Storing excess solar power in hot-water tanks on household level as power-to-heat system

Master Thesis

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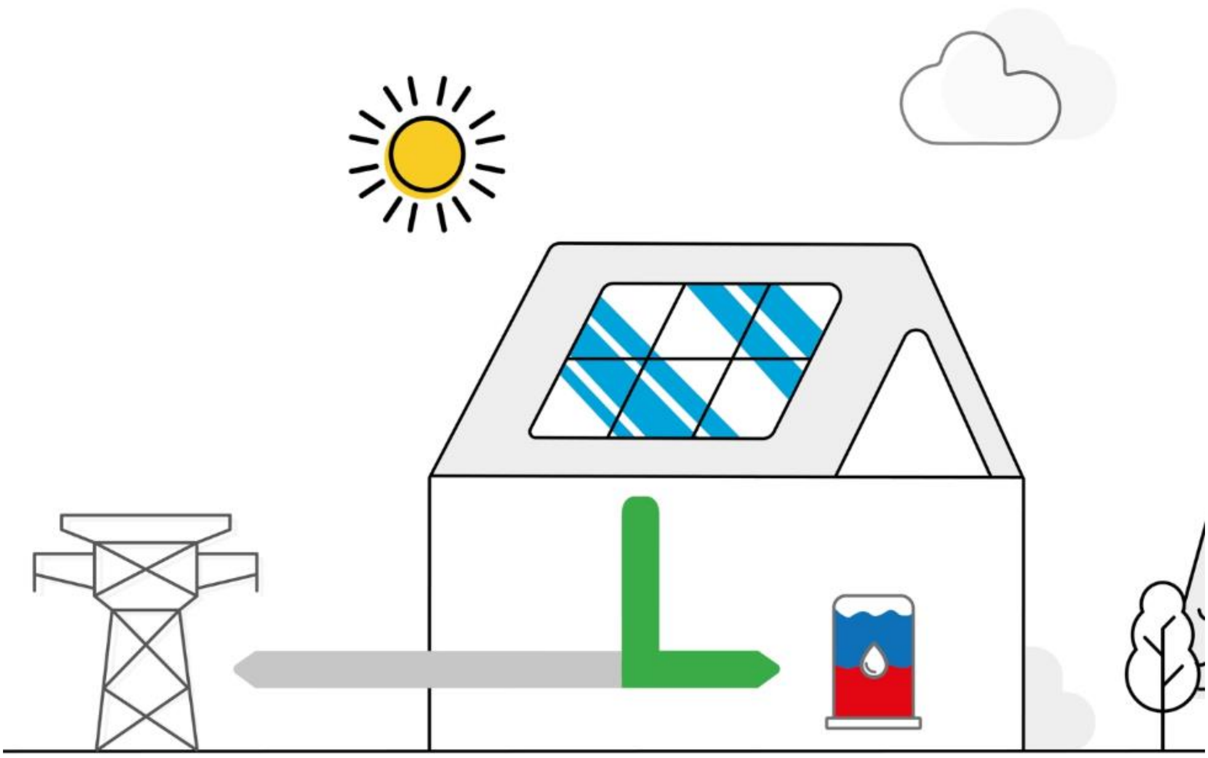

Abstract

With installed solar power increasing rapidly in the Netherlands, interest in technologies that allow for the storage and usage of excess solar energy is growing as well. A new technology that serves this purpose is the Water Battery of the company Solyx Energy. This set-up utilises surpluses of solar energy to heat tap water for showering and cleaning, thereby lowering gas use and leading to both monetary savings and reduction in CO_2 emissions.

The goal of this research was to create a model to analyse the effectiveness of the Water Battery in lowering energy costs for different types of households, especially with the planned termination of the netting system in the Netherlands. To accomplish this, the model simulates the average daily energy production and energy use per month of a household based on the household size and installed solar power. Based on these data, calculations were performed for the yearly savings in energy costs by utilising the Water Battery. The model also performs this function for similar technologies, such as a home battery, a heat-pump boiler, and a solar boiler. A multi-criteria analysis (MCA) was conducted in order to compare the benefits and drawbacks of all options.

The results show that for households with limited installed solar power (for example 3 kWp), the Water Battery has little benefit while the present netting system is in place, but the benefits become greater as the netting system is gradually terminated. The early benefits can be increased for such households by utilising smaller water storage containers, although this limits savings when netting is no longer an option. For households with higher installed power, the Water Battery immediately leads to savings in energy costs.

When comparing the technologies, the Water Battery and the heat-pump boiler score highest in the MCA. The heat-pump boiler is the most effective at lowering gas use and energy costs, while the Water Battery has lower initial costs and allows use of more excess solar energy. This means that the Water Battery is a good choice for households that want a simple way to make better use of their solar energy production. While less effective overall than a heat-pump boiler, the Water Battery does allow for an easier bottoms-up transition towards sustainability.

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1. Introduction

Solar power has become a mature technology in the past decades and now is a broadly applicable source of renewable energy for small-scale consumers. As efficiency and performance of solar cells increase thanks to improvements in technology, more people install solar panels for their homes. As a result, the total amount of installed solar power in the Netherlands has seen a great increase between 2013 and 2022 as shown in Figure 1, almost doubling from 2019 to 2022 (DNER, 2023). This is an important development for the Netherlands in the current energy transition away from fossil fuels (Donker & Halstead, 2020).

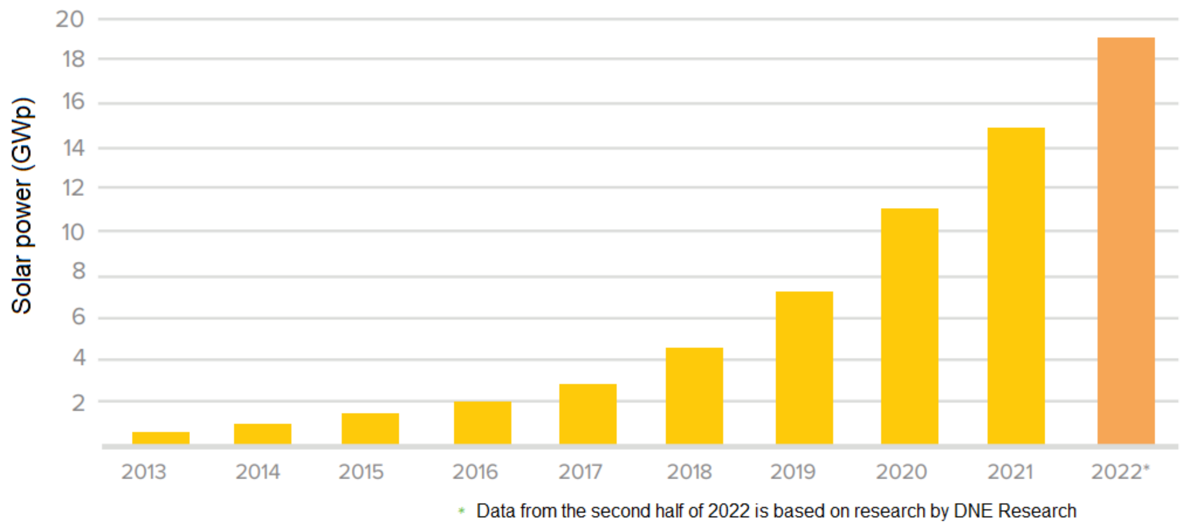

Figure 1. *Total amount of solar power added in the Netherlands in the period 2013 to 2022. From Nationaal Solar Trendrapport 2023 © Dutch New Energy Research (2023).*

However, while the total installed capacity of solar power is steadily increasing, there are obstacles when it comes to the full utilisation of the produced energy. One difficulty with solar power is its dependence on the weather and the time of day, since cloudy weather lowers energy production and solar cells do not function at all at night. This leads to situations where solar power is insufficient to meet the energy demand of consumers at specific times, meaning that electricity from the electricity grid is required to make up for the shortages. The opposite situation can also occur: there will be times when PV panels produce more electricity than the consumer requires at that moment. Ideally, consumers then choose to switch on extra devices to utilise the abundant electricity, or (predominantly) they can send it back onto the grid for a monetary compensation (Milieucentraal, 2022b). The Netherlands currently utilises a system that allows consumers to subtract their energy production from their energy usage, on an annual basis (Bakker et al., 2022). This netting system is very favourable for owners of solar panels, since they benefit from their solar panels regardless of when the energy is produced. However, plans are in place to fully terminate the netting system by 2031. While it has succeeded in making solar power more appealing to small-scale consumers, it has also led to extra costs for the government and non-users of solar energy due to providers increasing electricity prices (Londo et al., 2017).

The currently planned strategy is to start deconstructing the system in 2025 and ending the system in 2031, as seen in Table 1 (Bakker et al., 2022). Without netting, producers of solar energy receive a much lower compensation for energy surpluses that they return to the electricity grid. The exact value of the compensation depends on the provider.

Table 1. *Allowed netting percentages per year*

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031
Allowed Netting (%)	100	100	64	64	55	46	37	28	0

With the netting system becoming less profitable in the future, better alternatives for consumers are to increase self-consumption or utilise energy storage. The most commonly available way of storing solar power is by using specialised rechargeable batteries that can store anywhere between 2 kWh and 12 kWh of energy (Milieucentraal, 2022b). While this is a relatively simple solution, batteries with higher capacities also have much higher costs with a lithium-ion battery of 6 kWh costing between € 4000 and € 5000 excluding installation costs (Milieucentraal, 2022b). The internal battery of electric cars also allows for storage of solar power. Disadvantages of this method of storage include the cost of the car itself (which is too high for many people) and the fact that the car cannot be used while the battery is being charged.

Another option for utilising excess energy is power-to-heat, which refers to using electric energy to produce heat which can either be utilised immediately or stored for later usage (Bloess et al., 2018). There are multiple technologies that utilise power-to-heat conversion principles, with heat pumps being a prominent example (Naranjo-Mendoza et al., 2019). However, power-to-heat systems that include energy storage are not widespread yet, with the most effective ones being large-scale projects that individual households cannot easily benefit from (Zhang et al., 2022). Even small-scale power-to-heat projects are at the neighbourhood level, meaning that the implemented technologies are still centralised to a certain degree (Nami et al., 2020). To make energy storage easily available to users of solar energy, it would work best to provide options that function at household level. Therefore, alternative forms of small-scale energy storage are desirable to consumers in the Netherlands in order to make better use of their energy overproduction.

This thesis will focus on analysing a specific type of energy storage promoted by the company Solyx Energy: hot tap water that can be used for showering and to a lesser extent cleaning. For the average Dutch household, heating up tap water contributes to about 20% of the total energy usage (Milieucentraal, 2022a). This energy use is primarily natural gas-based, as most Dutch households utilise natural gas for the heating of water instead of electricity (CBS, 2022). Furthermore, even the majority of Dutch electricity is produced using natural gas (CBS, 2022). Heating tap water using solar power instead would therefore be beneficial in lowering natural gas usage and thus limiting the effects of climate change (Hall et al., 2021).

This research focusses specifically on utilising overproduction of solar energy for heating tap water. This is achieved with a device sold by Solyx Energy, the Solar iBoost, which is shown in Figure 2. The device dynamically compares a households' energy production to its energy consumption and uses any surplus to power an electric boiler. The combination of these devices is shown in Figure 2 as well and is called a Water Battery.

Figure 2. *The Solar iBoost (top) and the set-up of the Water Battery (bottom). The transmitter placed in the fuse box measures any electricity sent to the grid and wirelessly contacts the Solar iBoost, which redirects the electricity to power an electric boiler to heat tap water.*

Once the netting system gets decommissioned, the system can function as an alternative to sending power back to the grid. The primary benefits of this system are that it is simple and affordable: an electric boiler is used for the storage and the costs are generally about € 1500 for the boiler (Boilergarant, 2023c), Solar iBoost and installation of the devices (Solyx Energy, 2023). However, it has rather limited applications as a storage system compared to other options. While home batteries can power any electrical device, the Water Battery can only be used to heat tap water. Furthermore, the Water Battery provides relatively short-term storage, since the isolation of most electric boilers allows them to hold the heat for a maximum of one to two days before the water cools too much to be usable. Despite this limit, hot tap water is used daily in most households, which makes the shorter usage time less of a problem.

An alternative technology to the Water Battery is the heat-pump boiler. This boiler utilises a built-in heat pump to heat tap water, leading to very high efficiency (Beccali et al., 2022). However, a heat pump boiler is also limited to heating tap water and the costs range around € 2400 (Boilergarant, 2023a). Furthermore, while a heat-pump boiler requires less total energy to heat water, it has a longer heating time than an electric boiler (Boilergarant, 2023b). This means that a heat-pump boiler benefits less from larger energy peaks that might happen infrequently depending on the weather.
There is still little data available on the effectiveness of storing excess solar energy as hot tap water, and the Water Battery itself is still a relatively new technology. Therefore, this thesis aims to conduct a comparison between the Water Battery and alternative options like home batteries and heat-pump boilers to determine the best use for surplus solar energy. The research will focus on answering the following research question:

What are the environmental and economic benefits and drawbacks of storing solar energy surpluses in a Water Battery compared to other available methods of small-scale energy storage?

This research question is divided up into the following sub-questions:

1. *Without energy storage, what is the daily and yearly energy balance in an average Dutch household utilising solar panels with regard to solar electricity generation, usage, export, import, and the usage of tap water and natural gas?*
2. *What is the daily and yearly energy balance in an average Dutch household utilising solar panels in addition to a Water Battery?*
3. *What are the potential savings in natural gas use, costs and CO_2 emissions when using a Water Battery?*
4. *How efficient and applicable is the Water Battery compared to alternative technologies and what is the return on investment?*

2. Methodology

The methodology is divided into different parts, describing how each of the sub-questions will be answered. The primary goal of this project consists of developing an excel model that calculates monetary and CO_2 savings for Dutch households utilising a Water Battery on their installed PV capacity, taking into account the number of persons per household, efficiency of solar panels, and changes in energy and gas tariffs. For the various calculations, the model will utilise data obtained during a literature analysis. In order to account for uncertainty, a sensitivity analysis will be applied to the model. The variables changed for this analysis will be those that are most likely to change in the short term. For example, due to the war between Ukraine and Russia, gas prices in Europe have increased significantly compared to previous years (Berkhout et al., 2022), whereas in the first quarter of 2023 the electricity- and gas tariffs showed a sharp decline. This means that even in the short period between doing the calculations and submitting the thesis, the electricity- and gas tariffs can be a source of uncertainty. The model will be utilised by Solyx Energy to provide customers with information on their savings and return on investment when using the Water Battery. Furthermore, several scenarios will be created to test the outcomes of specific inputs, which will primarily be explained in sections 2.3 and 2.4. For these scenarios, the inputs changed during the sensitivity analysis will remain constant. Instead, variables depending on specific households will be varied, like the number of individuals and installed solar power capacity.

2.1. Sub-question 1

The first sub-question that will be answered is the following:

Without energy storage, what is the daily and yearly energy balance in an average Dutch household utilising solar panels with regard to solar electricity generation, usage, export, import, and the usage of tap water and natural gas?

The yearly energy balance is determined primarily with data from the Central Bureau of Statistics (CBS). This data is also utilised for the daily energy balance, so the specific values will be shown later. The daily energy balance will be defined as an hourly energy balance showing energy usage, energy production and gas usage for an average weekday and weekend day per month of the year. To accomplish this, the following data sets are utilised:

2.1.1 Energy profiles on electricity use

These profiles are obtained from MFFBAS, an organisation focussed on sharing energy data for the Dutch energy market (MFFBAS, 2023). Energy profiles are a way for net providers to gauge how the energy use of a customer is divided over the year. An energy profile consists of a data set showing fractions for every 15 minutes in a year. Each fraction shows a part of the total amount of power used that year, and all fractions added together give a value of 1. Therefore, multiplying a fraction value with a value for annual energy use in kWh will result in a value for energy use in kWh at a specific moment. Since energy profiles are not available for future years, one data set will be used as an average. This data set is the electricity use profile of 2022, specifically looking at category E1A (3-phase connection of 25 A per phase), since this is the most common connection for Dutch households (Enexis Netbeheer, 2023).

2.1.2 Energy profiles on gas use

These profiles are also obtained from MFFBAS and function largely the same as the electricity profiles. The most important difference is that gas profiles are divided into temperature-dependent and temperature-independent gas use. Temperature-dependent gas use refers to the fraction of gas required for heating, and naturally depends on the temperature of the surrounding area. Therefore, the data set provided requires an additional calculation utilising the temperature at a specific moment to determine the fraction of use. However, gas used for heating tap water can be considered to be mostly temperature independent, since heating water for showering is a more constant occurrence than powering central heating, which mostly occurs in colder months. Furthermore, the total percentage of temperature-independent gas use is around 24%, which is quite close to the 20% ascribed to heating for showering (Milieucentraal, 2022a). Ultimately, the daily energy balance is meant to show how much solar energy is available to replace the use of natural gas for heating tap water. Therefore, while the yearly energy balance will include temperature-dependent and temperature-independent gas use, only the temperature-independent data will be shown in the daily energy balance.

2.1.3 Solar energy generation data in the form of capacity factors

This data is obtained from the Correlations in Renewable Energy Sources tool (CorRES) developed by the Denmark Technical University (DTU Wind Energy, 2022). This tool utilises several types of data to simulate renewable energy generation time series for specific areas and timescales. The data inputs include time periods, historical weather data, geographical information on the locations of wind and solar farms, power production data of these farms, and optionally installed capacity if an exact amount of produced energy is required. The primary function of CorRES is to model and analyse correlations between production of solar energy and wind energy. However, it can also be utilised for energy production forecasts, which is what it is used for in this thesis. Required inputs consist of the latitude, longitude and altitude of the area to be analysed, surface azimuths and tilts of the solar cells. The result of such a time series is a number of hourly capacity factors that can be multiplied with the total installed capacity in an area to obtain a value for solar energy produced during that hour. For the purposes of this research, the same locations in the Netherlands are used as in the Pan-European Climate Database (De Felice, 2021), with a surface azimuth of 180° and a surface tilt of 25°. These areas and values allow the model to produce capacity factors that are on average applicable anywhere in the country. The current version of CorRES can only simulate time series up to 2020. In order to create an estimate for the future, a time series ranging from 2010 to 2020 is created so the average values can be used. This is done to compensate for weather variations between different years.

Most of these data sets provide data for every hour of a year. The only data set that differs is the electricity energy profile, which gives values every quarter of an hour. Therefore, the four values that correspond to the four quarters of each hour are added together, averaged and multiplied by 4 in order to get all hourly values for each day of the year.

The next step is to categorise the data in each data set into weekdays and weekend days per month. An example of the resulting data is shown in Table 2, showing the average fractions of electricity use for the first five hours of each specific weekday and weekend day in January 2022. For the solar generation data, the data in each month is based on the average hourly values of the specific weekdays and weekend days between 2010 and 2020.

Table 2. *Average fractions of electricity use for the first five hours per specific week/weekend day in January 2022*

Day/Hour	0	1	2	3	4	5
Monday	2.44E-05	2.00E-05	1.78E-05	1.67E-05	1.66E-05	1.79E-05
Tuesday	2.63E-05	2.12E-05	1.86E-05	1.74E-05	1.70E-05	1.81E-05
Wednesday	2.58E-05	2.09E-05	1.82E-05	1.72E-05	1.69E-05	1.80E-05
Thursday	2.55E-05	2.07E-05	1.83E-05	1.72E-05	1.70E-05	1.80E-05
Friday	2.60E-05	2.10E-05	1.86E-05	1.75E-05	1.71E-05	1.80E-05
Saturday	2.89E-05	2.38E-05	2.03E-05	1.83E-05	1.76E-05	1.77E-05
Sunday	2.72E-05	2.22E-05	1.91E-05	1.76E-05	1.69E-05	1.72E-05

The resulting tables are further divided into weekdays and weekend days: for each column, the values in the rows Monday to Friday are averaged, and the values in the rows Saturday and Sunday are separately averaged. However, these data sets only show fractions or capacity factors in the case of the solar generation data, therefore the annual values of energy and gas usage and installed solar cell capacity are needed to calculate tangible results from each data set.

The annual values can also differ depending on a number of variables. The most important variable for electricity- and gas use is the size of the household, since more occupants will use more electricity. For this research, a maximum size of six household members will be considered, based on calculations from the organisation Nibud (2023).

The most important variable for determining gas use is typically indoor temperature: since gas is primarily used for central heating, the temperature of a living space will strongly determine how much gas is required at a specific moment (Majcen et al., 2013). However, since this research focusses on gas use for water heating, which is largely independent of indoor temperature, the size of households will also be considered as the primary factor for determining different values. The obtained values are shown in Table 3.

Finally, the installed capacity can simply be determined by the number of solar panels installed and the power per panel. Currently, the highest achievable power of a solar panel is 500 Wp, while panels of 350 to 400 Wp are more common (Solvari BV, 2023). Variations in the number of solar panels and the power per panel will be used to define the scenarios introduced in section 2.3.

Table 3. *Average annual electricity and gas use depending on size of household (Nibud, 2023)*

Size Household	Annual electricity use (kWh)	Annual gas use (m^3)
1	1800	650
2	2810	1020
3	3370	1450
4	3940	1720
5	4270	1800
6	4445	1840

With all data sets completed, the results for this sub-question will be a number of figures representing electricity use, gas use and electricity production for week- and weekend days for each month of the year. For the inputs of these figures, the size of the household will be 3 and the number of solar panels will be 12 with a capacity of 375 Wp per panel. These numbers are chosen as something of a middle ground between the values that are used for the aforementioned scenarios. Note that the calculations mentioned only result in data for one year. Data for future years can be obtained by repeating the same steps, but since solar panels become less efficient by about 0.5% per year, the daily energy production is multiplied with a yield factor of 0.995 for each year.

2.2. Sub-question 2

The next sub-question to answer is:

What is the daily and yearly energy balance in an average Dutch household utilising solar panels in addition to a Water Battery?

This sub-question depends strongly on the amount of produced electricity from solar energy that is not directly utilised by the household itself, and instead sent back to the electricity grid. The boiler can heat a limited amount of water per time unit, which means that on sunny days there might be surplus energy that cannot be used for any purpose.

The first step is to determine the amount of daily produced solar energy that is not utilised by the household, the excess energy. This is accomplished by first comparing the hourly data per month for electricity use and electricity production. For each hour in a week- and weekend day, the electricity use will be subtracted from the corresponding electricity production value. If this results in a negative value due to the electricity use being higher, a value of 0 kWh will be filled in instead. This is done to ensure that an electricity surplus of a particular hour is not used up to meet the electricity use of another hour. The hourly values are then added up to obtain the total value for excess energy per day. This is shown in equations 1.1 and 1.2:

$$EE_{1my} = \sum_{h=0}^{23}\left(Yf^{x} * Ep_{1hmy} - Eu_{1hm}\right) \mid Yf^{x} * Ep_{1hmy} - Eu_{1hm} \geq 0 \qquad (1.1)$$

$$EE_{2my} = \sum_{h=0}^{23}\left(Yf^{x} * Ep_{2hmy} - Eu_{2hm}\right) \mid Yf^{x} * Ep_{2hmy} - Eu_{2hm} \geq 0 \qquad (1.2)$$

- EE_{1my} = Excess electricity produced on an average weekday for a month m in a year y (kWh)
- Yf = Yield factor of solar panels (99.5%)
- x = Number of years since 2023
- Ep_{1hmy} = Electricity produced on an average weekday at an hour h for a month m in a year y (kWh)
- Eu_{1hm} = Electricity used on an average weekday at an hour h for a month m (kWh)
- EE_{2my} = Excess electricity produced on an average weekend day for a month m (kWh)
- Ep_{2hmy} = Electricity produced on an average weekend day at an hour h for a month m (kWh)
- Eu_{2hm} = Electricity used on an average weekend day at an hour h for a month m (kWh)

The excess energy per day is then further divided into energy that can be used to heat tap water, and the remaining energy that will be sent back to the electricity grid. The amount of energy used depends on the size of the electric boiler: it is assumed that once every 24 hours, the boiler will heat its maximum amount of water to 60 °C, in order to prevent the risk of legionella (Doebbeling & Wenzel, 1987). The base temperature of tap water can vary depending on the time of the year due to the surrounding temperature, but in summer it is generally around 15 °C while in winter it is around 10 °C (Van der Molen et al., 2009). Therefore, it is assumed that in the spring and summer months, the temperature of the tap water must be increased by 45 °C, while in the autumn and winter months this increase is 50 °C. Taking these factors into account, we can use equation 2 to determine the energy required by the boiler per day, and thus the limit for utilising excess energy:

$$E_{boiler} = \frac{V_{boiler} * \rho_{water} * 1000 * c_{water} * \Delta T}{3600000} \qquad (2)$$

- E_{boiler} = Amount of electricity required by the boiler per day (kWh)
- V_{boiler} = Volume of the boiler (L)
- ρ_{water} = Specific density of water (1 kg/L)
- c_{water} = Specific heat capacity of water (J/(kg*K))
- ΔT = Change in temperature in boiler (45 °C in summer, 50 °C in winter)

If the amount of excess electricity on a day is less than or equal to the limit, no electricity is sent back to the grid. Otherwise, the amount of electricity sent back to the grid equals the amount of excess electricity minus the limit. This will result in the amount of energy that can be used to power the boiler and the amount of energy sent back to the electricity grid for each weekday and weekend day per month, as shown in equations 3.1 to 3.4.

The last data set to be calculated is the amount of electricity required from the grid to meet the daily electricity use. These values are obtained by subtracting the daily electricity production value from the daily electricity use value and adding the daily unused electricity value. Multiplying the daily values with the amount of weekdays and weekend days in each month will give a total value for the different data sets per month. Adding the monthly values of the respective data sets together results in an annual value for all categories. The process is also shown in equations 3.5 to 3.9:

$$BE_{1my} = EE_{1my} \vee E_{boiler} \tag{3.1}$$

$$BE_{2my} = EE_{2my} \vee E_{boiler} \tag{3.2}$$

$$EG_{1my} = 0 \vee EE_{1my} - E_{boiler} \tag{3.3}$$

$$EG_{2my} = 0 \vee EE_{2my} - E_{boiler} \tag{3.4}$$

$$ER_{1my} = Eu_{1m} - \sum_{h=0}^{23}(Y^{x} * Ep_{1hmy}) + EE_{1my} \tag{3.5}$$

$$ER_{2my} = Eu_{2m} - \sum_{h=0}^{23}(Y^{x} * Ep_{2hmy}) + EE_{2my} \tag{3.6}$$

$$TBE_{y} = \sum_{m=1}^{12}(BE_{1my} * ND_{1my}) + \sum_{m=1}^{12}(BE_{2my} * ND_{2my}) \tag{3.7}$$

$$TEG_{y} = \sum_{m=1}^{12}(EG_{1my} * ND_{1my}) + \sum_{m=1}^{12}(EG_{2my} * ND_{2my}) \tag{3.8}$$

$$TER_{y} = \sum_{m=1}^{12}(ER_{1my} * ND_{1my}) + \sum_{m=1}^{12}(ER_{2my} * ND_{2my}) \tag{3.9}$$

- BE_{1my} = Amount of electricity utilised by the boiler on a weekday for a month m in a year y (kWh)
- BE_{2my} = Amount of electricity utilised by the boiler on a weekend day for a month m in a year y (kWh)
- EG_{1my} = Energy sent back to the grid on a weekday for a month m in a year y (kWh)
- EG_{2my} = Energy sent back to the grid on a weekend day for a month m in a year y (kWh)
- ER_{1my} = Energy required from the grid on a weekday for a month m in a year y (kWh)
- ER_{2my} = Energy required from the grid on a weekend day for a month m in a year y (kWh)
- TBE_{y} = Total amount of electricity utilised by the boiler in a year y (kWh)
- TEG_{y} = Total amount of electricity sent back to the grid in a year y (kWh)
- ND_{1my} = Number of weekdays in a month m for a year y
- ND_{2my} = Number of weekend days in a month m for a year y

2.3. Sub-question 3

The next sub-question to answer is:

What are the potential savings in natural gas use, costs and CO_2 emissions when using a Water Battery?

This sub-question requires a comparison of the utilisation of excess solar energy with or without hot tap water storage. The calculations for the previous sub-questions have resulted in data sets showing annual amounts of energy surpluses used by the electric boiler, energy surpluses sent back to the electricity grid, and energy required from the electricity grid. These data sets will now be utilised to calculate the yearly energy costs of households with a Water Battery (household 1) and without a Water Battery (household 2). To account for the effects of the netting system, the calculations are performed for the period 2023 to 2031, using the different netting percentages for each year as listed in Table 1.

First the calculations for household 1 will be described. The maximum amount of energy that is allowed to be netted is equal to the amount of energy provided by the electricity grid. The amount of energy that is available for netting to household 1 is equal to the energy surpluses that are sent back to the electricity grid. Since netting allows consumers to lower their electricity costs, the amount of energy available for netting is subtracted from the amount of energy provided by the electricity grid, with any remaining required energy being multiplied by the electricity tariff to determine the electricity costs. The amount of energy used by the boiler is energy that replaces the use of gas. To calculate the savings, the amount of energy is divided by the lower heating value (LHV) of natural gas, which is 31.65 MJ/m^3 (Green & Southard, 2019; Heslinga, & Van Harmelen, 2006). This shows the amount of natural gas saved, which is then multiplied with the gas tariff in order to determine the gas savings yielded by the Water Battery. The amount of natural gas is also multiplied by the CO_2 content value of natural gas (1.78 kg CO_2/m^3) in order to determine the amount of reduced CO_2 emissions (Croezen et al., 2022). Finally, if the amount of energy sent back to the grid is higher than the allowed netting, the difference will be recompensed at the average market rate (Easyswitch, 2023).

The calculations for household 2 are mostly the same. The main difference is that no surplus energy is used to power a boiler. The amount of energy available for netting is equal to the total surplus of solar energy. As a result, there are no savings on the use of natural gas, and the respective values remain 0 for each year. This means that household 2 will send more energy back to the electricity grid and receive more compensation.

For both households, the cost calculations for the year 2023 are slightly altered because of a temporary price limit implemented by the Dutch government (Rijksoverheid, 2022). This means that for the first 1200 m^3 of gas used in 2023, a household pays a maximum of €1.45 per m^3 independent of higher market prices. For electricity, the first 2900 kWh in 2023 will have a maximum price of € 0.40 per kWh. Any amount of gas or electricity beyond these limits will cost the amount determined by the energy provider. These limits have been implemented for the calculations for the year 2023. There are also energy suppliers with prices lower than the price limit (Easyswitch, 2023). While this is not a problem for the average rate, the model does require the price limit input to be the same as the price of the energy supplier in these situations.

The next step for both households is to subtract the total savings per year from the electricity costs per year to obtain the total costs per year. This value can become negative depending on the energy production, which means that the household has made a profit. To complete the comparison, the total costs of household 1 are subtracted from the total costs of household 2. If this values is positive, then the Water Battery has provided monetary savings to the household. A negative value indicates that the Water Battery has incurred extra costs. As long as netting is still possible, this may occur for households with low amounts of excess energy.

In order to test savings for different situations, four different categories with three scenarios each are created based on the size of a household and the amount of installed solar power. The inputs per scenario are shown in Table 4, corresponding to the following descriptions:

1. **Small household, low installed power**
   1.1 Single person living in a house with older solar panels.
   1.2 Two elderly people living together, needing more time for showering.
   1.3 Single parent living with a young child.

2. **Large household, low installed power**
    2.1 Family with two young children living in an older house.
    2.2 Family with three children. One of the children is a young adult living on their own, but staying over regularly.
    2.3 Family with four children (all teenagers) living in an older house.
3. **Small household, high installed power**
    3.1 Rich businessperson who lives on their own, but often receives visitors.
    3.2 Married couple living in a modern (well insulated) house, with no plans to have children.
    3.3 Young couple with a Jacuzzi in their home.
4. **Large household, high installed power**
    4.1 Family with two children living in a modern (well insulated) house.
    4.2 Family with three children. One of the children is a young adult living on their own, but staying over regularly.
    4.3 Family with four children living in a modern (well insulated) house.

Table 4. *Inputs for different scenarios in the model*

1. Small household, low installed power				**2. Large household, low installed power**			
Number of occupants	Number of solar panels	Power per panel (Wp)	Size boiler (L)	Number of occupants	Number of solar panels	Power per panel (Wp)	Size boiler (L)
1	8	300	50	4	10	275	150
2	10	275	120	5	10	300	200
2	10	300	80	6	10	375	300
3. Small household, high installed power				**4. Large household, high installed power**			
Number of occupants	Number of solar panels	Power per panel (Wp)	Size boiler (L)	Number of occupants	Number of solar panels	Power per panel (Wp)	Size boiler (L)
1	12	400	150	4	15	400	200
2	15	375	100	5	18	375	200
2	15	400	150	6	20	400	300

The different tariffs will remain constant during these calculations: the gas tariff will be € 1.90 per m^3, the electricity tariff will be € 0.50 per kWh, and the tariff for electricity returned to the grid (when netting is not applicable) will be € 0.08 per kWh. These values approximate average values of different energy suppliers in the Netherlands as checked on March 1st 2023 (Easyswitch, 2023). For the results in the year 2023, the gas tariff and the electricity tariff will only be used if the household exceeds the electricity limit and/or the gas limit. The results for each scenario will be shown in tables for the years 2023 to 2031. If there are no savings in total costs for the first four years in a scenario, the boiler size will be altered to see if this leads to earlier savings in total costs. If this alteration still does not lead to improved savings, the installed power will be increased until there are savings in 2025. Furthermore, for each scenario an additional calculation will be conducted where there is no netting system in place from 2024 onward. This way the effect of the netting system on energy storage and monetary savings can be better understood.

2.4. Sub-question 4

The final sub-question to be answered is:

How efficient and applicable is the Water Battery compared to alternative technologies and what is the return on investment?

To answer this sub-question, a multi-criteria analysis (MCA) will be conducted to compare the Water Battery with a number of alternatives, utilising the steps explained by Dodgson et al. (2009):

1. The goal of the MCA is to find a technology that enables savings in energy costs and lowered emissions for Dutch households in the period 2023 to 2031, preferably by allowing excess solar energy to become usable for the household.
2. The options are a Water Battery, an electric home battery, a heat-pump boiler, and a solar boiler. For the purposes of comparison, the basic set-up of a household of 3 persons with 12 solar panels of 375 Wp per panel will be considered as the users of the technologies.
3. The following criteria are used:
    a. Total costs. This value will be based on the prices of the products per option and the respective installation costs. Naturally, lower costs are preferable.
    b. Return on investment (ROI). This value will be calculated using the following equation:

$$ROI = \frac{\sum_{y=2023}^{2031} Net\ Benefits_y}{Total\ installation\ costs} * 100\% \quad (4)$$

    - y = Year in the period 2023 to 2031

    A higher ROI value is preferable. While ROI is similar to total costs, the latter can be quite a hurdle for certain households, which is why both options are considered for the MCA.

    c. Payback period. Also known as simple payback time, this value refers to the number of years after which the monetary savings of the technology will cover the installation costs (Zhao et al., 2022). It can be described by the following equation:

$$Payback\ period = \frac{Total\ installation\ costs}{Annual\ savings} \quad (5)$$

    However, since the savings can vary per year due to the netting system, the annual savings will be added in steps per year until they meet or surpass the total costs. A lower payback period is preferred.

    d. Effectiveness. This value refers to how much unused solar energy becomes usable thanks to the technology, and is calculated using the following equations:

$$TET_y = \sum_{m=1}^{12}\left(ET_{1my} * ND_{1my}\right) + \sum_{m=1}^{12}\left(ET_{2my} * ND_{2my}\right) \qquad (6.1)$$

$$TEE_y = \sum_{m=1}^{12}\left(EE_{1my} * ND_{1my}\right) + \sum_{m=1}^{12}\left(EE_{2my} * ND_{2my}\right) \qquad (6.2)$$

$$Effectiveness = \frac{\sum_{y=2023}^{2031} TET_y}{\sum_{y=2023}^{2031} TEE_y} \qquad (6.3)$$

- ET_{1my} = Excess energy utilised by the technology on a weekday in a month m for a year y (kWh)
- ET_{2my} = Excess energy utilised by the technology on a weekend day in a month m for a year y (kWh)
- TET_y = Total excess energy utilised by the technology in a year y (kWh)
- TEE_y = Total excess electricity produced in a year y (kWh)
- ND_{1my} = Number of weekdays in a month m for a year y
- ND_{2my} = Number of weekend days in a month m for a year y

A higher effectiveness value is preferred.

e. Reduction in CO_2 emissions. This value refers to the reduction in CO_2 emissions over the time period obtained by each technology.

$$Reduction\ in\ CO_2\ emissions = \sum_{y=2023}^{2031} TET_y * \frac{3.6}{LHV_{natural\ gas}} * CO_2\ content_{natural\ gas} \quad (7)$$

A larger reduction in CO_2 emissions is preferred.

4. The criteria will be standardised using the maximum standardisation method (Mohamad & Usman, 2013). If a higher value is preferred for a criterion, the standardised score of a technology is equal to the normal score divided by the highest score. If a lower value is instead preferred, the standardised score is equal to the normal score divided by the highest score, multiplied by –1 and finally summed with 1.
5. Weights will be assigned to the criteria using the expected values method (Durbach & Stewart, 2009). Since there are five criteria, there will be five weight scores which are calculated with the following equations:

$$W_1 = \frac{1}{5*5} + \frac{1}{5*(5-1)} + \frac{1}{5*(5-2)} + \frac{1}{5*(5-3)} + \frac{1}{5*(5-4)} \approx 0.46 \qquad (8.1)$$

$$W_2 = \frac{1}{5*5} + \frac{1}{5*(5-1)} + \frac{1}{5*(5-2)} + \frac{1}{5*(5-3)} \approx 0.26 \qquad (8.2)$$

$$W_3 = \frac{1}{5*5} + \frac{1}{5*(5-1)} + \frac{1}{5*(5-2)} \approx 0.16 \qquad (8.3)$$

$$W_4 = \frac{1}{5*5} + \frac{1}{5*(5-1)} \approx 0.09 \qquad (8.4)$$

$$W_5 = \frac{1}{5*5} \approx 0.04 \qquad (8.5)$$

A number of weighing variations will be used to check how different priorities for certain criteria affect the outcome. When a criterion is preferred, W_1 will be assigned to that criterion, with the other weights being assigned to the other criteria depending on how important they are deemed compared to the preferred criterion. This means that W_5 is assigned to the least prioritised criterion in a specific situation. The distribution of weights for different priorities is shown in Table 5. When total costs are prioritised, payback period and ROI are given the second and third highest weights since the focus is on economic benefits. If ROI is prioritised, the second greatest weight is given to reduction in CO_2 emissions to analyse both economic and environmental benefits. Priority for payback period primarily results in economic benefits, which means that total costs and ROI are also given higher weights. Effectiveness and reduction in CO_2 emissions both focus on environmental benefits, so when either of these criteria is given priority, the other will receive the second highest weight.

6. A number of sensitivity analyses will be conducted by varying the value each weight between 0 and 1 in steps of 0.1 at a time. Whenever the value of a weight is changed, the values of the other weights are evenly distributed. For example, if total costs are given a weight of 0.5, the other four criteria will have a weight of 0.125.

Table 5. *Weights given to each criterion with different priorities*

Variable	**No Priority**	**Priority**				
		Total costs	ROI	Payback period	Effectiveness	Reduction in CO_2 emissions
Total costs	0.20	0.46	0.16	0.16	0.09	0.09
ROI	0.20	0.16	0.46	0.26	0.04	0.04
Payback period	0.20	0.26	0.09	0.46	0.16	0.16
Effectiveness	0.20	0.09	0.04	0.04	0.46	0.26
Reduction in CO_2 emissions	0.20	0.04	0.26	0.09	0.26	0.46

For this MCA, the model will be expanded to calculate results for the other technologies as well. Calculations for the home battery function very similar to those for the Water Battery. For each month, the electricity production of an average week- and weekend day is compared to the corresponding electricity use, and the electricity surplus is added to the home battery. For this research, the home battery will have a capacity of 6 kWh and total costs of € 4000,-, based on average values for home batteries (Milieucentraal, 2022b). An additional calculation is performed to determine the amount of energy taken from the home battery during hours when electricity use exceeds electricity production. This means that during sunny months, the home battery might not be fully drained from the previous day when it gets charged again on a new day. Since the home battery functions primarily to reduce electricity provided by the grid, it is not expected to reduce gas use. However, since electricity in the Netherlands is partly produced using natural gas and other fossil fuels, the home battery can still lead to reduce CO_2 emissions (Leestemaker et al., 2023). The average CO_2 emissions resulting from producing grey electricity is 0.396 kg CO_2/kWh (Leestemaker et al., 2023), so this value will be used to determine the reduction in CO_2 emissions.

The heat-pump boiler selected for the calculations has a capacity of 200 L and has a total cost of € 2815,- (Boilergarant, 2023b). This technology requires 0.43 kWh of electricity for 5 hours and 39 minutes in order to heat its full capacity to 60 °C (Boilergarant, 2023c). The time requirement increases to 7 h in autumn and winter months. This is implemented by increasing the electricity use of the household during a number of hours per day. These hours are selected as the hours with the most electricity production. The selected hours are 10:00 to 15:00 for spring and summer months, and 9:00 to 15:00 for autumn and winter months. The savings in gas use are determined by taking the amount of water heated each day and calculating how much gas it would take to perform the same function.

The solar boiler is an option specifically focussed on heating tap water without offering options for storing excess electricity. This makes it even more specialised than the Water Battery, and it is included to investigate if the specialisation has specific benefits for a household that utilises solar panels. A solar boiler consists of a number of solar thermal collectors, a container with a heat exchanger, and a pump and set of pipes connecting the container to the collectors (Milieucentraal, 2022c). The thermal collectors receive sunlight to heat up a fluid, which is then transferred to the container where the water is heated using a heat exchanger. The calculations for the solar boiler require an alternative version of the hourly electricity production, using heat obtained via the heat exchanger instead of electricity. This data is also obtained from CorRES in the form of a data set showing the global horizontal index (GHI) for the same inputs that were used to obtain the data set for sub-question 1. This data set is simplified to show the average hourly GHI values for a weekday and weekend day in each month. The GHI has units in W/m^2, which means that the surface area of the solar collectors is required to obtain a power value. For households of 4 persons or less, the solar collectors have a surface of 2.5 m^2 and total costs of € 2600,- while the collectors of households with 5 or more persons have a surface of 4 m^2 and total costs of € 4700,- (Milieucentraal, 2022c). For both options, the mentioned subsidies of € 1200,- and € 1800,- respectively are included to lower the costs (Milieucentraal, 2022c). Furthermore, while the data set on obtained energy from solar panels includes a correction factor, the data set for the GHI values requires an adjustment for the conversion of light to heat, known as the thermal efficiency. Therefore, the values are multiplied by a value of 0.6, which is the average thermal efficiency value for solar boilers (Lupu et al., 2018).

3. Results

3.1. Results sub-question 1

The following figures show the daily energy balance for an average weekday and an average weekend day in January and July 2023, as well as an average weekday and weekend day across the entire year. As mentioned in the methodology, the following inputs were given: a household size of 3 persons, and 12 solar panels of 375 Wp per panel. Furthermore, the gas use only shows the temperature-independent part. To compare gas use and electricity use, all values are shown in MJ. The figures showing the daily energy balance for the other months can be found in Appendix A.

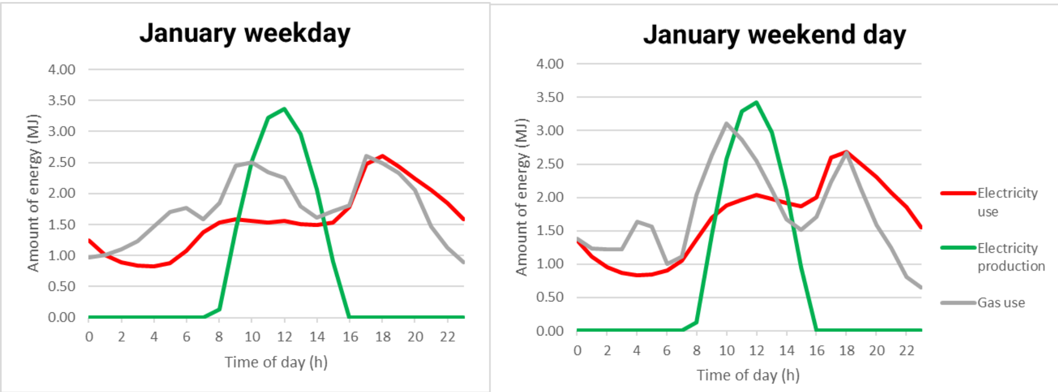

Figure 3. *Energy balance in MJ for an average weekday and weekend day in January 2023.*

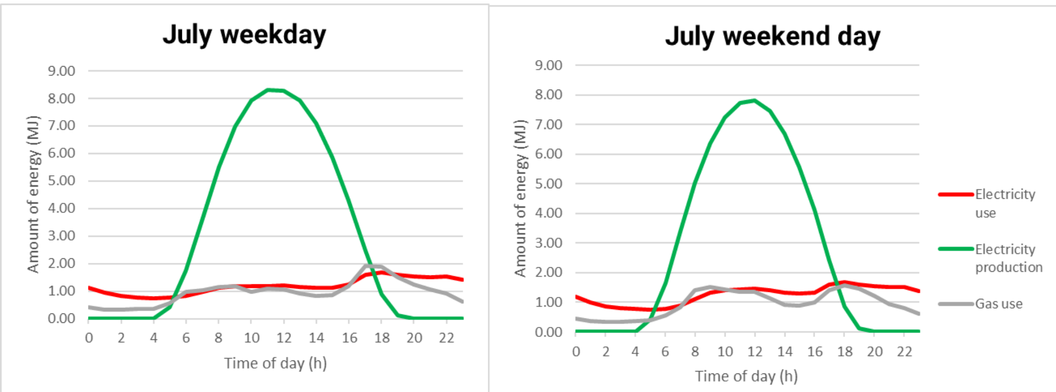

Figure 4. *Energy balance in MJ for an average weekday and weekend day in July 2023.*

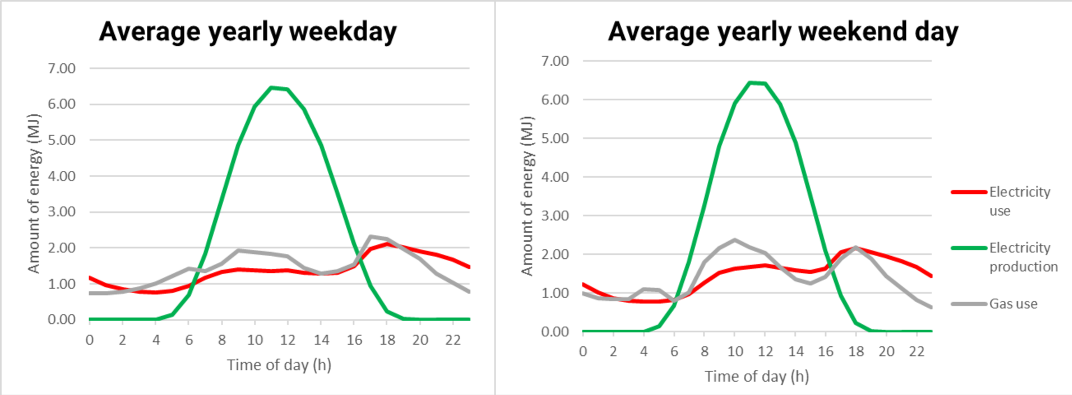

Figure 5. *Energy balance in MJ for an average weekday and weekend day across all months in the year 2023.*

As could be expected, Figure 3 and Figure 4 show that electricity production is larger in the summer; not only does electricity production reach higher peaks in July compared to January, but there is also active production for more hours per day. The gas use peaks most often in the morning around 9:00 and in the afternoon around 18:00, regardless of the month. This gas use can be attributed to showering and cooking, which fits the time of these peaks. However, both gas use and electricity use are higher in January compared to July. If the gas is indeed used to heat tap water for showering, then it can be explained by the fact that the water needs to be heated further to reach the required temperature. When comparing weekend and week days, in both months the gas use peak in the morning is higher on weekend days, although it is more noticeable in January. Figure 5 shows that this holds true across the year. The reason for this could simply be that people take slightly more time showering or cooking in the weekend, when there is less of a rush.

3.2. Results sub-question 2

Figure 6 shows a different energy balance for a situation where a Water Battery is utilised. Instead of an hourly division of values, the figure shows the division between excess solar energy that is utilised by the boiler of the Water Battery, and excess energy sent back to the grid.

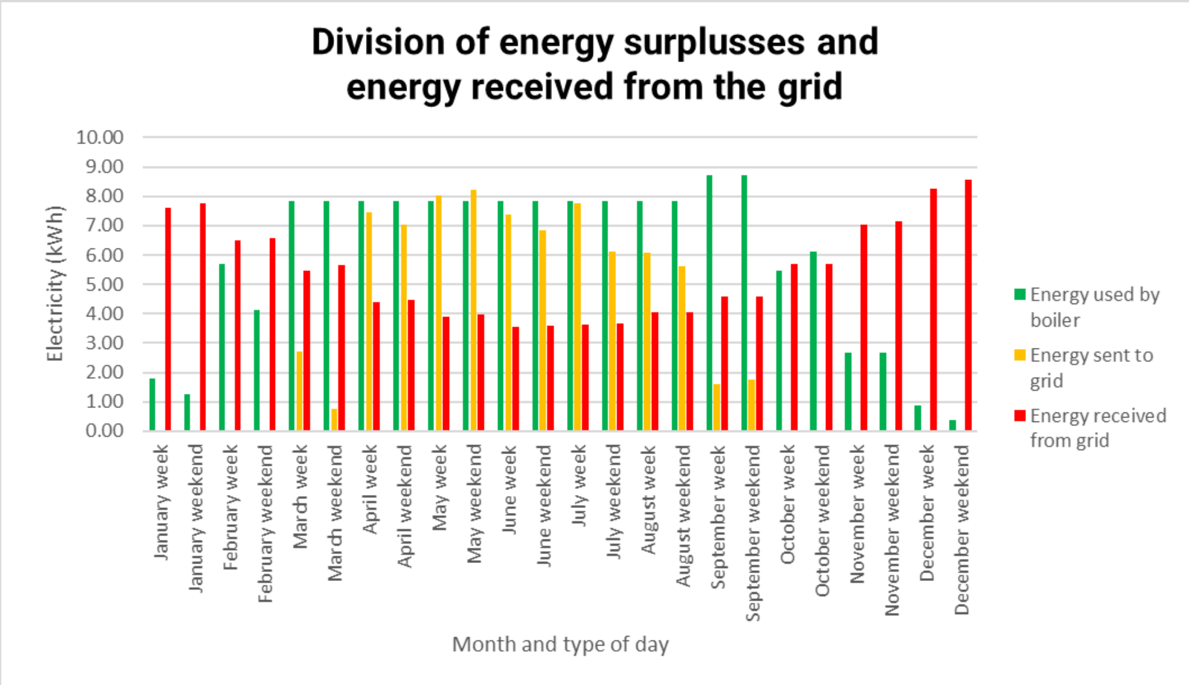

Figure 6. *Daily energy balance of a household utilising a Water Battery.*

This figure shows that in the months October to March, no energy is sent back to the grid, meaning the Water Battery utilises all the excess electricity produced. Another noteworthy result is the fact that the amount of energy used by the boiler is highest in September. This can be explained by the fact that September is an autumn month and thus the base temperature of tap water is lower. However, there is also enough excess energy available to fully power the boiler each day in September, which means that the boiler can store more energy. Similarly, the amount of energy sent to the grid in September is lower compared to the spring and summer months, apart from March.

3.3. Results sub-question 3

For the third sub-question, the results of the sensitivity analysis are shown in the spider-diagram in Figure 7. It can be seen that changes in the gas tariff have the largest impact on the total savings, while also being the only parameter that has positive correlation with the results rather than negative correlation. The second-most impactful parameter is the return-to-grid tariff, meaning that changes in these two tariffs will impact the usefulness of the Water Battery.

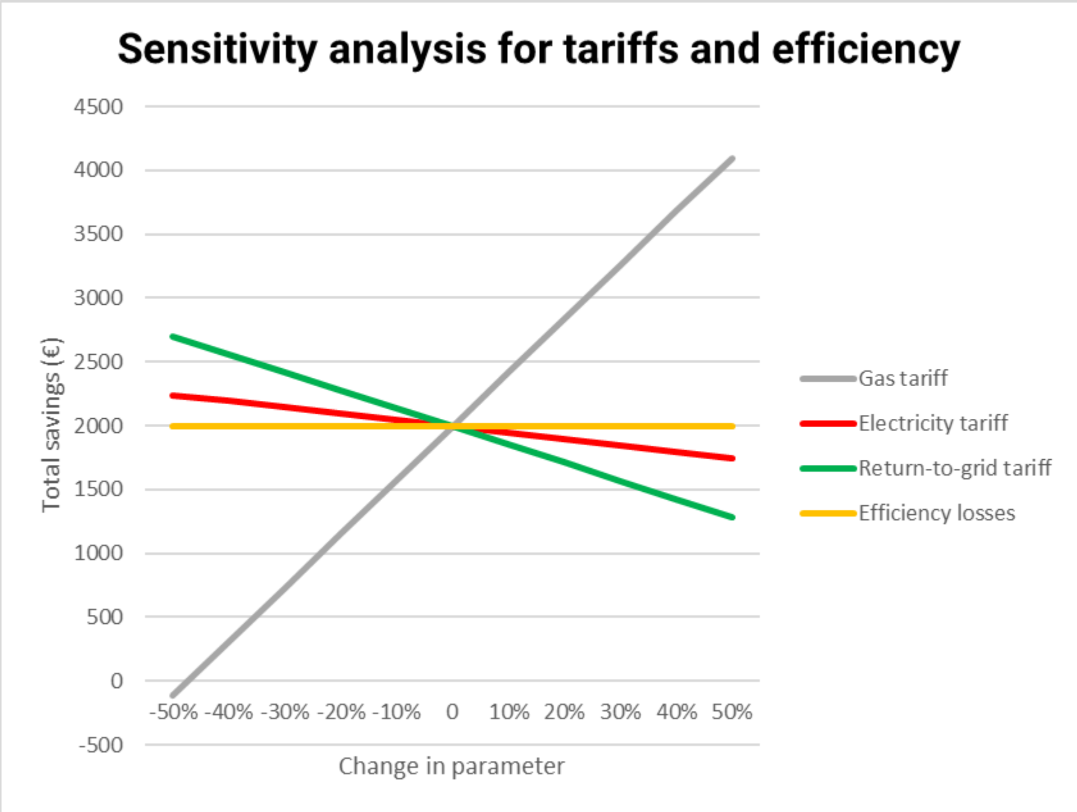

Figure 7. *Results of the sensitivity analysis conducted for the model, varying the values of the different tariffs and the efficiency losses of the solar panels.*

The results for savings and losses in the scenarios described in Table 4 are shown in Tables 6 and 7. The values in these tables are colour-coded; for Tables 6 and 7, the lower values shift to orange and red, while the higher values become more green. Table 6 shows that scenarios in category 1 and 2 (scenarios with low installed power) display losses for several years, or even nearly all years apart from 2031. When comparing this to Table 7, which shows savings for each scenario starting in 2023, it can be seen that the netting system limits savings for households with lower installed power.

Table 6. *Savings and losses resulting from utilising a Water Battery in different scenarios with regard to household size and amount of solar panels, with the netting system being gradually removed*

Scenario	2023	2024	2025	2026	2027	2028	2029	2030	2031	Total
1.1	€ 49.50	€ 78.78	€ 110.73	€ 110.48	€ 110.23	€ 110.33	€ 109.75	€ 109.50	€ 109.26	€ 898.57
1.2	-€ 315.25	-€ 382.91	-€ 129.53	-€ 133.73	-€ 74.33	-€ 16.32	€ 44.53	€ 104.49	€ 198.47	-€ 704.58
1.3	-€ 150.93	-€ 177.44	€ 72.44	€ 67.49	€ 125.54	€ 156.76	€ 156.03	€ 155.69	€ 155.34	€ 560.93
2.1	-€ 269.45	-€ 412.48	-€ 190.81	-€ 189.39	-€ 134.32	-€ 80.09	-€ 26.77	€ 25.45	€ 185.44	-€ 1,092.43
2.2	-€ 295.42	-€ 452.26	-€ 209.22	-€ 207.67	-€ 147.29	-€ 87.83	-€ 29.36	€ 27.92	€ 203.38	-€ 1,197.77
2.3	-€ 417.07	-€ 639.29	-€ 295.96	-€ 293.91	-€ 208.59	-€ 124.53	-€ 41.68	€ 39.66	€ 289.25	-€ 1,692.12
3.1	€ 207.87	€ 333.54	€ 331.91	€ 331.28	€ 330.65	€ 330.76	€ 329.00	€ 328.45	€ 327.90	€ 2,851.37
3.2	€ 149.97	€ 240.99	€ 239.99	€ 239.55	€ 239.11	€ 239.43	€ 238.43	€ 238.22	€ 238.01	€ 2,063.70
3.3	€ 214.80	€ 345.21	€ 343.67	€ 342.96	€ 342.28	€ 342.70	€ 341.02	€ 340.56	€ 340.10	€ 2,953.31
4.1	€ 235.38	€ 168.15	€ 403.39	€ 402.62	€ 401.86	€ 401.86	€ 400.05	€ 399.37	€ 398.69	€ 3,211.39
4.2	€ 365.35	€ 332.52	€ 417.88	€ 417.01	€ 416.15	€ 416.15	€ 414.08	€ 413.30	€ 412.53	€ 3,604.98
4.3	€ 483.91	€ 427.74	€ 603.42	€ 602.38	€ 601.35	€ 601.40	€ 598.81	€ 597.90	€ 596.99	€ 5,113.91

Table 7. *Savings and losses resulting from utilising a Water Battery in different scenarios with regard to household size and amount of solar panels, excluding the netting system*

Scenario	2023	2024	2025	2026	2027	2028	2029	2030	2031	Total
1.1	€ 69.28	€ 111.32	€ 110.73	€ 110.48	€ 110.23	€ 110.33	€ 109.75	€ 109.50	€ 109.26	€ 950.88
1.2	€ 127.35	€ 203.47	€ 202.41	€ 201.91	€ 201.42	€ 201.06	€ 199.93	€ 199.11	€ 198.47	€ 1,735.14
1.3	€ 98.74	€ 158.35	€ 157.55	€ 157.17	€ 156.80	€ 156.76	€ 156.03	€ 155.69	€ 155.34	€ 1,352.43
2.1	€ 199.45	€ 197.77	€ 195.74	€ 194.29	€ 192.69	€ 190.97	€ 188.96	€ 187.15	€ 185.44	€ 1,732.46
2.2	€ 218.67	€ 216.84	€ 214.63	€ 213.04	€ 211.29	€ 209.42	€ 207.23	€ 205.24	€ 203.38	€ 1,899.75
2.3	€ 308.72	€ 306.52	€ 303.60	€ 301.51	€ 299.21	€ 296.92	€ 294.13	€ 291.62	€ 289.25	€ 2,691.47
3.1	€ 207.87	€ 333.54	€ 331.91	€ 331.28	€ 330.65	€ 330.76	€ 329.00	€ 328.45	€ 327.90	€ 2,851.37
3.2	€ 149.97	€ 240.99	€ 239.99	€ 239.55	€ 239.11	€ 239.43	€ 238.43	€ 238.22	€ 238.01	€ 2,063.70
3.3	€ 214.80	€ 345.21	€ 343.67	€ 342.96	€ 342.28	€ 342.70	€ 341.02	€ 340.56	€ 340.10	€ 2,953.31
4.1	€ 404.86	€ 405.20	€ 403.39	€ 402.62	€ 401.86	€ 401.86	€ 400.05	€ 399.37	€ 398.69	€ 3,617.91
4.2	€ 419.54	€ 419.94	€ 417.88	€ 417.01	€ 416.15	€ 416.15	€ 414.08	€ 413.30	€ 412.53	€ 3,746.58
4.3	€ 605.39	€ 605.92	€ 603.42	€ 602.38	€ 601.35	€ 601.40	€ 598.81	€ 597.90	€ 596.99	€ 5,413.57

Since there is no netting system for both tables in 2031, the savings in each table are the same for that year. The losses seen in Table 6 also become less most years, which corresponds to the amount of allowed netting per year. The savings for scenarios in categories 3 and 4 change little per year, meaning that the households have enough excess solar energy to net all their electricity consumption, and still have additional leftover energy that can be utilised by the Water Battery. The biggest outlier here is in 2023 compared to 2024, which is caused by the limited gas and electricity prices in 2023 set by the Dutch government (Rijksoverheid, 2022). Beside those changes in savings, the only scenario that has a noteworthy change is scenario 4.1 in Table 6, which has a saving of € 168.15 in 2024, increasing to € 403.39 in 2025. This can once again be explained by the lower contribution of the netting system, since from 2025 onwards, there is enough excess energy to net the lower maximum amount and send a majority of the rest to the Water Battery. An outlier in both tables is scenario 3.2: the savings in this scenario are noticeably lower than those of the other scenarios in category 3. This can be explained by the fact that the boiler size in scenario 3.2 is 100 L. Since the amount of water that can be heated on a day is more limited, the highest possible savings are also lower. A similar but opposite outlier can be seen in Table 6 for scenario 1.2: the values for this scenario are noticeably lower than those of the other scenarios in category 1 and don't become positive until much later. The boiler size in scenario 1.2 is 120 L, which means that the boiler utilises more excess energy, but this is detrimental with netting still active because there is comparatively little excess energy produced.

The reduction in CO_2 emissions for each scenario are shown in Table 8. Since the amount of gas saved is not affected by the netting system, these values remain the same whether the netting system is active or not. While there are variations in the values between scenarios, the values generally increase from category 1 to 4. The biggest outlier is scenario 3.2, which can once again be explained by the different boiler size compared to scenarios 3.1 and 3.3.

Table 8. *Reduction in CO_2 emissions (kg CO_2) resulting from utilising a Water Battery in different scenarios with regard to household size and amount of solar panels*

Scenario	2023	2024	2025	2026	2027	2028	2029	2030	2031	Total
1.1	165.34	165.77	164.90	164.52	164.15	164.29	163.43	163.06	162.70	1478.16
1.2	303.94	302.99	301.42	300.68	299.95	299.41	297.72	296.50	295.55	2698.15
1.3	235.65	235.80	234.61	234.05	233.50	233.44	232.35	231.84	231.33	2102.57
2.1	297.00	294.51	291.49	289.32	286.93	284.38	281.39	278.69	276.15	2579.86
2.2	325.63	322.91	319.61	317.24	314.64	311.86	308.60	305.64	302.86	2828.98
2.3	459.72	456.45	452.11	448.98	445.57	442.16	438.00	434.26	430.73	4007.97
3.1	496.11	496.69	494.26	493.32	492.38	492.55	489.93	489.11	488.28	4432.64
3.2	357.93	358.87	357.37	356.72	356.07	356.54	355.05	354.74	354.43	3207.72
3.3	512.65	514.07	511.77	510.72	509.70	510.33	507.82	507.14	506.46	4590.65
4.1	602.89	603.40	600.71	599.56	598.43	598.42	595.74	594.72	593.71	5387.57
4.2	624.75	625.34	622.29	620.99	619.70	619.70	616.62	615.47	614.32	5579.17
4.3	901.51	902.30	898.58	897.03	895.49	895.57	891.71	890.35	888.99	8061.54

3.4. Results sub-question 4

The results of the basic MCA are listed in Table 9 and shown in Figure 8. Table 9 shows the initial scores of each technology for the different criteria. Figure 8 plots the results after standardising the scores and applying the weights.

Table 9. *Initial scores of each technology for the MCA, with marks showing for which criteria higher values are beneficial and for which criteria higher scores are detrimental*

		Units	Water Battery	Home Battery	Heat-pump boiler	Solar boiler
-	Total costs	euro	1675	4000	2915	2600
+	ROI	%	119	58	161	123
-	Payback period	years	8	12	6	8
+	Effectiveness	%	66	41	26	0
+	Reduced CO2 emissions	kg CO2	3949.65	4873.58	5514.88	2988.13

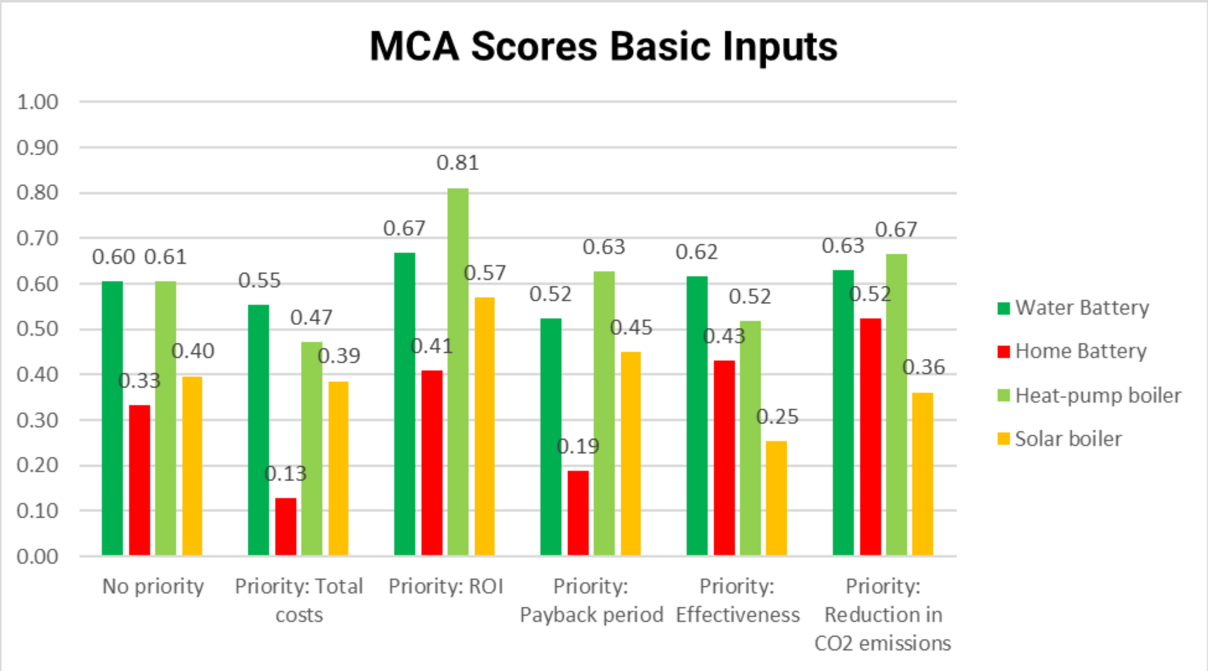

Figure 8. *Final scores of each technology for the basic MCA with different priorities.*

As can be seen in Figure 8, the highest scoring technologies for all priority variations are the Water Battery and the heat-pump boiler. Without any priorities, the heat-pump boiler scores the highest with 0.61, and is also the best choice when priority is given to ROI, payback period and reduction in CO_2 emissions. The Water Battery scores the highest when total costs or effectiveness are prioritised, and without priority scores very close to the heat-pump boiler. The home battery scores the lowest in each variation of weighing apart from effectiveness and reduction in CO_2 emissions, with the absolute lowest score being when total costs are prioritised. This makes sense, since the total costs of the home battery are the highest of all the options. The solar boiler scores the highest when ROI is prioritised, and scores the lowest when effectiveness is prioritised. Since the solar boiler has no way of utilising excess electricity, it also makes sense that its score would be impacted in this way.

The following figures show the sensitivity analyses used to test changes to each weight. Instead of showing the change to each weight value, the x-axis shows the weight values themselves. The values are varied in steps of 0.1 between a minimum of 0 and a maximum of 1.

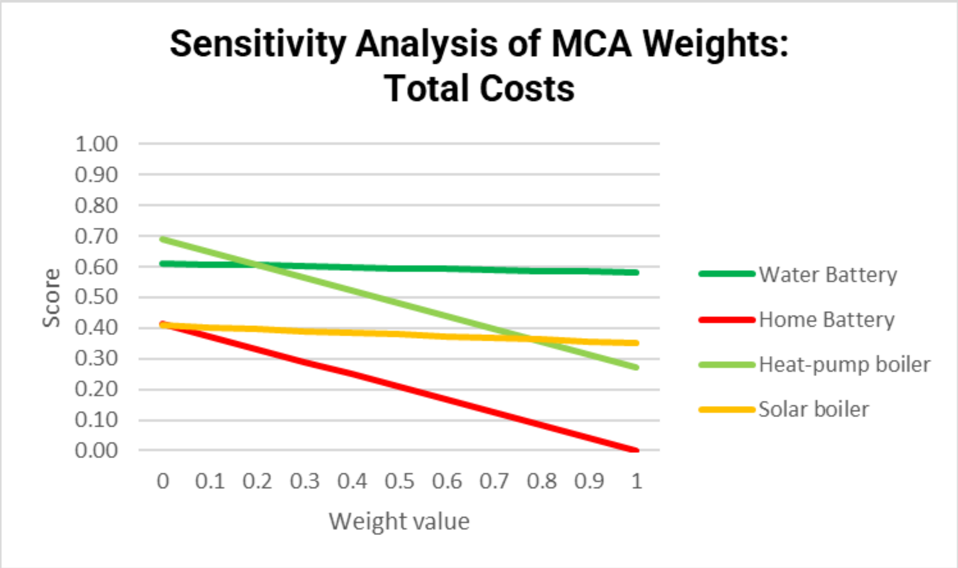

Figure 9. *Sensitivity analysis for changing the weight value of the total costs.*

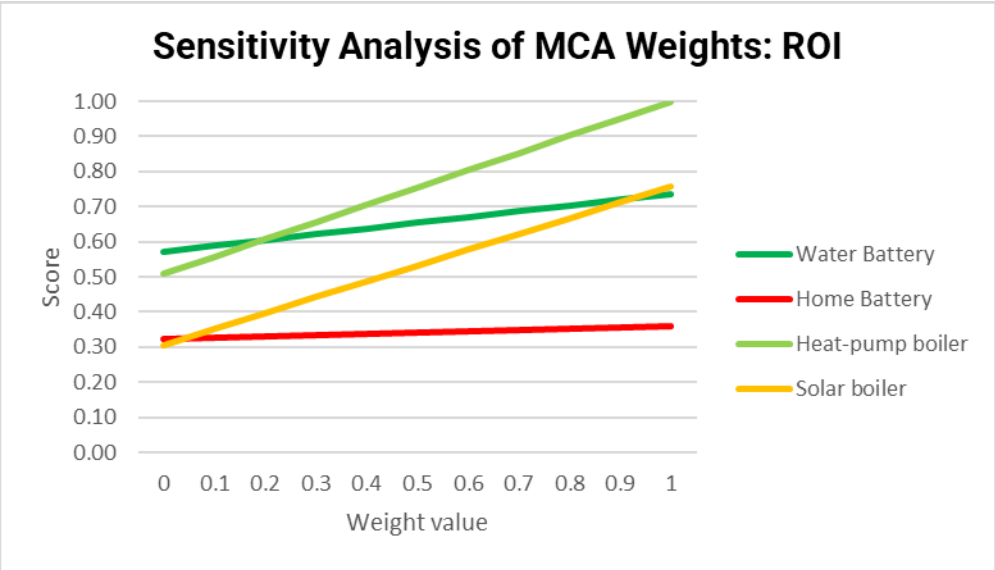

Figure 10. *Sensitivity analysis for changing the weight value of the ROI.*

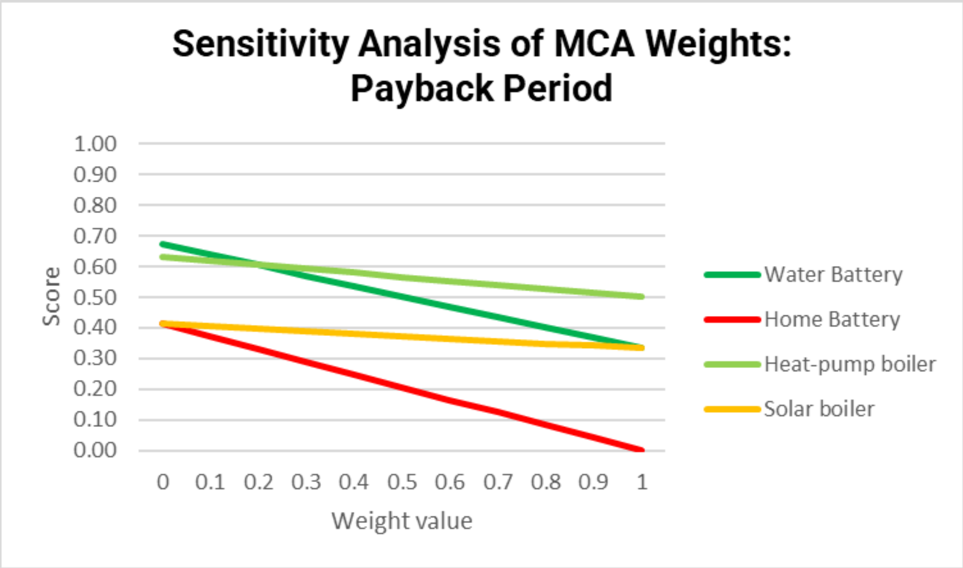

Figure 11. *Sensitivity analysis for changing the weight value of the Payback Period.*

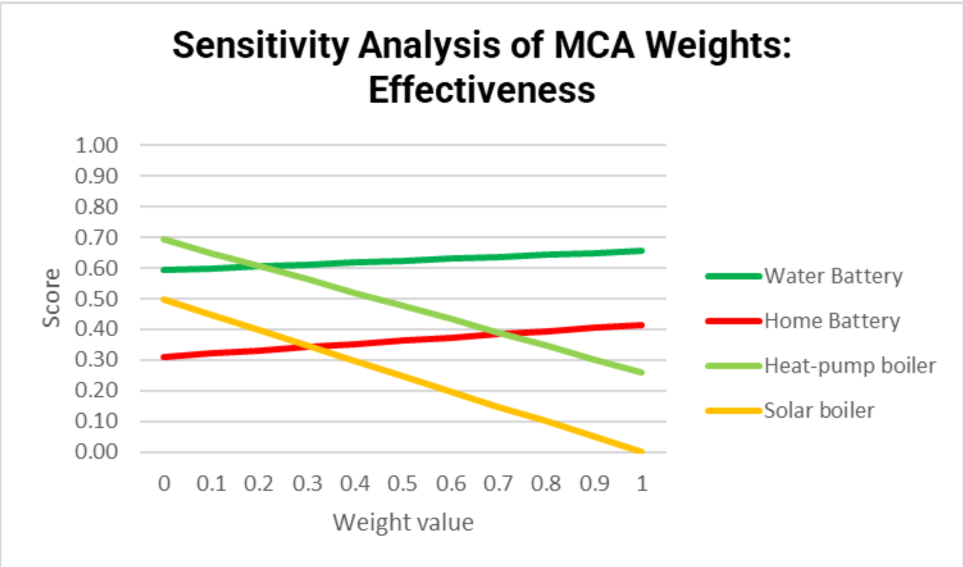

Figure 12. *Sensitivity analysis for changing the weight value of the Effectiveness.*

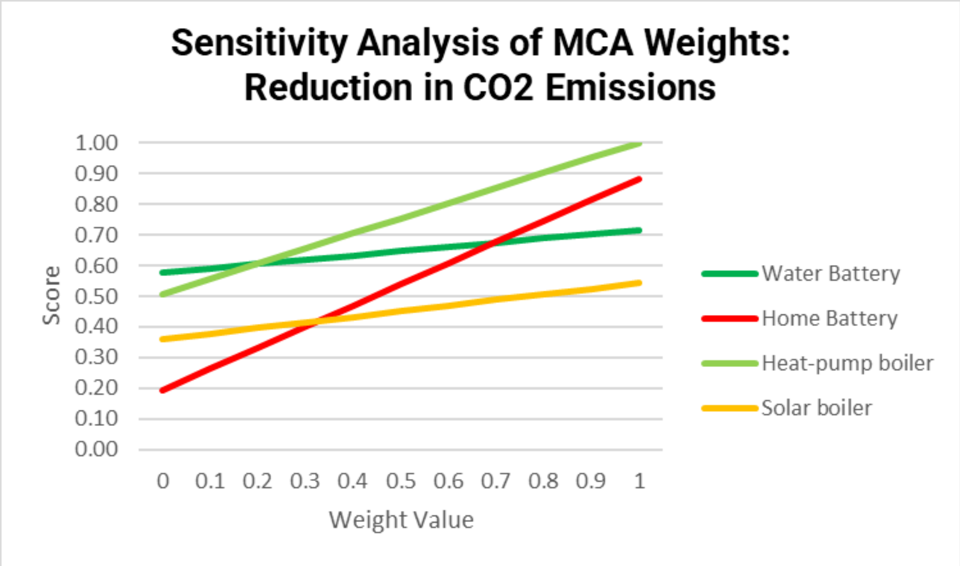

Figure 13. *Sensitivity analysis for changing the weight value of the reduction in CO_2 emissions.*

The figures show that the scores of the Water Battery are mostly impacted by the weight given to the payback period. For all other weight variations, the Water Battery scores remain relatively stable, indicating that apart from payback period, its performance is quite consistent regardless of how the weights are distributed. The home battery is most strongly affected by changes to the weight of total costs and reduction in CO_2 emissions. Its score changes based on changes to payback period and effectiveness are very similar to the corresponding score changes of the Water Battery. Since these technologies are the most similar when it comes to utilising excess energy, it makes sense that the effectiveness would impact both technologies similarly. The scores of the heat-pump boiler vary noticeably when the weights of any criterion apart from the payback period are changed. The scores of the solar boiler are most strongly affected by varying the weights of ROI and Effectiveness. For these two criteria, the scores of the heat-pump boiler and the scores of the solar boiler share the same shape. Both of these technologies are weakest when it comes to effectiveness, so it makes sense that varying that criterion would greatly impact their score.

The next figures show the results of MCAs with different inputs for households, corresponding to the scenarios described in Table 4. The first scenario of each category is shown, while the other figures can be found in appendix B. Figure 15 also shows scenario 1.2 since it differs noticeably from the other scenarios in category 1.

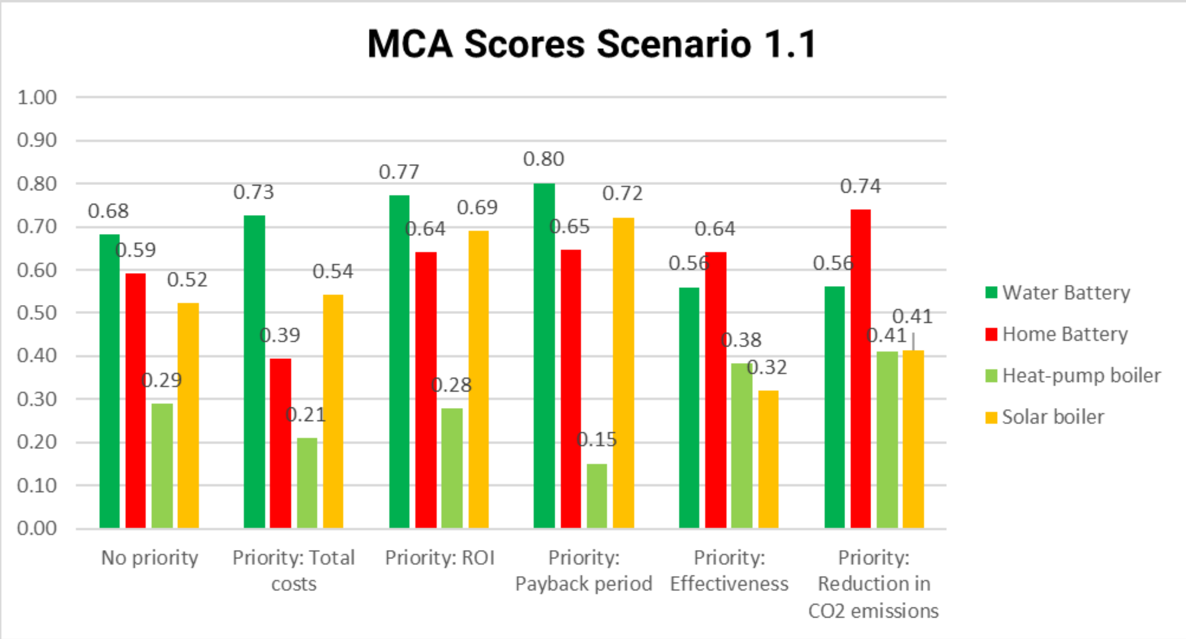

Figure 14. *Final scores of each technology for the MCA with different priorities in scenario 1.1: single person living in a house with older solar panels.*

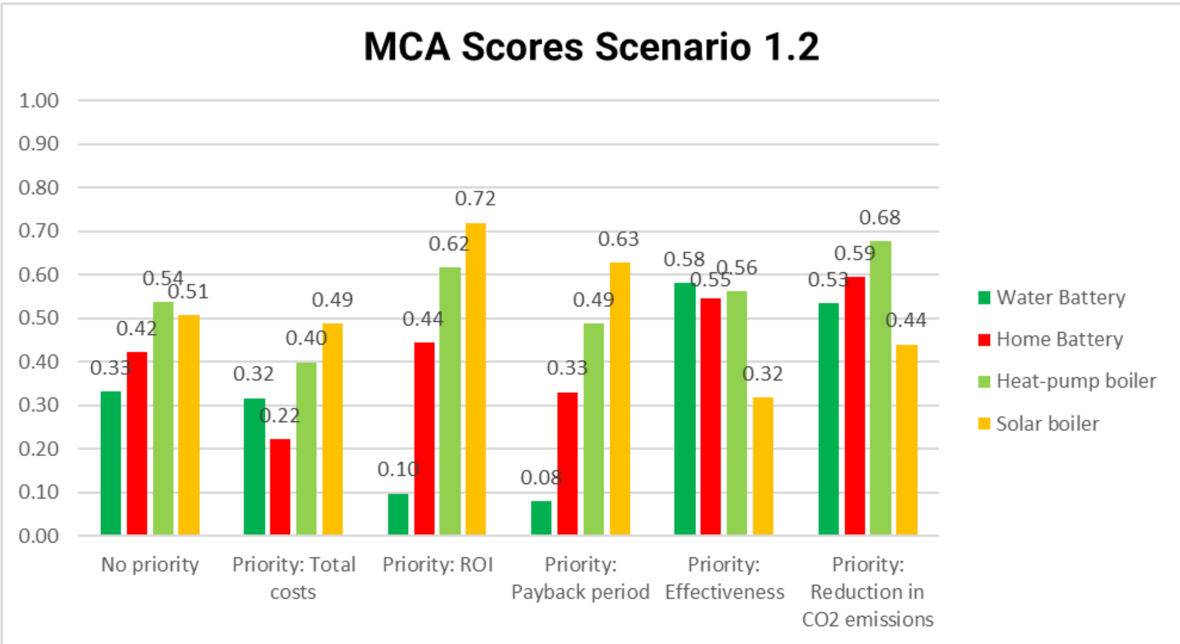

Figure 15. *Final scores of each technology for the MCA with different priorities in scenario 1.2: Two elderly people living together, needing more time for showering.*

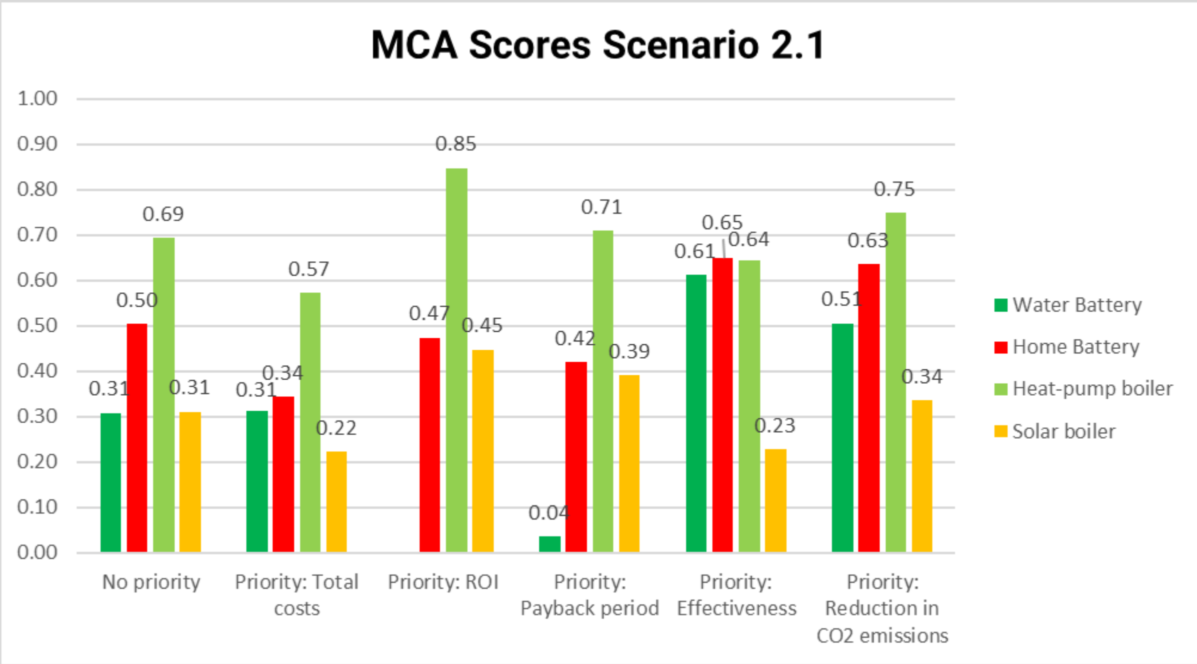

Figure 16. *Final scores of each technology for the MCA with different priorities in scenario 2.1: family with two young children living in an older house.*

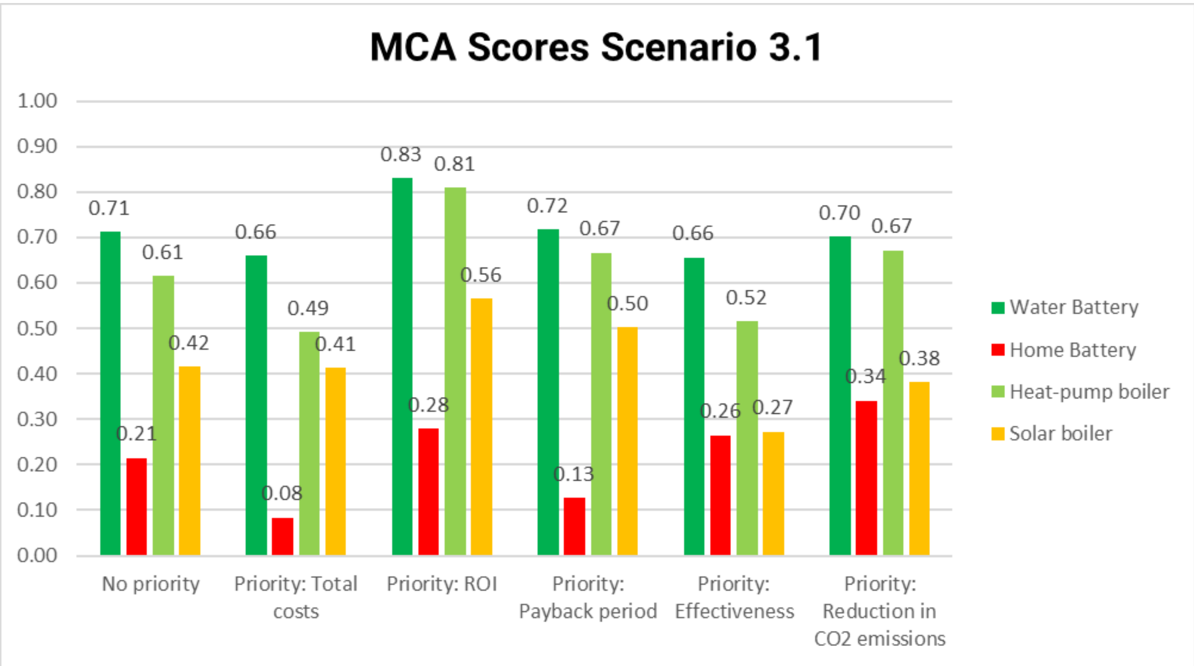

Figure 17. *Final scores of each technology for the MCA with different priorities in scenario 3.1: rich businessperson who lives on their own, but often receives visitors.*

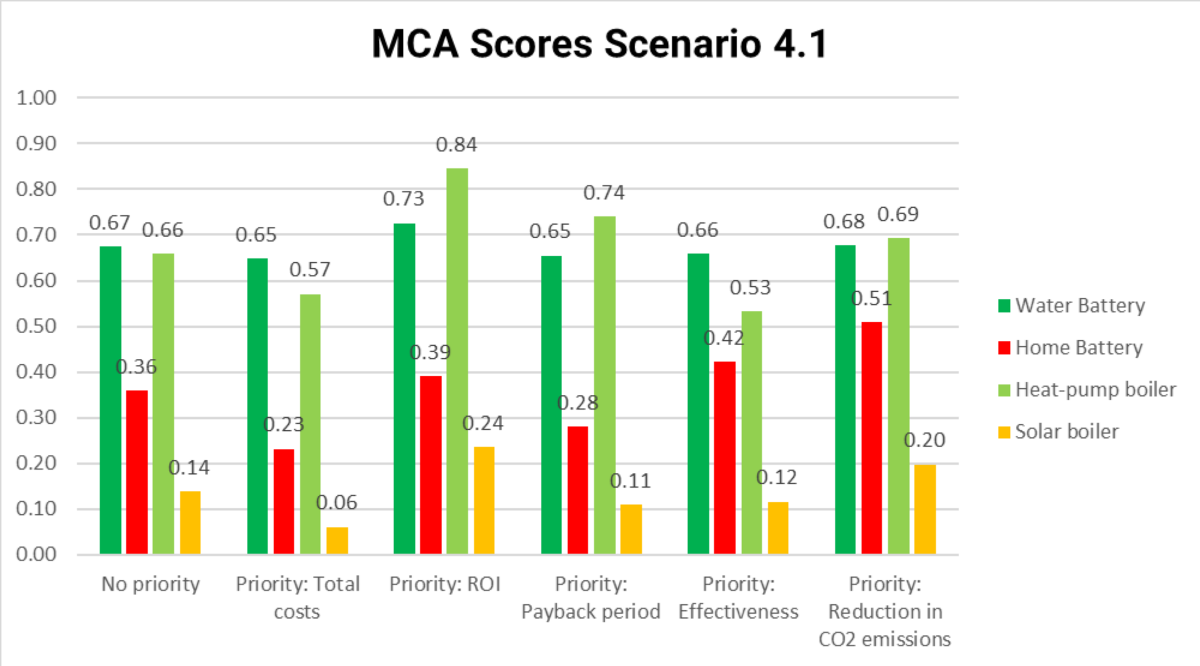

Figure 18. *Final scores of each technology for the MCA with different priorities in scenario 4.1: Family with two children living in a modern (well insulated) house.*

Figure 14 shows that the Water Battery scores the highest with most priority variations in scenario 1.1, apart from effectiveness and reduction in CO_2 emissions, where the home battery scores higher. In this scenario, the heat-pump boiler scores the lowest for all priority variations. This is likely because the amount of water required by the household (50 L) is much lower than the volume of the heat-pump boiler (200 L), while the heat-pump boiler does lead to higher electricity costs. Therefore, the effective amount of gas saved is lower because only a part of the heated water actually gets used. An opposite situation is shown for scenario 1.2 in Figure 15, where the heat-pump boiler is amongst the highest scoring technologies for all priorities. Since the household in scenario 1.2 utilises a larger boiler, the heat-pump boiler benefits more from its efficiency while the Water Battery scores lower for ROI and payback period priority due to the lower amount of excess energy. The solar boiler scores well with most priorities in both scenarios, but only reaches the highest score in scenario 1.2 when total costs, ROI or payback period are prioritised. The same can be seen with the home battery, except it instead scores highest in scenario 1.1 when effectiveness and reduction in CO_2 emissions are prioritised. The solar boiler also scores the lowest when effectiveness is prioritised for all scenarios, since it is unable to utilise excess electricity.

All figures showing scenarios from category 2 are quite similar, so only scenario 2.1 is shown. The Water Battery scores for the scenarios in category 2 are noticeably lower. This indicates that the largest hurdle for the Water Battery is a lack of excess solar energy that can be utilised, since the households in these scenarios have low installed power with a higher energy demand. The home battery also scores higher than the Water Battery for all priorities in scenario 2.1. This is also the case in scenario 2.2, but it changes in scenario 2.3 when priority is given to effectiveness and reduction in CO_2 emissions, as can be seen in Figure 31. The solar boiler has no noteworthy scores, and the heat-pump boiler scores the highest for nearly every score across the three scenarios.

For the scenarios in category 3, the Water Battery scores the highest for all priorities, with the heat-pump boiler generally being second best. Since there is a lot of excess energy available in these scenarios, the Water Battery is able to reach higher values for ROI and payback period, while the home battery is more hindered by its higher total costs. Once more, the scores of the solar boiler are not too noteworthy, generally being higher than the scores of the home battery but lower than the scores of the other two technologies.

The scores for the scenarios in category 4 are similar to those in category 3: the Water Battery and the heat-pump boiler score the highest with all priorities, although the heat-pump boiler consistently exceeds the score of the Battery when it comes to ROI and payback period. When compared to the scores in category 3, the home battery generally scores higher than the solar boiler. This is caused by the increased costs of the solar boiler: since the households in the scenarios of category 4 consist of more occupants, larger solar collectors are required for the solar boiler. This leads to higher costs and therefore lower scores in total costs, ROI and payback period.

4. Discussion

The first important points of discussion are the limitations of the model that was built for this thesis. The model utilises several data sets which were simplified to obtain average values. This allows for calculations for future years, but it also leads to a lack of variation in results. Every weekday in a month is given equal weight with regard to energy use and solar energy production. The same goes for weekend days, but since there are far fewer weekend days in a month than weekdays, any outliers present in the weekend days can lead to less accurate results. The main purpose of differentiating between weekdays and weekend days was the idea that energy use would increase during weekend days, since more people would be at home and use more energy in the weekends. While the gas use did indeed differ between most weekdays and weekend days, the electricity use only showed relatively small differences. Another factor that affects these results is the energy profile chosen for electricity use; only one profile was utilised due to the time investment of rendering the profile usable. Comparing profiles to check for differences would be useful to see how the profile alters the results. However, since it requires a significant amount of time to adjust an energy profile for compatibility with the model, only a small number of extra profiles could reasonably be compared. Furthermore, the annual values for electricity use and gas use were kept as static numbers. However, these values would likely vary for households of the same size due to them utilising different technologies and having different schedules. Utilising multiple annual energy use values for each household size is therefore recommended as well for future research.

The data utilised to determine solar energy production is based on patterns from the period 2010 to 2020 in order to account for variations in the weather. This means that the model considers the average weather per month to be the same each year. Adding an option to introduce more randomness would have been useful to test the effectiveness of the Water Battery in more varied weather situations. Leaving this option out was a necessary limitation given the time constraints, but it is a recommended improvement for future research. Another downside to the energy production data is that the input for the angle of the solar panels could not be easily changed to check for different household situations. Similarly to the energy profiles, it would take extra time to properly adjust the data sets obtained from CorRES. However, the input for areas in the Netherlands is one that might warrant the use of multiple data sets. The currently used data set covers multiple areas in the Netherlands at once. Creating separate data sets for different regions would allow for better comparison of people living in different areas in the Netherlands, since the weather can vary noticeably between different provinces on one day. If similar research is conducted for larger countries, this would certainly be an important addition to the methodology.

When calculating the savings provided by the Water Battery, a number of important assumptions were made. The first is the assumption that all the tap water heated during the day will be fully utilised by the household in the evening and morning. The boiler size is selected based on household size to partly accommodate for this fact, but it still means that every member of the household will shower at least once per day. While this is not an unreasonable assumption, it does not account for longer periods where no one will be home, like holidays. In these situations, there is no one to utilise the heated water, so there is no actual savings for the household since they would not have heated the water at all using gas. Therefore, the calculated savings will be the maximum savings possible, but in reality the savings will likely be lower unless the weather on a specific day is sunnier than the model accounts for and thus there is more excess energy that the Water Battery can utilise. Naturally, different households will have different holiday plans, but a general holiday period in the summer with no energy use could provide more accurate results.

Another important assumption is that certain inputs considered as constants actually remain constant. As mentioned before, the sensitivity analysis conducted for the tariffs and efficiency losses shows that changes in gas price will have the largest impact on the savings. This calculation expects the gas tariff to remain constant for each year in the period, which is why a slightly lower value is used than the current average gas tariff. However, it would be more realistic to apply different gas tariffs that increase each year due to the need to lower natural gas use. Due to time constraints, it was not possible to implement this properly, but it remains an important recommendation for improvement. Similarly, varying return-to-grid tariffs per year would also be realistic, as more people gain access to solar panels and there will be more power returned to the grid in the future.

The results for the various scenarios show that with the netting system still in place, the Water Battery won't be profitable for a number of years depending on installed capacity. Households that produce less excess energy than they use throughout the year gain more benefit from netting than from storing it in tap water, since the electricity tariff per MJ is on average higher than the gas tariff per MJ. Without netting, every scenario benefits immediately from the Water Battery, but since the Dutch government is planning to fully stop netting by 2031, for the coming years this is more of a hypothetical benefit. Since netting is not applied in other countries, these measurements also give an indication of how useful the Water Battery might be outside of the Netherlands. However, this falls outside the scope of this thesis, and is therefore mostly speculation. For households with lower installed power, it can be beneficial to use boilers with lower capacities in order to keep more energy for netting. However, this will be detrimental when netting is terminated, since it limits the potential savings. It also requires either gas or more electricity to heat up extra tap water, since the capacity of the boiler would not meet the daily warm water requirement.

The results of the MCA show that the best alternative for the Water Battery would be the heat-pump boiler, which generally has a shorter payback period, higher annual savings and higher reductions in CO_2 emissions. The Water Battery is superior when it comes to initial costs, and it allows for better utilisation of energy surpluses. The biggest deciding factor between the two would be whether or not a household can afford the initial costs. This depends strongly on the financial situation of individual households. The results from the scenarios have shown that houses with low installed power benefit less from the Water Battery, while households with higher installed capacity might not mind an extra investment for a more effective technology. This leaves the Water Battery as an option for people with a sufficient number of solar panels, who would still prefer to keep the initial costs lower. Since households can vary greatly in the amount of installed solar panels, it becomes more of a case-by-case decision to determine the best technology. However, there is one aspect of the Water Battery that could not be analysed, but is noteworthy: the ability to be coupled to a regular heat pump that takes care of central heating. This variation works by exchanging the boiler of the Water Battery with a container with a heat exchanger and a separate electric heating element, and connecting the heat exchanger to a heat pump present in a house. During sunny hours, the unused solar energy can be used to power the electric heating element, while the heat pump can maintain the heating of tap water the rest of the time.

Since heat-pump boilers have a built-in heat pump, they are only marginally useful for households with heat pumps. This is a niche application of the Water Battery, and extra research for this application would be recommended.

The biggest limit for the home battery is the high initial cost, which limits several factors for the MCAs, as well as its relatively lower capacity for the associated costs. Home batteries with higher capacities would cost more, which would make it more difficult for consumers to invest in the product. The solar boiler is not hindered by the netting system, but also scores lower due to its higher cost and its lack of utilising energy surpluses. Being able to use excess solar energy is less important to households if they save on costs through other mechanisms like with the solar boiler or the heat-pump boiler. However, with more people returning energy to the grid in future years due to increased installed solar power, the tariff can become lower or even turn negative due to net congestion. Therefore, higher effectiveness can still be profitable in the future.

Comparing the results of the MCAs conducted for the different scenarios, it is clear that in the majority of the scenarios, the Water Battery and the heat-pump boiler stand out as effective options for increasing sustainability on household level. The scenarios where the Water Battery is less effective involve households that do not produce a large amount of excess energy due to low amounts of installed solar power or a higher energy use. It makes sense that a technology designed to utilise excess solar energy would not perform well in these scenarios. Furthermore, since the Water Battery is a new technology, it might receive subsidies in the future when it becomes better known and its effectiveness is validated through more widespread use. This would lower the total costs and make it more appealing to households.

5. Conclusions

The purpose of this thesis was to answer the following research question:

What are the environmental and economic benefits and drawbacks of storing solar energy surpluses in a Water Battery compared to other available methods of small-scale energy storage?

In order to answer this question, an excel model was created that calculates average daily and annual energy production and energy use for households with variations in size and installed capacity. This data was then used by the model to determine the annual savings in costs and CO_2 emissions obtained by using a Water Battery, home battery, heat-pump boiler and solar boiler. The results were compared by means of an MCA to see how well the Water Battery performs. Out of the alternatives, the heat-pump boiler scores the highest with regard to annual savings and reduction in CO_2 emissions, but the Water Battery exceeds the former when focussing on initial costs and utilising excess solar energy. With several options available, the Water Battery does stand out as a viable alternative to other technologies and provides similar benefits to those of a heat-pump boiler, albeit with lower total results.

Furthermore, the Water Battery can be altered more easily by varying boiler size and can thus be applied in a variety of situations. The biggest limit for the Water Battery seems to be the netting system, since it requires consumers to produce more excess energy than they use on annual basis in order to gain the most benefit from the Water Battery. This means that the future viability of the Water Battery depends on how the netting system will be terminated in the Netherlands. Since the Dutch government is still debating this topic, it remains to be seen if the current planned removal starting in 2025 will be achieved. Ultimately, the Water Battery helps with utilising energy surpluses and lowering CO_2 emissions in an effective way compared to most other similar technologies, and is simple and affordable for different types of households looking for an attractive way to become more sustainable. While there are still no perfect solutions for utilising all solar energy produced by a household, the Water Battery appears to be a suitable alternative to other options once the netting system is removed.

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8. Appendix A

Additional figures showing the daily energy balance of weekdays and weekend days for several months in the year 2023.

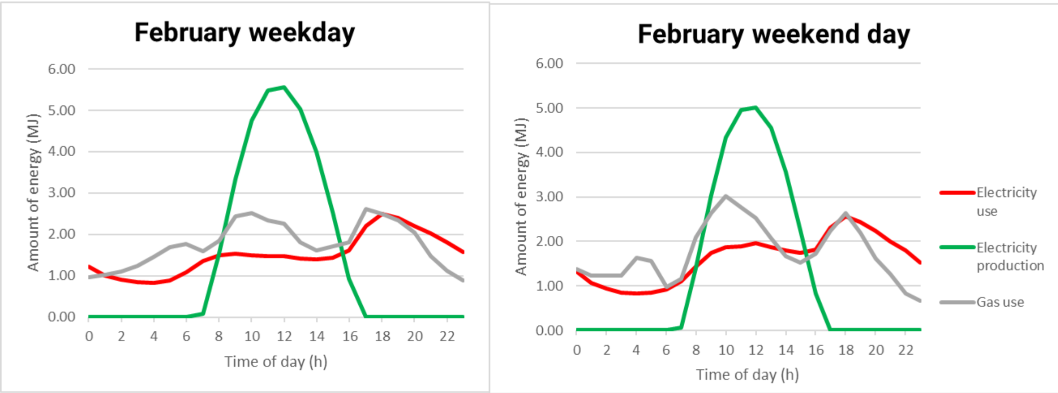

Figure 19. *Energy balance in MJ for an average weekday and weekend day in February 2023.*

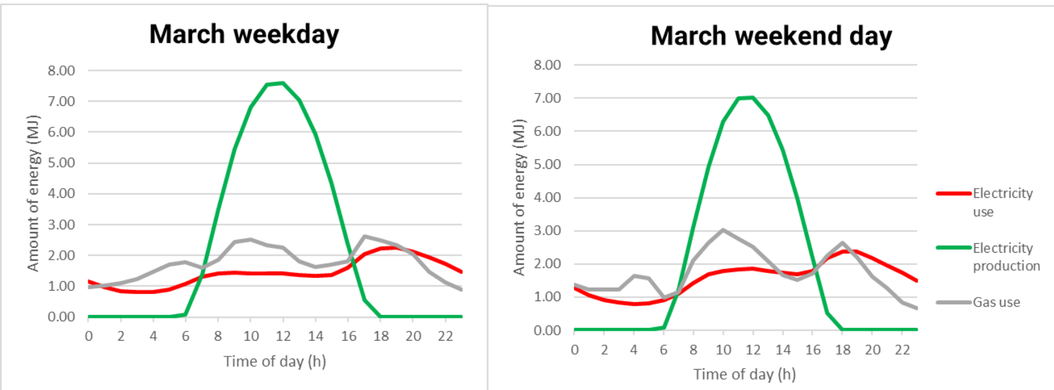

Figure 20. *Energy balance in MJ for an average weekday and weekend day in March 2023.*

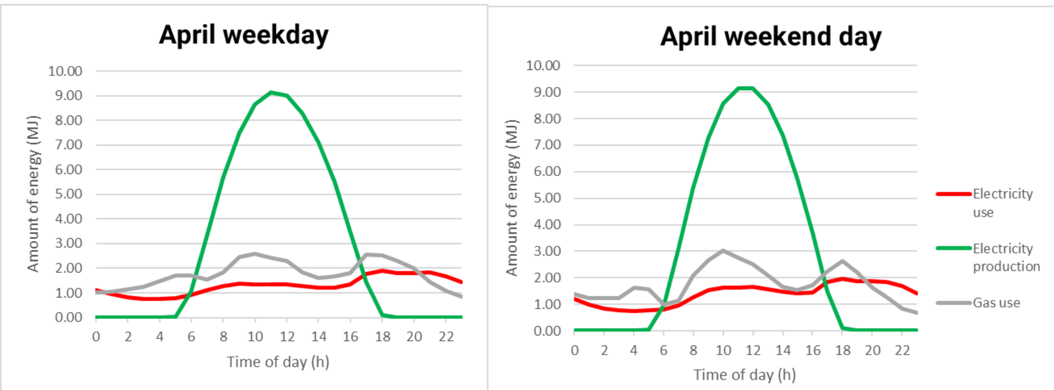

Figure 21. *Energy balance in MJ for an average weekday and weekend day in April 2023.*

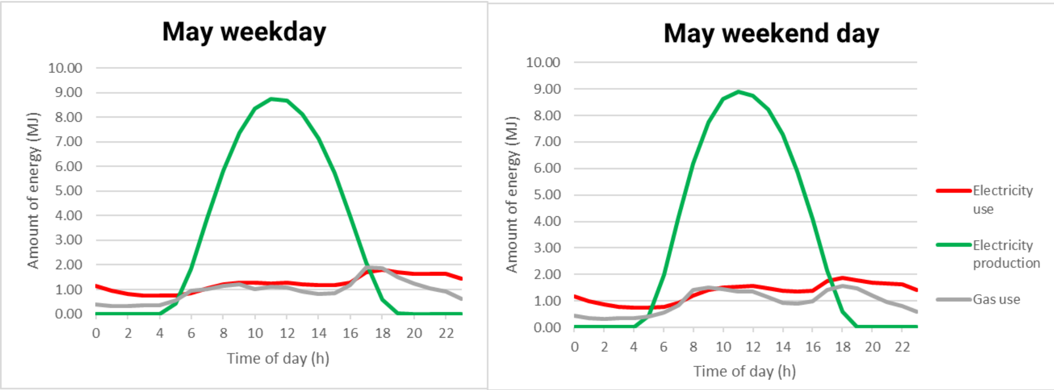

Figure 22. *Energy balance in MJ for an average weekday and weekend day in May 2023.*

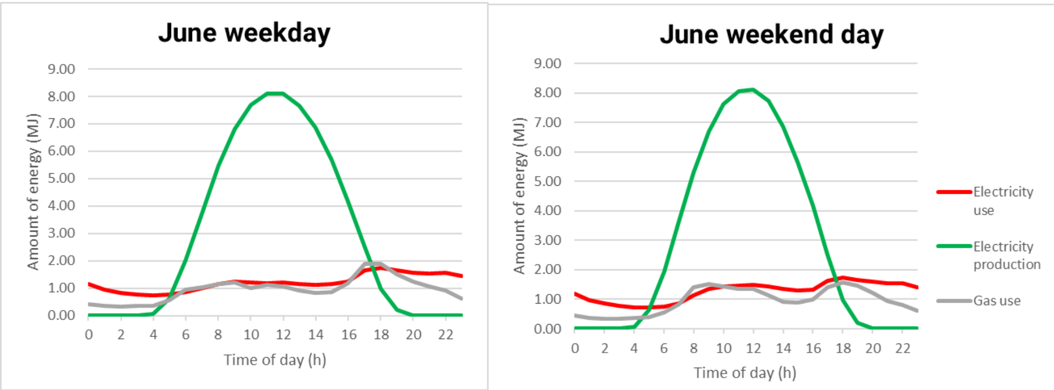

Figure 23. *Energy balance in MJ for an average weekday and weekend day in June 2023.*

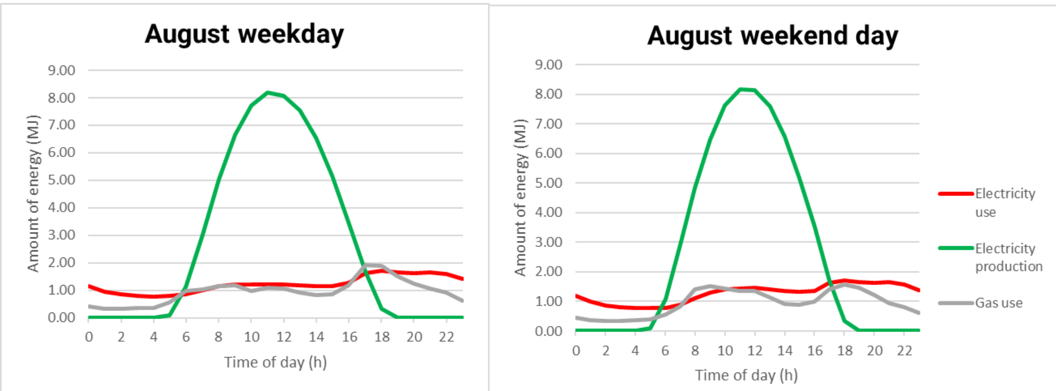

Figure 24. *Energy balance in MJ for an average weekday and weekend day in August 2023.*

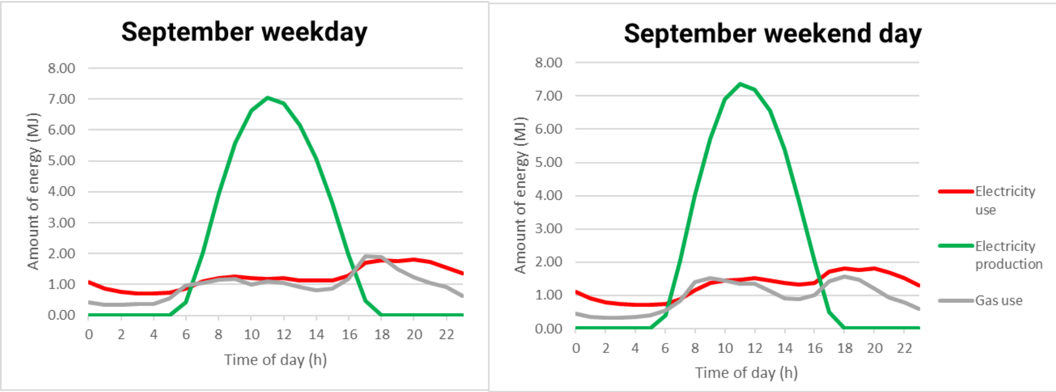

Figure 25. *Energy balance in MJ for an average weekday and weekend day in September 2023.*

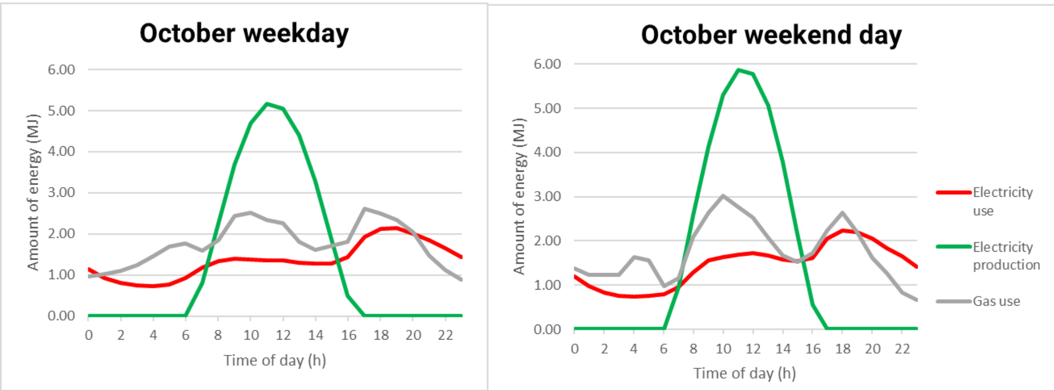

Figure 26. *Energy balance in MJ for an average weekday and weekend day in October 2023.*

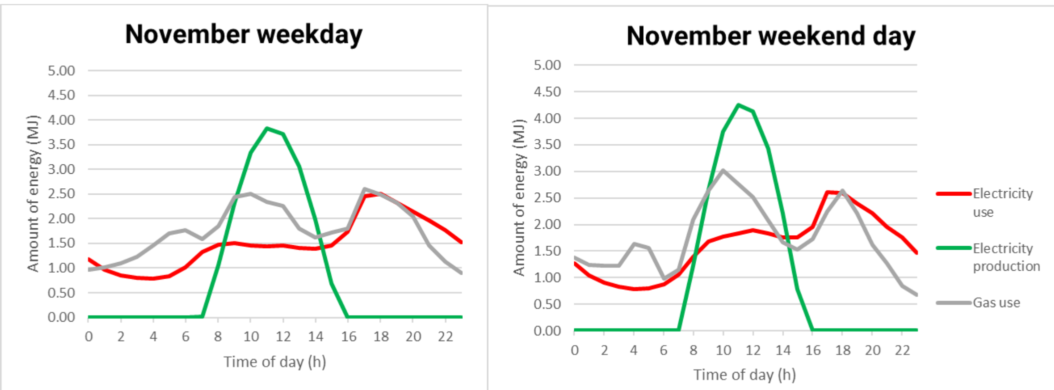

Figure 27. *Energy balance in MJ for an average weekday and weekend day in November 2023.*

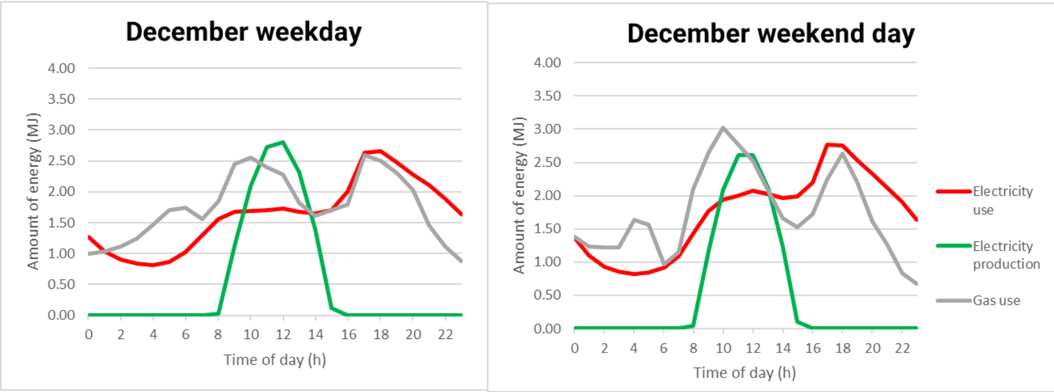

Figure 28. *Energy balance in MJ for an average weekday and weekend day in December 2023.*

9. Appendix B

Additional figures showing the scores of the MCAs conducted for several scenarios.

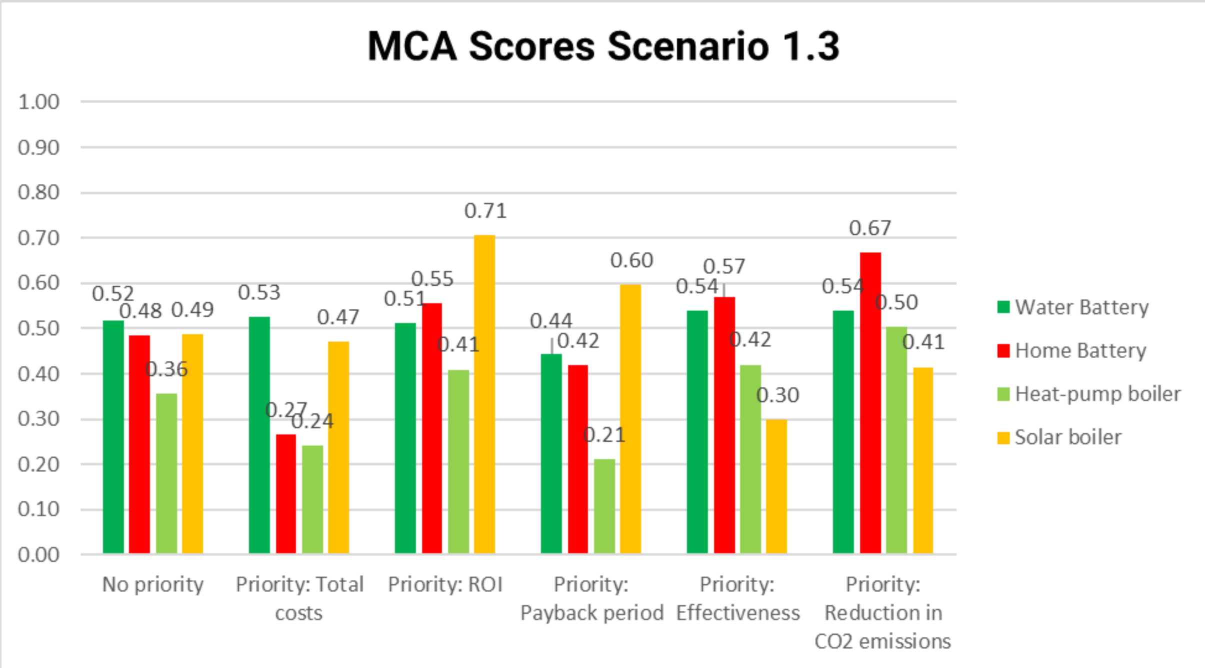

Figure 29. *Final scores of each technology for the MCA with different priorities in scenario 1.3: Single parent living with a young child.*

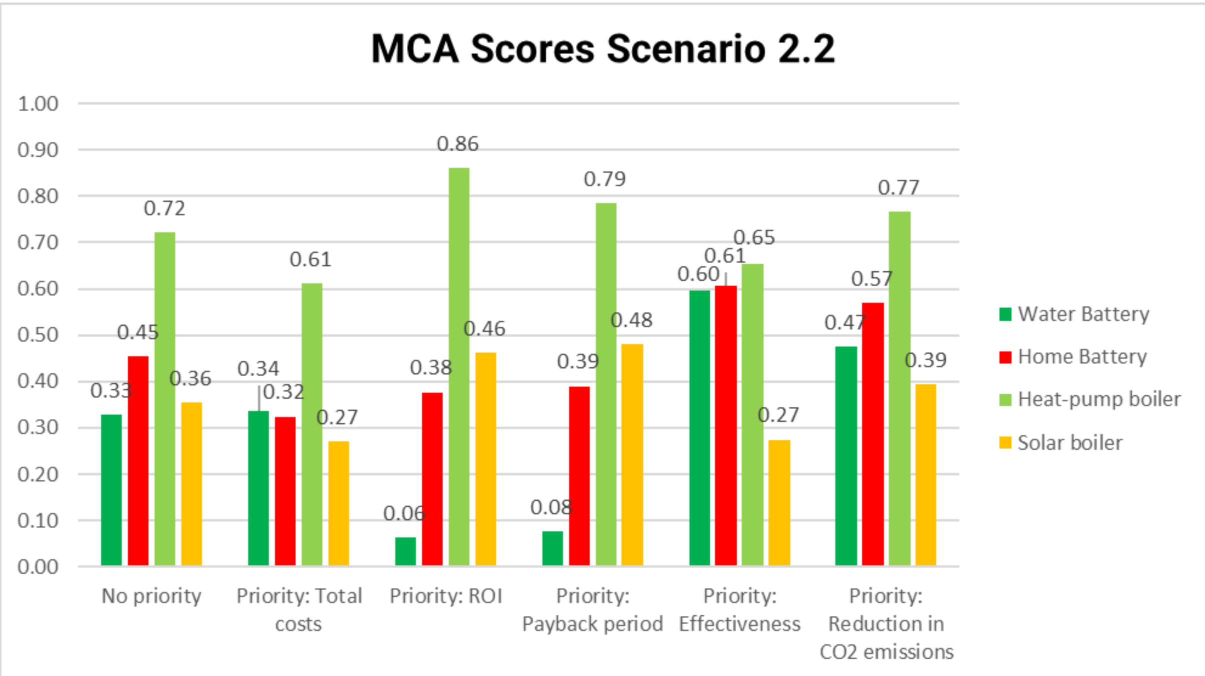

Figure 30. *Final scores of each technology for the MCA with different priorities in scenario 2.2: Family with three children. One of the children is a young adult living on their own, but staying over regularly.*

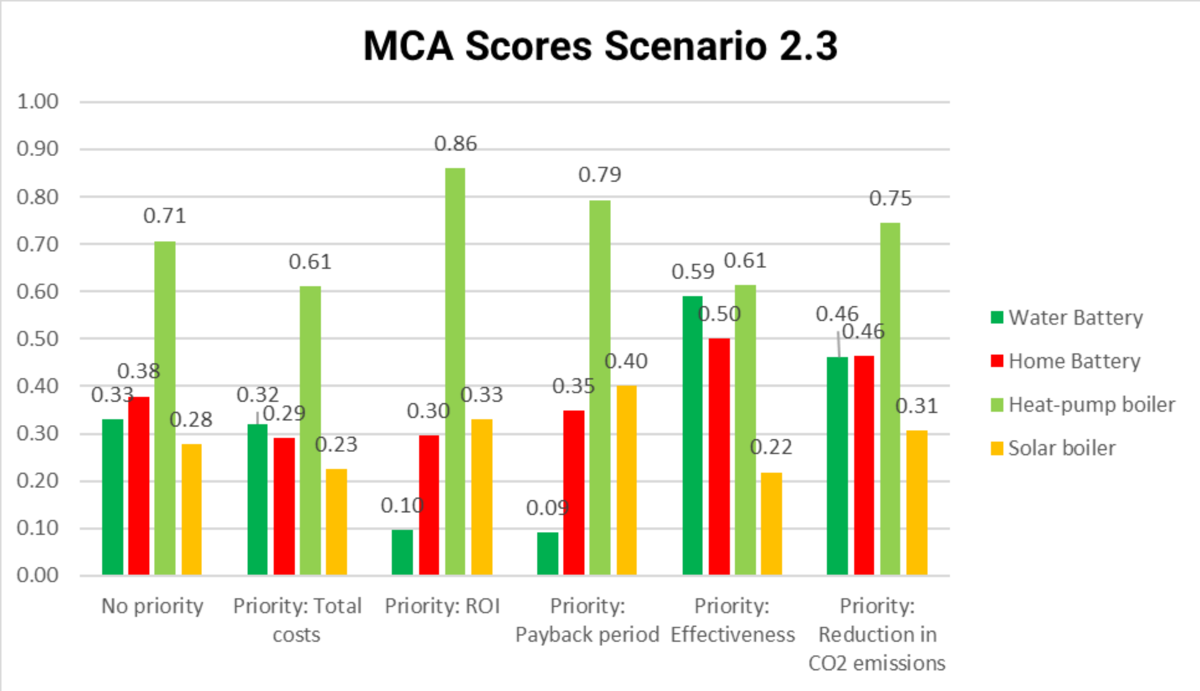

Figure 31. *Final scores of each technology for the MCA with different priorities in scenario 2.3: Family with four children (all teenagers) living in an older house.*

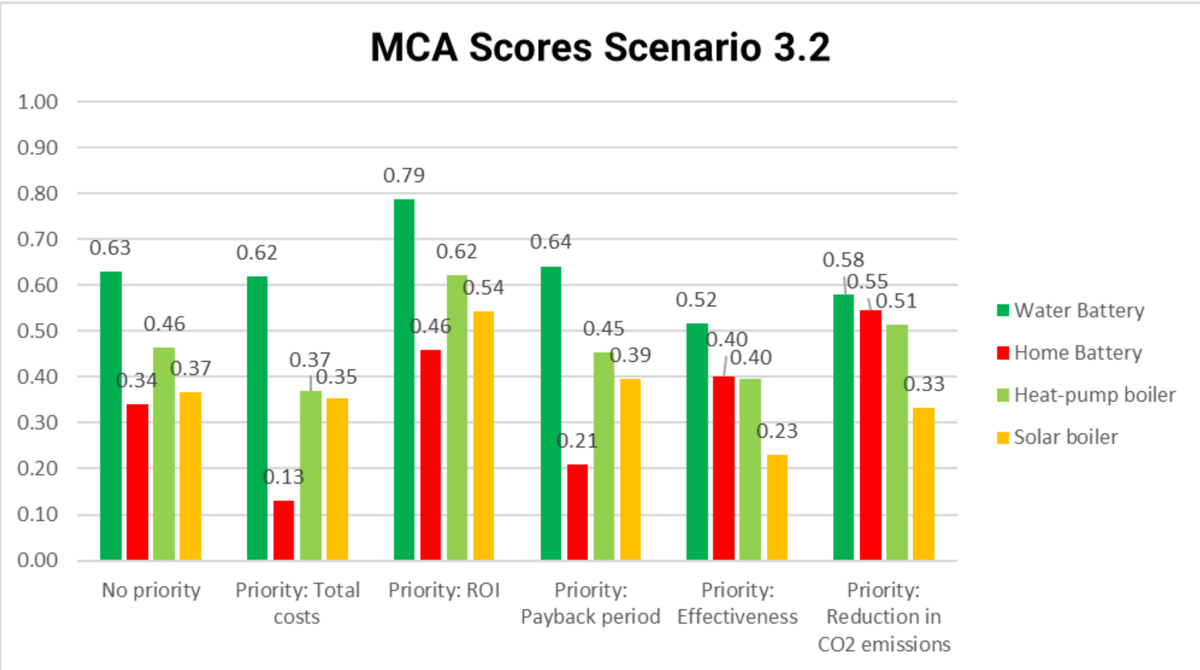

Figure 32. *Final scores of each technology for the MCA with different priorities in scenario 3.2: Married couple living in a modern (well insulated) house, with no plans to have children.*

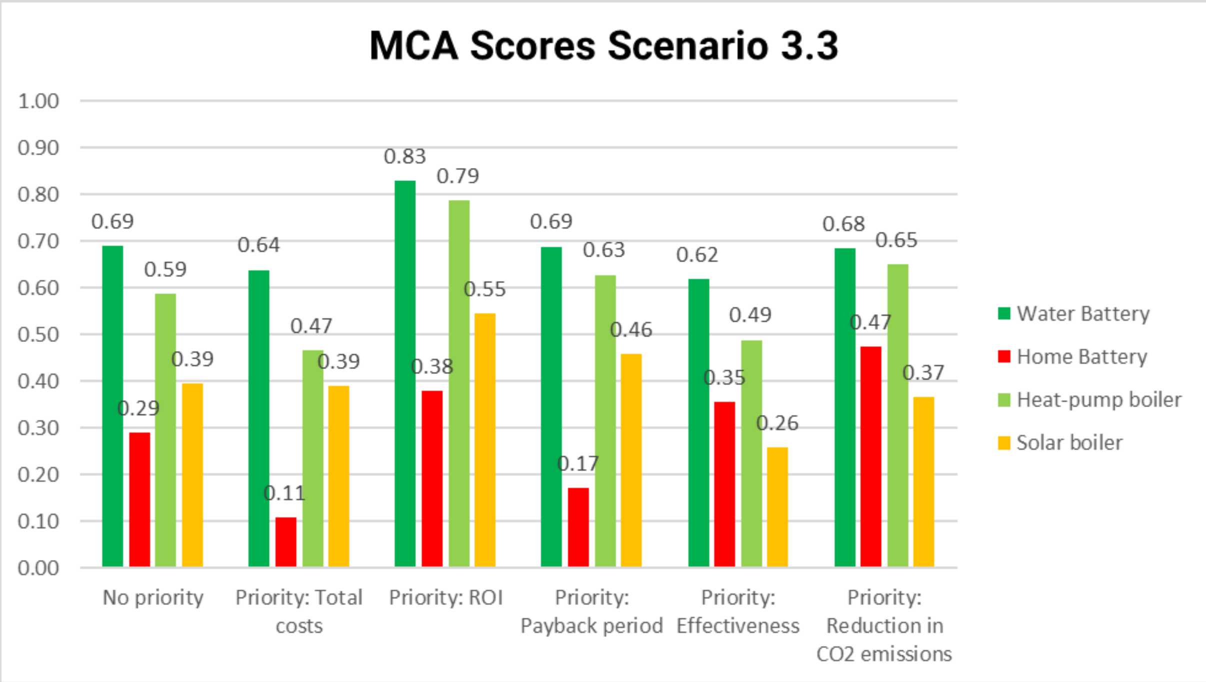

Figure 33. *Final scores of each technology for the MCA with different priorities in scenario 3.3: Young couple with a Jacuzzi in their home.*

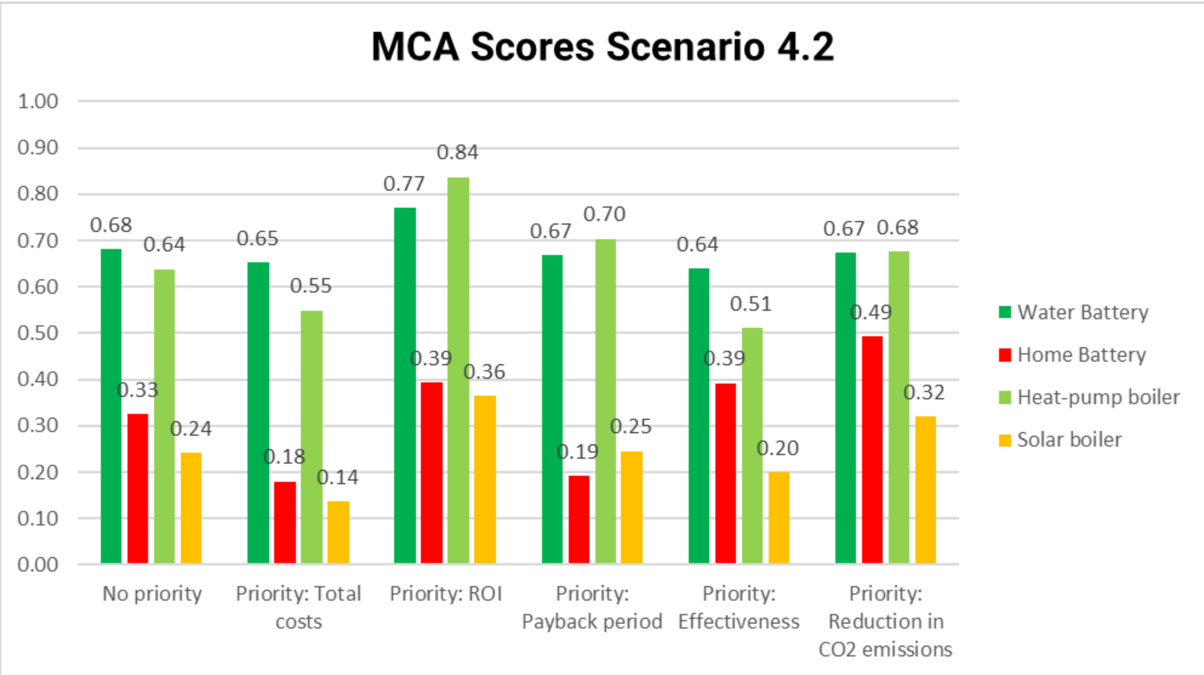

Figure 34. *Final scores of each technology for the MCA with different priorities in scenario 4.2: Family with three children. One of the children is a young adult living on their own, but staying over regularly.*

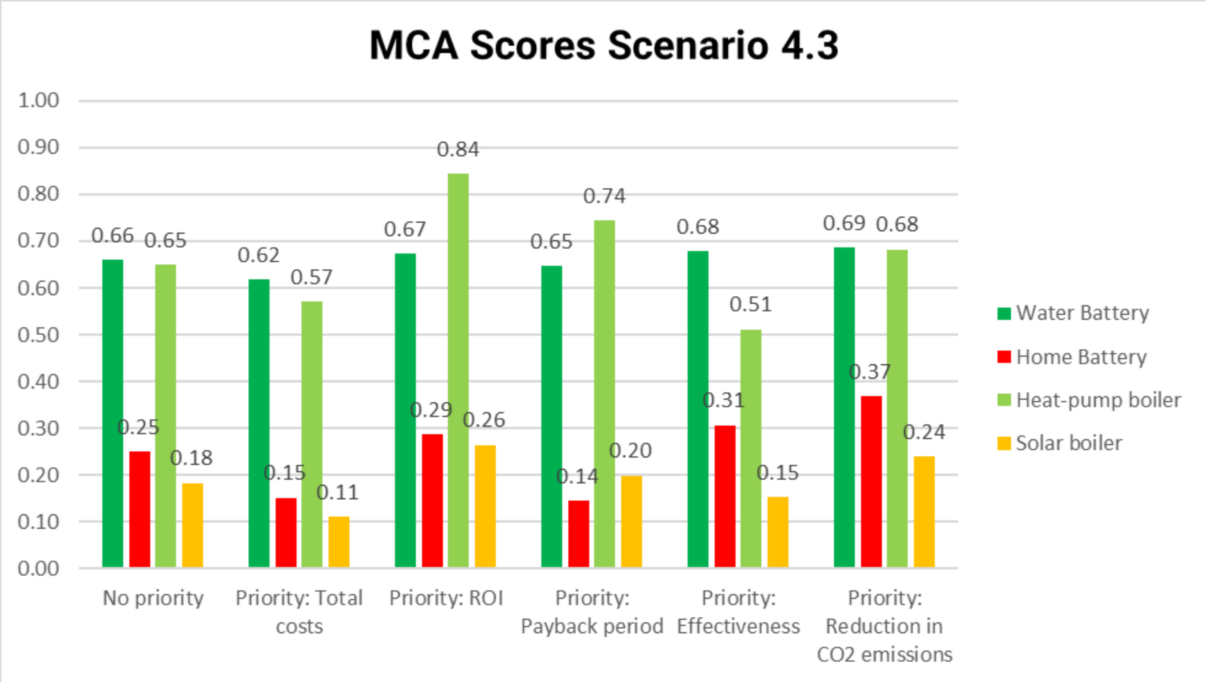

Figure 35. *Final scores of each technology for the MCA with different priorities in scenario 4.3: Family with four children living in a modern (well insulated) house.*