

    a. If the LCOE is at least 10% lower, 2.5% of dwelling owners of the household type defect from the grid. If the LCOE is at least 50% lower, 2.5% of renters of the household type defect from the grid. This lowers the total amount of grid connections in the next year.

2. Calculate the final electricity price of next year, through Equation 12.

These two steps were repeated from 2017 to 2050. The assumption was made that only the home owners defect from the electricity grid and that 2.5% of the owners do defect if the LCOE is at least 10% lower than the electricity price. Renters were assumed not to defect from the grid unless the LCOE is 50% lower, since they are generally much less inclined to invest in a dwelling they do not own (John & Booth, 2014). Since no data is available on actual defection rates, the model was built so that these assumptions can be tested in sensitivity analyses.

5.3.4. Rate of grid defection and impact on performance indicators

From the analysis described in 5.3.3, the main outputs are the amount of households that leave the grid each year and the final electricity price of electricity from the grid. Both were calculated per year and per household type. The impact of the amount of households that leave the grid was categorized in impact on three performance indicators of electricity supply: affordability, reliability and sustainability.

5.3.4.1. Affordability

The affordability of electricity was measured by dividing the annual electricity costs per household by its annual disposable income. The annual disposable income was determined per dwelling type by using an SPSS analysis on the WoOn 2015 data set. For each respondent, the annual disposable income in € of the respondent's household is given in the data set in variable 'disposable household income'. Through the 'aggregate' function in SPSS, a weighted average for each dwelling type was calculated by averaging the annual electricity consumption on break variables 'building year category', 'dwelling type' and 'home-ownership status'. For this variable, there was not enough data to make representative statements on household type level, separated by dwelling type and age and province. Therefore, the average annual disposable income was calculated per dwelling type and age, separated by renters and owners. Table 12.4 in Appendix III shows the annual disposable income per dwelling type.

First, the total expenditures of each dwelling type for each year from 2017-2050 were calculated for the on-grid households and for the off-grid households. To do so, the amount of grid-connected households were multiplied by their electricity consumption from the grid and their final electricity price. As can be seen in Equation 13, these figures were summed to find the annual total expenditure on electricity from the grid, aggregated per dwelling type, since the annual income of households was also only available per dwelling type. For the off-grid households, the amount of off-grid households and the LCOE of an off-grid system were used instead (Equation 14).

$$T1_{d,o,y} = \sum \left(P1_{d,y} * C_{d,y} * A1_{d,o,y}\right)$$

Equation 13. On-grid households' expenditures on electricity

$T1_{d,o,y}$ = Total on-grid expenditures of dwelling type d, separated by owners and renters, in year y, in €/year
$P1_{d,y}$ = Final electricity price of dwelling type d in year y, in €/kWh
$C_{d,y}$ = Annual electricity consumption of dwelling type d in year y, in kWh/year
$A1_{d,y}$ = Amount of grid-connected households of dwelling type d, separated by owners and renters, in year y

$$T2_{d,o,y} = \sum \left(P2_{d,y} * C_{d,y} * A2_{d,o,y}\right)$$

Equation 14. Off-grid households' expenditures on electricity

$T2_{d,o,y}$ = Total off-grid expenditures of dwelling type d, separated by owners and renters, in year y, in €/year
$P2_{d,y}$ = LCOE of off-grid system of dwelling type d in year y, in €/kWh
$C_{d,y}$ = Annual electricity consumption of dwelling type d in year y, in kWh/year
$A2_{d,y}$ = Amount of off-grid households of dwelling type d, separated by owners and renters, in year y

Then, the ratio between the annual costs per dwelling type and the annual disposable income per dwelling type was calculated for the on-grid and off-grid households, as shown in Equation 15 and Equation 16.

$$R1_{d,o,y} = \frac{T1_{d,o,y}}{I_d * A1_{d,o,y}}$$

Equation 15. On-grid electricity costs to income ratio

$R1_{d,o,y}$ = Ratio of annual costs of on-grid electricity to annual disposable income of dwelling type d, separated by owners and renters, in year y
$T1_{d,o,y}$ = Total on-grid expenditures of dwelling type d, separated by owners and renters, in year y, in €/year
I_d = Disposable income of dwelling type d
$A1_{d,o,y}$ = Amount of grid-connected households of dwelling type d, separated by owners and renters, in year y

$$R2_{d,o,y} = \frac{T2_{d,o,y}}{I_d * A2_{d,o,y}}$$

Equation 16. Off-grid electricity costs to income ratio

$R2_{d,o,y}$ = Ratio of annual costs of off-grid electricity to annual disposable income of dwelling type d, separated by owners and renters, in year y
$T2_{d,o,y}$ = Total off-grid expenditures of dwelling type d, separated by owners and renters, in year y, in €/year
I_d = Disposable income of dwelling type d
$A2_{d,o,y}$ = Amount of off-grid households of dwelling type d, separated by owners and renters, in year y

Then, for each year, weighted averages of these ratios were calculated for the total housing stock, separated by on-grid households and off-grid households. This was done through Equation 17 and Equation 18.

$$R1_y = \frac{\sum(R1_{d,o,y} * A1_{d,o,y})}{\sum A1_{d,o,y}}$$

Equation 17. Annual ratio of electricity costs to income for all on-grid households in housing stock

$R1_y$ = Annual ratio of electricity costs to income for all on-grid households in housing stock
$R1_{d,o,y}$ = Ratio of annual costs of on-grid electricity to annual disposable income of dwelling type d, separated by owners and renters, in year y
$A2_{d,o,y}$ = Amount of on-grid households of dwelling type d, separated by owners and renters, in year y

$$R2_y = \frac{\sum(R2_{d,o,y} * A2_{d,o,y})}{\sum A2_{d,o,y}}$$

Equation 18. Annual ratio of electricity costs to income for all off-grid households in housing stock

$R2_y$ = Annual ratio of electricity costs to income for all off-grid households in housing stock
$R2_{d,o,y}$ = Ratio of annual costs of off-grid electricity to annual disposable income of dwelling type d, separated by owners and renters, in year y
$A2_{d,o,y}$ = Amount of off-grid households of dwelling type d, separated by owners and renters, in year y

5.3.4.2. Reliability

The reliability of electricity supply is often indicated by the percentage of time in which electricity demand is fully met (Reichl, Schmidthaler, & Schneider, 2013; Sen & Bhattacharyya, 2014; Ward, 2013). This power availability can be measured at different levels of electricity load. For example, the reliability of electricity supply at the household or regional level is generally higher than at the national level, since blackouts on the entire electricity grid almost never occur. In the Netherlands, the reliability of the electricity grid is high. The average time that electricity is unavailable for Dutch households, is 20 minutes per year (Netbeheer Nederland, 2017).

The main factors that influence the reliability of electricity supply are weather conditions, grid maintenance and upgrades, diversification of electricity generating units, electricity storage availability and interconnections to other electricity markets. In this thesis, the assumption is made that grid defection has no impact on the reliability of electricity supply from the grid. This assumption builds on two premises. The first is that the total required grid fees remain constant as households defect from the grid. The second is that utilities and electricity traders will keep competing to supply the electricity at market prices, as these prices include a premium for the high reliability of electricity supply.

For the off-grid households, the reliability of electricity was measured. Since the PV, BESS and μCHP components were sized with the Matlab script to always match demand, the power availability for these systems is always 100%. In reality, this entails that the μCHP unit is sized to be able to provide the maximum load of the household. To measure the reliability, the amount of hours in a year that the μCHP unit has to provide more than 95% of the maximum output is used as an indicator. This indicator was one of the outputs of the Matlab script, as can be seen in sections 5.2.5 and 11.3. Although this is not an indicator for direct unavailability of supply, it serves as an approach to near-blackout situations.

Since the μCHP uses natural gas from the Dutch gas network, the reliability of electricity supply is also dependent on the reliability of this gas network. However, this factor is negligible, since the average time that gas is unavailable for Dutch households, is 3 minutes per year (Netbeheer Nederland, 2017).

5.3.4.3. *Sustainability*

The impact of grid defection on environmental sustainability of the electricity supply was measured for the households on the grid and the off-grid households separately. For the households on the grid, the total electricity consumption of the housing stock was multiplied by the average annual emission factor of electricity from the Dutch power grid. The emission factor is used to calculate the average amount of CO_2 equivalents emitted in the process of electricity production, per unit of electricity. As the share of renewables in the total electricity generation portfolio increases, the average emission factor decreases. Similarly, the emission factor lowers with fuel efficiency improvements in electricity generation units. Based on research by Ang & Su (2016), the average emission factor of electricity from the Dutch grid in 2017 was assumed to be 0.42 kg of CO_2 equivalents per kWh of electricity. Furthermore, a baseline annual reduction of 1.18% was used for the future emission factors, following the trend of the past 20 years (Ang & Su, 2016). Table 12.5 in Appendix III shows the future annual emission factors that were used.

The total amount of CO_2 equivalent emissions caused by electricity consumption from the grid was calculated by multiplying the total electricity consumption from the grid of each year with the emission factor of that year, as shown in Equation 19.

$$E1_y = F_y * \sum (C_{h,y} * A1_{h,y})$$

Equation 19. Annual amount of CO_2 eq. emissions from electricity consumption of on-grid households

$E1_y$ = Amount of CO_2 eq. emissions from electricity consumption of on-grid households in year y, in kg of CO_2 eq.
F_y = Annual emission factor of electricity consumption from the grid in year y, in kg CO_2 eq / kWh
$C_{h,y}$ = Annual electricity consumption of household type h in year y, in kWh/year
$A1_{h,y}$ = Amount of grid-connected households of household type h in year y

For the off-grid households, a PV+BESS+µCHP system is used to meet the electricity demand. The PV and BESS systems are assumed to have zero emissions of CO_2 equivalents per kWh, but the µCHP transforms natural gas into electricity, emitting CO_2 equivalents in the process. The total amount of CO_2 equivalent emissions caused by electricity consumption from off-grid households was calculated by multiplying the total amount of natural gas consumption with the emission factor of Dutch natural gas, as shown in Equation 20. This emission factor was assumed to remain constant at 1.887 kg of CO_2 equivalents per m^3 of natural gas (Ministerie van Infrastructuur en Milieu, 2015). The amounts of natural gas consumption per household type were extracted from the Matlab output.

$$E2_y = F * \sum (G_{h,y} * A2_{h,y})$$

Equation 20. Annual amount of CO_2 eq. emissions from electricity consumption of on-grid households

$E2_y$ = Amount of CO_2 eq. emissions from off-grid electricity consumption in year y, in kg of CO_2 eq.
F = Emission factor of natural gas, in kg CO_2 eq / kWh
$G_{h,y}$ = Annual gas consumption of household type h in year y, in m^3/year
$A1_{h,y}$ = Amount of grid-connected households of household type h in year y

Finally, the impact of grid defection on the sustainability of electricity supply was calculated by determining the difference in the annual amounts of CO_2 equivalents emitted for the total housing stock. See Equation 21.

$$\Delta E_y = \left(F_y * \sum\left(C_{h,y} * A_{h,y}\right)\right) - E2_y$$

Equation 21. Annual amount of CO_2 eq. emissions saved due to grid defection

$\Delta E2_y$ = Difference in CO_2 eq. emissions due to grid defection in year y, in kg of CO_2 eq.
F_y = Annual emission factor of electricity consumption from the grid in year y, in kg CO_2 eq. / kWh
$C_{h,y}$ = Annual electricity consumption of household type h in year y, in kWh/year
$A1_{h,y}$ = Total amount of households of household type h in year y
$E2_y$ = Amount of CO_2 eq. emissions from off-grid electricity consumption in year y, in kg of CO_2 eq.

5.4. Scenarios and sensitivity analyses

5.4.1. Scenarios

In this research, multiple assumptions were made regarding economic and technical parameters of PV, BESS and µCHP technologies. In addition, assumptions were made for future gas and electricity prices and rates of technological progress. Given that the temporal scope of this study reaches to 2050, variations in the assumptions can have substantial impact on the outcome of the research. Examples of factors that influence these assumptions are policies regarding subsidies and levies, commodity prices and overall attitude of society towards the energy transition. Two scenarios were used besides the base case scenario that is described in sections 5.2 and 5.3. Since the purpose of this research is not to provide accurate predictions on the grid defection rate, these scenarios serve mainly to show the impact of the underlying assumptions.

The first alternative scenario is called the 'green-tech' scenario, where there is more technological progress in renewable technology than anticipated. This impacts the cost reduction rate of the PV, BESS and µCHP technologies. Gas prices are increasing faster in the green-tech scenario, due to increased taxes on this fuel type. Moreover, the levy for renewables that is charged on the electricity from the grid increases as well. As the cost reduction for renewable technologies does not only apply for households, the business case of larger (renewable) distributed generation initiatives also improves in the green-tech scenario. This decreases the overall emission factor of electricity from the grid, which is used to assess the impact of grid defection on the environmental sustainability of electricity supply.

The third scenario is called the 'slow change' scenario, in which less progress in renewable technologies is made than anticipated. Furthermore, the gas price continues to increase only with inflation. The emission factor of electricity from the Dutch grid does not decrease as fast as in the base case scenario, since less of the fossil fuelled electricity generation capacity is replaced by (renewable) distributed generation units. Table 5.11 shows the values that were chosen in the base case scenario, the green-tech scenario and the slow change scenario.

Parameter	Base case scenario	Green-tech scenario	Slow change scenario
Investment costs PV	-9% per year	-12% per year	-5% per year
Installation costs PV	-2% per year	-5% per year	-1% per year
Investment costs BESS	-8% per year	-12% per year	-5% per year
Installation costs BESS	-2% per year	-5% per year	-1% per year
Investment costs µCHP	Constant	Constant	Constant
Installation costs µCHP	Constant	Constant	Constant
Natural gas price	+1% per year	+2% per year	+1% per year
Levy for renewables	Increase until 2023	Increase until 2050	Increase until 2023
Grid emission factor	-1.18% per year	-2.5% per year	-.75% per year

Table 5.11. Research assumptions and their used values in different scenarios

5.4.2. *Sensitivity analysis*

Besides the three mentioned scenarios, a sensitivity analysis was conducted on the most uncertain parameters: the decision variables of households to defect from the grid. As no empirical evidence on this subject has been found, the base case values were the result of an educated estimation. These variables have been split in the criterion of minimum cost difference between off-grid and on-grid electricity and the amount of households that defect if this cost difference is met. Table 5.12 shows the analysed parameters, with their base case values and minimum and maximum values in the sensitivity analysis. The maximum defection rate was set at 10% per year for both renting households and household owners.

Another sensitivity analysis was conducted on the annual change in electricity consumption, since there are many predictions on the electricity demand in the future. In this analysis, a range from -2.5% to +2.5% until 2030 was used. After 2030, the electricity consumption was assumed to be constant.

Parameter	Base case scenario	Minimum	Maximum
Minimum cost difference to defect for owners	10%	0%	100%
Amount of owners that defect each year	2.5%	0%	10%
Minimum cost difference to defect for renters	50%	0%	100%
Amount of renters that defect each year	2.5%	0%	10%
Annual change in electricity consumption	-.5% until 2030	-2.5% until 2030	+2.5% until 2030

Table 5.12. Parameters subject to sensitivity analyses, with their assessed minimums and maximums

6. Results

This chapter presents the results from the exploratory literature study and the simulation model. To draw conclusions from this research, the final outcomes are presented according to the performance indicators that were set up in the research framework. The purpose is to objectively present the results, while an in-depth interpretation and discussion of these results will follow in the next chapter.

6.1. Technical feasibility of grid defection at household level

In the exploratory literature study to grid defection, 11 studies were examined, of which 9 studies included case studies in various regions. The main conclusion regarding the technical feasibility of household grid defection is that it is possible for a household to defect from the electricity grid through a combination of solar photovoltaics (PV) and battery energy storage systems (BESS). However, this only applies in regions with high solar irradiance throughout the year. In the Netherlands, an extra form of electricity generation is needed to provide power during the longer periods of little solar irradiance, due to an unfeasible size of the battery unit that would be required otherwise. The most feasible option to reliably generate electricity at household level in the Netherlands is a micro combined heat and power (µCHP).

6.2. Economic viability of grid defection at household level

Given that an off-grid system would require a combination of PV+BESS+µCHP technologies, the economic viability of an off-grid system at household level was determined for various households. In this assessment, different sizes of PV modules and different sizes of battery systems were compared, with a decrease in cost in future years. The economic viability was measured with the indicator of grid parity, which occurs when the levelized cost of electricity (LCOE) of the off-grid system is less than the price of purchasing power from the grid.

Using current values for technical and economic parameters of the PV, BESS and µCHP technologies, the LCOE's of off-grid systems with optimized sizing were calculated with the Matlab script that can be found in Appendix II. Yearly LCOE's were calculated for the years 2017 to 2050. Table 6.1 and Table 6.2 show the initial values of the LCOE's of 2017 and the final LCOE's in 2050, while all other tables can be found in the Appendix IV. In these tables, the province labels and dwelling codes stand for:

FR=Friesland, DR= Drenthe, OV=Overijssel, FL=Flevoland, GD=Gelderland, UT=Utrecht, NH=Noord-Holland, ZH=Zuid-Holland, ZL=Zeeland, NB=Noord-Brabant, LB=Limburg.

F=Flat/Apartment, R=Row house, S=Semi-detached, D=Detached.

Building year periods: 1= pre 1965, 2=1965-1974, 3=1975-1991 and 4=after 1991.

LCOE's (2017) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type											
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.569	0.563	0.571	0.571	0.570	0.569	0.563	0.565	0.566	0.559	0.566	0.567
R1	0.574	0.569	0.572	0.568	0.566	0.567	0.559	0.563	0.563	0.565	0.562	0.561
S1	0.569	0.571	0.569	0.568	0.563	0.565	0.562	0.564	0.564	0.557	0.563	0.565
D1	0.570	0.563	0.571	0.568	0.564	0.566	0.559	0.563	0.563	0.560	0.563	0.562
F2	0.569	0.564	0.571	0.571	0.564	0.568	0.564	0.566	0.568	0.558	0.565	0.565
R2	0.573	0.571	0.570	0.568	0.565	0.565	0.558	0.563	0.563	0.564	0.562	0.563
S2	0.569	0.564	0.570	0.567	0.571	0.564	0.560	0.563	0.565	0.563	0.562	0.563
D2	0.571	0.565	0.571	0.570	0.567	0.568	0.558	0.565	0.565	0.559	0.564	0.565
F3	0.570	0.565	0.571	0.569	0.567	0.565	0.561	0.565	0.566	0.559	0.566	0.564
R3	0.571	0.571	0.572	0.568	0.564	0.564	0.558	0.562	0.562	0.559	0.562	0.562
S3	0.569	0.563	0.569	0.569	0.567	0.566	0.561	0.564	0.566	0.558	0.564	0.564
D3	0.571	0.566	0.571	0.568	0.567	0.566	0.561	0.566	0.563	0.561	0.562	0.563
F4	0.572	0.566	0.570	0.570	0.571	0.568	0.564	0.568	0.567	0.564	0.568	0.567
R4	0.568	0.568	0.568	0.566	0.563	0.563	0.559	0.563	0.563	0.559	0.561	0.561
S4	0.571	0.563	0.571	0.570	0.566	0.568	0.562	0.565	0.563	0.560	0.564	0.565
D4	0.571	0.567	0.571	0.567	0.564	0.564	0.558	0.562	0.562	0.558	0.562	0.562

Table 6.1. LCOE's of off-grid systems with optimized sizing (2017) for different household types

LCOE's (2050) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type											
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.319	0.312	0.319	0.317	0.320	0.313	0.303	0.314	0.315	0.301	0.307	0.309
R1	0.319	0.313	0.318	0.316	0.314	0.310	0.303	0.315	0.315	0.301	0.308	0.309
S1	0.317	0.309	0.318	0.316	0.312	0.310	0.305	0.314	0.314	0.301	0.307	0.308
D1	0.315	0.309	0.315	0.312	0.316	0.307	0.304	0.310	0.311	0.296	0.303	0.303
F2	0.325	0.318	0.326	0.325	0.317	0.320	0.315	0.324	0.329	0.304	0.314	0.313
R2	0.317	0.310	0.315	0.313	0.312	0.309	0.304	0.313	0.315	0.297	0.307	0.302
S2	0.317	0.311	0.312	0.311	0.306	0.305	0.302	0.309	0.315	0.294	0.302	0.301
D2	0.315	0.308	0.312	0.309	0.307	0.303	0.296	0.306	0.306	0.295	0.299	0.299
F3	0.329	0.317	0.329	0.324	0.324	0.318	0.310	0.324	0.326	0.311	0.321	0.315
R3	0.318	0.310	0.314	0.315	0.315	0.311	0.302	0.316	0.317	0.299	0.307	0.306
S3	0.316	0.310	0.313	0.313	0.312	0.307	0.301	0.310	0.313	0.298	0.306	0.302
D3	0.315	0.308	0.312	0.309	0.306	0.303	0.292	0.306	0.306	0.295	0.300	0.299
F4	0.330	0.320	0.323	0.323	0.329	0.319	0.310	0.326	0.325	0.318	0.320	0.316
R4	0.325	0.313	0.322	0.320	0.320	0.316	0.308	0.323	0.323	0.303	0.314	0.309
S4	0.316	0.309	0.313	0.311	0.311	0.307	0.298	0.311	0.312	0.296	0.303	0.301
D4	0.316	0.311	0.314	0.314	0.310	0.308	0.301	0.311	0.312	0.300	0.306	0.303

Table 6.2. LCOE's of off-grid systems with optimized sizing (2050) for different household types

With the LCOE's of 2017 to 2050, the rate of grid defection was calculated for the base case. The next sections elaborate on these rates of grid defection and their impact on the affordability, reliability and sustainability of electricity supply.

6.3. Model results

6.3.1. Base Case

6.3.1.1. Grid defection rate

The forward-looking model calculated the grid defection rate based on the technical and economic parameters that were described in chapter 5. The result of this calculation is depicted in the graphs in Figure 6.1 and Figure 6.2. The first graph shows the amount of grid connections for each dwelling type, from 2017 to 2050. Figure 6.2 shows the amounts of grid-connected households for each of the twelve provinces in the Netherlands. In these graphs, the renters and home owners are aggregated and the legend entries are ranked by the amount of grid connections in 2017.

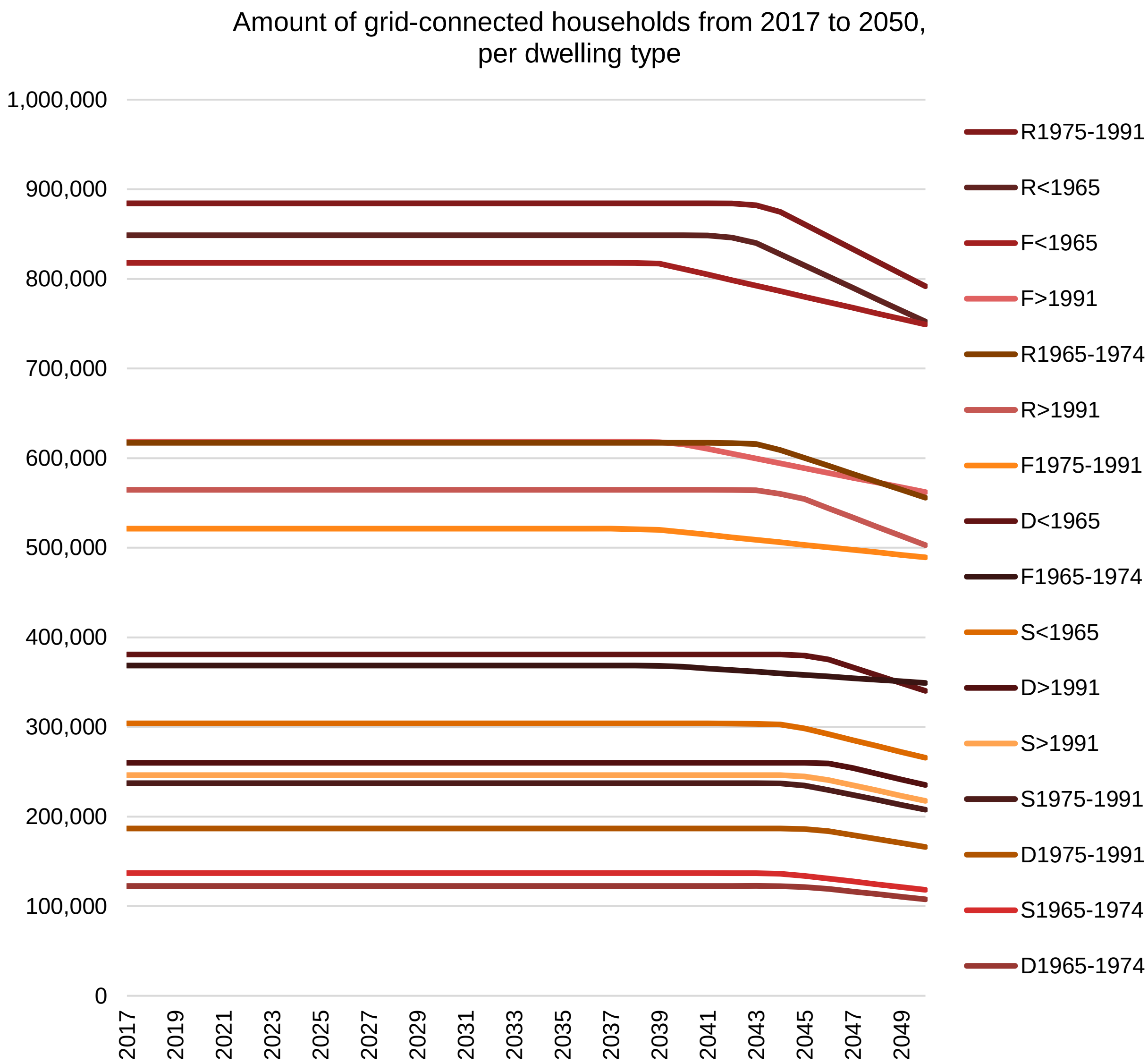

Figure 6.1. Base case results – Grid-connected households from 2017-2050, separated per dwelling type

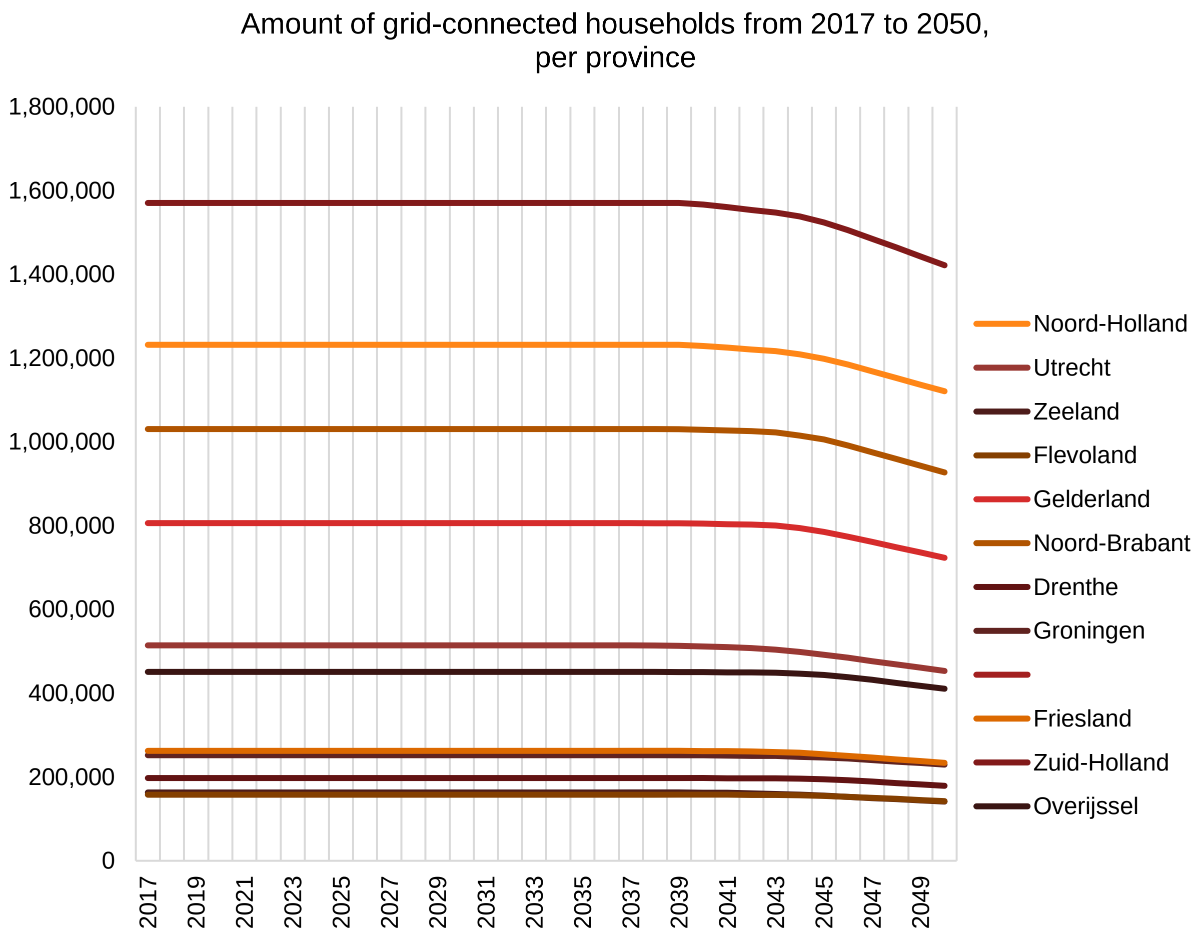

Figure 6.2. Base case results – Grid-connected households from 2017-2050, separated per province

Although decreasing costs of off-grid system components and increasing electricity prices from the grid have been taken into account in the base case, the model results show that grid parity of off-grid PV+BESS+μCHP systems will not be reached before 2037. Another outcome is that the households in flats and apartments are the first to go off-grid, even though these dwelling types have a low amount of available rooftop surface for solar PV. This can be explained by the fact that flats and apartments are also characterized by low annual electricity consumption, so that a smaller and cheaper PV+BESS+μCHP system is needed. Secondly, due to the fixed cost components in the electricity price, a low annual consumption is associated with a high final price of electricity.

The faster grid defection rate of Zuid-Holland, Noord-Holland, Noord-Brabant and Gelderland can be explained by the relatively high amount of flats and apartments in the distribution of dwelling types in these provinces.

The total grid defection rate is depicted in Figure 6.3. In this graph it can be seen that the amount of grid-connected households decreases from 7.1 million to 6.4 million between 2037 and 2050 in the base case.

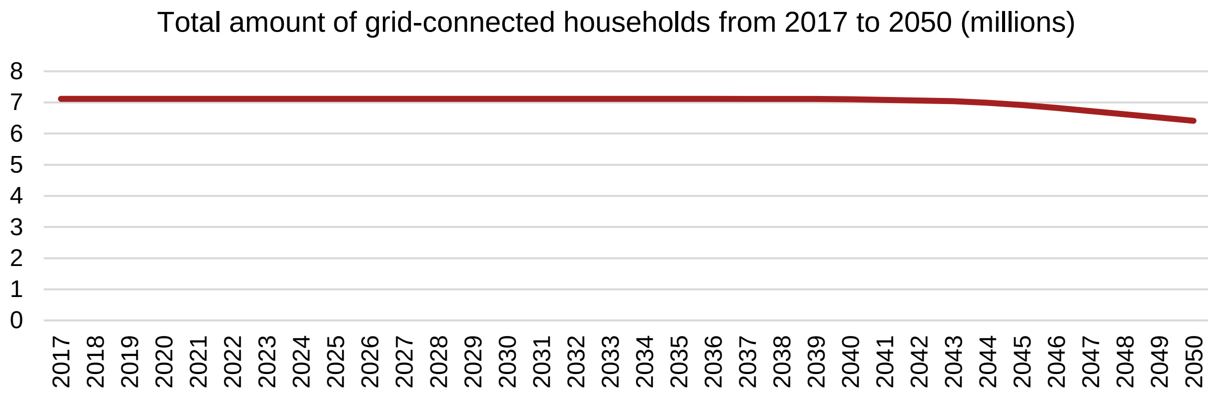

Figure 6.3. Base case results – Total amount of grid-connected households

6.3.1.2. *Impact on affordability*

To measure the impact of this grid defection rate on the affordability of electricity supply in the Netherlands, the annual costs of electricity were divided by the annual disposable income per household type, calculated with Equation 13 to Equation 18. The results are depicted in Figure 6.4, where the relative electricity costs are used as an inverse indicator of affordability of electricity.

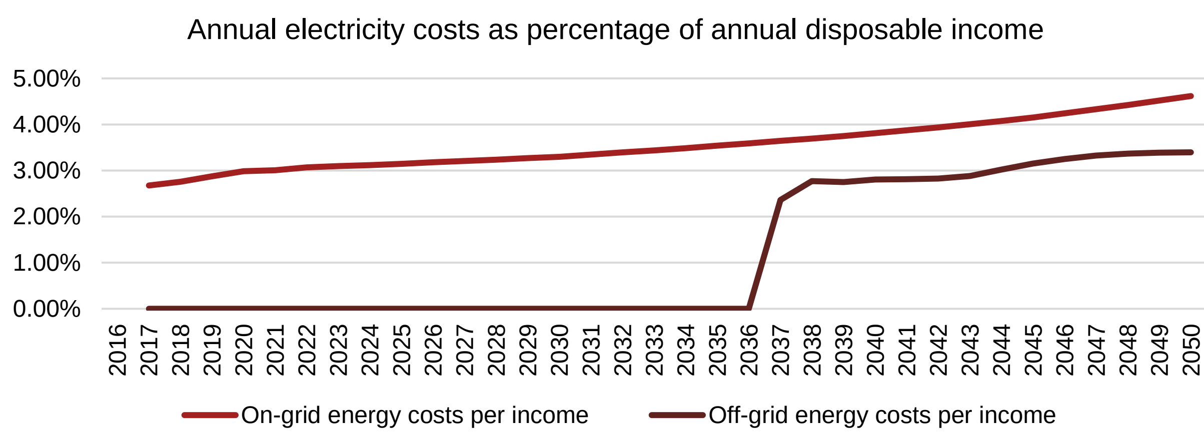

Figure 6.4. Base case results – Affordability of electricity supply for on-grid and off-grid households

This figure shows the weighted average of the relative annual electricity costs for all on-grid households and off-grid households separately. It can be seen that the affordability decreases slightly over time, due to autonomously increasing electricity prices. As grid defection starts to occur in 2037, the relative costs of electricity for grid-connected households rises faster. The overall affordability of off-grid electricity is non-existent until households go off-grid. The small increase bumps of the relative electricity costs for off-grid households can be explained by years in which a larger portion of the housing stock defects from the grid.

6.3.1.3. *Impact on reliability*

The impact of grid defection on the reliability of electricity supply is only measured for the off-grid households, as the assumption was made that the reliability of supply does not change for on-grid households. The amount of hours per year that the off-grid system relies on the µCHP unit for more than 95% of its maximum output was used as indicator. For most household types, this was around 50 hours per year. The graph in Figure 6.5 shows the weighted average of all off-grid households.

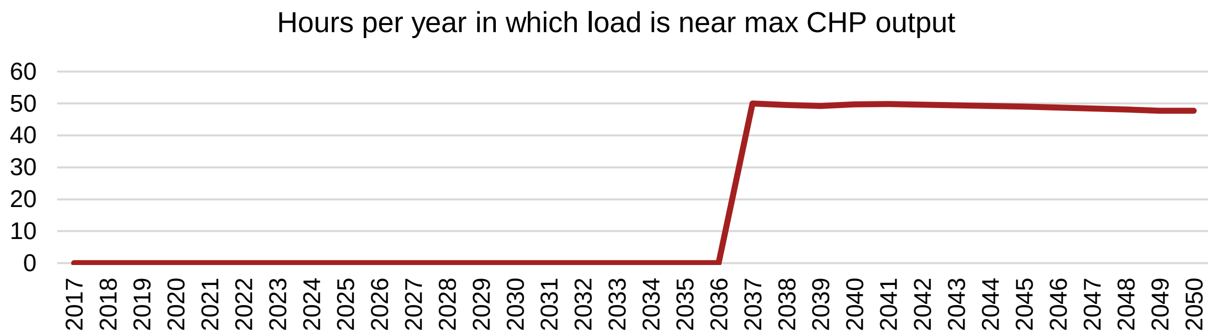

Figure 6.5. Base case results – Reliability of electricity supply for off-grid households

6.3.1.4. *Impact on sustainability*

The impact of grid defection on the (environmental) sustainability of electricity supply is measured through the total amount of CO_2 emissions avoided through households that supply their own electricity. Figure 6.6 shows the annual amount of CO_2 emissions from the total on-grid housing stock and the total off-grid housing stock. The cumulative amount of avoided CO_2 emissions show that grid defection has a positive effect on the overall sustainability of electricity supply in the Netherlands. In 2050, 1.5 Mt of CO_2 emissions have been avoided if grid defection occurs as in this base case scenario.

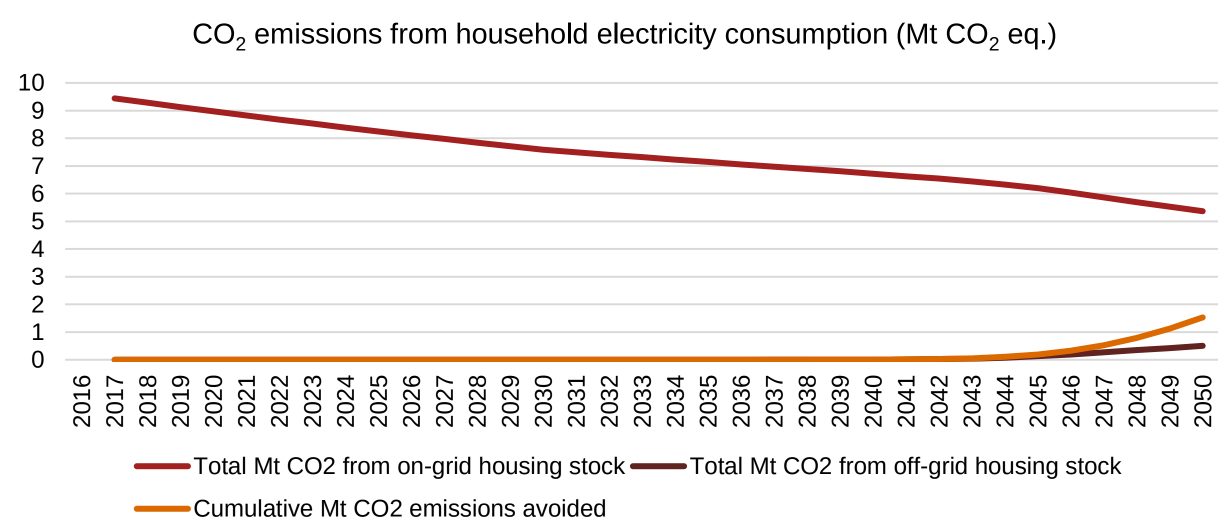

Figure 6.6. Base case results – Impact on sustainability of electricity supply

6.3.2. Green-tech scenario

For the green-tech scenario, the total grid defection rate and its impact on the affordability, reliability and sustainability of electricity supply are shown in Figure 6.7 to Figure 6.9. From these results, several points of interest arise. As to be expected, the rate of grid defection is higher (5.8M households connected in 2050) than in the base case scenario (6.4M households connected). The impact on the affordability of electricity of households that remain on the grid can also be seen. The relative costs of electricity are 5.0% of annual disposable income in 2050, as opposed to 4.6% in the base case. The amount of hours in which the µCHP generates more than 95% of its maximum output range between 46 and 49, similar to the base case. The greatest difference in impact can be seen in the amount of emissions avoided. For the base case, this accumulates to 1.53Mt of CO_2 eq. emissions in 2050, while the green-tech scenario causes a cumulative reduction of emissions of 5.41Mt CO_2 eq until 2050.

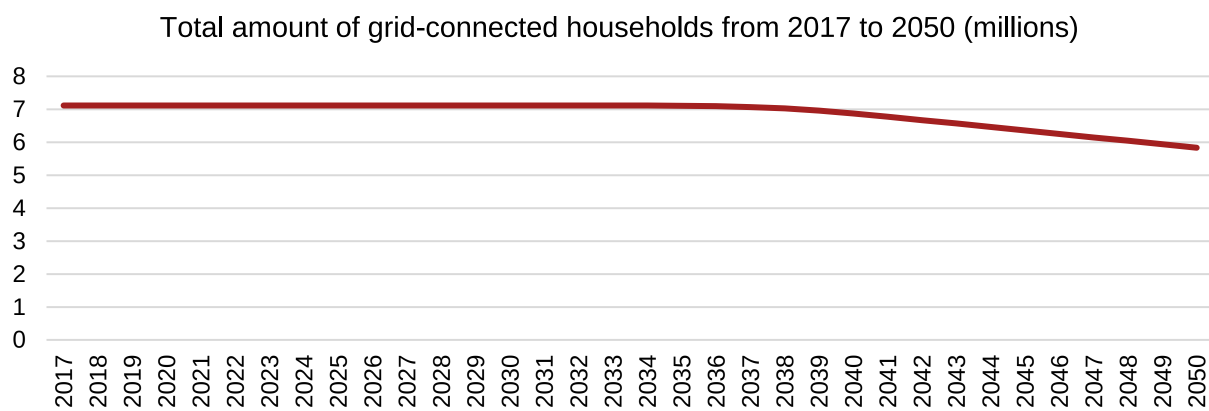

Figure 6.7. Green-tech scenario results – Total amount of grid-connected households

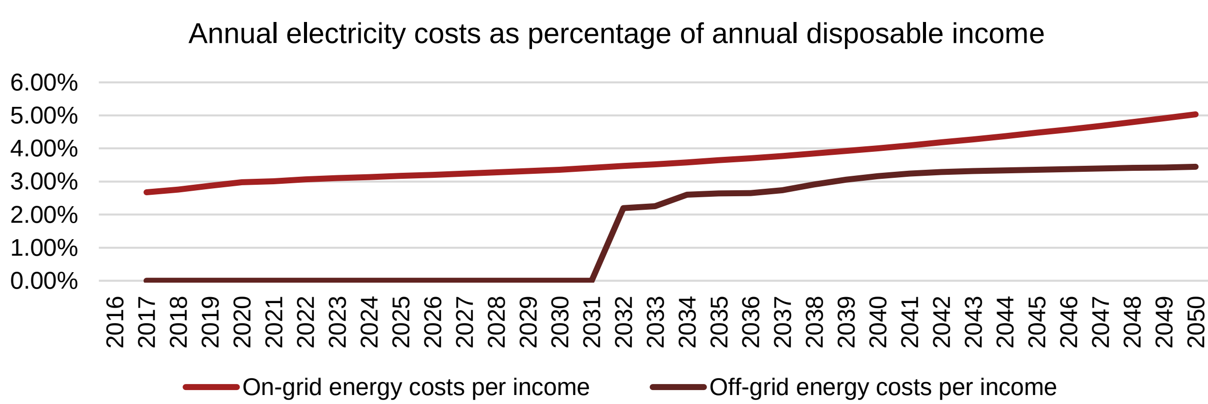

Figure 6.8. Green-tech scenario results – Affordability of electricity supply

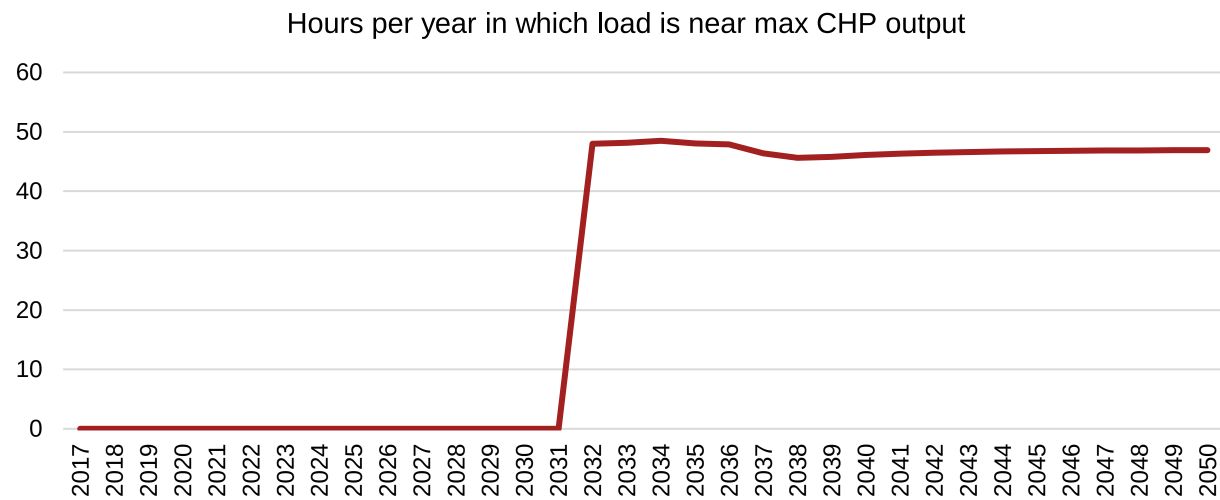

Figure 6.10. Green-tech scenario results – Reliability of electricity supply for off-grid households

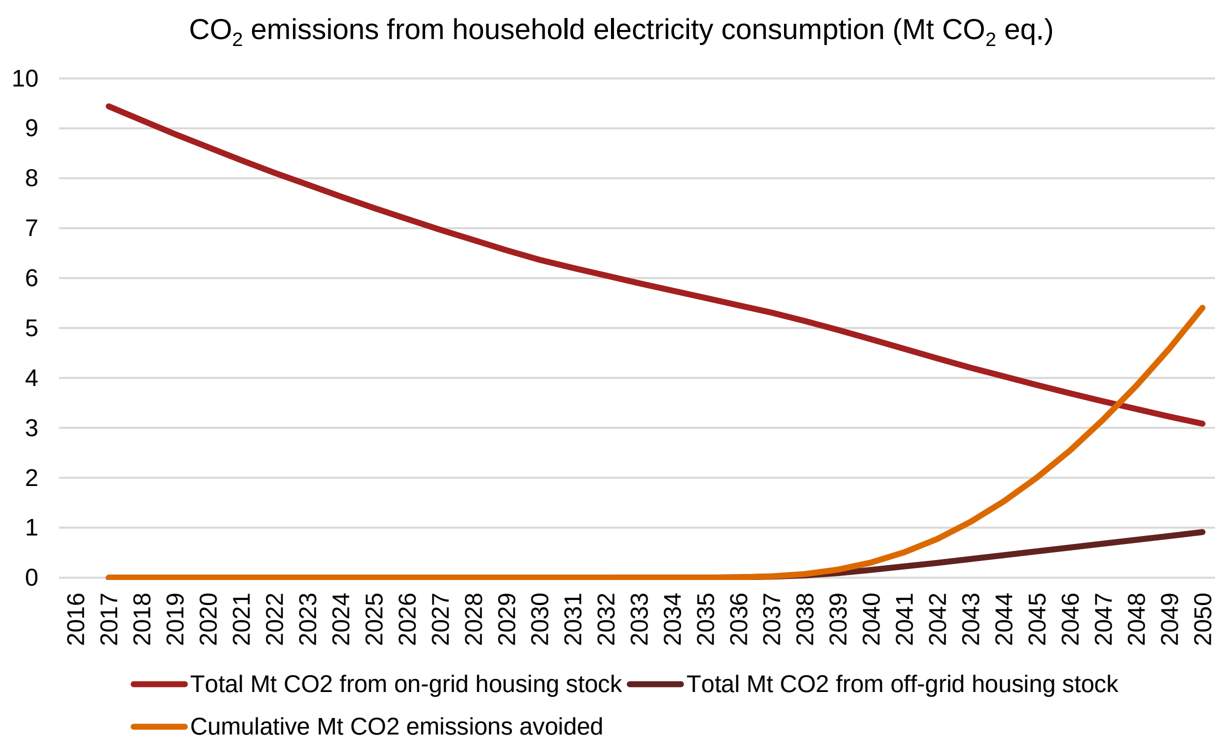

Figure 6.9. Green-tech scenario results – Impact on sustainability of electricity supply

6.3.3. *Slow change scenario*

For the slow change scenario, the total grid defection rate and its impact on the affordability, reliability and sustainability of electricity supply are shown below. In this scenario, there is nearly no grid defection, as there are 7.07M households connected in 2050, as opposed to 7.11 in 2017 (Figure 6.12). Therefore, there is no visible impact on the affordability of electricity of households that remain on the grid, as can be seen in Figure 6.12. For the households that do defect from the grid, the weighted average of the relative costs of electricity is low, but increases over time, due to households with less affordability that defect later. Figure 6.14 shows the amount of hours in which the µCHP generates more than 95% of its maximum output, which is near 50. No significant impact can be seen on the amount of emissions avoided. Until 2050, this accumulates to 18.64 kiloton of CO_2 eq. emissions in 2050, which is only 0.3% of the emissions of all on-grid households in 2050 alone.

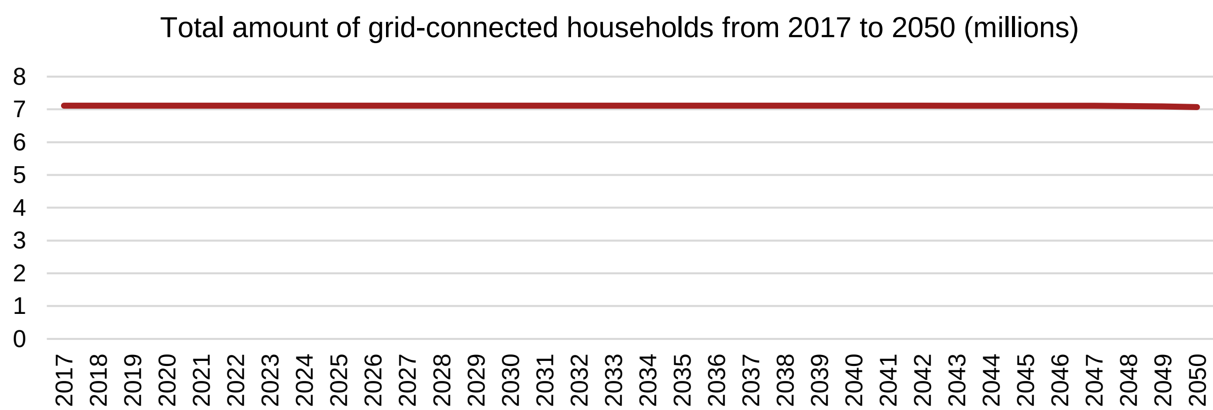

Figure 6.11. Slow change scenario results – Total amount of grid-connected households

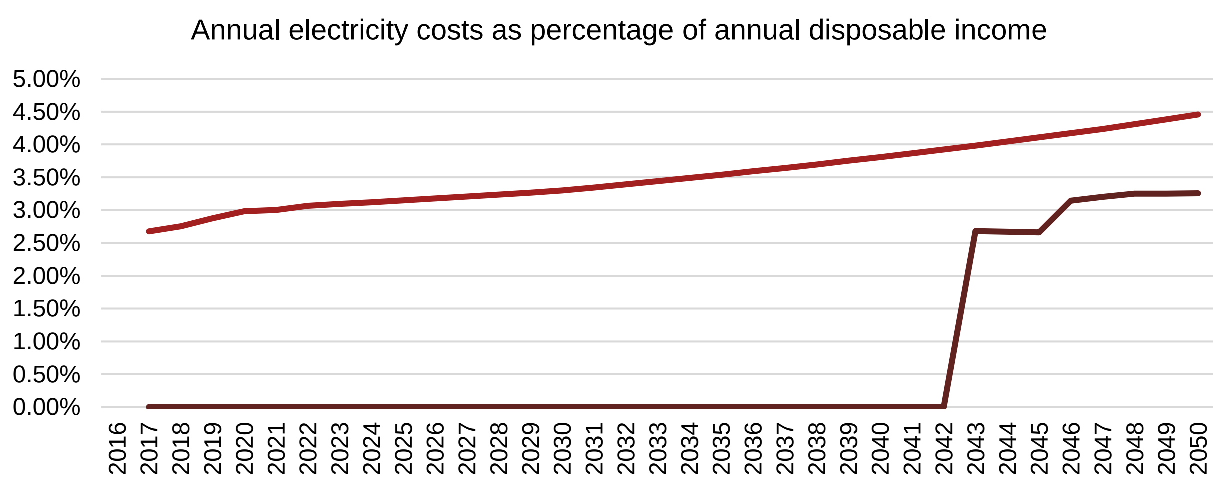

Figure 6.12. Slow change scenario results – Affordability of electricity supply

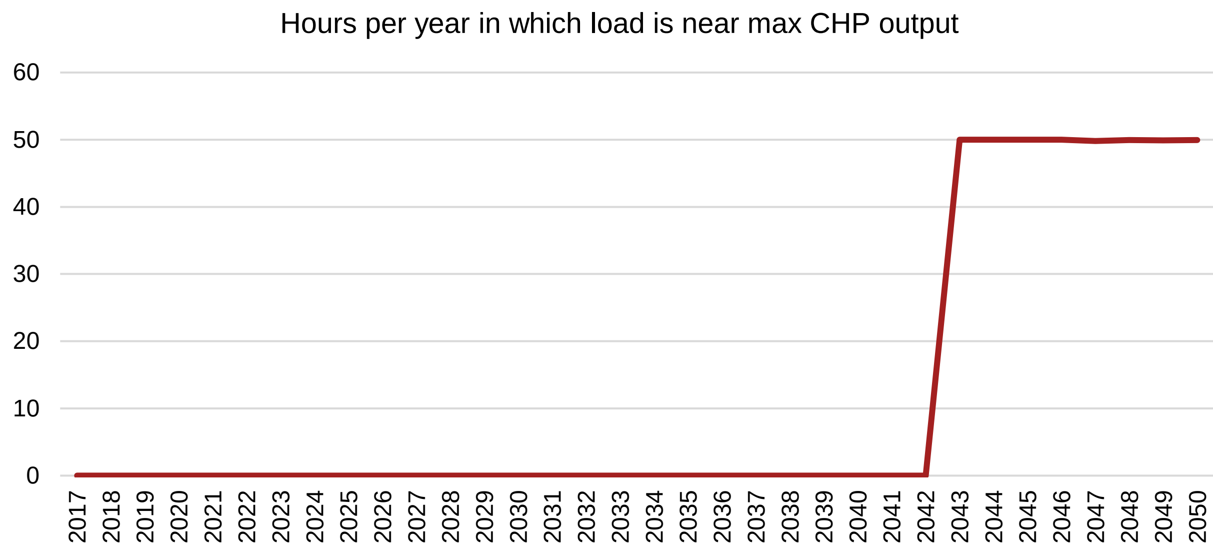

Figure 6.14. Slow change scenario results – Reliability of electricity supply for off-grid households

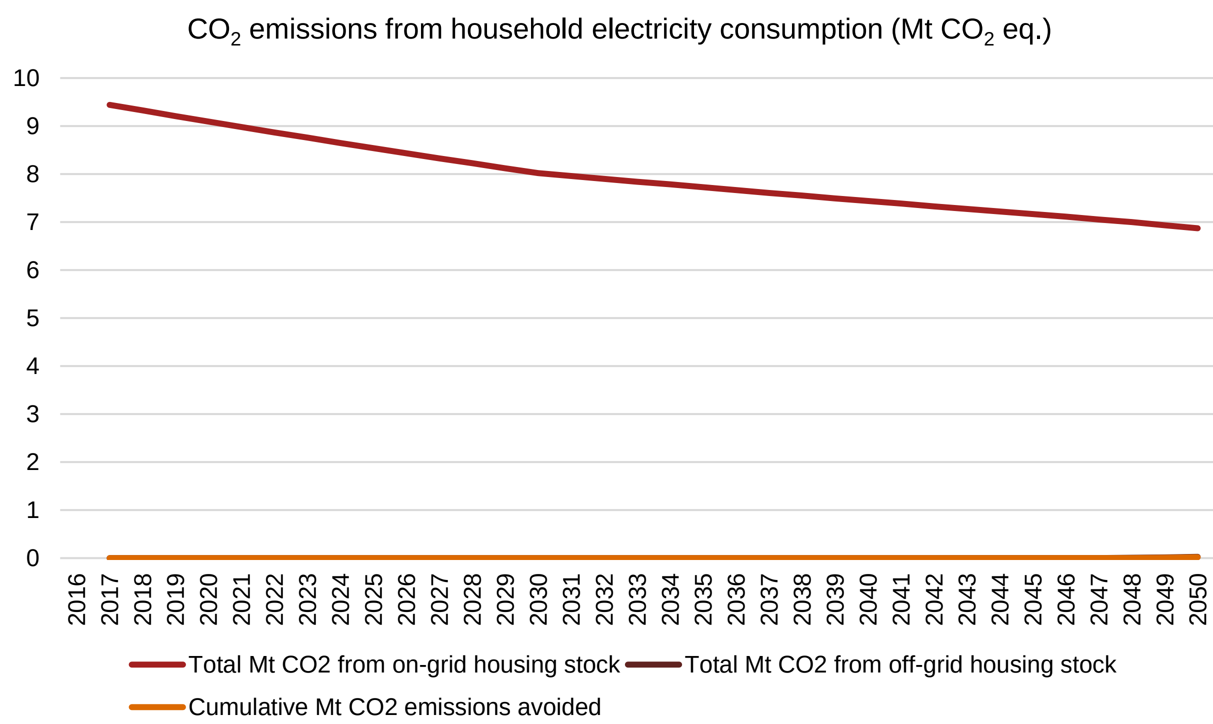

Figure 6.13. Slow change scenario results – Impact on sustainability of electricity supply

6.3.4. Sensitivity analyses

The results of the sensitivity analyses on the household decision variables are shown in Figure 6.15 and Figure 6.16. In these graphs, the total amount of grid-connected households in 2050 is shown, while the decision variables have been varied. It can be seen that the decision variable with the most impact is the amount of buyers that defect each year if their cost criterion is met. This is to be expected, since the largest group of households are home owners. The amount of renters that defect if their cost criterion is met does not have an impact on the total grid defection rate, since the initial cost criterion was set at 50%. From Figure 6.15, it can be seen that renters only start defecting if their cost criterion is lower than 43%. For buyers, this is 39%.

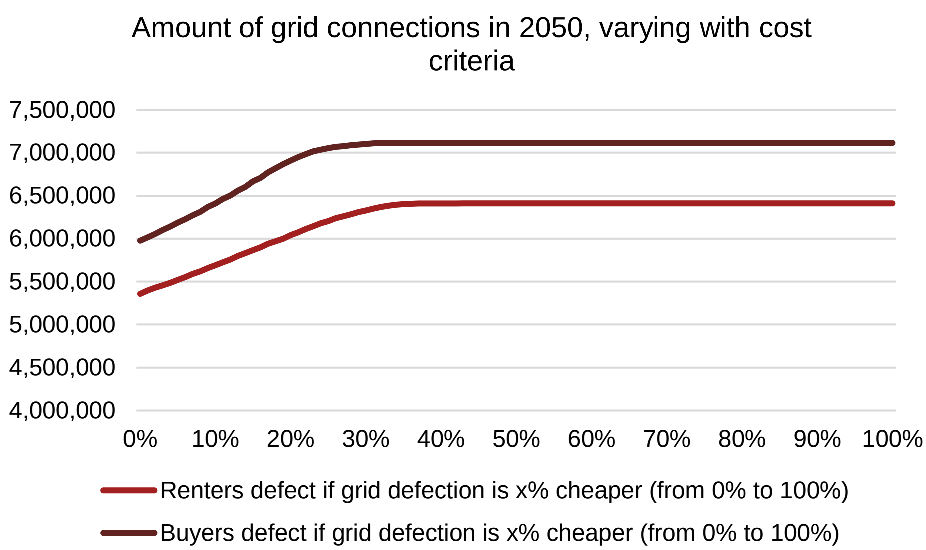

Figure 6.15. Sensitivity analysis results – Impact of difference in cost criteria

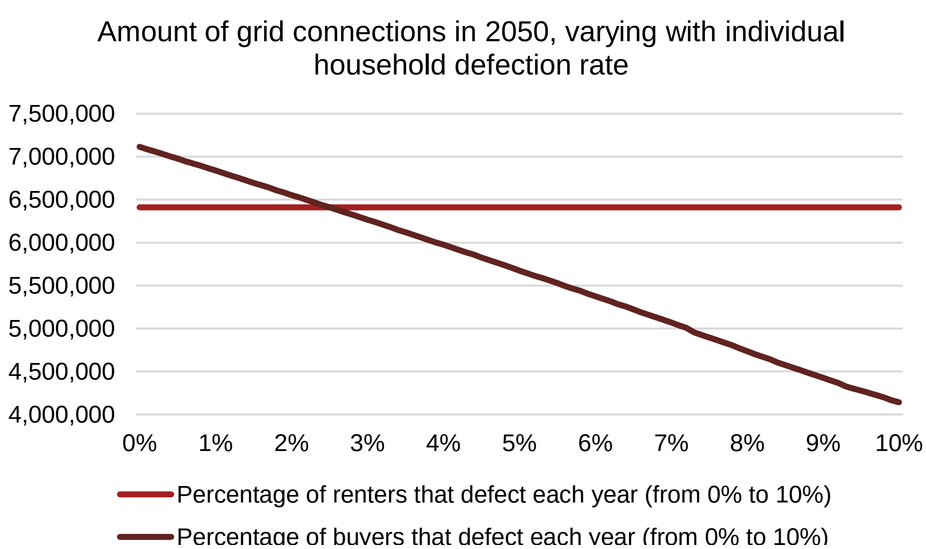

Figure 6.16. Sensitivity analysis results – Impact of difference in individual household defection rate

Finally, the sensitivity analysis on the impact of electricity consumption on the grid defection rate supports the outcomes presented in Figure 6.1: it is more economically viable for households with lower annual electricity consumption to defect from the grid than for households with a high electricity consumption. This analysis also shows that even if electricity consumption would increase with 2.5% per year until 2030, the total potential of grid defectors would be over 300.000 households in the base case.

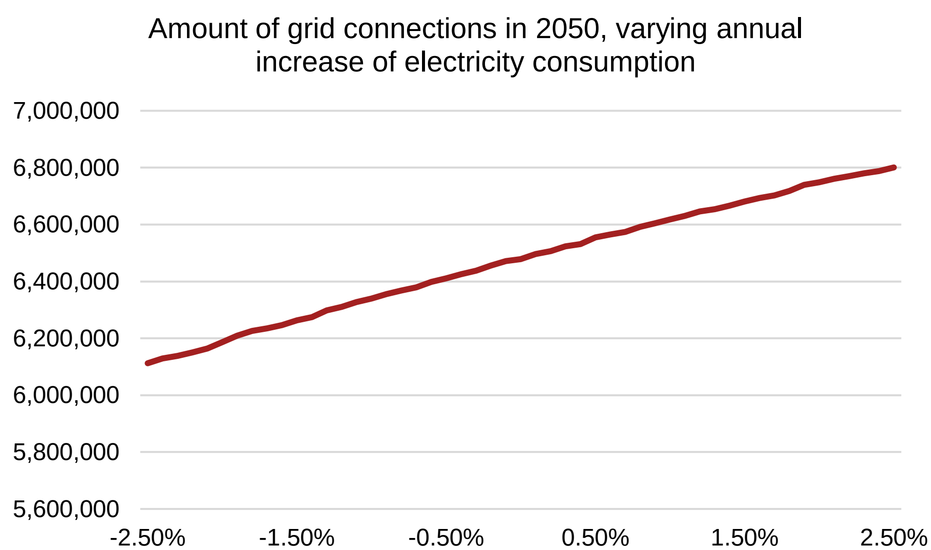

Figure 6.17. Sensitivity analysis results – Impact of difference in increase of electricity consumption

7. Conclusions

In this chapter, a concluding answer is given to the research question:

“What is the feasibility of massive household defection from the electricity grid in the Netherlands and what would be its impact?”

First, concluding remarks are given on sub-questions one and two. The last three sub-questions are answered in the main conclusion, to avoid repetition.

7.1. What are drivers for the technical feasibility and economic viability of grid defection for a household in the Netherlands?

The first driver is the choice of technology or combination of technologies that can be used to disconnect from the grid. This choice is dependent on the second driver; the region in which the household is located. For grid defection of all individual households in the Netherlands, a system that combines photovoltaics (PV), battery energy storage systems (BESS) and a micro combined heat and power unit (µCHP) is currently the only feasible option, given the long periods of little solar irradiance in the winter. The battery that would be required for a PV+BESS system would be too large to be feasible. Developments in other technologies that generate electricity at household level can also increase the feasibility of grid defection.

In summary, the economic viability depends mostly on the investment costs of PV, BESS and µCHP technologies, as can be seen from the large difference in LCOE of off-grid systems in 2017 and in 2050, depicted in section 6.2. Furthermore, the electricity consumption of the household plays a major role in the economic viability. This can be seen from Figure 6.1, in which the households with lower electricity consumption (Table 10.1) have lower LCOE’s for off-grid systems. Another finding that supports this conclusion is that households with lower electricity consumption have a higher final electricity price, since there are fixed costs involved. This means that if DSO’s or utilities would increase their fixed costs, the incentive for smaller households to go off-grid is higher than for households with a higher electricity consumption.

7.2. Which types of households can be determined in the Netherlands, and how can they be categorized in terms of potential for grid defection?

Given that grid defection with a PV+BESS combination alone is not feasible for Dutch households, the size of the dwelling, the available rooftop surface for PV and the region in which the household is located are not as distinctive for the potential of grid defection as the annual electricity demand. Therefore, the flats and apartments are the households with the highest grid defection rates, followed by row houses, semi-detached houses and detached houses, since this is the order of descending annual electricity consumption. This order is congruent with the dwelling size, which in turn is congruent with the household size. Therefore, a smaller household has a higher potential to go off-grid, especially if the household income is high enough to overcome required investment costs.

7.3. What is the feasibility of massive household defection from the electricity grid in the Netherlands and what would be its impact?

7.3.1. Overall feasibility

From the results in Figure 6.1 and Figure 6.2 can be seen that from 2037 and onwards, grid parity is reached for off-grid households, depending on the household type. Before this year, it might be technically feasible but not economically viable to disconnect, if current cost reductions in PV, BESS and μCHP are continued. However, when off-grid systems reach grid parity, the feasibility of massive grid defection is still largely reliant on the actual decision of households to disconnect from the grid. The sensitivity analyses depicted in Figure 6.15 and Figure 6.16 show these dependencies. For renters, the criterion to start grid defection is that the LCOE of an off-grid system must be maximally 43% of the electricity price. For home owners, this criterion must be 39% or lower. Unless these criteria are met, no households defect from the grid, based on economic parameters alone.

Furthermore, the scenario analyses show that if progress in PV and BESS technologies is not as fast as anticipated, the potential for grid defection based on economic parameters is near zero. The same effect can be seen if household electricity demand rises over time (Figure 6.17). One factor that causes a potential increase in electricity demand is the rising adoption rate of electric vehicles. This increases the dependency on the electricity grid, and thus has a negative effect on the overall grid defection potential.

7.3.2. Impact

The results from the simulation model show that grid defection has an impact on all three assessed factors of the quality of electricity supply. The affordability of electricity supply is lower for households that stay on the grid, if grid defection occurs. The extent of this effect was expected to be higher, as it is the main effect that is found in literature to grid defection. In the simulation, the households with the lowest electricity consumption are the first to go off-grid. These households are also the ones with the lowest disposable income, which means that the richer households stay on the grid and pay the increased grid fees. This limits the impact of grid defection on the overall affordability of electricity supply. Still, the results show a

For the reliability, the results show that households that disconnected from the grid with an optimized PV+BESS+μCHP system have approximately 50 hours per year a load that is near their system's maximum electricity supply. This can be seen as 50 hours per year in which a near-blackout can occur. Moreover, in the occasion of a breakdown of the μCHP unit, the total reliability of the system is diminished, since there is no other backup source. Especially during the winter, the dependency on the μCHP unit is high, given that the unit also supplies part of the required heat. Finally, electricity from the grid generally has no limits in supply, which increases the effect of grid defection on the reliability of electricity supply even more. On the grid connected households, the effect of grid defection on the reliability of supply is limited, given that these households pay a higher premium for a well maintained grid.

A scenario in which massive grid defection occurs would have high impact on the overall emissions of CO_2 that are associated with electricity supply, since the off-grid systems only emit CO_2 while their µCHP unit is running. In the base case scenario, the annual avoided emissions ranged from 2.3 ton CO_2 in 2037 to 400 kton in 2050 (Figure 6.6). Compared to the total emissions from household electricity consumption, these reductions are 0% and 6.85%, respectively.

7.3.3. Final conclusions

To conclude, the results from both the literature study and the simulation model show that massive disconnection from the electricity grid in the Netherlands requires a perfect storm of circumstances, consisting of increasing grid fees and electricity prices, decreasing electricity demand, rapid decreasing costs of off-grid system components and increasing societal willingness to go off-grid. Although the economic conditions for grid defection will be met for some individual household types, there are other reasons why (and why not) households would decide to invest in a form of self-sufficient electricity supply. The most important ones are the reliability and sustainability of supply, which both do not significantly improve or even get worse in the case of a disconnection from the grid. Future possibilities that might trigger massive defection from the electricity grid include joint grid defection of multiple households and developments in new forms of distributed generation at household level.

The policy implication of this study is that from both economic and socially desirable perspectives, widespread individual disconnection from the electricity grid is not a realistic projection of the future. Given the plans of the Dutch government to phase out natural gas consumption in the built environment, the adoption of µCHP units is not likely to be stimulated, unless biogas is used. Still, although a disconnection from the electricity grid is not to be expected, load defection is very realistic, given the decreasing costs of photovoltaics and batteries and a potential shutdown of the net metering program in the Netherlands.

As controlled gas grid defection is more likely to take place and the electricity grid is less strained than anticipated, the interaction between the two grids is an interesting topic of research. DSO's will have to base the investment decisions for their grids not only on the current trends in adoption rates of photovoltaics, batteries and electric vehicles, but also on the expected rate of gas grid disconnection.

8. Discussions

8.1. Research methods and relevance

This study has critically looked at the economic viability of disconnecting from the electricity grid of households in the Netherlands. As most studies in this field only focus on climates with high solar irradiance, this research fills a gap in the literature. Although other studies have researched off-grid households in colder climates, there was no combination found of a distinction between household types and optimized system sizes. Furthermore, the feedback loop effect of grid defection was included in this research, through a forward looking simulation model.

Since the outcome of this research is that massive disconnection of households from the electricity grid is unlikely, the societal impact of the study is limited, as this was already expected. Current developments in the out phasing of gas consumption in the Netherlands are only increasing the dependence on the electricity grid. However, one of the findings of the study was that a small battery unit has the potential to shift the load on the grid substantially. Although electric vehicles are also more often mentioned as household electricity storage mediums, their costs are still high and adoption rates relatively low. With the simulation results of this study, my expectation is that stationary battery units will see a surge in adoption rates, especially if net metering would be halted in the Netherlands.

8.2. Limitations and further research

One of the main conclusions of the study regarding the feasibility of disconnection from the electricity grid is also one of the main limitations of this study. Besides PV and µCHP units, there are little to no proven alternatives to generate electricity at household level in an efficient way. Despite its technical efficiency due to combined electricity and heat production, the µCHP technology is not very cost-efficient. Therefore, the assumption that every household with a gas connection will also adopt a µCHP unit is a weakness, especially since the use of fossil fuels is being discouraged. On the other hand, the benefits of the µCHP were calculated conservatively in the simulation model, since decreased energy costs due to a lower heat demand were not taken into account. In future research, off-grid generation units such as small wind turbines can be assessed to supplement this research.

Secondly, only one load profile was used for all types of households to calculate the hourly electricity consumption for different household types. After interviews with two of the three large DSO's in the Netherlands, still no other profiles were found. Further research to the load profiles can be beneficial for two reasons. To supplement this research, it could be used for a more realistic simulation to determine the feasibility of grid defection of different households, including the ownership of electric vehicles, for example. Secondly, DSO's can make use of specified load profiles per dwelling type or household type to perform more accurate estimations on the (future) electricity load profile on neighbourhood or city level. This information can then be used for substantiated grid investment decision processes.

Thirdly, the grid defection rates focus only on the economic feasibility of defecting from the electricity grid. However, besides high investment costs and uncertainty of financial return, there are more factors influencing a household's decision to disconnect from the grid. These include societal knowledge on the subject, concerns about aesthetics of renewable systems, and the environmental attitude. Future research to grid defection in the Netherlands could include these factors to make realistic forecast for the rate of grid defection. My hypothesis is that if these factors are taken into account, the outcome would probably be that it is even less likely that massive grid defection will occur.

Another limitation to this research was the access to the HOMER or other renewable energy modelling software. Much time and attention were drawn to the development of the Matlab script needed to process the large datasets and perform the calculations. If this analysis would have gone faster, other scenarios could have been explored. For example, Laws et al., (2017) have built a sophisticated system dynamics model which included three pricing mechanisms of utilities and DSO's that have different impacts on the grid defection rates. In this thesis, only a linear reaction of increasing grid fees to decreasing grid connections is assumed. Future research that includes different electricity pricing structures and the effect of a shutdown of net metering, could shed light on the rate of adoption of PV and battery systems in the Netherlands, without only looking at grid defection.

Although the approach was thorough and 192 household types were assessed, demographic changes in the total housing stock were not included in the research. This was chosen due to high uncertainties in these changes. Ultimately, the household type itself did not prove to be the most important factor in the viability of grid defection, but rather the amount of electricity consumption. Therefore, if demographic analyses would be included in future studies to grid defection, an emphasis would still be required on the electricity consumption data, besides the transition from older to newer dwellings, for example.

Finally, performing this research has given insights in how to combine a bottom up analysis on household level with a top down analysis on the total housing stock level of a neighborhood, city or region to estimate the potential for gas grid defection. Although this subject is already being researched by various institutes and researchers, no literature was found so far that uses the same bottom up approach, by matching household heat supply and demand on hourly basis, for different gas-replacing technologies. This could prove to be an interesting topic for further research.

9. Personal reflection and acknowledgements

Conducting this research was alternately fulfilling, challenging and sometimes frustrating, most of the time in reverse order. In the process I have had to explore the limits of Excel, learn the Matlab coding language and refresh my SPSS analyses skills, which were great learning opportunities. I found that sometimes one comment of a colleague could mean 4 weeks' worth of extra work, and sometimes one other's insight could save a few moments of despair. All in all, the experience was educational on multiple levels and I am content with the end result.

I would like to thank my supervisor Ernst Worrell for the feedback and getting-back-on-track moments, and for his quote 'You cannot research the whole world', which helped me to stay in scope. To Christian Swager, my supervisor at my host institution Strategy&, I would like to say thanks for the work, time and support he has put in for me and my thesis. It helped me focus on the things that had impact and kept me from lingering in the smallest details. Others at Strategy& that I would like to thank are Paul Nillesen, Rick van Koppen, Rutger Bots and Jochem Meeuwissen, who were always prepared to share their insights with me. Furthermore, thanks go to Armin Boonstra at Enexis and David Peters, Ravish Mehairjan and Katinka van Beek at Stedin for their time and validation of the research methods. Finally, I would like to thank my wife, Loïs for her support during the past two years of my MSc degree. Where I have worked, she worked at least as hard, with an ever-positive attitude.

10. Appendix I – Used data per household type to calculate LCOE's

The province labels represent: GR=Groningen, FR=Friesland, DR= Drenthe, OV=Overijssel, FL=Flevoland, GD=Gelderland, UT=Utrecht, NH=Noord-Holland, ZH=Zuid-Holland, ZL=Zeeland, NB=Noord-Brabant, LB=Limburg. For the dwelling codes: F=Flat/Apartment, R=Row house, S=Semi-detached, D=Detached. The numbers represent building year periods: 1= pre 1965, 2=1965-1974, 3=1975-1991 and 4=after 1991

Annual electricity consumption of households (2015) per household type (kWh per year)												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	1955	1819	2098	2133	2346	2202	2203	2101	2160	1931	2120	2224
R1	2397	2415	2881	3029	3028	2903	3117	3097	3123	2670	3107	3199
S1	3100	2530	3649	3815	3502	3744	4233	3812	3871	3460	3855	4090
D1	3972	3344	4393	4515	5548	4468	5581	4626	4804	3933	4562	4770
F2	1880	1752	2106	2181	1887	2140	2323	2201	2382	1656	2086	2036
R2	2787	2633	3024	3065	3173	3151	3526	3266	3393	2689	3301	3043
S2	3688	3262	3115	3393	2451	3532	4481	3846	4446	2709	3790	3798
D2	2940	3682	4122	4425	3051	4267	5263	4129	4500	3656	4709	4144
F3	1958	1551	2068	1957	2078	1890	2005	2074	2151	1942	2218	1979
R3	2947	2681	2903	3256	3409	3324	3410	3534	3626	3010	3323	3313
S3	3357	3353	3577	4097	4286	3942	4418	4038	4319	3800	4390	3945
D3	3826	3623	4124	4652	4077	4502	4683	4163	4935	4288	4992	4666
F4	2238	2042	2048	2180	2488	2193	2218	2371	2320	2404	2346	2244
R4	3321	2822	3334	3333	3474	3388	3562	3744	3761	3019	3513	3293
S4	4026	3557	4013	4156	4482	4298	4472	4475	4774	4015	4406	4171
D4	4070	4224	4423	5061	4791	4858	5268	4829	5127	4762	5213	4809

Table 10.1. Electricity consumption of households per household type. Source: WoonOnderzoek (2016)

Average available rooftop surface for PV (m²)

Dwelling type	**Built in**											
	1600	1800	1900	1920	1940	1960	1970	1980	1990	1995	2000	2010
Detached	79.7	80.6	54.1	56.5	58	47.9	85.3	50.7	71.6	64.6	60.2	24.5
Semi-detached	45	66.5	32.2	45.1	39.6	41.7	50.7	44.7	45.7	58.5	46.1	58.1
Row house	36.5	27.7	29.1	30.3	32.1	32.1	38.5	33.2	33.9	35.8	36.3	21.3
Flat <4 floors	29.1	18.8	24.6	20.4	17.5	15.6	22.2	16.6	18.7	19.9	20.8	17.9
Flat>4 floors		24.6	24.3	13.3	13.5	10.6	6.6	15.6	12.6	16.3	22.7	26.1
Single storey apt.	25.6	27.6	24.2	22.8	23.1	26.1	22.8	19.3	12.9	17.6	21.4	12.8
Apartment	22.2	27.7	23.4	22.8	45	20.7	19.5	16.2	19.3	29.1	26.6	6.2
Mansion	48.2	36.1	32.2	33.5	37.6	40.7	38.7	26.5	24.7	33.2	16.3	34.6
Retirement apt.	71.3	33.2	33.1	31	22.9	15.8	36.9	23.3	22.2	31.5	11.3	33.5
Farmhouse	21.8	191.2	177.7	97.2	76.2	88.1	87.4	50	122.8	78.3	138	78.2
Student apt.	40.6	50.6	32.5	30.5	9.2	3.2	3.6	13.2	125.7	20.8	34.4	

Table 10.2. Average available rooftop surface for PV per dwelling type. Source: PBL & DNV-GL (2014)

11. Appendix II – Matlab script to calculate minimum LCOE's

11.1. Module 1: Load the load profile, annual consumption data, solar data and surfaces data and include technical and economic parameters

```
load('Profile.mat')
load('AnnualConsumption.mat')
load('Solar.mat')
load('Surfaces.mat')

L = 30; % lifetime of the system
inf = 0.01; % Inflation rate
r = 0.03; % Discount rate 3%
El_Cons_Reduction(1:13) = 0.005; % Electricity consumption decreases with 0.5% until
2030
El_Cons_Reduction(13:34) = 0; % Electricity consumption stabilizes after 2030
PV_Eff(1:34) = .143;
CHP_Eff(1:6) = [.15,.16,.17,.18,.19,.20]; % 15% (electric efficiency)
CHP_Eff(7:34) = .2;
Bat_Size = 2; % 2 kWh per battery pack
Bat_Charge_Eff = .85; % 85% charging efficiency
Bat_DoD = .80; % 80% Max depth of discharge
Replacement_Costs = zeros(1,30); % empty vector of replacement costs, will be filled
with Inverter, battery and CHP replacement costs
%% Store investment costs and O&M costs in vectors
PV_Price_Reduction = 0.09;
PV_Installation_Price_Reduction = 0.02;
PV_System_Price = 1460; %€/kWp
PV_Installation_Price = 400; %€/kWp
PV_Price = (PV_Installation_Price .* (1-PV_Installation_Price_Reduction) .^ (0:53) +
PV_System_Price .* (1-PV_Price_Reduction) .^ (0:53));

Bat_Price_Reduction = 0.08;
Bat_Installation_Price_Reduction = 0.02;
Bat_System_Price = 430; %€/kWh
Bat_Installation_Price = 100; %€/kWh
Bat_Price = (Bat_Installation_Price .* (1-Bat_Installation_Price_Reduction) .^ (0:53)
+ Bat_System_Price .* (1-Bat_Price_Reduction) .^ (0:53));

CHP_Price_Reduction = 0.00;
CHP_Price = 1230 .* (1-CHP_Price_Reduction) .^ (0:53); % €/kWe
Gas_Price_m3 = .65; % €/m3
Gas_kwh_per_m3 = 9.769; % kWh/m3
Gas_Price_kwh = (Gas_Price_m3 / Gas_kwh_per_m3) .*(1+inf).^(0:48+L); % €/kWh

PV_OM_Costs = 0.005 .* (1) .^ (1:30); % 1% of investment costs per year, constant
Bat_OM_Costs = 0.005 .* (1) .^ (1:30); % 1% of investment costs per year, constant
CHP_OM_Costs = 0.01 .* (1) .^ (1:30); % 1% of investment costs per year, constant
```

11.2. Module 2: Create load profile for each household type and compare it to the solar radiation profile

```
Loads = zeros(8760,192,34);
El_Consumption = zeros(34,192);
El_Consumption(1,:) = AnnualConsumption * (1-El_Cons_Reduction(1));
for y = 2:34
    El_Consumption(y,:) = El_Consumption(y-1,:) * (1-El_Cons_Reduction(y));
        % all household types are assumed to have the same profile, with different
demand values
end

for y = 1:34
    Loads(:,:,y) = El_Consumption(y,:) .* Profile;
        % all household types are assumed to have the same profile, with different
demand values
end

Net_Solar = zeros(8760,16,12,11,34);
for i = 1:16 % 16 Dwelling types
    for j = 1:12 % 12 Provinces
        for s = 1:11 % 0% - 100% of dwelling surface (m2) used for Solar Panels with
steps of 10%
            for y = 1:34 % 34 years
                Net_Solar(:,i,j,s,y) = (Solar(:,j) * Surfaces(i) * (0.10*(s-1)) *
PV_Eff(y)) - Loads(:,(j-1)*16+i,y);
                % The excess or shortage of solar power, compared to the electricity
load
            end
        end
    end
end
```

11.3. Module 3: Iterate over dwelling types, provinces, years, PV sizes and battery sizes to find LCOE's for all possibilities

```
LCOE = zeros(16,12,34,11,11);
Invest = zeros(16,12,34,11,11);
Total_Gas_Costs = zeros(16,12,34,11,11);
Total_Gas_Cons = zeros(16,12,34,11,11);
Hours_Near_Max_CHP = zeros(16,12,34,11,11);
for i = 1:16 % 16 Dwelling types
    for j = 1:12 % 12 Provinces
        for y = 1:34 % 34 years (2017-2050)
            for s = 1:11 % 0% - 100% of dwelling surface (m2) used for Solar Panels,
with steps of 10%
                for b = 1:11 % 0-20 kWh, with steps of 2kWh
                    B_Cons = zeros(8760,1);
                    CHP_Cons = zeros(8760,1);
                    B_SOC = zeros(8761,1);
                    B_Total = (b-1) * Bat_Size*Bat_DoD; % this ensures that the
battery is never discharged below the max DoD
                    B_SOC(1) = B_Total; % Battery starts fully charged
                    for x = 1:8760 % 8760 Hours per year
                        if Net_Solar(x,i,j,s,y) > 0 % Is there more solar power than
load at hour x?
                            B_SOC(x+1) = min(B_Total, B_SOC(x) + Net_Solar(x,i,j,s,y)
* Bat_Charge_Eff);
                            % Battery is charged with maximum excess solar power, at
85% efficiency
                        else
                            B_SOC(x+1) = max(0, B_SOC(x) - abs(Net_Solar(x,i,j,s,y)));
                            B_Cons(x) = max(0,B_SOC(x)-B_SOC(x+1));
                            % Battery is discharged at 100% efficiency
                            CHP_Cons(x) = max(0, Loads(x,(j-1)*16+i,y) - Solar(x,j) *
Surfaces(i) * (0.10*(s-1))* PV_Eff(y)) - B_Cons(x);
                            % What cannot be supplied by solar power and battery, must
be supplied by CHP
                        end
                    end
                    Gas_Costs = sum(CHP_Cons) / CHP_Eff(y) .* Gas_Price_kwh(y:y+L-1);
                    PV_Costs = Surfaces(i) * (0.10*(s-1)) * PV_Eff(y) * PV_Price(y);
                    Bat_Costs = B_Total / Bat_DoD * Bat_Price(y);
                    CHP_Costs = max(CHP_Cons) / CHP_Eff(y) * CHP_Price(y);
                    CAPEX = PV_Costs + Bat_Costs + CHP_Costs;
                    Replacement_Costs(10) = (Surfaces(i) * (0.10*(s-1)) * PV_Eff(y) *
PV_Price(y+10)) + (B_Total/Bat_DoD * Bat_Price(y+10));
                    Replacement_Costs(15) = CHP_Costs;
                    Replacement_Costs(20) = (Surfaces(i) * (0.10*(s-1)) * PV_Eff(y) *
PV_Price(y+20)) + (B_Total/Bat_DoD * Bat_Price(y+20));
                    OM_Costs = (PV_Costs .* PV_OM_Costs) + (Bat_Costs .* Bat_OM_Costs)
+ (CHP_Costs .* CHP_OM_Costs);
                    OPEX  = Gas_Costs + OM_Costs + Replacement_Costs;
                    NUM = CAPEX + sum(OPEX ./ (1+r) .^ (1:L));
                    DEN = sum(sum(Loads(:,(j-1)*16+i,y)) ./ (1+r) .^ (1:L));
                    LCOE(i,j,y,s,b) = NUM / DEN;
                    Invest(i,j,y,s,b) = CAPEX;
                    Total_Gas_Cons(i,j,y,s,b) = sum(CHP_Cons);
                    Hours_Near_Max_CHP(i,j,y,s,b) = sum(CHP_Cons>.95*max(CHP_Cons));
                end
            end
        end
    end
end
clear Net_Solar
```

11.4. Module 4: Find the minimum LCOE's for each household type, with corresponding investment costs

```
LCOEs = permute(LCOE,[4 5 1 2 3]);
Invest_2 = permute(Invest,[4 5 1 2 3]);
Gas_Cons_2 = permute(Total_Gas_Cons, [4 5 1 2 3]);
Reliability_2 = permute(Hours_Near_Max_CHP, [4 5 1 2 3]);
z=min(min(LCOEs));

B=zeros(16,12,34);
Invest_3=zeros(16,12,34);
Gas_Cons_3=zeros(16,12,34);
Reliability_3=zeros(16,12,34);

for i = 1:16
    for j = 1:12
        for y = 1:34
            B(i,j,y) = find(z((y-1)*(12*16)+(j-1)*16+i)==LCOEs(:,:,i,j,y));
            C = Invest_2(:,:,i,j,y);
            Invest_3(i,j,y) = C(B(i,j,y));
            D = Gas_Cons_2(:,:,i,j,y);
            Gas_Cons_3(i,j,y) = D(B(i,j,y));
            E = Reliability_2(:,:,i,j,y);
            Reliability_3(i,j,y) = E(B(i,j,y));
        end
    end
end
```

11.5. Module 5: Store minimum LCOE's and investment costs in separate tables, then export to Excel file

```
T = NaN(18*34-2,12);
z=reshape(z,16,12,34);
for t = 1:34
    T(18*(t-1)+[1:16], :) =  z(:,:,t);
end

S = NaN(18*34-2,12);
for s = 1:34
    S(18*(s-1)+[1:16], :) =  Invest_3(:,:,s);
end

R = NaN(18*34-2,12);
for q = 1:34
    R(18*(q-1)+[1:16], :) =  Gas_Cons_3(:,:,q);
end

Q = NaN(18*34-2,12);
for p = 1:34
    Q(18*(p-1)+[1:16], :) =  Reliability_3(:,:,p);
end

%xlswrite1 start
Excel = actxserver ('Excel.Application');
File='C:\Users\twaleson001\Documents\3. University\Thesis\Grid Defection\Model\Base
Case Model.xlsm';
if ~exist(File,'file')
    ExcelWorkbook = Excel.workbooks.Add;
    ExcelWorkbook.SaveAs(File,1);
    ExcelWorkbook.Close(false);
end
invoke(Excel.Workbooks,'Open',File);

xlswrite1('Base Case Model.xlsm', T, 'LCOE (Matlab input)', 'B2');
xlswrite1('Base Case Model.xlsm', S, 'Investments (Matlab input)', 'B2');
xlswrite1('Base Case Model.xlsm', R, 'Gas Cons (Matlab input)', 'B2');
xlswrite1('Base Case Model.xlsm', Q, 'Reliability (Matlab input)', 'B2');

%xlswrite1 stop
invoke(Excel.ActiveWorkbook,'Save');
Excel.Quit
Excel.delete
clear Excel
system('taskkill /F /IM EXCEL.EXE');
```

12. Appendix III – Used data per household type to calculate grid defection rate and impact on performance indicators

Final electricity price (2017) per household type (€/kWh)												
Dwelling/ province	GR	FR	DR	OV	FL	GD	UT	NH	ZH	ZL	NB	LB
F1	0.2577	0.2623	0.2535	0.2526	0.2475	0.2509	0.2508	0.2535	0.2519	0.2585	0.2529	0.2503
R1	0.2464	0.2461	0.2381	0.2361	0.2361	0.2378	0.2350	0.2352	0.2349	0.2414	0.2351	0.2340
S1	0.2352	0.2438	0.2294	0.2280	0.2308	0.2286	0.2249	0.2280	0.2275	0.2312	0.2276	0.2259
D1	0.2267	0.2324	0.2238	0.2231	0.2182	0.2234	0.2181	0.2225	0.2215	0.2270	0.2228	0.2217
F2	0.2601	0.2648	0.2533	0.2514	0.2599	0.2524	0.2480	0.2509	0.2468	0.2687	0.2539	0.2553
R2	0.2395	0.2420	0.2361	0.2356	0.2343	0.2346	0.2305	0.2332	0.2318	0.2411	0.2328	0.2359
S2	0.2290	0.2333	0.2350	0.2318	0.2454	0.2305	0.2233	0.2277	0.2235	0.2407	0.2282	0.2281
D2	0.2373	0.2291	0.2256	0.2237	0.2358	0.2246	0.2194	0.2256	0.2232	0.2293	0.2220	0.2255
F3	0.2576	0.2736	0.2544	0.2576	0.2541	0.2598	0.2562	0.2542	0.2521	0.2581	0.2505	0.2569
R3	0.2372	0.2412	0.2378	0.2333	0.2317	0.2326	0.2317	0.2305	0.2296	0.2363	0.2326	0.2327
S3	0.2322	0.2323	0.2300	0.2258	0.2245	0.2270	0.2237	0.2262	0.2243	0.2281	0.2239	0.2269
D3	0.2279	0.2296	0.2256	0.2223	0.2260	0.2232	0.2222	0.2253	0.2209	0.2245	0.2206	0.2223
F4	0.2500	0.2551	0.2549	0.2514	0.2446	0.2511	0.2505	0.2470	0.2481	0.2463	0.2475	0.2499
R4	0.2326	0.2390	0.2325	0.2325	0.2310	0.2319	0.2302	0.2286	0.2284	0.2362	0.2307	0.2329
S4	0.2263	0.2302	0.2264	0.2254	0.2233	0.2244	0.2234	0.2234	0.2217	0.2264	0.2238	0.2253
D4	0.2260	0.2249	0.2237	0.2203	0.2216	0.2213	0.2193	0.2214	0.2200	0.2217	0.2196	0.2215

Table 12.1. Final electricity prices (2017) per household type, calculated through Equation 11.

Amount of households (2015) per household type (renters)												
Dwelling/ province	GR	FR	DR	OV	FL	GD	UT	NH	ZH	ZL	NB	LB
F1	25837	10020	2769	20441	323	25567	31451	200679	196045	3201	33137	20934
R1	8780	15903	9674	27678	2493	39183	22931	53923	69487	8767	59687	28690
S1	2775	2553	855	4220	0	10477	1114	3650	3982	606	7019	4862
D1	1726	2153	2285	4704	195	6820	366	3078	3468	746	4749	850
F2	10824	6859	4946	17479	544	29774	28487	47473	95119	6274	29581	19185
R2	13838	18015	10745	17925	3147	43492	13324	26229	37872	10897	53036	14124
S2	757	578	1312	277	0	2261	0	1052	635	295	2299	2727
D2	544	384	0	934	0	579	75	773	363	116	1799	1436
F3	11490	7842	6811	14855	10214	35320	30324	94658	121060	4182	46131	26547
R3	12295	10358	8551	21856	16656	41587	24889	45711	62637	7352	59667	19707
S3	918	3015	2465	698	263	1876	877	1350	275	290	2038	2817
D3	0	183	686	794	0	721	587	844	968	338	3192	531
F4	13394	10540	7183	22511	9123	40120	30037	84520	99215	6247	57822	23604
R4	2499	3090	2647	10705	9022	20183	14350	27496	33200	1549	22449	6257
S4	1690	809	762	1015	639	3725	755	653	581	183	1997	1132
D4	710	1068	442	1122	628	1047	796	366	1125	221	528	612

Table 12.2. Used amount of renting households per household type. Source: WoonOnderzoek (2016).

Amount of households (2015) per household type (owners)												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	7380	1225	659	3489	0	15184	13599	73413	117895	1163	9073	4318
R1	10275	16983	5130	31418	2350	41100	43049	104673	120441	16226	72425	37407
S1	12279	9983	8496	18691	627	41154	23686	33887	26570	7813	39935	38746
D1	29869	28452	21908	24253	1321	58733	15896	42987	28630	14997	48733	33955
F2	1709	910	403	2666	66	5174	5076	18258	27415	112	6629	3527
R2	9748	12786	12021	21045	5744	49574	29169	49695	79457	11038	60922	13222
S2	4324	6451	6061	9130	224	17361	4769	9950	6806	4045	29455	26109
D2	5503	6389	8059	9879	577	15006	4019	7442	6858	4406	32370	14998
F3	1417	727	1528	2413	2103	6435	11075	25502	43243	1466	8575	7319
R3	15746	11499	11720	31271	25698	67824	52065	92069	134375	9152	77578	24050
S3	6967	13626	11977	25027	5344	31982	12960	13333	20454	5724	48468	24475
D3	8039	13496	10422	19505	2770	27326	5515	10613	11554	7699	43586	17291
F4	4164	3063	3826	7377	5806	18556	21688	45051	62556	3680	31221	7051
R4	5736	5054	7723	24266	31022	46669	45360	67524	111198	6124	47255	13211
S4	8241	14996	13178	26043	11480	30098	15441	20769	26199	7086	42049	16704
D4	12552	23469	12304	27264	9357	31245	10552	24234	20785	11191	47289	21054

Table 12.3. Used amount of owning households per household type. Source: WoonOnderzoek (2016).

Disposable annual income per dwelling type (renters and owners)		
Dwelling	**Renters**	**Owners**
F1	24600	36183
R1	25622	41503
S1	27175	45041
D1	30052	47017
F2	22899	31063
R2	26935	38661
S2	26951	41177
D2	39034	46382
F3	21977	32011
R3	27821	42062
S3	29089	45711
D3	33540	51021
F4	25508	37786
R4	31157	46362
S4	39572	52003
D4	29793	57293

Table 12.4. Annual disposable income of Dutch renters and owners. Source: WoonOnderzoek (2016).

Future emission factors of electricity from the Dutch grid									
Year	**Emission factor**	**Year**	**Emission factor**	**Year**	**Emission factor**	**Year**	**Emission factor**	**Year**	**Emission factor**
2017	0.420	**2024**	0.386	**2031**	0.355	**2038**	0.327	**2045**	0.301
2018	0.415	**2025**	0.382	**2032**	0.351	**2039**	0.323	**2046**	0.297
2019	0.410	**2026**	0.377	**2033**	0.347	**2040**	0.319	**2047**	0.294
2020	0.405	**2027**	0.373	**2034**	0.343	**2041**	0.316	**2048**	0.290
2021	0.400	**2028**	0.368	**2035**	0.339	**2042**	0.312	**2049**	0.287
2022	0.395	**2029**	0.364	**2036**	0.335	**2043**	0.308	**2050**	0.284
2023	0.391	**2030**	0.360	**2037**	0.331	**2044**	0.305		

Table 12.5. Future emission factors, based on continuous trend in research from (Ang & Su, 2016)

13. Appendix IV – Results of the LCOE calculation of optimized off-grid PV+BESS+μCHP systems

The following pages contain the resulting LCOE's of 34 years from the Matlab script for the base case scenario. The LCOE's that resulted from the other scenarios are not depicted, given the size and amount of these tables.

LCOE's (2017) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.569	0.563	0.571	0.571	0.570	0.569	0.563	0.565	0.566	0.559	0.566	0.567
R1	0.574	0.569	0.572	0.568	0.566	0.567	0.559	0.563	0.563	0.565	0.562	0.561
S1	0.569	0.571	0.569	0.568	0.563	0.565	0.562	0.564	0.564	0.557	0.563	0.565
D1	0.570	0.563	0.571	0.568	0.564	0.566	0.559	0.563	0.563	0.560	0.563	0.562
F2	0.569	0.564	0.571	0.571	0.564	0.568	0.564	0.566	0.568	0.558	0.565	0.565
R2	0.573	0.571	0.570	0.568	0.565	0.565	0.558	0.563	0.563	0.564	0.562	0.563
S2	0.569	0.564	0.570	0.567	0.571	0.564	0.560	0.563	0.565	0.563	0.562	0.563
D2	0.571	0.565	0.571	0.570	0.567	0.568	0.558	0.565	0.565	0.559	0.564	0.565
F3	0.570	0.565	0.571	0.569	0.567	0.565	0.561	0.565	0.566	0.559	0.566	0.564
R3	0.571	0.571	0.572	0.568	0.564	0.564	0.558	0.562	0.562	0.559	0.562	0.562
S3	0.569	0.563	0.569	0.569	0.567	0.566	0.561	0.564	0.566	0.558	0.564	0.564
D3	0.571	0.566	0.571	0.568	0.567	0.566	0.561	0.566	0.563	0.561	0.562	0.563
F4	0.572	0.566	0.570	0.570	0.571	0.568	0.564	0.568	0.567	0.564	0.568	0.567
R4	0.568	0.568	0.568	0.566	0.563	0.563	0.559	0.563	0.563	0.559	0.561	0.561
S4	0.571	0.563	0.571	0.570	0.566	0.568	0.562	0.565	0.563	0.560	0.564	0.565
D4	0.571	0.567	0.571	0.567	0.564	0.564	0.558	0.562	0.562	0.558	0.562	0.562
LCOE's (2018) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.535	0.529	0.536	0.536	0.536	0.534	0.529	0.531	0.532	0.525	0.531	0.533
R1	0.539	0.535	0.538	0.534	0.532	0.533	0.525	0.530	0.530	0.530	0.528	0.527
S1	0.536	0.538	0.534	0.534	0.529	0.531	0.528	0.529	0.529	0.523	0.530	0.531
D1	0.535	0.530	0.537	0.534	0.530	0.532	0.525	0.529	0.528	0.526	0.529	0.528
F2	0.535	0.529	0.536	0.536	0.531	0.533	0.530	0.532	0.534	0.523	0.531	0.530
R2	0.539	0.537	0.536	0.533	0.530	0.530	0.524	0.528	0.528	0.530	0.528	0.528
S2	0.535	0.529	0.535	0.533	0.536	0.531	0.526	0.530	0.532	0.529	0.528	0.529
D2	0.537	0.532	0.537	0.535	0.532	0.534	0.524	0.532	0.530	0.526	0.529	0.531
F3	0.535	0.530	0.536	0.534	0.533	0.531	0.527	0.531	0.532	0.525	0.532	0.530
R3	0.536	0.537	0.537	0.533	0.530	0.530	0.524	0.528	0.528	0.525	0.528	0.528
S3	0.534	0.529	0.535	0.535	0.533	0.532	0.527	0.531	0.532	0.525	0.530	0.530
D3	0.538	0.530	0.537	0.533	0.534	0.532	0.526	0.532	0.528	0.527	0.528	0.528
F4	0.538	0.532	0.536	0.536	0.536	0.534	0.529	0.534	0.533	0.530	0.533	0.532
R4	0.534	0.534	0.533	0.532	0.529	0.529	0.524	0.528	0.529	0.526	0.527	0.527
S4	0.536	0.529	0.537	0.536	0.532	0.533	0.527	0.530	0.529	0.527	0.530	0.531
D4	0.536	0.532	0.536	0.532	0.530	0.530	0.525	0.528	0.528	0.524	0.527	0.527

LCOE’s (2019) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type											
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.505	0.500	0.506	0.505	0.505	0.503	0.499	0.501	0.501	0.494	0.500	0.502
R1	0.508	0.504	0.507	0.504	0.501	0.502	0.495	0.499	0.499	0.499	0.498	0.497
S1	0.505	0.507	0.503	0.503	0.499	0.500	0.498	0.498	0.499	0.493	0.498	0.500
D1	0.504	0.500	0.506	0.503	0.500	0.501	0.495	0.499	0.498	0.495	0.498	0.497
F2	0.504	0.498	0.506	0.505	0.501	0.503	0.500	0.502	0.503	0.493	0.500	0.500
R2	0.509	0.507	0.505	0.503	0.500	0.500	0.494	0.498	0.497	0.500	0.497	0.498
S2	0.504	0.499	0.504	0.501	0.505	0.500	0.496	0.500	0.500	0.499	0.499	0.499
D2	0.506	0.500	0.507	0.504	0.500	0.503	0.495	0.502	0.500	0.495	0.498	0.501
F3	0.504	0.500	0.505	0.503	0.502	0.500	0.496	0.500	0.501	0.494	0.502	0.499
R3	0.506	0.507	0.506	0.502	0.499	0.499	0.494	0.497	0.498	0.495	0.497	0.497
S3	0.503	0.498	0.503	0.505	0.503	0.502	0.497	0.501	0.501	0.495	0.500	0.500
D3	0.505	0.499	0.508	0.502	0.504	0.501	0.495	0.503	0.498	0.496	0.497	0.497
F4	0.507	0.501	0.506	0.505	0.506	0.503	0.499	0.503	0.503	0.499	0.503	0.502
R4	0.504	0.503	0.503	0.502	0.499	0.499	0.494	0.498	0.498	0.495	0.496	0.497
S4	0.505	0.498	0.505	0.505	0.501	0.502	0.496	0.500	0.498	0.496	0.499	0.501
D4	0.505	0.502	0.506	0.501	0.500	0.499	0.494	0.498	0.497	0.494	0.496	0.497
LCOE’s (2020) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.477	0.472	0.478	0.477	0.477	0.476	0.471	0.474	0.474	0.467	0.473	0.474
R1	0.481	0.477	0.478	0.475	0.473	0.474	0.468	0.471	0.471	0.472	0.471	0.470
S1	0.477	0.479	0.475	0.475	0.472	0.472	0.470	0.471	0.471	0.466	0.471	0.473
D1	0.477	0.474	0.479	0.476	0.472	0.474	0.468	0.473	0.471	0.467	0.471	0.470
F2	0.476	0.471	0.479	0.478	0.472	0.475	0.472	0.475	0.476	0.466	0.473	0.473
R2	0.481	0.478	0.478	0.475	0.472	0.472	0.467	0.471	0.470	0.472	0.469	0.470
S2	0.476	0.472	0.476	0.474	0.478	0.471	0.469	0.472	0.472	0.472	0.471	0.472
D2	0.478	0.472	0.480	0.476	0.473	0.475	0.467	0.475	0.472	0.467	0.470	0.474
F3	0.477	0.473	0.478	0.476	0.475	0.473	0.469	0.473	0.474	0.467	0.474	0.472
R3	0.479	0.478	0.479	0.474	0.471	0.471	0.466	0.470	0.470	0.468	0.469	0.469
S3	0.475	0.471	0.475	0.478	0.475	0.474	0.469	0.473	0.473	0.467	0.472	0.473
D3	0.477	0.471	0.479	0.475	0.475	0.473	0.467	0.474	0.470	0.469	0.469	0.470
F4	0.480	0.474	0.478	0.478	0.478	0.476	0.471	0.476	0.476	0.472	0.475	0.475
R4	0.475	0.475	0.476	0.474	0.472	0.472	0.466	0.471	0.471	0.467	0.469	0.470
S4	0.477	0.472	0.477	0.477	0.474	0.475	0.468	0.473	0.471	0.468	0.472	0.473
D4	0.478	0.474	0.479	0.474	0.473	0.472	0.466	0.472	0.470	0.467	0.469	0.470

LCOE’s (2021) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.453	0.446	0.454	0.453	0.452	0.451	0.446	0.449	0.450	0.444	0.448	0.450
R1	0.456	0.453	0.453	0.450	0.448	0.449	0.443	0.447	0.446	0.447	0.445	0.445
S1	0.451	0.454	0.451	0.450	0.448	0.448	0.446	0.447	0.447	0.442	0.446	0.448
D1	0.452	0.448	0.454	0.452	0.447	0.450	0.443	0.448	0.447	0.443	0.447	0.445
F2	0.451	0.447	0.454	0.454	0.447	0.451	0.448	0.450	0.451	0.442	0.449	0.448
R2	0.455	0.453	0.453	0.451	0.448	0.448	0.442	0.447	0.446	0.447	0.445	0.446
S2	0.450	0.447	0.452	0.449	0.453	0.446	0.444	0.447	0.448	0.448	0.446	0.446
D2	0.454	0.447	0.454	0.451	0.448	0.450	0.442	0.449	0.448	0.442	0.445	0.449
F3	0.452	0.448	0.453	0.451	0.450	0.448	0.444	0.449	0.449	0.443	0.449	0.447
R3	0.454	0.452	0.454	0.449	0.447	0.447	0.442	0.445	0.445	0.444	0.445	0.444
S3	0.451	0.447	0.450	0.452	0.450	0.449	0.444	0.448	0.449	0.442	0.447	0.447
D3	0.451	0.446	0.453	0.450	0.450	0.449	0.443	0.449	0.446	0.445	0.444	0.445
F4	0.455	0.449	0.452	0.453	0.454	0.451	0.447	0.452	0.451	0.448	0.451	0.450
R4	0.450	0.451	0.450	0.449	0.447	0.447	0.442	0.447	0.447	0.442	0.445	0.444
S4	0.452	0.448	0.452	0.452	0.450	0.451	0.444	0.449	0.447	0.443	0.447	0.448
D4	0.453	0.450	0.453	0.449	0.449	0.448	0.442	0.447	0.446	0.443	0.445	0.446
LCOE’s (2022) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.429	0.424	0.431	0.431	0.430	0.429	0.424	0.427	0.428	0.421	0.426	0.428
R1	0.434	0.431	0.431	0.427	0.426	0.427	0.420	0.424	0.424	0.424	0.423	0.422
S1	0.429	0.431	0.429	0.428	0.425	0.425	0.423	0.425	0.425	0.419	0.424	0.425
D1	0.430	0.425	0.430	0.428	0.425	0.426	0.420	0.424	0.424	0.421	0.424	0.423
F2	0.428	0.425	0.431	0.431	0.425	0.428	0.425	0.427	0.429	0.420	0.426	0.425
R2	0.432	0.430	0.430	0.428	0.426	0.426	0.419	0.424	0.424	0.424	0.423	0.424
S2	0.428	0.425	0.430	0.426	0.431	0.424	0.421	0.424	0.425	0.425	0.423	0.423
D2	0.432	0.424	0.431	0.429	0.426	0.428	0.419	0.426	0.426	0.419	0.423	0.427
F3	0.429	0.426	0.431	0.428	0.428	0.425	0.422	0.426	0.427	0.420	0.427	0.425
R3	0.430	0.429	0.431	0.427	0.425	0.425	0.419	0.423	0.423	0.421	0.422	0.422
S3	0.429	0.425	0.428	0.429	0.428	0.426	0.421	0.425	0.427	0.419	0.424	0.424
D3	0.428	0.424	0.430	0.428	0.427	0.427	0.420	0.426	0.424	0.423	0.422	0.423
F4	0.432	0.426	0.430	0.430	0.432	0.429	0.425	0.429	0.429	0.426	0.429	0.428
R4	0.428	0.428	0.427	0.426	0.424	0.424	0.420	0.424	0.424	0.420	0.422	0.422
S4	0.430	0.426	0.430	0.429	0.427	0.427	0.422	0.425	0.425	0.421	0.425	0.426
D4	0.431	0.427	0.430	0.427	0.425	0.425	0.419	0.424	0.424	0.420	0.422	0.423

LCOE’s (2023) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.424	0.418	0.426	0.425	0.425	0.424	0.419	0.422	0.423	0.415	0.421	0.423
R1	0.430	0.426	0.424	0.421	0.419	0.420	0.413	0.418	0.418	0.417	0.416	0.416
S1	0.422	0.426	0.423	0.422	0.419	0.420	0.416	0.419	0.419	0.413	0.418	0.419
D1	0.425	0.419	0.423	0.422	0.419	0.419	0.414	0.418	0.418	0.415	0.417	0.417
F2	0.423	0.419	0.425	0.425	0.419	0.423	0.420	0.422	0.425	0.414	0.420	0.420
R2	0.425	0.423	0.423	0.422	0.420	0.419	0.413	0.418	0.418	0.416	0.416	0.417
S2	0.422	0.419	0.424	0.420	0.427	0.418	0.414	0.418	0.419	0.418	0.417	0.417
D2	0.425	0.418	0.425	0.423	0.420	0.422	0.413	0.421	0.420	0.413	0.416	0.420
F3	0.424	0.420	0.425	0.422	0.422	0.419	0.416	0.421	0.422	0.415	0.422	0.419
R3	0.424	0.422	0.424	0.421	0.419	0.419	0.413	0.418	0.418	0.414	0.416	0.416
S3	0.423	0.419	0.422	0.424	0.421	0.420	0.414	0.420	0.420	0.414	0.417	0.419
D3	0.423	0.419	0.425	0.422	0.421	0.420	0.414	0.421	0.418	0.417	0.416	0.417
F4	0.427	0.421	0.424	0.425	0.426	0.423	0.419	0.424	0.424	0.421	0.424	0.422
R4	0.422	0.422	0.422	0.420	0.418	0.418	0.414	0.418	0.418	0.414	0.416	0.416
S4	0.425	0.420	0.424	0.424	0.420	0.420	0.415	0.419	0.418	0.416	0.418	0.419
D4	0.425	0.421	0.423	0.421	0.419	0.419	0.413	0.418	0.418	0.414	0.417	0.417
LCOE’s (2024) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.419	0.413	0.421	0.420	0.420	0.419	0.413	0.417	0.417	0.410	0.415	0.417
R1	0.425	0.421	0.418	0.415	0.413	0.413	0.407	0.412	0.412	0.410	0.410	0.410
S1	0.417	0.419	0.417	0.416	0.414	0.414	0.409	0.413	0.414	0.408	0.412	0.413
D1	0.419	0.414	0.418	0.416	0.413	0.414	0.408	0.413	0.413	0.410	0.411	0.411
F2	0.417	0.413	0.421	0.421	0.414	0.418	0.415	0.418	0.420	0.407	0.415	0.415
R2	0.419	0.417	0.418	0.416	0.413	0.413	0.407	0.412	0.412	0.410	0.410	0.411
S2	0.417	0.413	0.417	0.415	0.420	0.412	0.408	0.413	0.413	0.411	0.412	0.412
D2	0.418	0.413	0.420	0.416	0.413	0.414	0.407	0.416	0.413	0.408	0.410	0.413
F3	0.419	0.414	0.420	0.417	0.417	0.414	0.410	0.416	0.417	0.410	0.417	0.414
R3	0.418	0.416	0.418	0.415	0.413	0.412	0.407	0.412	0.412	0.408	0.410	0.410
S3	0.417	0.413	0.416	0.418	0.414	0.415	0.408	0.415	0.413	0.408	0.411	0.414
D3	0.418	0.413	0.420	0.415	0.417	0.413	0.407	0.416	0.412	0.409	0.410	0.410
F4	0.423	0.416	0.419	0.421	0.419	0.419	0.414	0.420	0.420	0.414	0.418	0.418
R4	0.416	0.415	0.416	0.414	0.413	0.412	0.408	0.413	0.413	0.407	0.411	0.410
S4	0.419	0.414	0.419	0.418	0.414	0.415	0.408	0.413	0.412	0.410	0.412	0.413
D4	0.420	0.415	0.417	0.415	0.414	0.413	0.407	0.413	0.412	0.408	0.410	0.411

LCOE's (2025) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.414	0.409	0.415	0.415	0.414	0.414	0.408	0.411	0.412	0.404	0.410	0.412
R1	0.419	0.414	0.412	0.409	0.407	0.407	0.401	0.406	0.406	0.403	0.405	0.404
S1	0.411	0.412	0.412	0.411	0.408	0.408	0.402	0.408	0.408	0.402	0.407	0.406
D1	0.414	0.409	0.412	0.410	0.408	0.408	0.402	0.407	0.407	0.404	0.405	0.404
F2	0.412	0.408	0.416	0.416	0.409	0.413	0.408	0.413	0.413	0.401	0.410	0.409
R2	0.414	0.411	0.412	0.409	0.407	0.407	0.402	0.406	0.406	0.404	0.404	0.404
S2	0.412	0.407	0.411	0.409	0.415	0.407	0.402	0.409	0.407	0.404	0.407	0.407
D2	0.412	0.409	0.413	0.410	0.407	0.408	0.402	0.409	0.407	0.403	0.404	0.406
F3	0.414	0.408	0.415	0.412	0.412	0.409	0.405	0.411	0.412	0.404	0.412	0.408
R3	0.413	0.410	0.412	0.409	0.407	0.407	0.401	0.407	0.407	0.402	0.404	0.404
S3	0.411	0.407	0.411	0.411	0.408	0.410	0.402	0.409	0.407	0.403	0.405	0.407
D3	0.413	0.408	0.414	0.409	0.411	0.407	0.401	0.409	0.406	0.403	0.404	0.404
F4	0.418	0.411	0.415	0.416	0.412	0.414	0.409	0.413	0.414	0.407	0.411	0.413
R4	0.411	0.409	0.411	0.409	0.408	0.407	0.402	0.408	0.408	0.401	0.405	0.404
S4	0.414	0.408	0.414	0.412	0.408	0.408	0.401	0.407	0.406	0.405	0.405	0.406
D4	0.414	0.409	0.412	0.409	0.408	0.407	0.401	0.407	0.407	0.402	0.405	0.404
LCOE's (2026) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.409	0.404	0.411	0.410	0.408	0.409	0.404	0.407	0.408	0.399	0.406	0.406
R1	0.412	0.408	0.406	0.404	0.402	0.402	0.395	0.401	0.402	0.397	0.399	0.399
S1	0.407	0.406	0.407	0.406	0.403	0.403	0.396	0.403	0.404	0.397	0.402	0.400
D1	0.409	0.403	0.406	0.404	0.403	0.402	0.396	0.401	0.401	0.399	0.399	0.399
F2	0.408	0.403	0.411	0.411	0.404	0.408	0.401	0.409	0.407	0.396	0.405	0.404
R2	0.408	0.405	0.406	0.404	0.402	0.401	0.396	0.401	0.401	0.398	0.399	0.399
S2	0.408	0.402	0.405	0.404	0.408	0.403	0.396	0.404	0.402	0.397	0.402	0.401
D2	0.406	0.404	0.407	0.404	0.402	0.402	0.396	0.403	0.401	0.398	0.399	0.399
F3	0.409	0.402	0.410	0.407	0.407	0.404	0.400	0.406	0.408	0.399	0.407	0.403
R3	0.407	0.405	0.406	0.404	0.402	0.401	0.396	0.402	0.402	0.396	0.399	0.399
S3	0.406	0.402	0.406	0.405	0.403	0.403	0.396	0.403	0.402	0.398	0.399	0.400
D3	0.409	0.404	0.407	0.404	0.404	0.401	0.395	0.403	0.401	0.396	0.399	0.398
F4	0.414	0.407	0.410	0.411	0.406	0.409	0.403	0.407	0.408	0.400	0.404	0.406
R4	0.407	0.403	0.406	0.404	0.403	0.402	0.396	0.403	0.403	0.396	0.400	0.399
S4	0.409	0.403	0.408	0.405	0.402	0.402	0.395	0.401	0.401	0.398	0.399	0.400
D4	0.408	0.404	0.406	0.404	0.402	0.401	0.396	0.401	0.401	0.396	0.400	0.399

LCOE’s (2027) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type

Dwelling/ province	GR	FR	DR	OV	FL	GD	UT	NH	ZH	ZL	NB	LB
F1	0.404	0.399	0.406	0.406	0.402	0.403	0.397	0.402	0.404	0.394	0.401	0.400
R1	0.406	0.401	0.401	0.399	0.397	0.397	0.389	0.396	0.396	0.391	0.394	0.393
S1	0.402	0.400	0.402	0.401	0.398	0.399	0.390	0.399	0.398	0.391	0.395	0.394
D1	0.403	0.398	0.401	0.399	0.397	0.396	0.390	0.396	0.396	0.392	0.393	0.393
F2	0.404	0.398	0.406	0.407	0.400	0.404	0.395	0.404	0.401	0.391	0.400	0.399
R2	0.402	0.399	0.400	0.398	0.397	0.396	0.391	0.396	0.397	0.391	0.394	0.393
S2	0.404	0.397	0.400	0.400	0.401	0.398	0.389	0.398	0.397	0.391	0.396	0.395
D2	0.401	0.401	0.401	0.399	0.397	0.396	0.391	0.397	0.396	0.394	0.394	0.394
F3	0.404	0.397	0.406	0.402	0.403	0.399	0.395	0.402	0.404	0.394	0.400	0.398
R3	0.401	0.399	0.401	0.399	0.398	0.397	0.390	0.398	0.398	0.390	0.394	0.394
S3	0.401	0.398	0.402	0.400	0.397	0.398	0.390	0.397	0.397	0.392	0.394	0.395
D3	0.404	0.399	0.401	0.399	0.398	0.396	0.390	0.397	0.396	0.390	0.394	0.393
F4	0.408	0.402	0.405	0.407	0.400	0.403	0.397	0.401	0.401	0.394	0.398	0.399
R4	0.401	0.398	0.401	0.399	0.398	0.397	0.391	0.398	0.398	0.391	0.395	0.394
S4	0.403	0.398	0.402	0.399	0.397	0.396	0.390	0.396	0.396	0.391	0.393	0.394
D4	0.403	0.398	0.401	0.399	0.397	0.396	0.391	0.396	0.397	0.390	0.395	0.393

LCOE’s (2028) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type

Dwelling/ province	GR	FR	DR	OV	FL	GD	UT	NH	ZH	ZL	NB	LB
F1	0.400	0.395	0.403	0.401	0.396	0.397	0.390	0.399	0.398	0.389	0.396	0.393
R1	0.400	0.396	0.396	0.394	0.392	0.391	0.384	0.391	0.391	0.386	0.388	0.388
S1	0.396	0.395	0.398	0.395	0.393	0.393	0.384	0.393	0.393	0.387	0.390	0.389
D1	0.398	0.393	0.395	0.394	0.392	0.391	0.385	0.391	0.392	0.386	0.388	0.389
F2	0.399	0.394	0.403	0.401	0.395	0.398	0.388	0.398	0.395	0.386	0.396	0.395
R2	0.397	0.394	0.396	0.394	0.392	0.391	0.386	0.392	0.393	0.386	0.389	0.388
S2	0.399	0.393	0.396	0.395	0.395	0.393	0.384	0.393	0.391	0.386	0.390	0.390
D2	0.397	0.395	0.396	0.394	0.392	0.391	0.386	0.392	0.391	0.388	0.389	0.388
F3	0.400	0.393	0.402	0.398	0.398	0.394	0.390	0.398	0.398	0.390	0.394	0.394
R3	0.396	0.393	0.396	0.394	0.393	0.392	0.385	0.393	0.393	0.385	0.389	0.389
S3	0.397	0.393	0.398	0.395	0.392	0.392	0.384	0.392	0.392	0.387	0.388	0.389
D3	0.398	0.396	0.396	0.394	0.392	0.391	0.385	0.392	0.392	0.385	0.390	0.389
F4	0.402	0.398	0.401	0.401	0.394	0.397	0.390	0.395	0.396	0.388	0.392	0.393
R4	0.397	0.393	0.396	0.394	0.393	0.392	0.386	0.393	0.393	0.385	0.390	0.389
S4	0.397	0.394	0.396	0.394	0.392	0.391	0.385	0.391	0.392	0.386	0.388	0.388
D4	0.397	0.393	0.395	0.395	0.392	0.391	0.385	0.392	0.392	0.386	0.389	0.389

LCOE's (2029) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.396	0.390	0.398	0.395	0.390	0.391	0.383	0.393	0.392	0.386	0.389	0.387
R1	0.395	0.390	0.391	0.389	0.387	0.386	0.379	0.387	0.387	0.380	0.384	0.384
S1	0.392	0.390	0.393	0.390	0.389	0.387	0.379	0.388	0.388	0.383	0.384	0.383
D1	0.392	0.389	0.391	0.389	0.387	0.386	0.379	0.387	0.387	0.380	0.384	0.384
F2	0.395	0.390	0.398	0.394	0.391	0.392	0.381	0.392	0.389	0.381	0.390	0.390
R2	0.392	0.388	0.391	0.389	0.388	0.386	0.381	0.387	0.388	0.380	0.384	0.383
S2	0.394	0.389	0.392	0.390	0.389	0.388	0.379	0.388	0.386	0.380	0.384	0.384
D2	0.392	0.390	0.391	0.389	0.388	0.387	0.380	0.387	0.387	0.382	0.384	0.384
F3	0.397	0.388	0.398	0.394	0.394	0.390	0.385	0.394	0.392	0.386	0.387	0.390
R3	0.392	0.388	0.391	0.389	0.388	0.387	0.380	0.389	0.389	0.381	0.384	0.384
S3	0.393	0.390	0.393	0.389	0.387	0.387	0.379	0.387	0.386	0.381	0.383	0.383
D3	0.393	0.390	0.391	0.390	0.387	0.387	0.380	0.387	0.388	0.380	0.384	0.384
F4	0.396	0.394	0.397	0.394	0.389	0.391	0.383	0.389	0.390	0.382	0.386	0.387
R4	0.392	0.388	0.392	0.390	0.389	0.388	0.381	0.388	0.388	0.380	0.386	0.384
S4	0.392	0.390	0.391	0.389	0.387	0.386	0.379	0.387	0.387	0.380	0.384	0.383
D4	0.392	0.388	0.391	0.390	0.388	0.387	0.380	0.387	0.388	0.381	0.384	0.384

LCOE's (2030) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.393	0.387	0.392	0.389	0.384	0.385	0.377	0.387	0.386	0.382	0.383	0.381
R1	0.389	0.385	0.386	0.384	0.383	0.381	0.374	0.382	0.383	0.375	0.379	0.379
S1	0.387	0.384	0.388	0.385	0.385	0.382	0.374	0.383	0.382	0.377	0.378	0.378
D1	0.387	0.385	0.387	0.384	0.382	0.381	0.373	0.382	0.383	0.375	0.379	0.379
F2	0.391	0.386	0.392	0.388	0.387	0.386	0.375	0.386	0.384	0.377	0.383	0.384
R2	0.387	0.383	0.386	0.384	0.383	0.382	0.375	0.383	0.384	0.375	0.380	0.378
S2	0.389	0.385	0.387	0.386	0.384	0.383	0.374	0.382	0.382	0.376	0.379	0.378
D2	0.388	0.384	0.387	0.384	0.384	0.381	0.374	0.383	0.382	0.377	0.379	0.378
F3	0.393	0.384	0.393	0.390	0.388	0.386	0.380	0.388	0.386	0.382	0.381	0.385
R3	0.388	0.383	0.386	0.385	0.384	0.383	0.376	0.384	0.383	0.376	0.380	0.380
S3	0.389	0.385	0.388	0.384	0.382	0.381	0.374	0.382	0.382	0.376	0.378	0.378
D3	0.388	0.385	0.387	0.385	0.383	0.382	0.374	0.382	0.383	0.376	0.379	0.379
F4	0.391	0.390	0.393	0.388	0.383	0.385	0.377	0.384	0.384	0.376	0.380	0.381
R4	0.388	0.383	0.388	0.386	0.385	0.383	0.375	0.383	0.383	0.376	0.380	0.380
S4	0.387	0.385	0.387	0.384	0.382	0.381	0.374	0.382	0.383	0.376	0.378	0.378
D4	0.387	0.383	0.386	0.385	0.383	0.382	0.374	0.383	0.383	0.376	0.379	0.379

LCOE’s (2031) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.389	0.383	0.386	0.383	0.379	0.379	0.371	0.382	0.381	0.377	0.377	0.375
R1	0.384	0.380	0.382	0.380	0.378	0.377	0.370	0.378	0.378	0.370	0.375	0.375
S1	0.383	0.379	0.382	0.379	0.379	0.376	0.369	0.377	0.377	0.372	0.373	0.373
D1	0.383	0.381	0.382	0.380	0.377	0.377	0.369	0.378	0.378	0.371	0.374	0.374
F2	0.388	0.382	0.386	0.382	0.384	0.380	0.370	0.380	0.378	0.373	0.377	0.377
R2	0.383	0.379	0.382	0.380	0.379	0.377	0.370	0.379	0.379	0.371	0.376	0.374
S2	0.383	0.380	0.382	0.381	0.379	0.377	0.369	0.377	0.378	0.371	0.373	0.373
D2	0.385	0.380	0.382	0.379	0.379	0.376	0.368	0.378	0.378	0.372	0.375	0.373
F3	0.389	0.379	0.387	0.386	0.382	0.382	0.374	0.382	0.381	0.376	0.375	0.378
R3	0.383	0.379	0.382	0.381	0.380	0.379	0.370	0.379	0.378	0.371	0.376	0.375
S3	0.385	0.381	0.383	0.379	0.378	0.376	0.369	0.377	0.377	0.370	0.374	0.373
D3	0.383	0.380	0.382	0.380	0.378	0.377	0.370	0.378	0.378	0.371	0.374	0.374
F4	0.386	0.384	0.387	0.382	0.378	0.379	0.371	0.378	0.379	0.371	0.374	0.375
R4	0.385	0.379	0.383	0.381	0.379	0.378	0.370	0.378	0.378	0.371	0.374	0.375
S4	0.383	0.380	0.382	0.379	0.378	0.376	0.369	0.378	0.378	0.370	0.374	0.373
D4	0.383	0.379	0.382	0.380	0.379	0.377	0.368	0.379	0.378	0.371	0.373	0.374
LCOE’s (2032) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.384	0.380	0.381	0.377	0.374	0.373	0.365	0.376	0.375	0.371	0.371	0.369
R1	0.379	0.375	0.377	0.376	0.374	0.372	0.366	0.374	0.374	0.366	0.370	0.370
S1	0.380	0.374	0.377	0.375	0.374	0.372	0.364	0.373	0.373	0.366	0.369	0.368
D1	0.379	0.376	0.377	0.375	0.373	0.372	0.364	0.374	0.373	0.366	0.370	0.369
F2	0.385	0.379	0.380	0.377	0.380	0.374	0.364	0.375	0.373	0.369	0.371	0.372
R2	0.378	0.375	0.378	0.376	0.375	0.373	0.364	0.375	0.374	0.366	0.370	0.370
S2	0.379	0.377	0.378	0.376	0.374	0.372	0.365	0.373	0.373	0.366	0.369	0.368
D2	0.380	0.376	0.377	0.375	0.375	0.372	0.364	0.373	0.373	0.366	0.369	0.368
F3	0.384	0.376	0.381	0.380	0.376	0.378	0.368	0.376	0.375	0.370	0.370	0.373
R3	0.379	0.374	0.377	0.377	0.374	0.373	0.364	0.374	0.373	0.367	0.370	0.370
S3	0.380	0.376	0.378	0.375	0.374	0.372	0.364	0.373	0.373	0.365	0.369	0.368
D3	0.379	0.375	0.377	0.376	0.373	0.372	0.364	0.373	0.373	0.366	0.369	0.369
F4	0.380	0.378	0.381	0.377	0.373	0.373	0.365	0.373	0.374	0.366	0.369	0.369
R4	0.380	0.375	0.379	0.376	0.374	0.373	0.364	0.373	0.373	0.367	0.369	0.370
S4	0.378	0.375	0.377	0.375	0.374	0.372	0.365	0.373	0.373	0.366	0.369	0.368
D4	0.379	0.375	0.377	0.375	0.373	0.372	0.364	0.373	0.373	0.366	0.368	0.369

LCOE's (2033) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.379	0.376	0.375	0.372	0.369	0.368	0.360	0.370	0.370	0.365	0.366	0.364
R1	0.374	0.370	0.373	0.372	0.370	0.368	0.361	0.370	0.370	0.361	0.366	0.365
S1	0.376	0.370	0.373	0.370	0.369	0.367	0.360	0.368	0.368	0.361	0.364	0.364
D1	0.374	0.371	0.373	0.371	0.369	0.368	0.359	0.369	0.368	0.361	0.364	0.364
F2	0.380	0.375	0.375	0.372	0.374	0.368	0.359	0.370	0.368	0.365	0.366	0.366
R2	0.374	0.370	0.374	0.372	0.371	0.369	0.359	0.370	0.369	0.361	0.365	0.366
S2	0.374	0.372	0.374	0.371	0.369	0.367	0.359	0.369	0.369	0.361	0.364	0.364
D2	0.375	0.370	0.373	0.371	0.370	0.367	0.359	0.368	0.369	0.361	0.364	0.364
F3	0.379	0.372	0.376	0.375	0.371	0.372	0.362	0.371	0.370	0.365	0.365	0.367
R3	0.375	0.370	0.373	0.372	0.369	0.368	0.359	0.369	0.368	0.363	0.365	0.364
S3	0.375	0.371	0.373	0.371	0.369	0.367	0.359	0.369	0.369	0.361	0.365	0.364
D3	0.375	0.371	0.373	0.371	0.369	0.368	0.359	0.369	0.368	0.362	0.364	0.364
F4	0.375	0.373	0.376	0.372	0.368	0.368	0.359	0.369	0.369	0.361	0.364	0.364
R4	0.376	0.371	0.374	0.372	0.369	0.368	0.359	0.368	0.368	0.363	0.364	0.365
S4	0.374	0.371	0.373	0.370	0.369	0.368	0.360	0.369	0.369	0.361	0.365	0.364
D4	0.374	0.370	0.373	0.370	0.369	0.367	0.359	0.368	0.368	0.361	0.364	0.364

LCOE's (2034) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.374	0.372	0.370	0.367	0.364	0.363	0.354	0.366	0.365	0.360	0.361	0.359
R1	0.370	0.366	0.369	0.368	0.367	0.364	0.355	0.366	0.366	0.357	0.361	0.360
S1	0.372	0.366	0.369	0.366	0.364	0.363	0.355	0.364	0.364	0.357	0.360	0.360
D1	0.370	0.367	0.369	0.366	0.365	0.363	0.354	0.364	0.364	0.357	0.360	0.359
F2	0.375	0.372	0.370	0.367	0.368	0.363	0.354	0.365	0.364	0.362	0.361	0.361
R2	0.370	0.366	0.371	0.368	0.365	0.364	0.354	0.365	0.364	0.357	0.360	0.361
S2	0.370	0.367	0.370	0.367	0.364	0.363	0.354	0.364	0.365	0.357	0.360	0.359
D2	0.371	0.366	0.369	0.367	0.367	0.363	0.355	0.365	0.364	0.356	0.359	0.360
F3	0.374	0.368	0.371	0.369	0.366	0.367	0.357	0.366	0.365	0.360	0.360	0.362
R3	0.372	0.366	0.370	0.367	0.364	0.363	0.354	0.364	0.364	0.359	0.360	0.359
S3	0.371	0.366	0.369	0.367	0.365	0.363	0.354	0.365	0.365	0.357	0.360	0.359
D3	0.370	0.366	0.369	0.366	0.365	0.363	0.354	0.365	0.364	0.357	0.359	0.359
F4	0.371	0.368	0.371	0.367	0.364	0.363	0.354	0.364	0.364	0.356	0.359	0.359
R4	0.371	0.367	0.369	0.367	0.364	0.363	0.354	0.364	0.364	0.358	0.359	0.360
S4	0.370	0.366	0.369	0.367	0.365	0.363	0.355	0.365	0.364	0.357	0.360	0.360
D4	0.370	0.367	0.369	0.366	0.364	0.362	0.355	0.364	0.364	0.356	0.360	0.359

LCOE's (2035) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.369	0.367	0.366	0.363	0.360	0.358	0.349	0.361	0.361	0.355	0.356	0.355
R1	0.366	0.362	0.366	0.364	0.362	0.360	0.350	0.361	0.361	0.353	0.356	0.355
S1	0.368	0.362	0.364	0.362	0.360	0.358	0.350	0.360	0.360	0.352	0.355	0.356
D1	0.366	0.362	0.365	0.362	0.360	0.358	0.349	0.360	0.360	0.353	0.355	0.355
F2	0.370	0.368	0.365	0.362	0.363	0.359	0.349	0.360	0.360	0.358	0.356	0.356
R2	0.367	0.362	0.366	0.363	0.361	0.359	0.349	0.360	0.360	0.353	0.355	0.356
S2	0.366	0.362	0.366	0.362	0.360	0.358	0.350	0.360	0.360	0.353	0.355	0.355
D2	0.368	0.362	0.365	0.362	0.362	0.359	0.350	0.361	0.360	0.352	0.355	0.355
F3	0.369	0.365	0.366	0.364	0.361	0.361	0.351	0.361	0.360	0.354	0.355	0.356
R3	0.368	0.362	0.366	0.362	0.360	0.358	0.350	0.360	0.360	0.353	0.355	0.355
S3	0.367	0.362	0.364	0.363	0.361	0.359	0.350	0.361	0.360	0.352	0.355	0.355
D3	0.366	0.362	0.365	0.362	0.361	0.358	0.350	0.361	0.360	0.352	0.355	0.355
F4	0.366	0.363	0.366	0.362	0.360	0.358	0.350	0.360	0.360	0.352	0.355	0.355
R4	0.366	0.363	0.365	0.362	0.360	0.358	0.350	0.360	0.360	0.353	0.355	0.355
S4	0.367	0.362	0.365	0.363	0.360	0.359	0.350	0.360	0.360	0.353	0.355	0.356
D4	0.367	0.363	0.365	0.362	0.360	0.358	0.350	0.360	0.360	0.352	0.356	0.355
LCOE's (2036) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.365	0.362	0.361	0.358	0.356	0.354	0.345	0.356	0.356	0.350	0.351	0.350
R1	0.362	0.358	0.362	0.359	0.357	0.356	0.346	0.357	0.357	0.349	0.351	0.350
S1	0.363	0.358	0.360	0.358	0.356	0.354	0.345	0.356	0.357	0.347	0.352	0.351
D1	0.363	0.358	0.360	0.358	0.356	0.354	0.345	0.356	0.356	0.349	0.350	0.350
F2	0.366	0.363	0.361	0.358	0.359	0.354	0.345	0.356	0.356	0.354	0.351	0.351
R2	0.364	0.359	0.362	0.359	0.356	0.354	0.345	0.356	0.356	0.349	0.350	0.351
S2	0.362	0.358	0.361	0.358	0.356	0.354	0.345	0.356	0.356	0.350	0.351	0.351
D2	0.365	0.358	0.361	0.358	0.357	0.354	0.346	0.357	0.356	0.348	0.351	0.351
F3	0.364	0.362	0.361	0.360	0.356	0.357	0.346	0.357	0.356	0.349	0.351	0.351
R3	0.364	0.359	0.363	0.358	0.356	0.354	0.345	0.356	0.356	0.349	0.350	0.350
S3	0.362	0.358	0.360	0.359	0.356	0.355	0.345	0.357	0.356	0.348	0.350	0.352
D3	0.362	0.358	0.361	0.358	0.357	0.354	0.345	0.357	0.356	0.348	0.351	0.350
F4	0.362	0.359	0.361	0.358	0.356	0.354	0.345	0.356	0.356	0.348	0.351	0.350
R4	0.362	0.360	0.360	0.358	0.356	0.354	0.345	0.356	0.356	0.348	0.351	0.350
S4	0.363	0.358	0.361	0.359	0.356	0.354	0.345	0.356	0.356	0.349	0.350	0.350
D4	0.363	0.358	0.361	0.358	0.356	0.354	0.345	0.356	0.356	0.348	0.351	0.350

LCOE’s (2037) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type											
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.360	0.357	0.357	0.354	0.352	0.349	0.341	0.352	0.352	0.345	0.346	0.346
R1	0.358	0.354	0.359	0.355	0.352	0.351	0.341	0.352	0.352	0.345	0.346	0.346
S1	0.359	0.354	0.357	0.355	0.352	0.350	0.341	0.353	0.353	0.343	0.348	0.346
D1	0.359	0.353	0.356	0.354	0.352	0.349	0.341	0.352	0.352	0.344	0.346	0.346
F2	0.361	0.358	0.356	0.354	0.354	0.350	0.341	0.352	0.352	0.349	0.346	0.346
R2	0.360	0.355	0.357	0.354	0.352	0.350	0.341	0.352	0.352	0.346	0.346	0.346
S2	0.359	0.353	0.357	0.354	0.352	0.350	0.341	0.353	0.352	0.346	0.347	0.347
D2	0.360	0.354	0.357	0.354	0.352	0.350	0.341	0.352	0.352	0.345	0.346	0.346
F3	0.360	0.359	0.357	0.355	0.352	0.352	0.342	0.352	0.352	0.345	0.347	0.347
R3	0.360	0.355	0.358	0.354	0.352	0.349	0.341	0.352	0.352	0.344	0.346	0.346
S3	0.358	0.353	0.356	0.354	0.352	0.351	0.341	0.353	0.352	0.345	0.346	0.347
D3	0.359	0.354	0.357	0.354	0.352	0.350	0.341	0.352	0.352	0.343	0.347	0.346
F4	0.358	0.354	0.357	0.354	0.353	0.349	0.341	0.352	0.352	0.344	0.347	0.346
R4	0.358	0.356	0.356	0.354	0.352	0.349	0.341	0.352	0.352	0.344	0.346	0.346
S4	0.359	0.354	0.357	0.354	0.352	0.350	0.341	0.352	0.352	0.344	0.346	0.346
D4	0.359	0.354	0.356	0.355	0.352	0.350	0.341	0.352	0.352	0.344	0.346	0.346

LCOE’s (2038) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type											
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.356	0.353	0.352	0.350	0.348	0.345	0.337	0.348	0.347	0.340	0.342	0.341
R1	0.355	0.350	0.354	0.350	0.348	0.347	0.337	0.348	0.348	0.342	0.342	0.341
S1	0.355	0.351	0.353	0.351	0.348	0.347	0.337	0.349	0.349	0.339	0.343	0.342
D1	0.355	0.350	0.352	0.350	0.347	0.346	0.337	0.348	0.348	0.340	0.342	0.342
F2	0.357	0.354	0.353	0.350	0.350	0.346	0.338	0.348	0.349	0.344	0.342	0.342
R2	0.357	0.351	0.353	0.350	0.347	0.345	0.337	0.348	0.348	0.342	0.342	0.342
S2	0.355	0.350	0.352	0.350	0.349	0.346	0.337	0.349	0.348	0.342	0.344	0.343
D2	0.356	0.351	0.353	0.350	0.348	0.345	0.337	0.348	0.348	0.340	0.343	0.341
F3	0.356	0.356	0.353	0.351	0.348	0.347	0.338	0.349	0.349	0.340	0.344	0.343
R3	0.356	0.352	0.354	0.350	0.348	0.345	0.337	0.348	0.348	0.339	0.342	0.341
S3	0.354	0.350	0.353	0.350	0.347	0.346	0.337	0.348	0.348	0.340	0.342	0.342
D3	0.356	0.351	0.353	0.350	0.348	0.345	0.337	0.348	0.349	0.339	0.342	0.342
F4	0.354	0.350	0.353	0.350	0.349	0.345	0.337	0.348	0.348	0.340	0.343	0.342
R4	0.354	0.352	0.352	0.350	0.348	0.345	0.337	0.349	0.349	0.339	0.342	0.341
S4	0.355	0.350	0.353	0.350	0.348	0.345	0.337	0.348	0.348	0.339	0.342	0.342
D4	0.355	0.350	0.352	0.350	0.348	0.346	0.337	0.348	0.348	0.340	0.342	0.342

LCOE's (2039) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type											
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.352	0.348	0.348	0.346	0.344	0.341	0.333	0.344	0.344	0.336	0.338	0.337
R1	0.351	0.347	0.350	0.346	0.344	0.342	0.333	0.344	0.344	0.337	0.338	0.337
S1	0.351	0.348	0.349	0.347	0.344	0.343	0.333	0.345	0.345	0.335	0.339	0.337
D1	0.351	0.346	0.348	0.346	0.344	0.341	0.333	0.344	0.345	0.335	0.338	0.338
F2	0.352	0.349	0.349	0.347	0.345	0.342	0.334	0.345	0.346	0.339	0.338	0.338
R2	0.353	0.348	0.349	0.346	0.344	0.341	0.333	0.344	0.344	0.337	0.338	0.337
S2	0.351	0.346	0.348	0.346	0.345	0.342	0.333	0.345	0.344	0.337	0.339	0.338
D2	0.352	0.347	0.348	0.346	0.344	0.341	0.333	0.344	0.344	0.337	0.339	0.337
F3	0.352	0.353	0.350	0.347	0.345	0.343	0.334	0.345	0.345	0.336	0.340	0.339
R3	0.351	0.349	0.349	0.346	0.344	0.341	0.333	0.344	0.345	0.335	0.338	0.337
S3	0.351	0.346	0.349	0.346	0.344	0.342	0.333	0.344	0.344	0.336	0.338	0.338
D3	0.352	0.347	0.348	0.346	0.344	0.341	0.333	0.344	0.344	0.335	0.338	0.338
F4	0.351	0.346	0.349	0.346	0.346	0.342	0.333	0.345	0.345	0.337	0.340	0.338
R4	0.350	0.348	0.348	0.346	0.344	0.341	0.334	0.345	0.345	0.335	0.339	0.337
S4	0.351	0.346	0.349	0.346	0.344	0.341	0.333	0.344	0.345	0.335	0.338	0.337
D4	0.351	0.346	0.348	0.346	0.345	0.342	0.333	0.345	0.344	0.336	0.338	0.338

LCOE's (2040) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type											
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.348	0.344	0.344	0.342	0.341	0.338	0.329	0.340	0.340	0.331	0.334	0.333
R1	0.348	0.343	0.345	0.342	0.340	0.338	0.329	0.340	0.340	0.333	0.334	0.333
S1	0.347	0.344	0.346	0.343	0.341	0.339	0.329	0.341	0.341	0.332	0.334	0.333
D1	0.347	0.342	0.344	0.342	0.340	0.338	0.329	0.341	0.341	0.331	0.334	0.334
F2	0.349	0.345	0.346	0.343	0.341	0.339	0.331	0.342	0.343	0.335	0.335	0.334
R2	0.349	0.345	0.345	0.342	0.340	0.337	0.329	0.340	0.340	0.333	0.334	0.333
S2	0.348	0.342	0.344	0.342	0.342	0.339	0.329	0.341	0.340	0.333	0.335	0.334
D2	0.348	0.344	0.344	0.342	0.340	0.337	0.328	0.340	0.340	0.332	0.335	0.333
F3	0.349	0.348	0.347	0.344	0.342	0.340	0.330	0.342	0.342	0.333	0.338	0.336
R3	0.348	0.344	0.345	0.342	0.340	0.338	0.329	0.341	0.342	0.331	0.334	0.333
S3	0.347	0.342	0.345	0.342	0.340	0.338	0.329	0.340	0.340	0.332	0.334	0.333
D3	0.348	0.343	0.344	0.343	0.340	0.338	0.330	0.340	0.340	0.331	0.334	0.334
F4	0.348	0.342	0.345	0.343	0.344	0.339	0.330	0.342	0.342	0.334	0.337	0.335
R4	0.347	0.343	0.345	0.342	0.341	0.338	0.330	0.342	0.342	0.331	0.335	0.333
S4	0.347	0.343	0.345	0.342	0.340	0.337	0.329	0.340	0.341	0.331	0.334	0.333
D4	0.347	0.342	0.344	0.342	0.341	0.338	0.328	0.341	0.340	0.331	0.334	0.334

LCOE's (2041) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.344	0.340	0.341	0.338	0.338	0.334	0.325	0.336	0.336	0.327	0.330	0.330
R1	0.345	0.340	0.341	0.338	0.336	0.334	0.325	0.336	0.336	0.329	0.330	0.330
S1	0.343	0.341	0.342	0.339	0.338	0.335	0.325	0.337	0.337	0.328	0.330	0.330
D1	0.344	0.339	0.341	0.339	0.336	0.334	0.325	0.337	0.337	0.327	0.331	0.330
F2	0.345	0.341	0.343	0.341	0.338	0.336	0.329	0.339	0.341	0.330	0.332	0.331
R2	0.345	0.341	0.341	0.338	0.336	0.334	0.326	0.336	0.337	0.329	0.330	0.329
S2	0.345	0.338	0.341	0.339	0.339	0.335	0.325	0.337	0.337	0.329	0.330	0.330
D2	0.344	0.340	0.341	0.339	0.336	0.334	0.325	0.336	0.337	0.328	0.331	0.329
F3	0.346	0.344	0.344	0.341	0.339	0.336	0.327	0.339	0.340	0.330	0.335	0.332
R3	0.344	0.340	0.341	0.338	0.337	0.334	0.325	0.338	0.338	0.327	0.330	0.330
S3	0.343	0.339	0.342	0.338	0.336	0.334	0.325	0.336	0.336	0.327	0.330	0.329
D3	0.344	0.340	0.341	0.339	0.336	0.335	0.326	0.336	0.337	0.327	0.330	0.330
F4	0.345	0.339	0.342	0.340	0.341	0.336	0.327	0.340	0.339	0.332	0.334	0.332
R4	0.343	0.339	0.341	0.339	0.337	0.335	0.327	0.339	0.340	0.327	0.332	0.330
S4	0.343	0.340	0.341	0.338	0.337	0.334	0.325	0.337	0.337	0.327	0.330	0.329
D4	0.343	0.338	0.341	0.338	0.337	0.334	0.324	0.337	0.336	0.327	0.330	0.330
LCOE's (2042) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.340	0.336	0.337	0.335	0.335	0.331	0.322	0.333	0.333	0.323	0.326	0.327
R1	0.342	0.337	0.338	0.335	0.333	0.330	0.321	0.333	0.333	0.325	0.326	0.326
S1	0.340	0.338	0.339	0.335	0.334	0.331	0.322	0.333	0.333	0.325	0.327	0.326
D1	0.340	0.335	0.338	0.335	0.333	0.331	0.322	0.334	0.333	0.323	0.327	0.326
F2	0.342	0.337	0.340	0.338	0.334	0.333	0.326	0.336	0.339	0.326	0.329	0.328
R2	0.341	0.337	0.337	0.335	0.333	0.330	0.323	0.333	0.334	0.325	0.327	0.325
S2	0.341	0.335	0.337	0.336	0.336	0.332	0.321	0.333	0.333	0.324	0.327	0.326
D2	0.340	0.336	0.337	0.335	0.332	0.330	0.320	0.333	0.334	0.324	0.327	0.325
F3	0.343	0.340	0.341	0.338	0.336	0.333	0.325	0.337	0.337	0.327	0.333	0.330
R3	0.340	0.336	0.338	0.335	0.334	0.331	0.322	0.335	0.335	0.323	0.327	0.326
S3	0.340	0.335	0.339	0.335	0.333	0.330	0.321	0.333	0.333	0.323	0.327	0.325
D3	0.340	0.336	0.337	0.336	0.333	0.331	0.321	0.333	0.333	0.323	0.326	0.326
F4	0.342	0.336	0.339	0.337	0.339	0.333	0.324	0.337	0.337	0.329	0.332	0.330
R4	0.340	0.335	0.338	0.336	0.335	0.332	0.324	0.337	0.337	0.323	0.329	0.327
S4	0.340	0.336	0.337	0.335	0.333	0.330	0.321	0.333	0.333	0.323	0.327	0.325
D4	0.340	0.335	0.338	0.334	0.333	0.330	0.321	0.333	0.333	0.323	0.326	0.326

LCOE’s (2043) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type

Dwelling/ province	GR	FR	DR	OV	FL	GD	UT	NH	ZH	ZL	NB	LB
F1	0.337	0.332	0.334	0.332	0.332	0.328	0.319	0.330	0.330	0.319	0.323	0.324
R1	0.339	0.334	0.334	0.332	0.329	0.327	0.318	0.330	0.330	0.321	0.323	0.323
S1	0.336	0.334	0.335	0.332	0.331	0.327	0.319	0.330	0.330	0.321	0.323	0.323
D1	0.336	0.332	0.334	0.332	0.330	0.328	0.319	0.330	0.329	0.319	0.323	0.322
F2	0.339	0.334	0.338	0.336	0.331	0.331	0.324	0.334	0.337	0.323	0.327	0.326
R2	0.337	0.333	0.334	0.331	0.329	0.326	0.319	0.330	0.331	0.320	0.323	0.322
S2	0.337	0.332	0.334	0.332	0.332	0.328	0.318	0.329	0.330	0.320	0.323	0.322
D2	0.337	0.332	0.334	0.332	0.329	0.327	0.317	0.329	0.330	0.320	0.323	0.322
F3	0.340	0.336	0.339	0.336	0.334	0.331	0.322	0.334	0.335	0.324	0.331	0.327
R3	0.337	0.332	0.334	0.331	0.331	0.327	0.318	0.332	0.332	0.319	0.324	0.323
S3	0.337	0.332	0.335	0.331	0.329	0.326	0.318	0.329	0.330	0.320	0.323	0.322
D3	0.337	0.332	0.334	0.332	0.329	0.328	0.317	0.329	0.329	0.320	0.322	0.322
F4	0.340	0.333	0.336	0.335	0.337	0.330	0.321	0.335	0.335	0.327	0.329	0.327
R4	0.338	0.332	0.335	0.333	0.332	0.329	0.321	0.335	0.335	0.320	0.326	0.324
S4	0.336	0.333	0.334	0.331	0.330	0.327	0.318	0.330	0.330	0.319	0.323	0.322
D4	0.336	0.331	0.334	0.331	0.329	0.326	0.317	0.329	0.329	0.320	0.323	0.322

LCOE’s (2044) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type

Dwelling/ province	GR	FR	DR	OV	FL	GD	UT	NH	ZH	ZL	NB	LB
F1	0.333	0.328	0.331	0.329	0.330	0.325	0.316	0.327	0.327	0.316	0.320	0.321
R1	0.336	0.331	0.331	0.329	0.326	0.324	0.315	0.327	0.327	0.317	0.321	0.321
S1	0.333	0.330	0.332	0.329	0.327	0.324	0.317	0.327	0.327	0.318	0.320	0.320
D1	0.333	0.329	0.331	0.329	0.328	0.324	0.316	0.326	0.326	0.315	0.320	0.319
F2	0.336	0.331	0.335	0.334	0.329	0.329	0.322	0.332	0.335	0.319	0.324	0.323
R2	0.334	0.329	0.330	0.328	0.326	0.323	0.317	0.327	0.328	0.316	0.320	0.318
S2	0.334	0.328	0.330	0.329	0.329	0.324	0.315	0.326	0.327	0.316	0.319	0.318
D2	0.333	0.328	0.330	0.329	0.326	0.323	0.313	0.326	0.327	0.316	0.319	0.318
F3	0.338	0.333	0.337	0.333	0.332	0.328	0.320	0.332	0.333	0.321	0.329	0.325
R3	0.333	0.329	0.330	0.328	0.328	0.324	0.315	0.329	0.329	0.316	0.321	0.320
S3	0.334	0.329	0.332	0.328	0.326	0.323	0.315	0.326	0.326	0.316	0.320	0.318
D3	0.334	0.329	0.330	0.328	0.325	0.324	0.314	0.326	0.326	0.316	0.319	0.319
F4	0.338	0.331	0.334	0.332	0.336	0.328	0.319	0.334	0.333	0.325	0.327	0.325
R4	0.335	0.328	0.333	0.330	0.330	0.326	0.319	0.332	0.332	0.317	0.324	0.321
S4	0.333	0.329	0.330	0.328	0.327	0.323	0.314	0.327	0.326	0.315	0.320	0.318
D4	0.333	0.328	0.331	0.328	0.326	0.323	0.314	0.326	0.326	0.316	0.320	0.318

LCOE’s (2045) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.330	0.325	0.328	0.326	0.327	0.323	0.313	0.324	0.325	0.313	0.318	0.319
R1	0.333	0.327	0.328	0.326	0.324	0.321	0.313	0.324	0.325	0.314	0.318	0.318
S1	0.330	0.326	0.329	0.326	0.324	0.321	0.314	0.324	0.324	0.314	0.318	0.318
D1	0.330	0.326	0.328	0.325	0.325	0.321	0.314	0.323	0.323	0.312	0.316	0.315
F2	0.334	0.328	0.333	0.332	0.326	0.327	0.321	0.330	0.334	0.316	0.322	0.321
R2	0.330	0.326	0.327	0.325	0.323	0.320	0.314	0.324	0.325	0.312	0.318	0.315
S2	0.331	0.325	0.327	0.326	0.325	0.321	0.313	0.322	0.325	0.312	0.315	0.315
D2	0.330	0.325	0.327	0.326	0.322	0.320	0.310	0.322	0.323	0.312	0.315	0.315
F3	0.336	0.330	0.335	0.331	0.330	0.326	0.317	0.330	0.331	0.319	0.327	0.323
R3	0.330	0.325	0.327	0.326	0.325	0.322	0.313	0.326	0.327	0.312	0.318	0.317
S3	0.331	0.326	0.328	0.325	0.323	0.319	0.312	0.323	0.324	0.312	0.317	0.315
D3	0.330	0.325	0.327	0.325	0.322	0.320	0.310	0.322	0.322	0.312	0.315	0.315
F4	0.336	0.328	0.331	0.330	0.334	0.326	0.317	0.332	0.331	0.324	0.326	0.323
R4	0.333	0.325	0.331	0.328	0.327	0.324	0.317	0.330	0.330	0.314	0.322	0.319
S4	0.330	0.325	0.327	0.325	0.323	0.320	0.311	0.324	0.323	0.311	0.317	0.315
D4	0.330	0.325	0.328	0.325	0.323	0.320	0.311	0.323	0.323	0.313	0.317	0.315
LCOE’s (2046) of off-grid PV+BESS+µCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.328	0.322	0.326	0.324	0.326	0.320	0.311	0.322	0.322	0.310	0.315	0.316
R1	0.330	0.324	0.326	0.324	0.321	0.318	0.310	0.322	0.322	0.311	0.316	0.316
S1	0.327	0.323	0.326	0.324	0.321	0.319	0.312	0.322	0.322	0.311	0.315	0.316
D1	0.327	0.323	0.325	0.322	0.323	0.317	0.312	0.320	0.320	0.308	0.313	0.312
F2	0.332	0.326	0.332	0.330	0.324	0.325	0.319	0.328	0.332	0.313	0.320	0.319
R2	0.327	0.322	0.324	0.322	0.320	0.318	0.312	0.321	0.323	0.308	0.315	0.312
S2	0.327	0.322	0.324	0.323	0.321	0.317	0.310	0.319	0.322	0.308	0.312	0.312
D2	0.327	0.321	0.324	0.322	0.319	0.317	0.307	0.319	0.319	0.308	0.312	0.312
F3	0.334	0.327	0.334	0.329	0.329	0.324	0.316	0.329	0.330	0.317	0.326	0.321
R3	0.327	0.322	0.324	0.323	0.323	0.319	0.310	0.324	0.324	0.309	0.315	0.315
S3	0.328	0.323	0.324	0.322	0.321	0.316	0.309	0.320	0.321	0.309	0.315	0.312
D3	0.327	0.322	0.324	0.321	0.319	0.317	0.305	0.319	0.319	0.309	0.312	0.311
F4	0.335	0.326	0.329	0.329	0.333	0.324	0.315	0.330	0.329	0.322	0.324	0.321
R4	0.331	0.322	0.329	0.326	0.326	0.322	0.315	0.328	0.329	0.311	0.320	0.316
S4	0.327	0.322	0.324	0.321	0.320	0.317	0.308	0.321	0.321	0.308	0.314	0.312
D4	0.327	0.322	0.325	0.322	0.320	0.317	0.309	0.320	0.321	0.310	0.314	0.312

LCOE’s (2047) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.325	0.319	0.324	0.322	0.324	0.318	0.309	0.319	0.320	0.307	0.313	0.314
R1	0.327	0.321	0.323	0.322	0.319	0.316	0.308	0.320	0.320	0.308	0.313	0.314
S1	0.324	0.319	0.324	0.321	0.318	0.316	0.310	0.319	0.320	0.309	0.313	0.314
D1	0.324	0.319	0.322	0.319	0.321	0.314	0.309	0.317	0.318	0.304	0.310	0.310
F2	0.330	0.323	0.330	0.329	0.322	0.323	0.318	0.327	0.331	0.310	0.318	0.317
R2	0.324	0.319	0.322	0.319	0.318	0.315	0.310	0.319	0.321	0.305	0.313	0.309
S2	0.324	0.319	0.321	0.319	0.317	0.314	0.308	0.317	0.320	0.305	0.309	0.309
D2	0.324	0.318	0.321	0.319	0.316	0.314	0.304	0.316	0.316	0.305	0.308	0.309
F3	0.333	0.324	0.332	0.328	0.327	0.322	0.314	0.327	0.329	0.315	0.324	0.319
R3	0.324	0.319	0.321	0.321	0.321	0.317	0.308	0.322	0.322	0.307	0.313	0.312
S3	0.325	0.319	0.321	0.319	0.318	0.314	0.307	0.317	0.319	0.306	0.313	0.309
D3	0.324	0.318	0.321	0.318	0.316	0.313	0.302	0.316	0.315	0.305	0.309	0.308
F4	0.333	0.325	0.328	0.327	0.332	0.323	0.314	0.329	0.328	0.321	0.323	0.320
R4	0.329	0.320	0.327	0.324	0.324	0.320	0.313	0.327	0.327	0.309	0.318	0.314
S4	0.324	0.318	0.321	0.319	0.318	0.314	0.305	0.318	0.318	0.305	0.311	0.309
D4	0.324	0.319	0.322	0.320	0.317	0.314	0.307	0.317	0.318	0.307	0.312	0.309
LCOE’s (2048) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.323	0.317	0.322	0.320	0.322	0.316	0.307	0.317	0.318	0.305	0.311	0.312
R1	0.324	0.318	0.321	0.320	0.317	0.314	0.306	0.318	0.318	0.305	0.311	0.312
S1	0.321	0.315	0.322	0.319	0.316	0.314	0.308	0.317	0.318	0.306	0.311	0.312
D1	0.321	0.316	0.320	0.317	0.319	0.312	0.308	0.315	0.315	0.301	0.308	0.307
F2	0.328	0.321	0.329	0.328	0.320	0.322	0.317	0.326	0.330	0.308	0.317	0.315
R2	0.321	0.316	0.319	0.317	0.316	0.313	0.308	0.317	0.319	0.302	0.311	0.307
S2	0.322	0.316	0.318	0.316	0.314	0.311	0.306	0.314	0.318	0.301	0.307	0.306
D2	0.321	0.315	0.318	0.315	0.313	0.310	0.301	0.312	0.312	0.301	0.305	0.306
F3	0.331	0.322	0.331	0.326	0.326	0.320	0.312	0.326	0.327	0.314	0.323	0.317
R3	0.322	0.316	0.319	0.319	0.319	0.315	0.306	0.320	0.320	0.304	0.311	0.310
S3	0.322	0.316	0.318	0.317	0.316	0.311	0.305	0.315	0.317	0.303	0.310	0.306
D3	0.320	0.315	0.318	0.315	0.313	0.310	0.298	0.313	0.312	0.302	0.305	0.305
F4	0.332	0.323	0.326	0.326	0.331	0.321	0.312	0.328	0.327	0.320	0.322	0.318
R4	0.327	0.317	0.325	0.322	0.322	0.318	0.311	0.325	0.325	0.306	0.317	0.313
S4	0.321	0.315	0.318	0.316	0.315	0.312	0.303	0.315	0.316	0.302	0.308	0.306
D4	0.321	0.316	0.319	0.318	0.315	0.312	0.304	0.315	0.316	0.304	0.310	0.307

LCOE’s (2049) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.321	0.314	0.320	0.318	0.321	0.315	0.305	0.315	0.317	0.303	0.309	0.311
R1	0.321	0.315	0.319	0.318	0.315	0.312	0.304	0.316	0.317	0.303	0.310	0.310
S1	0.319	0.312	0.320	0.318	0.314	0.312	0.306	0.315	0.316	0.304	0.309	0.310
D1	0.318	0.312	0.317	0.314	0.318	0.309	0.306	0.312	0.313	0.298	0.305	0.305
F2	0.326	0.319	0.328	0.326	0.318	0.321	0.316	0.325	0.329	0.306	0.316	0.314
R2	0.319	0.313	0.317	0.315	0.314	0.311	0.306	0.315	0.317	0.299	0.309	0.304
S2	0.319	0.313	0.315	0.313	0.310	0.308	0.304	0.312	0.316	0.297	0.304	0.303
D2	0.318	0.311	0.315	0.312	0.310	0.306	0.298	0.309	0.309	0.298	0.302	0.302
F3	0.330	0.320	0.330	0.325	0.325	0.319	0.311	0.325	0.326	0.312	0.322	0.316
R3	0.320	0.313	0.316	0.317	0.317	0.313	0.304	0.318	0.318	0.302	0.309	0.308
S3	0.319	0.313	0.316	0.315	0.314	0.309	0.303	0.312	0.315	0.300	0.308	0.304
D3	0.317	0.311	0.315	0.312	0.310	0.306	0.295	0.309	0.309	0.298	0.302	0.302
F4	0.331	0.321	0.325	0.324	0.330	0.320	0.311	0.327	0.326	0.319	0.320	0.317
R4	0.326	0.315	0.324	0.321	0.321	0.317	0.310	0.324	0.324	0.304	0.315	0.311
S4	0.318	0.312	0.315	0.313	0.313	0.310	0.300	0.313	0.314	0.299	0.306	0.304
D4	0.318	0.313	0.317	0.316	0.312	0.310	0.302	0.313	0.314	0.302	0.308	0.305
LCOE’s (2050) of off-grid PV+BESS+μCHP systems, optimized in size, depending on household type												
Dwelling/ province	**GR**	**FR**	**DR**	**OV**	**FL**	**GD**	**UT**	**NH**	**ZH**	**ZL**	**NB**	**LB**
F1	0.319	0.312	0.319	0.317	0.320	0.313	0.303	0.314	0.315	0.301	0.307	0.309
R1	0.319	0.313	0.318	0.316	0.314	0.310	0.303	0.315	0.315	0.301	0.308	0.309
S1	0.317	0.309	0.318	0.316	0.312	0.310	0.305	0.314	0.314	0.301	0.307	0.308
D1	0.315	0.309	0.315	0.312	0.316	0.307	0.304	0.310	0.311	0.296	0.303	0.303
F2	0.325	0.318	0.326	0.325	0.317	0.320	0.315	0.324	0.329	0.304	0.314	0.313
R2	0.317	0.310	0.315	0.313	0.312	0.309	0.304	0.313	0.315	0.297	0.307	0.302
S2	0.317	0.311	0.312	0.311	0.306	0.305	0.302	0.309	0.315	0.294	0.302	0.301
D2	0.315	0.308	0.312	0.309	0.307	0.303	0.296	0.306	0.306	0.295	0.299	0.299
F3	0.329	0.317	0.329	0.324	0.324	0.318	0.310	0.324	0.326	0.311	0.321	0.315
R3	0.318	0.310	0.314	0.315	0.315	0.311	0.302	0.316	0.317	0.299	0.307	0.306
S3	0.316	0.310	0.313	0.313	0.312	0.307	0.301	0.310	0.313	0.298	0.306	0.302
D3	0.315	0.308	0.312	0.309	0.306	0.303	0.292	0.306	0.306	0.295	0.300	0.299
F4	0.330	0.320	0.323	0.323	0.329	0.319	0.310	0.326	0.325	0.318	0.320	0.316
R4	0.325	0.313	0.322	0.320	0.320	0.316	0.308	0.323	0.323	0.303	0.314	0.309
S4	0.316	0.309	0.313	0.311	0.311	0.307	0.298	0.311	0.312	0.296	0.303	0.301
D4	0.316	0.311	0.314	0.314	0.310	0.308	0.301	0.311	0.312	0.300	0.306	0.303

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