Household Resilience to Power Outages

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Abstract

The purpose of this study is to investigate the resilience capabilities of households in case of power shortages/outages and their ability to adapt to these situations and to find out how long a villa district can maintain power with basic living conditions from an electric power supply point of view. By using Matlab, an artificial test environment was created in order to simulate how much power consumption behavior affects the overall consumption, specifically focusing on the heat pump and the electrical water heater. Using data from monthly generated solar power in Stockholm Sweden and the power storage capabilities of electric vehicles in order to prolong the resilience time of the households in these situations. The results of implementing the combination of solar panels and vehicle to grid technologies has shown that with some changes to daily life power consumption, the residential area can potentially provide sufficient energy locally for up to 65% of the year without grid support, given weather conditions do not stay dark for longer periods of time.

Acknowledgments

We want to show our gratitude to the support and inspiration that was given to us by our supervisor, family and friends. Firstly we want to thank our supervisor Torbjörn Thiringer for his patience and enthusiasm in the topic which has helped to see a wider view of the possibilities of this project. Then we want to thank our families for their support with encouragement, knowledge and suggestions. Lastly we want to express our deepest gratitude to Sindhu Ramakrishna for her help with our simulation code.

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1 Introduction

1.1 Problem background

All households need energy to live comfortably and access to electricity from the power grid is taken for granted in daily life. This results in households being unprepared for potential power outages or sabotage of the electrical grid, leaving them without access to electricity. In today's society, the vast majority of households depend on electricity for essential needs such as heating, lighting, cooking, and food preservation through refrigerators and freezers. Without these functions, most households face significant challenges as only a few households have access to self-sufficiency solutions, for instance, solar panels or battery storage. Most of these outages are caused by grid maintenance and weather conditions, for example, storms, snowstorms and debris causing damage to the grid. Recent international conflicts and events have led to the Swedish government taking action and issued a book called *In case of crisis or war* in order to prepare the population for what may come [1]. This further supports the premise that this is an issue of high priority and importance.

1.2 Purpose

This project will investigate the resilience capabilities of households in case of power shortages/outages and their ability to adapt to these situations. A clear analysis of the power needs of the households is essential in order to investigate what countermeasures that are required to improve the resilience. Using already present power generating sources, assuming that the households are equipped with solar panels and electric vehicles. This is made to find out how long a household can hold out in case of power outages with currently available technology.

1.3 Limitations

This project is focused on power loads for household appliances, solar power generation and electrical vehicle battery for power storage. The technologies behind these all have certain amounts of power losses. In order to focus on adaptations and power management, it was decided to assume ideal conditions where there are no losses. The same principle applies to the solar panels where there are different weather conditions that can result in different results such as cloudy days and dust/snow covering the panels. This project does not take the economical aspect into consideration when selecting products.

2 Collection of known usable theory

2.1 Electric vehicle integration

Vehicle-to-Home (V2H) and vehicle to grid (V2G) are technologies that enables bidirectional energy flow between an electric vehicle, households and the power grid, allowing the vehicle's battery to supply power to the home. This system enhances energy efficiency, supports backup power during outages, and integrates seamlessly with renewable energy sources like solar panels. V2H is a system where an electric vehicle connects to a DC to three phase AC inverter in order to power the household, this also allows the solar power to connect to the same inverter shown in Figure 1 allowing direct power usage in the household or charge the electric vehicle when the demand is low. The V2G system is also connected to the power grid, enabling it to stabilize and support the power peaks and drops [2].

In the event of a power outage, households may need to use the batteries of their electric vehicles to meet their basic energy needs. The following sequence of the process is from the input into the V2H/V2G charger shown in Figure 1. The amount of energy transferred into the household using vehicle to home (V2H), is found as

$$E_{home} = \int_0^t P_{\mathrm{EV}}(t)\, dt \tag{1}$$

where E_{home} is the energy supplied to the home and P_{EV} is the power output of the electric vehicle battery. It's the same when calculating vehicle to grid (V2G) but due to the conversions in the system, such as switches, causes energy losses, which needs to be considered, giving

$$E_{grid} = P_{EV} t \eta \tag{2}$$

where η is the transfer efficiency coefficient which is usually 90%. In order to transfer energy from the vehicles battery into the grid using V2G it needs to be converted from DC to AC using a three-phase inverter. After converting the battery's DC voltage to AC, it becomes essential to calculate the power output without exceeding the limits of the grid. The power towards the grid is represented as

$$P_{\mathrm{out}} = \sqrt{3} U_{\mathrm{in}} I_{\mathrm{in}} \cos(\theta) \tag{3}$$

Here, U_{in} represents the input DC voltage, I_{in} the incoming current and $\cos(\theta)$ accounts the for the phase difference between them. The voltage and frequency matching to the grid is crucial to avoid instability or any damage to the system. Once DC is converted to three-phase AC, the inverter introduces harmonic frequencies due to the switching process. However, power grids require a pure 50 Hz waveform for stable and efficient energy transfer. The LCL filter is essential here, it acts as a low-pass filter, suppressing unwanted harmonics while allowing the fundamental frequency to pass through. This ensures smooth grid integration, prevents interference, and maximizes energy efficiency.

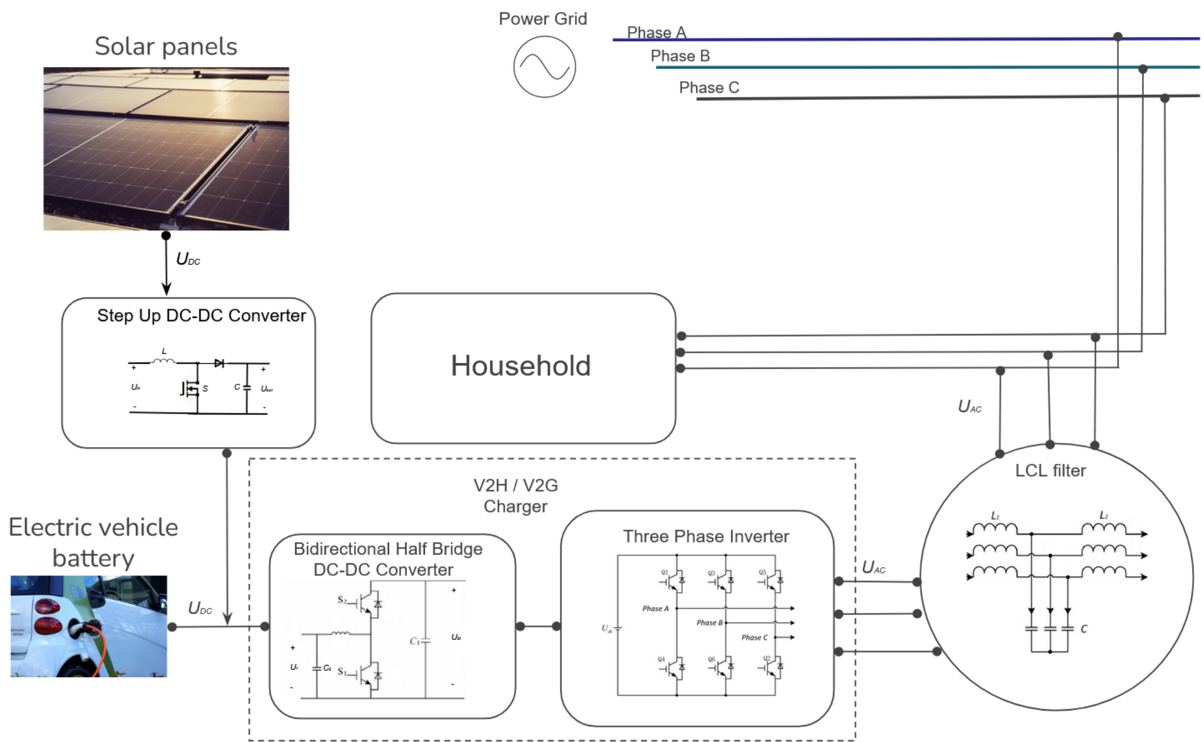

Figure 1: Electric vehicles and solar power to grid

3 Case set-up

3.1 Outage definition

In order to analyze the resilience of the households, three different situations where set up to supply of power would be reduced by a certain amount. The cases of reduced power supply can happen when the power generation is low and the method called ”steering electricity to prioritized power consumers” is implemented. In this way the power is rationed out to different sectors [3].

- Outage 1: Power supply reduced to 33%
- Outage 2: Power supply reduced to 29%
- Outage 3: Power supply reduced to 22%
- Outage 4: Total power outage 0% power supply

Each of these are based on the peak consumption of the households and then reduced to the set amount.

3.2 Structures of the households

Considering that the energy consumption between different households are rarely identical, a predetermined structure has been set. The different households are of different varying family sizes which have been categorized into three types 1, 2 and 3. Where each household consists of the following family sizes:

Type 1: Two adults and two children
Type 2: Two adults
Type 3: Two elderly

In this project, 10 households are investigated, in which there are four houses of type 1 and 2 and two houses of type 3.

The households consist of identical houses meaning that all types of households have the same amount of large appliances, constant loads and lighting. Each house consists of 3 bedrooms, a living room, hallway, a bathroom and kitchen. To create an accurate representation of reality it's assumed that around 6 lamps are used simultaneously. The only difference between the households is the usage time of the power loads, such as a family of four uses their vehicle more due driving children to and from school and sport activities while the two elderly mainly drive for errands.

3.3 Heating appliances

An important contributor to power consumption in households is indoor heating. Heatpumps are one of the most common ways in Sweden to heat up and maintain indoor temperatures. In this study the different heat pumps connected to the households are set to turn off when the outdoor temperature goes above 10-15°C and to maintain an indoor temperature of 19-21°C. In order to analyze the heatpump consumption, data from SMHI:s weather station located at Arlanda airport in Stockholm was used [4]. In one scenario, the households are equipped with fireplaces which allows the households to lower the power consumption of the heatpump.

In addition to the heat pump, electric water heaters play a crucial role in Swedish households. Unlike most appliances where power consumption can be regulated to use less energy, electric water heaters must maintain a constant energy consumption to maintain their temperature so the growth of Legionella bacteria does not occur. Each household will be fitted with an electric water heater of 150 L at 3 kWh/h.

3.4 Power adaptation

For the households to sustain living conditions during the power supply reductions and outages, they need to adapt their lifestyle until the power grid is restored to normal functionality. These adaptations can reduce excessive power consumption such as using entertainment devices etc and also more necessary functions such as indoor heating.

3.5 Self sufficiency

Each household is in this study set to have solar panels for power generation. The data used in this study comes from the most common type of solar panel installation in Sweden, the 10 kW installation. To simulate the amount of daily generated power from the solar panels, a simulation tool was created in MATLAB. The parameters used were generalized based on data from monthly generated solar power in Stockholm Sweden[5]. Using these values would simulate static weather condition. In order to create a more realistic tool the values needs vary on a day to day basis and in the tool they vary from 70% to 130%. This method is not truly realistic, as weather conditions, such as snow or dust, can completely block the panels.

All the households all have an electric vehicle each which is mainly used for transportation but also as an excess solar power storage battery, in this work the total battery storage for the 10 households is 720 kWh. During most cases of outages, the households are limited to consuming 75% , 540 kWh, of the total battery capacity in order to save 25% for transportation which in this project is considered to be a necessary amount of power in order to enable the households to resupply with food or evacuate. If the scenario allows it, the 25% limit can be overwritten in order to prolong the resilience time.

The vehicle to grid technology in Figure 1 enables all houses to be connected through a local power grid which enables a larger energy storage pool as well as optimized solar power usage.

4 Analysis

4.1 Power load analysis

The setup of the case is to calculate the energy consumption of common household items seen in Table 1. With the calculated values, it is possible to adapt their time usage based on the different types of family home structures in the residential area. By applying the differences in usage time, it will be possible to get realistic energy consumption data during the different seasons. These sets of values will be used to determine which loads can be removed to facilitate the electrical grid during breakdown or sabotage. Simulating Table 1 values for a year, seen in Figure 2, creates a clear view of what power loads contribute the most to total power demand, which then makes it easier to adjust when needed.

Table 1: House type 1 list of power loads and their individual load, excluding heat pump

Group	Load	Estimated seasonal usage (h) Winter / Spring and fall / Summer	kWh/h
Large appliances	Stove	1 / 1 / 0.5	1.8
	Oven	0.5 / 0.5 / 0.5	2.2
	Dishwasher	1 / 1 / 1	1.5
	Washing machine	1 / 1 / 1	0.5
	Dryer	1 / 1 / 1	1.37
	Electric vehicle	8 / 8 / 8	2
	Microwave	0.25 / 0.25 / 0.25	0.8
	Waterheater	5 / 4 / 3	3
Small appliances	Kettle	0.2 / 0.2 / 0.1	1.85
	Coffee machine	0.3 / 0.2 / 0.2	1.52
	Game console	3 / 3 / 2	0.21
	PC	4 / 3 / 2	0.35
	Tv	4 / 4 / 2	0.085
	Usb adapter	4 / 3 / 3	0.015
	Laptop charger	1 / 1 / 1	0.075
Constant loads	Fridge	24	0.013
	Freezer	24	0.024
Lighting	Ceiling LED	7 / 6 / 4	0.007
	LED lights	7 / 6 / 4	0.003

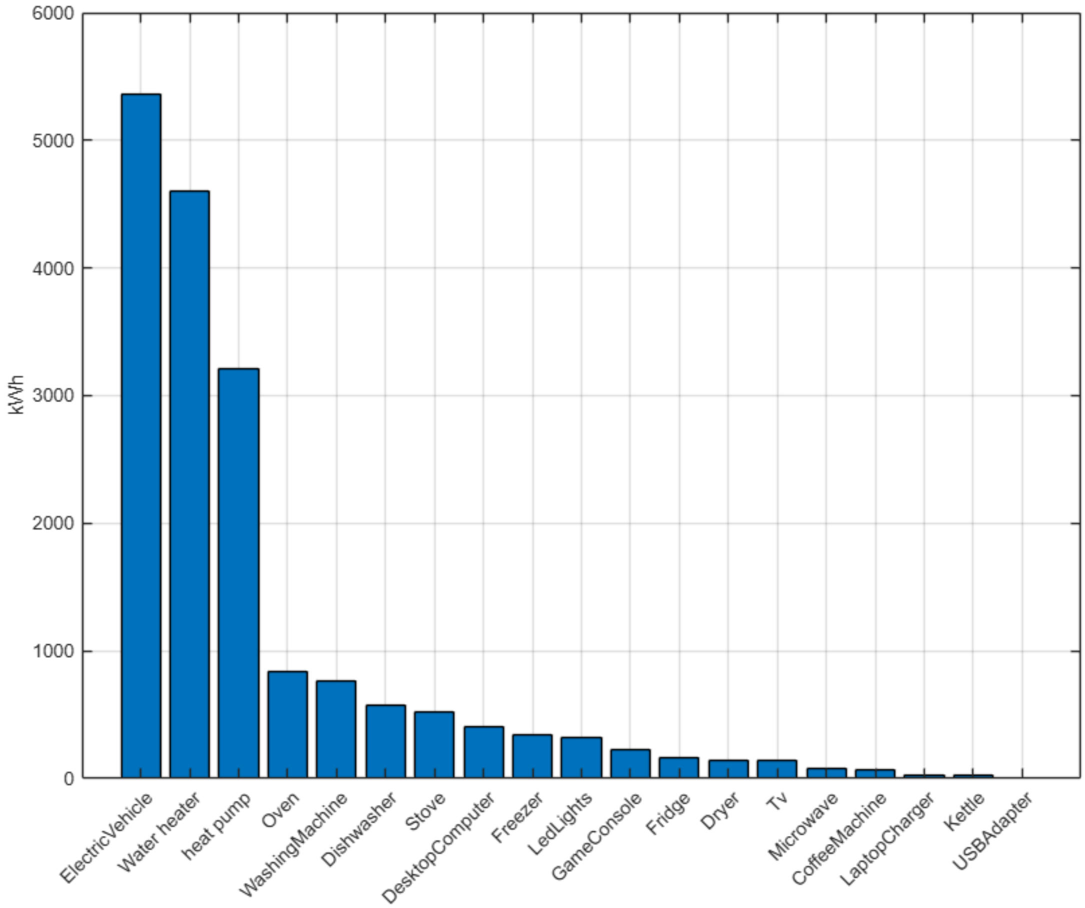

Figure 2: All loads annual consumption, for household type 1

4.2 Outage power usage

During these scenarios where the EV battery isn't enough to cover normal consumption for a longer period of time, some actions have to take place such as reduced power consumption. This includes the following:

- Lower indoor temperature
- Less hot water usage
- Reduce stove, oven and microwave usage
- Minimize entertainment device usage such as TV, game console, PC and laptop.

The two largest power consumers being the heat pump and water heater where these consume approximately consume 3000 kWh respectively 4000 kWh annually. Lowering the indoor temperature from 21°C to 20°C during winter reduces energy consumption from the heatpump by 4.4%. Reducing usage of the water heater during winter from 5h to 4h per day reduces power consumption by 20%. The average shower head uses 9.5 L of water per minute with a hot water ratio between 60% - 70%, which means that a 10-minute shower uses 57 L to 67 L [6]. With a tank capacity of 150 L at 3 kW where it takes approximately 4.5 h to heat all 150 L.

Spreading out device usage so that no more than one of the large appliance are active at the same time such as stove, oven, microwave, dishwasher, washing machine and dryer, will reduce the large power peaks during the day. This will in turn reduce the amount of power drained from the EV battery during the cases where the power grid has a reduced capacity.

During a total power outage crisis where the household can only rely on solar power and the electric vehicle battery in order to last, special measures need to be taken. The method used in this project is meant to simulate the most extreme case, which was found to be during the period between the third and tenth of December 2023, where the temperature got down to -20°C, further increasing the load of the heat pump. Clouds and heavy snowfall caused the solar panels to produce nearly no power at all. In this case, households should only use the absolute necessary devices for food preservation, cooking, communication and heating. The most significant changes were indoor heating and the amount of hot water used. For example during normal power consumption the households had a set indoor temperature of 19°C to 21°C and during a crisis it was reduced to between 15°C - 17°C, looking at Figure 3 and Figure 4 this change alone changed the power consumption of the heat pumps during these 8 days from approximately 2990 kWh to 2500 kWh. The water heater is normally on for 5 hours per 24 hour cycle during winter, but by reducing the heat and time used when showering this usage time was changed to 2 hours per day, this changed the total power consumption of the water heaters from approximately 1200 kWh to 480 kWh during the period. As an example looking at the changes after applying the crisis adaptation method in a single household of type 1 seen in Figure 4, where excessive power usage were lowered and non essential loads, colored blue in Figure 3, were removed resulting in 8 remaining power loads instead of the original 19.

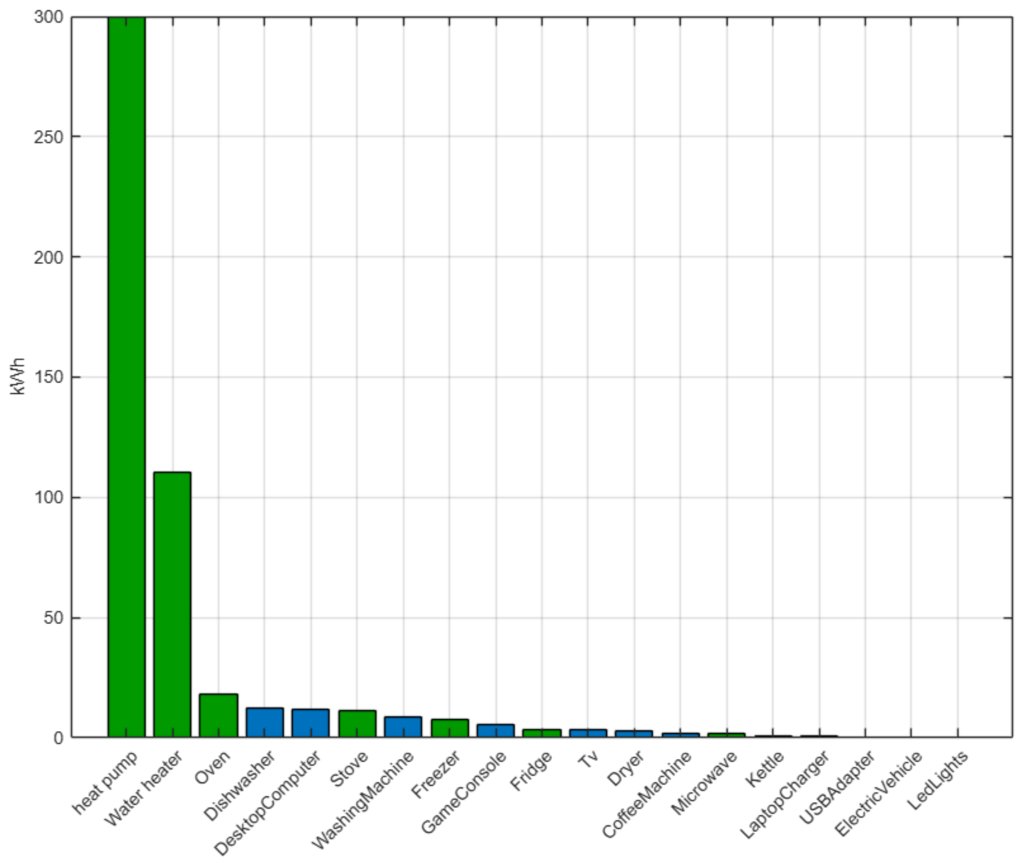

Figure 3: Normal consumption power loads during worst case scenario
, household type 1

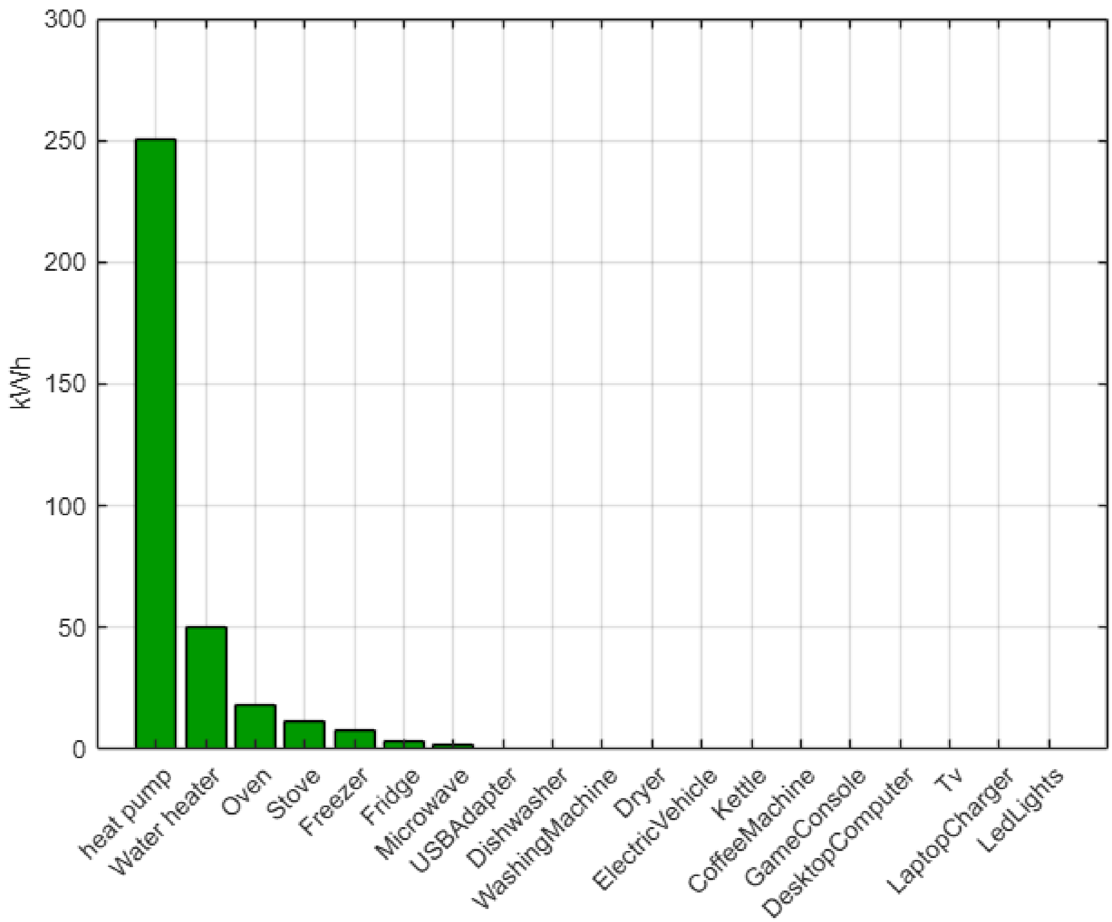

Figure 4: Crisis adaptation method consumption power loads during worst case scenario, household type 1

4.3 Power consumption and generation

4.3.1 Yearly power overview

Energy consumption in households varies greatly depending on the season, due to variations in weather and temperature, which in return affects daily habits of residents. Seasonal pattern recognition is a critical part in adopting efficient energy practices during breakdown or sabotage of the electrical grid. Especially for the heat pump where the outdoor temperature heavily affects power consumption. Looking at Figure 5 which emphasizes the power demand differences of the households in different seasons.

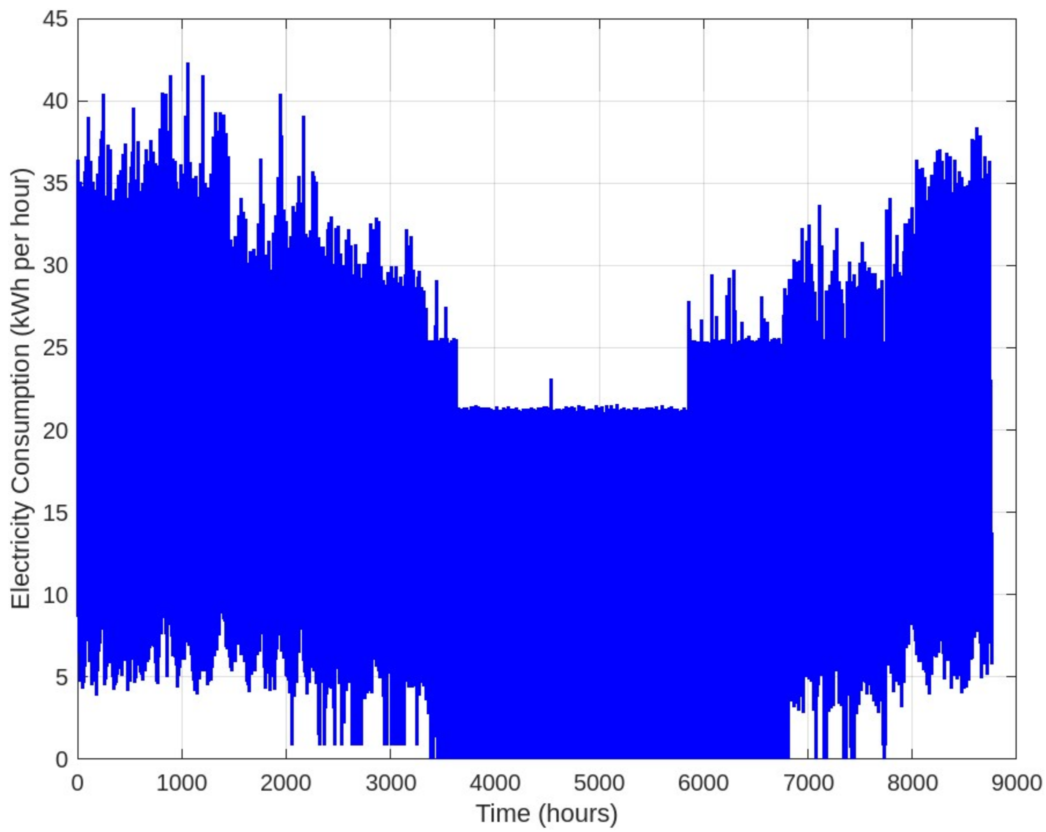

Figure 5: Power demand of all households 2020

The solar power simulation shown in Figure 6 displays a total of 90991 kWh, combining all houses, annual solar power output from collected data published by Hemsol [5]. However, this simulation data does not represent reality perfectly since most of the power is generated in the daytime and summer. During the daytime most of the houses don't consume much power for household appliances except heating and food preservation. Another important piece of information to remember is that cars are not usually charged in the daytime since most of the cars are used as transportation for work, so the energy produced is not stored anywhere and is sold to the power grid and does not directly impact the energy consumption. During summer, when energy generation from the solar panels are at their peaks is also the period when the houses consume the lowest amount of energy as the outside temperature is the highest and the heat pumps no longer need much energy. However this simulation does not take weather conditions into consideration, which in turn means that the power fluctuations are larger in reality, yielding lower power output and especially in winter.

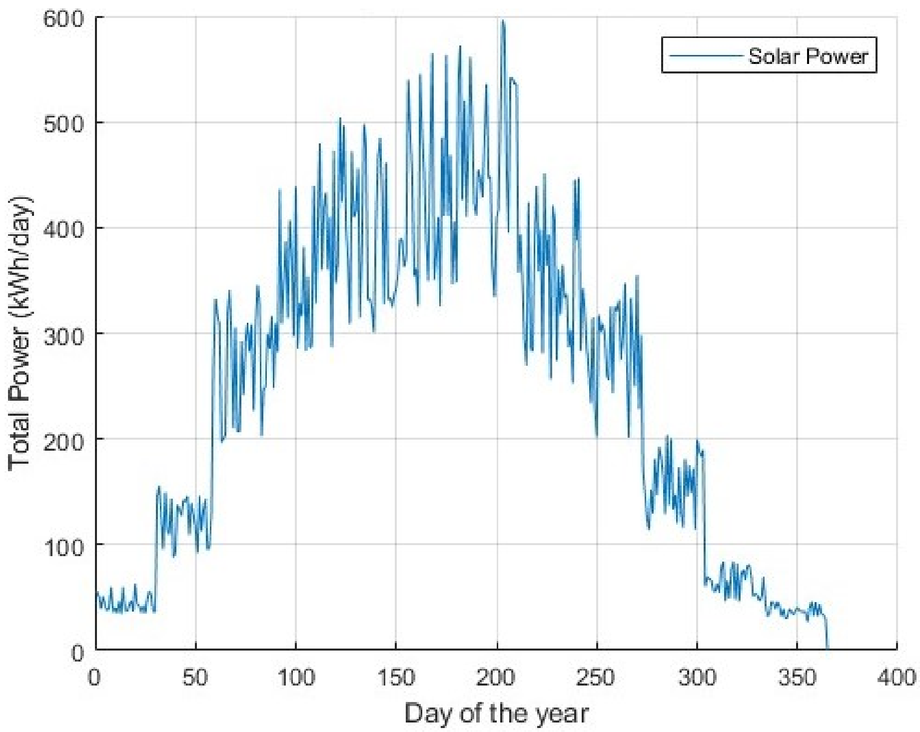

Figure 6: Solar generated power of all households, averaged per month, with a variation added. 2023

Converting Figure 5 to daily total consumption and then combining it with Figure 6 for one household results in Figure 7, which shows that during the period from the 22nd of May to the 28th of August solar power is enough to completely power the household. This amounts to 27% of the year.

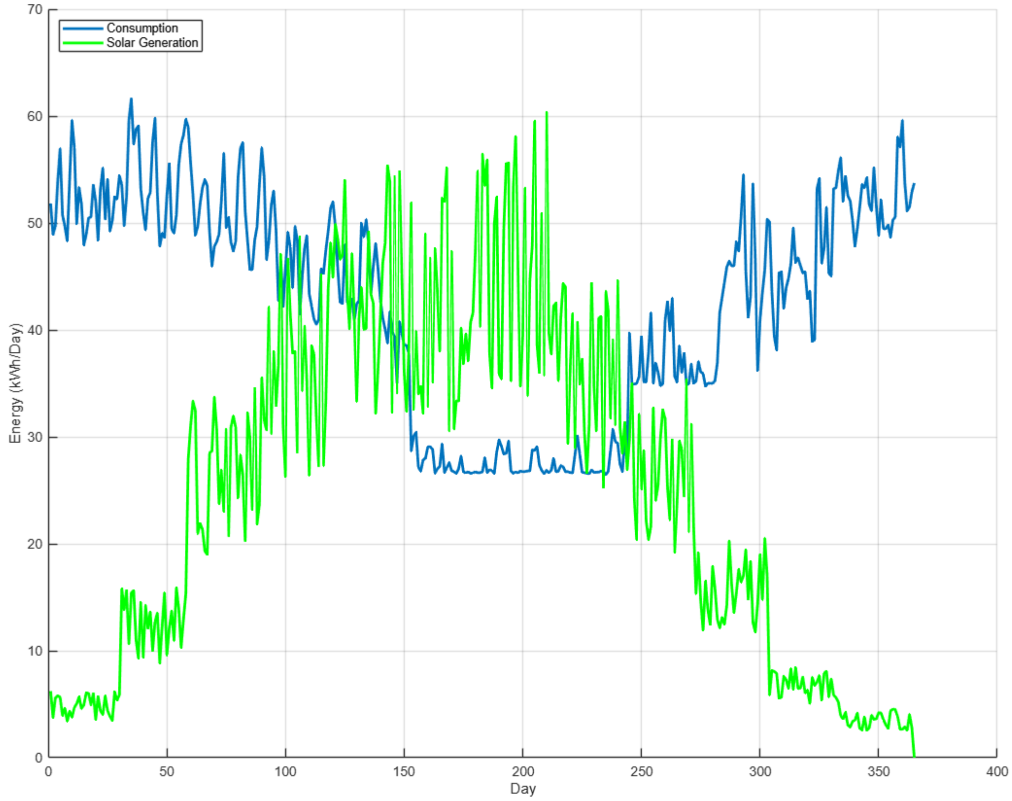

Figure 7: Normal consumption and solar power per day over a year, for household type 1 2020

The average daily normal consumption for all households during summer is 252 kWh and when all 10 households have a 10 kW solar panel installation the production is approximately 430 kWh per day, shown in Figure 5. The 430 kWh per day is the result of each house having 50 m^2 solar panels, giving a total of 500 m^2, each panel of this effect is 2 m^2. In order to meet the minimum power requirement during summer, the households need 293 m^2 which leads to 147 panels and this means that only 3 households need to have a 10 kW solar installation in order to make the villa district self sufficient during the summer.

4.3.2 Seasonal differences

Going through each season in the order from easiest to the most challenging to handle. Household type one was chosen because the larger family size increases their power consumption. Summer, in this case as shown in Figure 7 demonstrates that the household will have more than enough power and therefore there is no need to adjust.

Continuing with spring and fall where the normal power consumption is higher than the solar generation. This period is where the households no longer can completely rely on solar power generation without changing power consumption behavior. In this case Figure 8 and Figure 9 displays solely the period that is considered spring and fall where the winter and summer months have been removed in order to get a closer look at their consumption, as these periods have similar power consumption behavior.

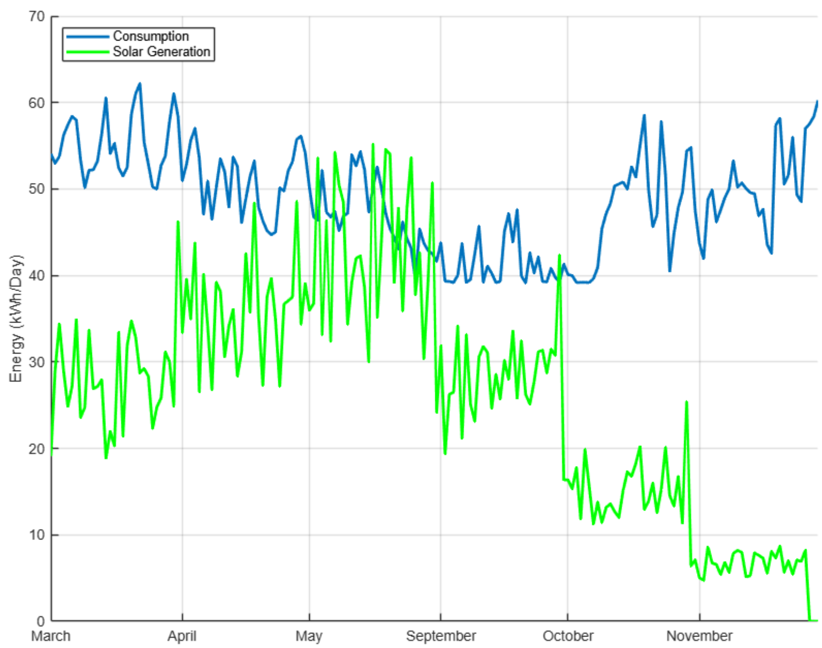

Figure 8: Normal consumption and solar power per day during spring and fall 2020, for household type 1

In order to fully rely on the power generation and electric vehicle battery, the household has to adapt their power consumption. In the case shown in Figure 9 where the crisis adaptation method is used, it can be deduced that utilizing the method is sufficient for the majority of the period until it started to get colder in the middle of October and solar power declines heavily.

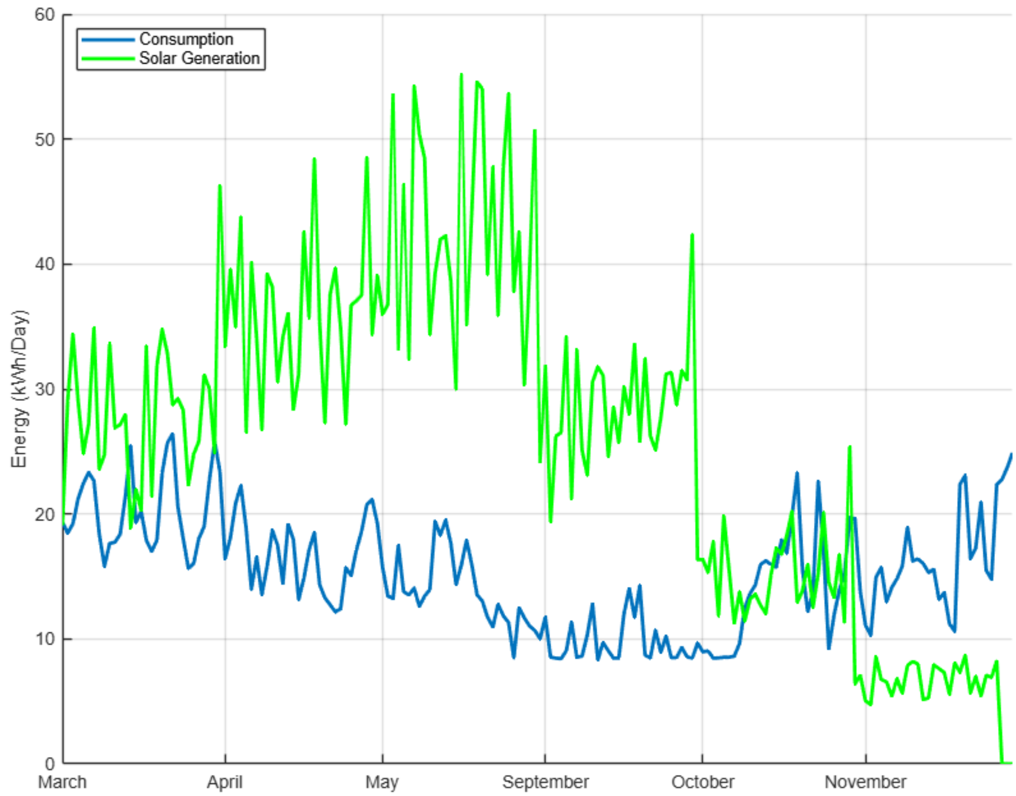

Figure 9: Crisis adaptation method consumption and solar power per day during spring and fall 2020, for household type 1

Following spring and fall comes winter, where the household must adapt in order to keep power up for their necessities. With normal consumption the gap power gap between consumption and solar generated power was nearly 50 kWh/day, shown in Figure 10.

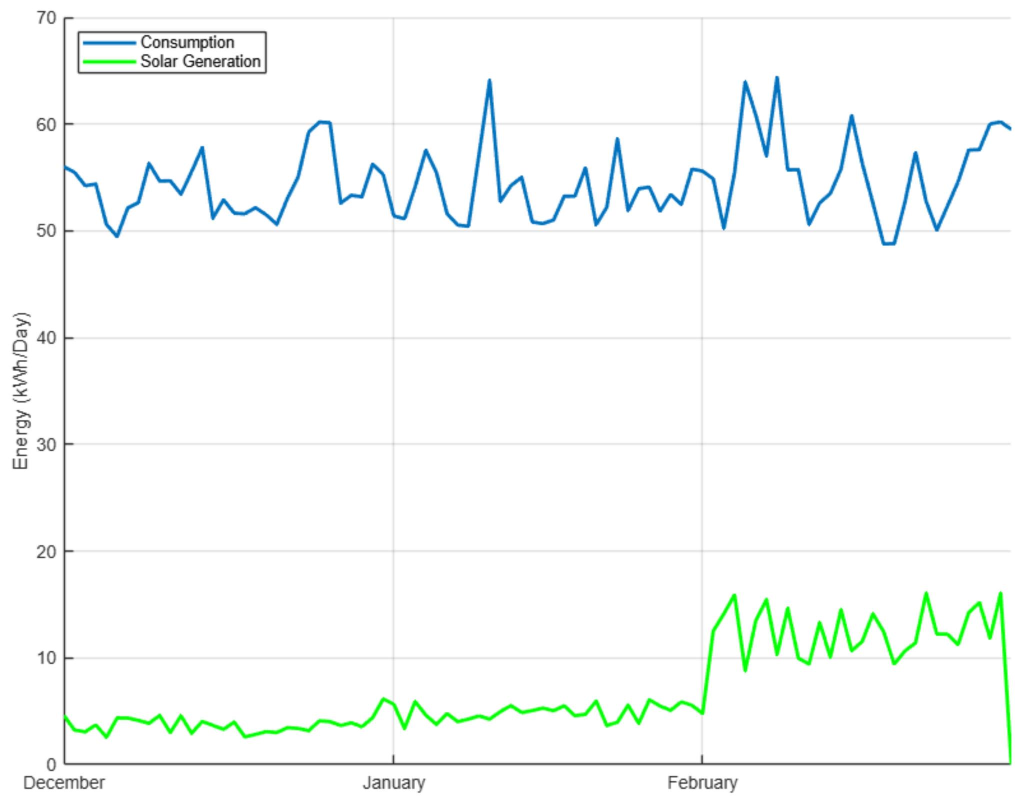

Figure 10: Normal consumption and solar power per day winter 2020, for household type 1

Utilizing the crisis adaptation method, shown in Figure 11, reduces the power gap to an average of 20 kWh/day which is a difference of 30 kWh/day compared to normal consumption. Considering the most common electric vehicle battery size being between 70 - 100 kWh, proves that using the crisis adaptation method has a big impact on how long a household maintain living conditions even without any grid support.

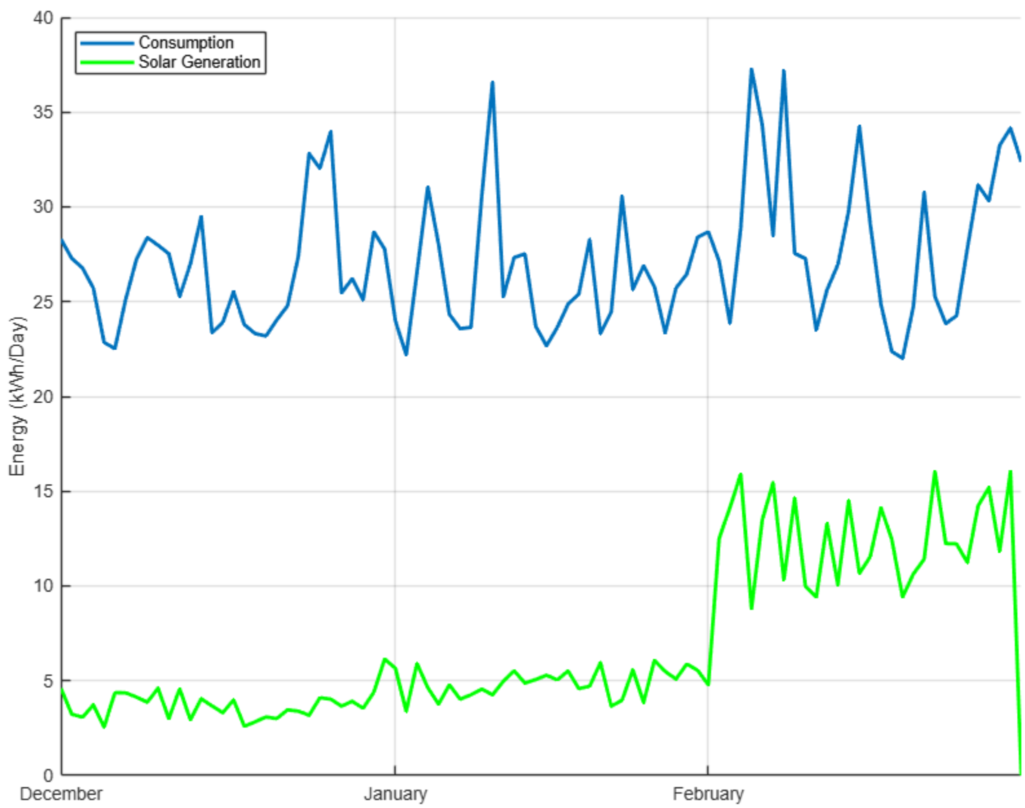

Figure 11: Crisis adaptation method consumption and solar power per day during winter 2020, for household type 1

Combining Figures 7 - 11 gives Figure 12 where the clear difference between using the crisis adaptation method. The max power consumption is reduced by 50% and the potential period that the households can be self sufficient by relying on the solar panels is increased from 27% to 65%. In this case however it is evident that the crisis adaptation method is not needed or unnecessarily reduced too much. The time period between day 100 and day 250 where the difference between generated power and power consumption is large which in turn means that the living conditions can be increased while still being self sufficient.

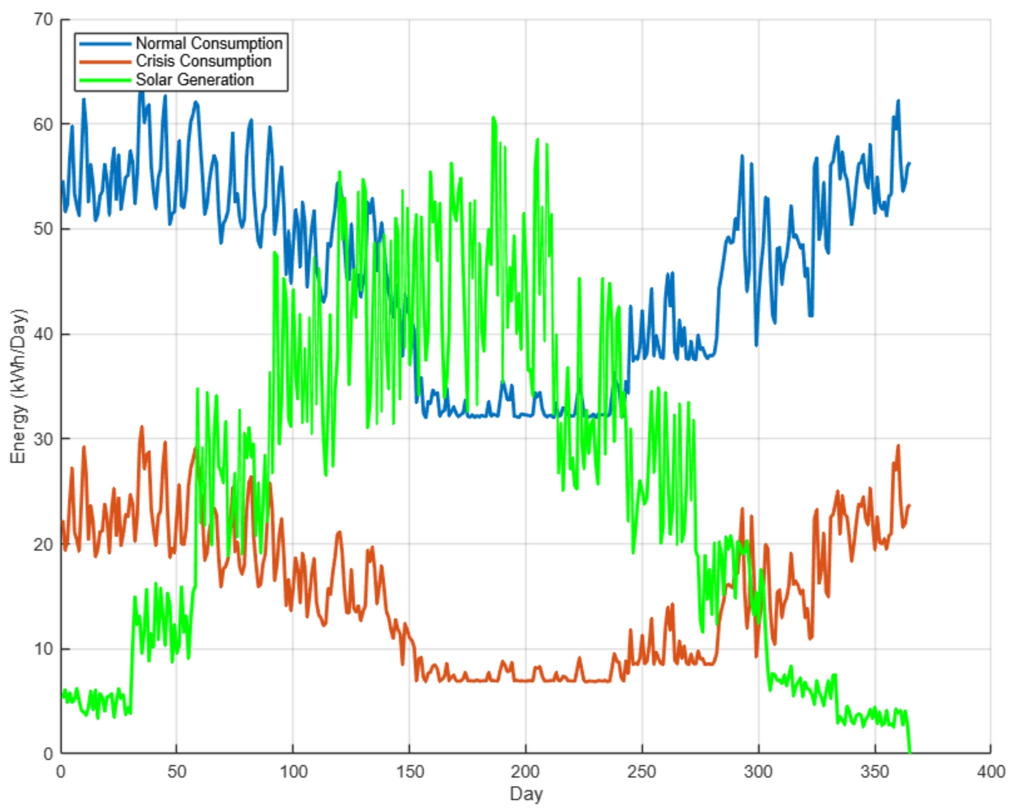

Figure 12: Normal power consumption, crisis consumption and solar power generation, total per day for household type 1 during year 2020

4.4 Electric vehicle as power source

When the car is plugged into the house it can save as power storage and contribute with power whenever there are high power peaks or not enough power supported from the power grid. The power outage types consists of 33%, 29%, 22% and 0%, of the total power supply which can be seen in Figure 5 where the max power consumption is 43 kWh/h, where the max power supply is assumed to be 45 kWh/h. Using the max power supply to calculate the exact power outage values gives 15, 13, 10 and 0 kWh/h. In the case of power outages the car will be used almost exclusively for household power, but in order to be able to be driven it needs power. This leads to the household never completely empties the battery but instead only uses 75% of its total capacity, 540 kWh. Figure 13 depicts how the batteries in the cars operate. In this example there is a power outage of type 3, where the blue colored line is when the electric vehicle is powering the house and when it turns black the battery is empty. As shown when the power consumption is lower than the provided power from the grid, the battery is recharging.

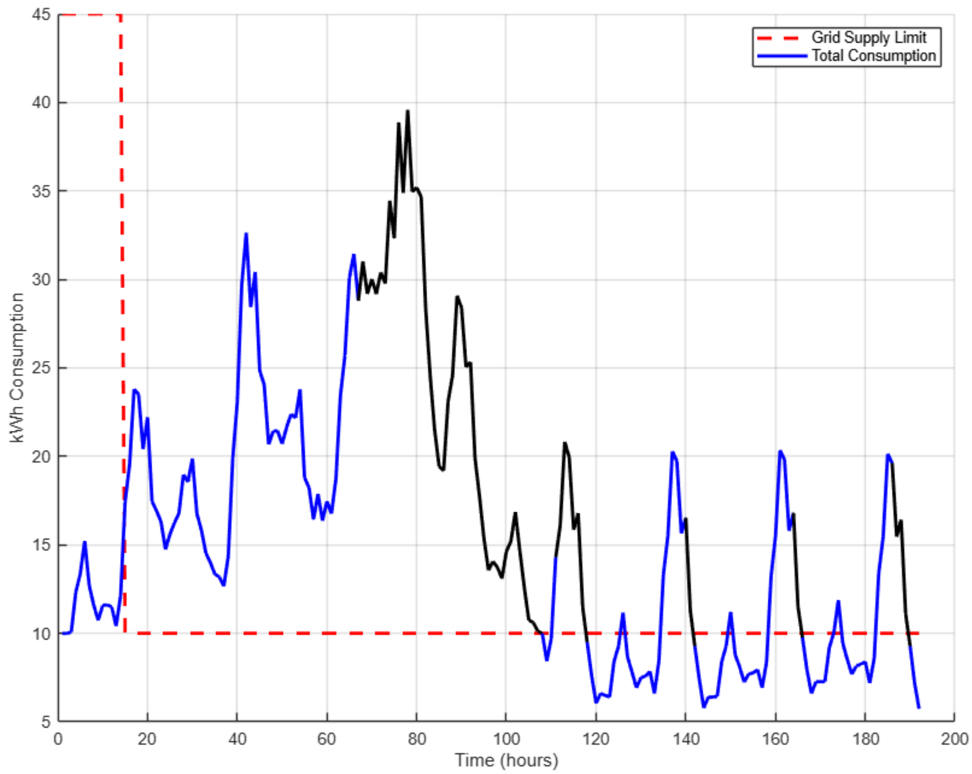

Figure 13: Harsh winter week power demand and supply with 10 kWh/h grid support and 540 kWh battery capacity, where blue represents the car battery supplying the villa and black when the battery is empty, all households 2023

The worst case scenario, shown in Figure 13, takes place during the 3rd to the 10th of December 2023, where the weather conditions were extreme which resulted in a significant increase of power usage. This case brings light upon what the self sufficiency technologies can truly handle to the maximum. The state of charge of the electric vehicle relative to the week presented in Figure 13 is shown in Figure 14, together with the rest of the outage types. If during the same week there were to be sunshine instead of the original case, where the entire week was cloudy and snow filled, the battery lasts for long and the biggest difference is the recharge rate when the largest power surge subsides, provided in Figure 14. If no changes were made to the power consumption behavior of the households they would last a drastically shorter amount of time, shown in Figure 16.

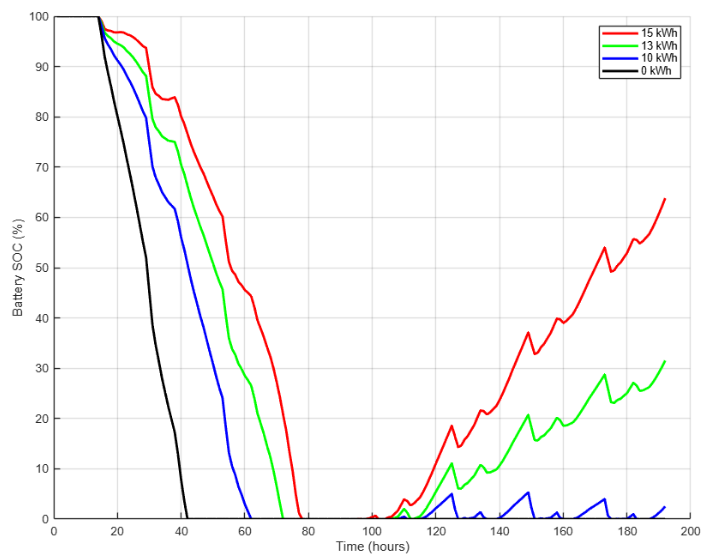

Figure 14: Harsh winter week power demand and supply using crisis method 2023 with 540 kWh battery capacity, all households

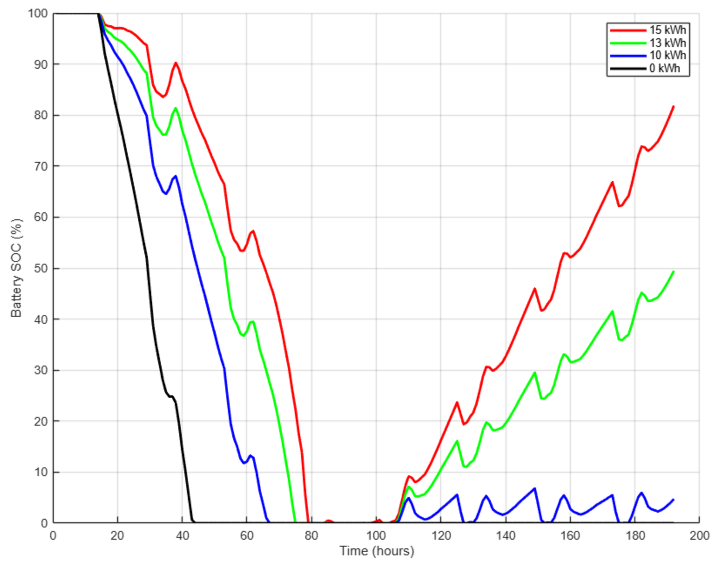

Figure 15: Harsh winter week power demand and supply using crisis method with solar power 2023 with 540 kWh battery capacity, all households

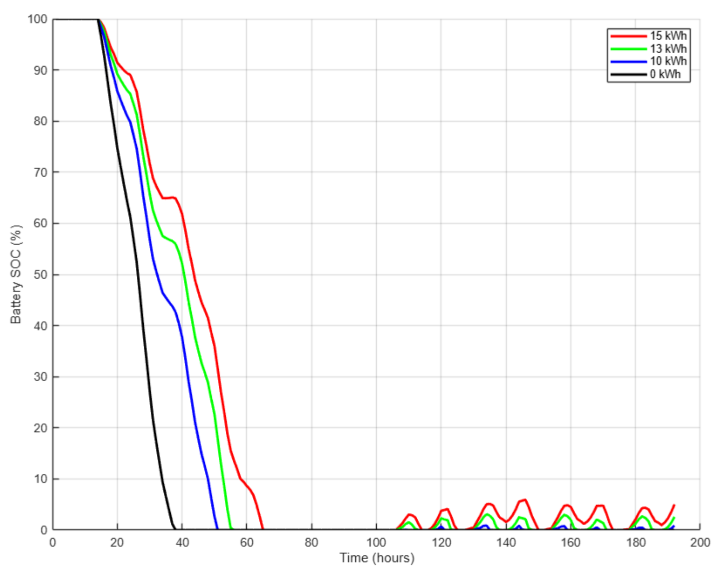

Figure 16: Harsh winter week power demand and supply with normal consumption 2023 with 540 kWh battery capacity, all households

Comparing the harsh winter week in 2023 with the same week in the mild winter of 2020 where the minimum temperature was 0.1°C. This week was sunny and thus solar generation was applied. The supply and generation can be seen in Figure 17., where effective supply is the combined power supply of the reduced grid supply and solar power. The state of charge in the electrical vehicle can be seen in Figure 19 and Figure 20. Looking at Figure 19 it is shown that without adapting with the crisis adaptation method, the households would last a significantly shorter time without any grid support. The most significant power consumption difference between these two weeks is the heatpump consumption which is based on the outside temperature, this difference can be seen in Figure 18 and clearly represent the consumption curves in Figure 13 and Figure 17.

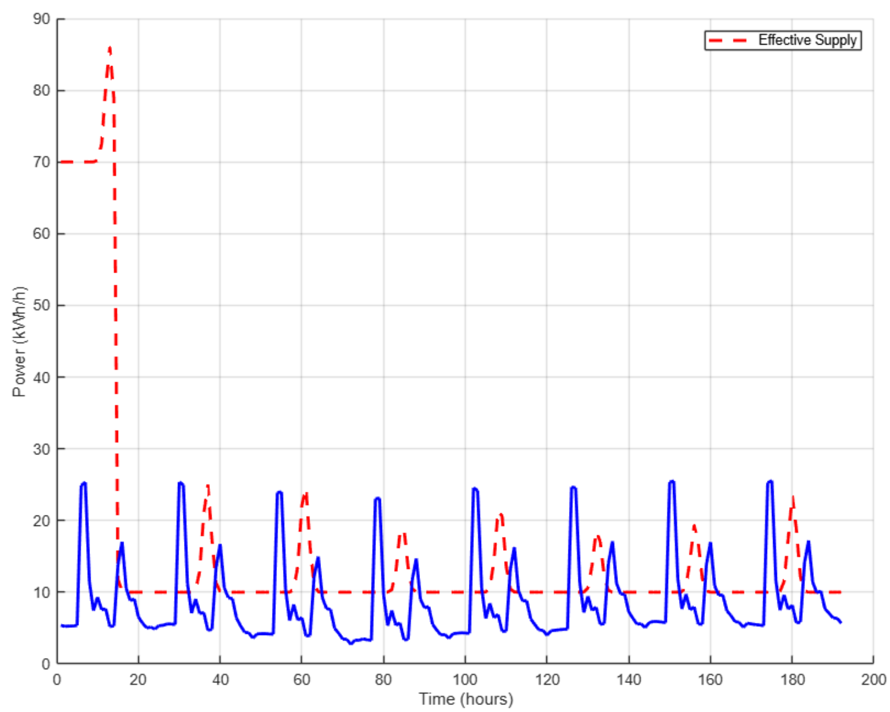

Figure 17: Mild winter week power demand and supply using the crisis method 2020 with 540 kWh battery capacity, all households

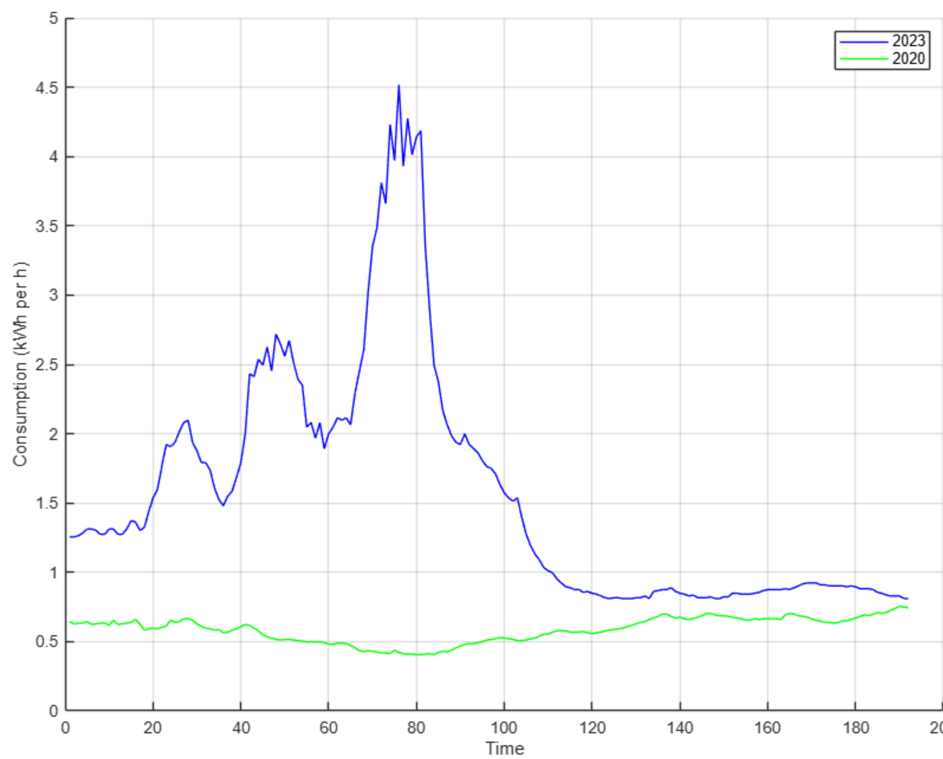

Figure 18: Harsh winter 2023 week heat pump consumption compared to mild winter week 2020 heat pump consumption, with normal consumption, one household

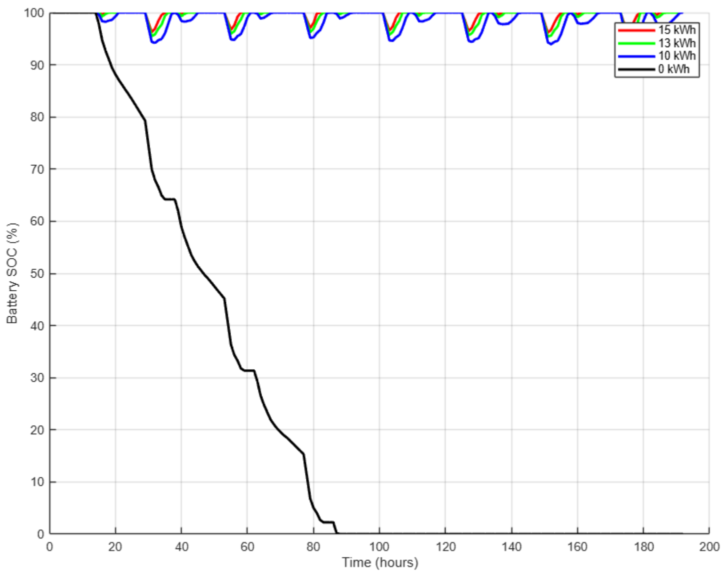

Figure 19: Mild winter week power demand and supply crisis method applied with solar power 2020 with 540 kWh battery capacity, all households

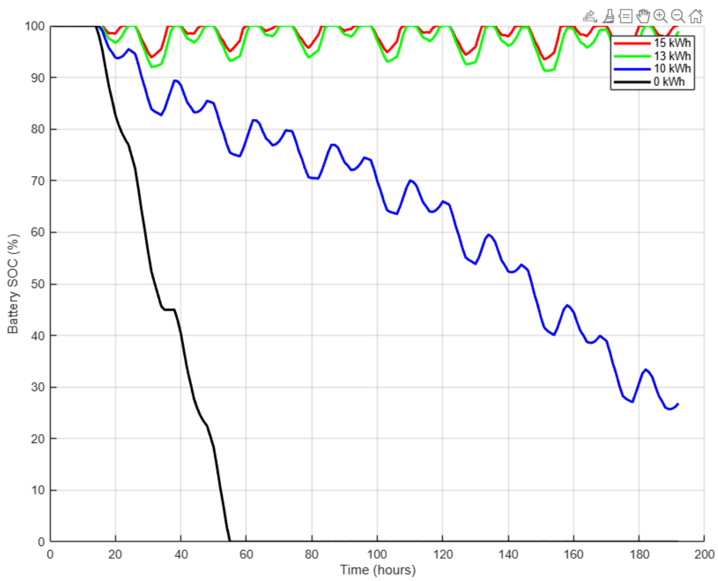

Figure 20: Mild winter week power demand and supply with normal consumption with solar power 2020 with 540 kWh battery capacity, all households

Then continuing with the week in 2020 but removing the solar energy, creating the scenario where the weather conditions match that of the harsh winter weeks original conditions, the results differ by a lot especially the type 2 and 3 outage lines seen in Figure 21. Figure 22 representing state of charge with and without applying the crisis adaptation method.

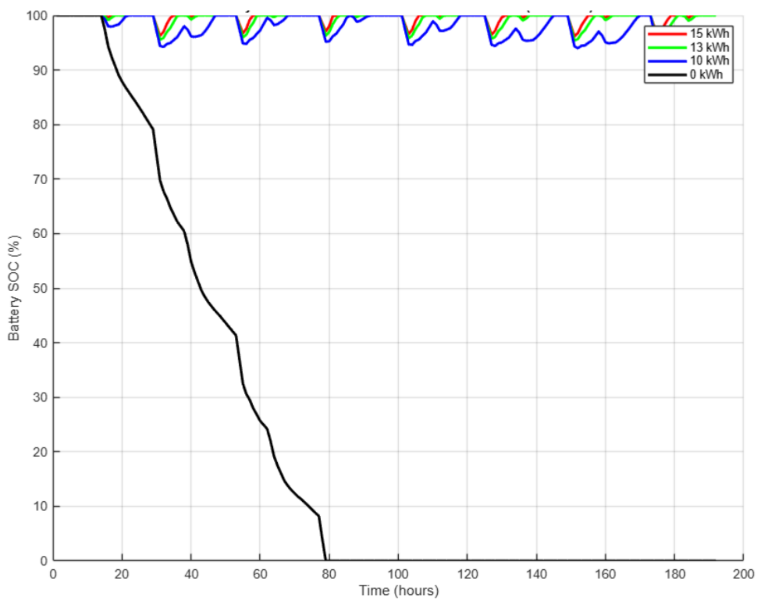

Figure 21: Mild winter week power demand and supply crisis method applied without solar power 2020 with 540 kWh battery capacity, all households

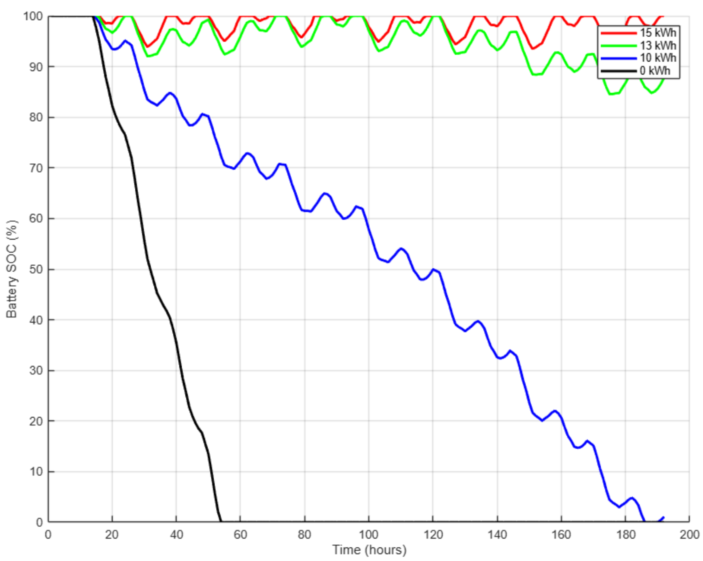

Figure 22: Mild winter week power demand and supply with normal consumption without solar power 2020 with 540 kWh battery capacity, all households

The same simulations were run when setting the condition to overwrite the 75% battery usage condition, leading to enabling the households to use the stored 720 kWh. Most electric vehicles with V2H systems have a limit to what SOC the V2H can be used to minimize degradation of the battery and to be able to operate the vehicle.

When analyzing the data it was shown that the resilience time increased by between 5 and 27 hours during the 2020 scenario. During 2023 however, it was noticed that the time gained was increased by between 7 hours and the entire studied period depending on the scenarios. It was noticed that once the batteries lasted longer than the power peak between hours 60 and 90, shown in Figure 13, they lasted the entire period since the batteries would start to recharge when the demand was low at hour 100.

4.4.1 Varied indoor temperature

The next case to be studied is how the indoor temperature changes the power consumption and resilience time of the household while using the electric vehicle batteries. The data provided by Figure 23 shows the defined power outage types with lowered indoor heat measured at each degree between 8°C and 21°C and the corresponding resilience time. These indoor temperatures are below what this project view of decent living conditions are, therefore in this case it is provided that the households each have a fireplace installed which allows for a deeper analysis of how significant the indoor temperature curve of the heatpump is in terms of power conservation. Using the fireplace 3 hours in the evening daily, during the period between October to March, normally saves an average of 27,32 kWh per day [7]. Comparing Figure 23 with Figure 14 where all the conditions are the same, but Figure 13 has the indoor temperature set to 16°C, which shows that there is a breaking point in the outage types 15 kWh/h and 13 kWh/h where only changing the indoor temperature the households can be provided with electricity the entire period.

Normally there is a thermostat in the house measuring the indoor temperature, but since this is a simulated household it was replaced with forced indoor temperature values for the heatpump in the code in order to replicate reality.

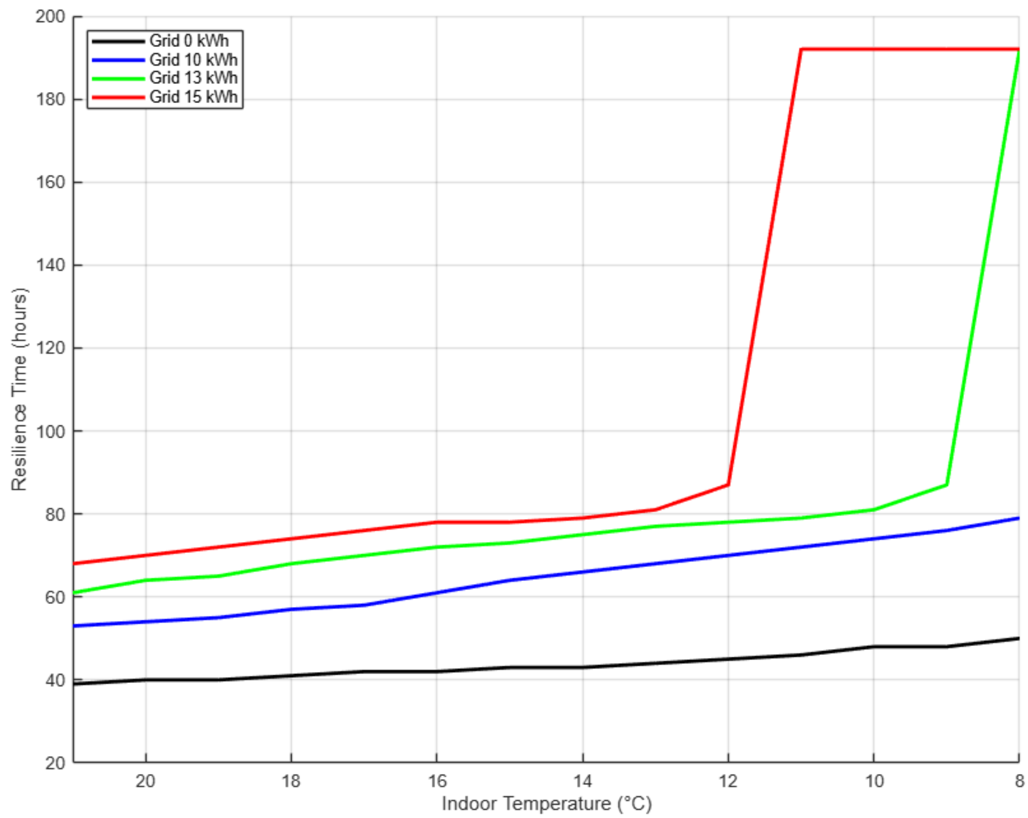

Figure 23: Resilience time with reduced indoor temperature curve of the heat pump while using a fireplace, using crisis method during harsh winter week 2023, total battery capacity 540 kWh

5 Results

5.1 Summer

Starting from the summer cases where the weather conditions are the most favorable and the resilience times are the highest. This is the period where the solar panels matter the most, providing all the households with more than sufficient power for normal everyday consumption during the duration from the 22nd of May to the 28th of August.

With the focus on the data in Figure 7 where only one household of type 1 is represented, it can be deduced that with all the households combined this would still be true. The reason being that since household type 1 is the type that consumes the most amount of power and the rest of the six households consume less power, overall brings the conclusion that the difference between consumption and solar generated power would be significantly increased. During mid summer where average daily solar power generation is 430 kWh per day and daily power consumption is approximately 252 kWh per day which in turn means that the solar panels can provide enough energy to completely cover the normal power demand without relying on the power grid or any type of power adaptation and still being capable of charging the electric vehicles 178 kWh per day.

Some benefits can be seen in using the crisis adaptation method in these cases as the excess power consumption are sent to the grid. This course of action enables energy transfer for backup power to important locations such as hospitals as well as other households for a collective support system for those without solar panels.

5.2 Spring and fall

Continuing on with spring and fall, where things take a turn and solar power slowly reaches the point where its production is no longer sufficient enough for normal power consumption. Starting of with looking at Figure 12 where with normal consumption and generated solar power was not enough to power the home during any of the spring and fall months. In order to cover the most of the period, the crisis adaptation method was needed. By using the method, day 58 marks the start of March where the household starts to be self sufficient with solar power. Continuing on with looking at Figure 9 where it is shown that the method makes the household self sufficient until the middle of October. When the crisis adaptation method is used, the heatpump indoor temperature value is set to 16°C. To further increase the resilience time, by using the fireplace which allows the household to lower the power consumption of the heatpump, which was set to 10°C in order to simulate the automated process. The fireplace lowered the consumption up to 32%, which made the household able to be self sufficient all of October as well, shown in Figure 24.

In order to see how long the households would be self sufficient without power after this change including the power storage, it was needed to look at the period where the solar power was not sufficient, namely February and November. Looking att all the households combined and utilizing the electric vehicles, the additional resilience days for February were given by

$$P_{\text{Deficit}} = 153kWh - 120kWh = 33kWh \tag{4}$$

$$t_{\text{Days}} = \frac{540kWh}{33kWh} = 16.4 \tag{5}$$

On the other end of the year, November, the extra resilience days were calculated using the same method, resulting in 27 additional days. Looking closer at what dates where the solar panels start and stop to supply the household with sufficient power, which in this case is day 59 and day 301. By extending this period with the amount of days calculated, the period can be increased to 86% of the year. Using this method can only show how much potential the system has in one go but it would leave the battery empty afterwards. This percentage however is abnormally high due to the year 2020 being record warm during the period between November and February.

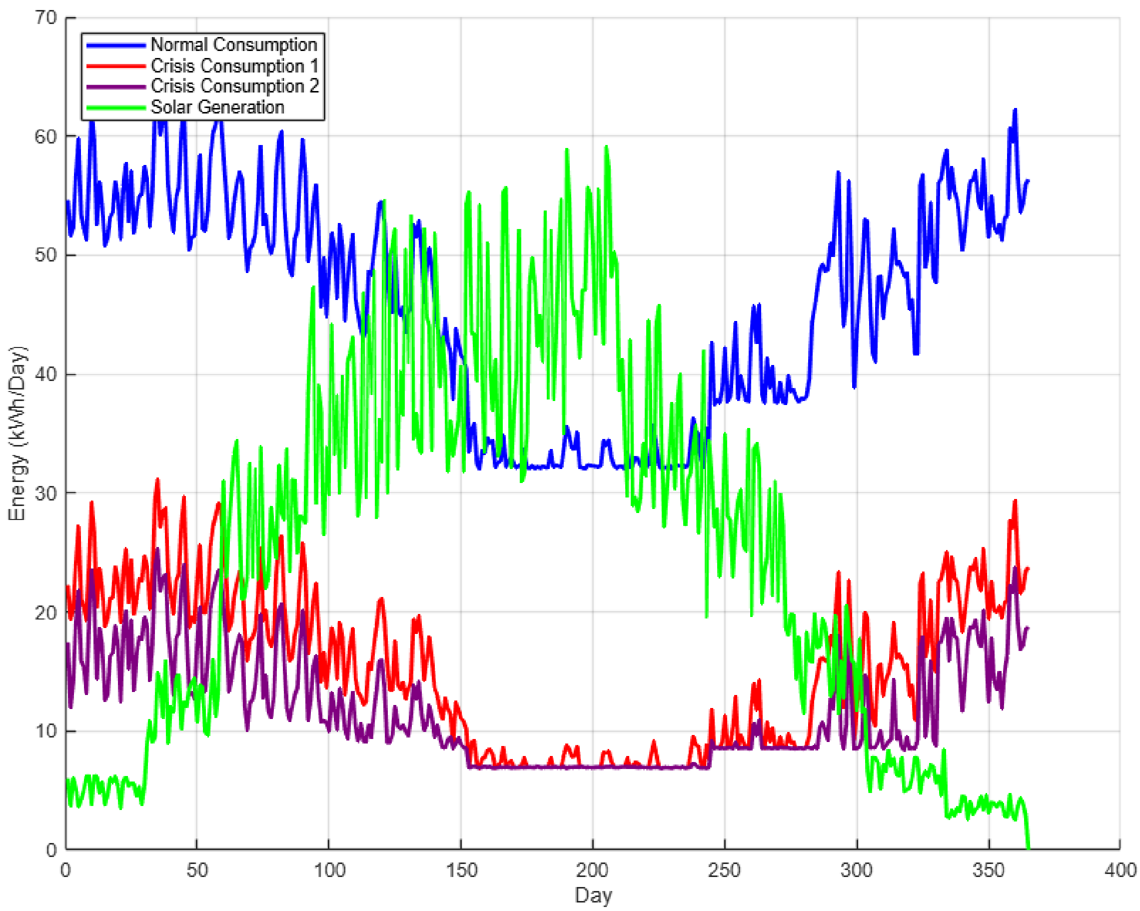

Figure 24: Normal power consumption, crisis consumption 16°C and 10°C and solar power generation, total per day for household type 1 during year 2020

5.3 Winter

Moving on to the winter season where solar power is rendered almost powerless, as the average solar power generated by all 10 of the households per day, such as during the winter shown in Figure 6 is 46 kWh per day. Winter is also the season where the most significant load, the heat pump, consumes the most power. This however is heavily dependent on outside and inside temperatures. Comparing the two different winter scenario weeks where outside temperatures vary a lot, since winter 2020 was a record mild winter where the temperature was the lowest at -8.4°C, compared to 2023 where the lowest temperature was -21.6°C. As an example the difference in the outside temperature alone changes the appearance of the consumption curve shown in Figure 18 when comparing Figure 13 with Figure 17. Even when applying the crisis adaptation method, solar power will never be enough, as presented in Figures 10 and 11, to power the household and therefore the households only option to last longer in relying on the electric vehicle.

5.4 EVs and solar power in winter outages

Having an electrical vehicle and charger with V2H and V2G technologies has created a possibility for these households to prepare for outages lasting a longer period of time. In these two example weeks of the harsh winter week in 2023 and the mild winter week in 2020 shows the significant impact that the solar panels and electrical vehicle can provide. The difference between the sunny or dark week shows a clear difference in time gained with and without the crisis power adaptation method.

Starting of with the 540 kWh total power storage, when looking at Table 2 and Figure 25 representing the resilience times given by the methods discussed in this work in the winter week of 2023. Solar power has increased the resilience time by 3% with normal consumption and 28.6% with the crisis adaptation method. Comparing the original case when there was no solar power generated, using the crisis method increased the time the households lasted by 16.7%. Whereas the 2020 winter week, shown in Table 3 and Figure 26, changed to 9.3% with normal consumption and 17.7% during the applied crisis method between using solar and without. Comparing the original case of 2020, when solar power was generated, between normal and the crisis method where the resilience time increased by 57.6% during a total outage.

Weather conditions proved to be the largest factor for the power consumption, for example the difference between using the crisis adaptation method during 2020 and 2023. Looking at the total power outage without solar power shown in Table 2 and 3, it is shown that the duration difference is 37 hours which is a difference of 88%. It can also be argued that this is because of the power peak of the heatpump which defines the curve of the total consumption in both 2020 and 2023 shown in Figure 18, in 2023 a peak occurs 40 hours after the start of the simulation, compared to the 2020 heatpump curve where there are no drastic power peaks.

Continuing on with how much longer the households lasted by using 720 kWh storage. During the 2020 week where outage type 1, 2 and 3 all lasted the entire studied period which was the same at 540 kWh storage. The total outage however was different, the resilience time increase was mostly linear for most of the cases with an average increase of 32%. During the normal consumption without solar comparison the time only increased by 9%. Now looking at 2023 where the result was the same linear increase that was expected except for the scenario of crisis consumption with solar, where the time gained was 113 hours to the end of the period. Solar power never had a big impact on the result. Comparing crisis consumption without solar to the result, it was expected that the time gained was to be 2 to 4 hours, yet it seems like those hours were enough to get over the power peak at between hour 60 and 90 shown in Figure 13. This was further confirmed by the fact that lowering the indoor temperature with the help of a fireplace down to 10°C, during the 15 kWh/h outage, where the power was enough to last the entire period even at 540 kWh, shown in Figure 23. Considering this result it goes to show that the last 25% of the battery can be saved for situations where the household can plan beforehand if they know that a cold period is coming and use the last power only if it is deemed to be recoverable after the hurdle is over.

Table 2: Time until battery depletion for all households during harsh winter week 2020

Battery size		Outage type (kWh/h)	15	13	10	0
540 kWh		Normal consumption without solar (h)	192	192	192	54
		Crisis consumption without solar (h)	192	192	192	79
		Normal consumption with solar (h)	192	192	192	55
		Crisis consumption with solar (h)	192	192	192	93
720 Kwh		Normal consumption without solar (h)	192	192	192	59
		Crisis consumption without solar (h)	192	192	192	103
		Normal consumption with solar (h)	192	192	192	75
		Crisis consumption with solar (h)	192	192	192	120

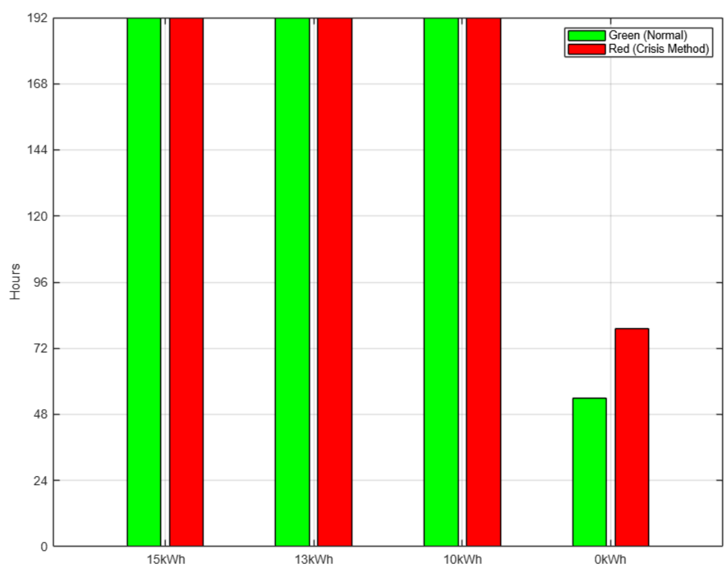

Figure 25: All households resilience time during mild winter week 2020, with 540 kWh capacity

Table 3: Time until battery depletion for all households during harsh winter week 2023

Battery size		Outage type (kWh/h)	15	13	10	0
540 kWh		Normal consumption without solar (h)	56	53	48	36
		Crisis consumption without solar (h)	77	73	62	43
		Normal consumption with solar (h)	68	59	55	37
		Crisis consumption with solar (h)	79	76	67	44
720 Kwh		Normal consumption without solar (h)	74	60	59	44
		Crisis consumption without solar (h)	85	79	73	50
		Normal consumption with solar (h)	76	72	65	46
		Crisis consumption with solar (h)	192	81	76	51

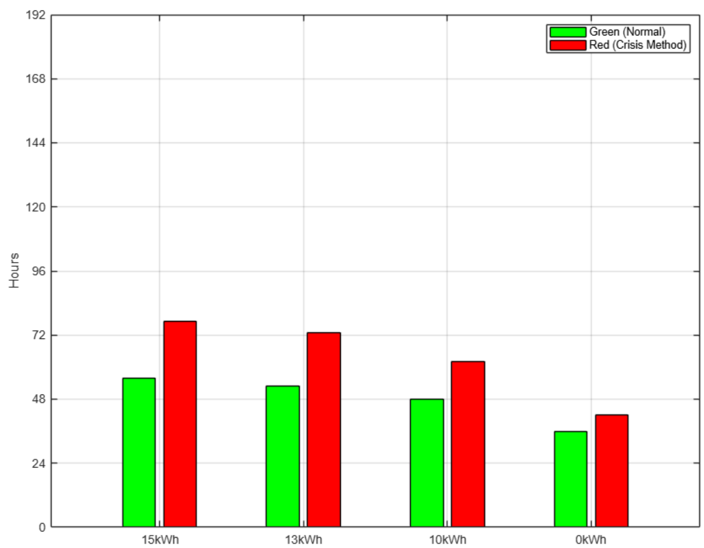

Figure 26: All households resilience time during the harsh winter week 2023, with 540 kWh capacity

6 Discussion

6.1 Interpretation of results

The hours gained by implementing the crisis adaptation method during the worst case period shown in Tables 2 and 3 might seem like a short amount of gained time, but this is not the case. In case of severe crisis, every hour of resilience is of great value as households gain the opportunity to prepare for food rations and clean water in case the power outage lasts for a longer period of time.

6.2 Solar power and electric vehicle importance

Seeing the presented outage types 1, 2 and 3, results might seem like the households end up with no power at all but this is not the case. The important difference is that each of the households will still be able to use small power loads and will need to prioritize only those loads necessary even though heating and hot water are still unavailable. In these cases the households would need to prioritize power loads such as charging phones and power banks in order to have means of communications and payment methods. This is where the importance of the electric vehicle comes into play. In order to retain heat and hot water the households need sufficient power supply and this is obtained through the bidirectional power conversion unit in the electric vehicle charger which is marked as 11 kW peak power. This is more than enough to keep heating on while preparing for the case of a lasting outage.

6.3 Economical difficulties

Due to the demanding economical preconditions for this projects methods, only a few households are able to adapt to solutions provided where these families belong to the middle to high end economical class. The electrical vehicles battery lifespan also decreases faster than normal conditions where the batteries does not go through charging and discharging at such a rapid pace, which further increases the economical demand. Economy is outside this projects bounds and therefor is an interesting and important topic to research further.

6.4 Hypothesized results

Prior to the start of the project, it was assumed that households could sustain themselves during winter, spring and fall for a maximum of 7 days without relying on the electrical grid in case of an outage. These expectations were based on the belief that using the solar panels and a reduced amount of energy consumption, such as lowered indoor temperature and reduced entertainment appliances usage to a minimum, would reduce the energy consumption to such a degree that the energy stored in the electric vehicle would sustain the household for a week maximum. During the summer it was expected that the households would be able to sustain themselves with only solar panels since power consumption is at its lowest and solar panel generation is at its maximum ,and if a situation rises, it would be enough to reduce consumption to only necessities.

7 Conclusions

7.1 Results from present work

The purpose of this project was to find out how long households can hold out in case of a power outage, as most households are ill prepared. The main focus on using electric vehicles and solar power as a power source proved to be sufficient for 27% of the year and could be further improved, by altering power consumption behavior leading to a household potentially being able to be self sufficient for 65% of the year. The winter is not included even though it´s the period where power is the most needed. By further investigating the winter period it was found that the resilience time varied heavily depending on the outside temperature. Studying one specific week but in different weather conditions, it was found that using the same crisis adaptation method for lowering the power consumption the result of the two different years during a complete power outage would vary by up to 88% depending on weather conditions. Considering that the outside temperature was the largest factor in resilience time it was decided to further look into how much lowering the indoor temperature would impact the result. By using a fireplace allowed the household to lower the power consumption of the heatpump which resulted in the resilience time to increase by 10 hours in the worst case and the best cases it would allow the household to last the entire studied period. It was discovered that the time difference between using 75% and 100% of the total battery capacity is not significant enough to give up transportation, especially so if the electric vehicle is their only form of transportation. The only reason to use all of the stored power would be if it is deemed to be recoverable after the foreseen hurdle is over.

7.2 Future work

The results of this project helps to provide a clear picture of what these systems are capable of and how much of an impact they can have in terms of self sufficiency as well as how much a small community can help each other in case of these outages as some households use less power than others. As of right now most households are not prepared for a power outage and this work sheds some light upon a possible solution. These technologies are available on the market but combined shows great promise in the future considering the pace as these technologies progresses.

The support of the power grid and backup power today is lacking but there are solutions covered before in terms of stabilizing the power grids to remove power surges, such as unused electrical vehicles being used as a large power bank, by using these as a way to support outages would also benefit more households that cannot supply themselves with energy. Researching this further would create more opportunities for adapting to the types of outages covered in this work.

Currently there are many workplaces that provide their employees the possibility of charging their vehicle at work which means that the amount of charging at home decreases. This work was made under the circumstances where all of the households were charging their cars exclusively at home. As mentioned previously, the system called "Styrel" shuts down different sectors and power lines when electric power is scarce in order to prioritize essential facilities. This does not only apply to facilities such as hospitals but the entire sector where the hospital is located, which in turn leads to certain electric vehicle charging stations still being functional. This creates a new scenario where, during these kinds of situations, some households can rely on that their electric vehicles are able to recharge their batteries in different sectors in order to prolong their resilience. While this is not their intended purpose today it may become a solution for these situations in the future, requiring further research. If the same investigation would be done considering people charging their cars at work or at charging stations instead of completely stop charging them at home during a power outage, the results would change significantly.

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