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Simulation and analysis of a photovoltaic system

with accumulation into hot water

Bachelor Thesis Project by

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Degree Program: Electrical Engineering and Computer Science

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II. Bachelor's thesis details

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Simulation of PV system with accumulation into hot water

Bachelor's thesis title in Czech:

Simulace FV systému s ukládáním energie do vody

Guidelines:

1. Literature survey
2. Mastering the simulation tool PV*SOL
3. Based on real consumption profiles calculate daily excess energy
4. Compare daily excess energy with hot water consumption profile
5. Calculate financial savings for a given type of electircity tarrif
6. Analyse system performance with one boiler and with two boilers in series

Bibliography / sources:

[1] Guillermo García Torres, Simulation and verification of PV system without accumulation in case of medium climate and low feed-in (inofficial master thesis)
[2] website: https://www.dzd-fv.cz/en
[3] book: Konrad Mertens, Photovoltaics: Fundamentals, Technology and Practice, ISBN: 978-1118634165
[4] e-book: Arno Smets, Klaus Jäger, Olindo Isabella, René van Swaaij, Miro Zeman, Solar Energy: The Physics and Engineering of Photovoltaic Conversion, Technologies and Systems

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

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Date: 04.01.2021   Sahithi Angara

Abstract

The topic of this Bachelor's thesis was to analyse the photovoltaic (PV) system performance of a house based in Czech Republic. Some of the main tasks that were performed included: the simulation of the PV installed house in the software PV*SOL, the creation of an electricity and water consumption profile and the calculation of daily excess PV energy available for this system. The objective was to provide usage for the daily excess PV energy, in the form of water heating for the house. In this way, the PV system performance was analysed for two possible solutions- a single boiler and two boilers connected in series. Additionally, an introductory look was presented that showed the current electricity state in my home country, South Africa- briefly discussing the need and potential for household PV system installations.

Abstraktní

Tématem této bakalářské práce bylo analyzovat výkonnost fotovoltaického (FV) systému rodinného domu se sídlem v České Republice. Některé z hlavních úkolů, které byly provedeny, zahrnovaly: simulaci instalovaného FV domu v softwaru PV*SOL, vytvoření profilu spotřeby elektřiny a vody a výpočet denního přebytku FV energie dostupné pro tento systém. objektivní bylo zajistit využití denní přebytečné FVE ve formě ohřevu vody pro dům. Tímto způsobem byl analyzován výkon FV systému pro dvě možná řešení – jeden bojler a dva bojler zapojené do série. Kromě toho byl představen úvodní pohled na elektřinu, který ukázal aktuální stav v mé domovské zemi, Jižní Africe – krátce pojednávající o potřebě a potenciálu instalace fotovoltaických systémů v domácnostech.

Acknowledgements

I would like to first express my deepest gratitude to my supervisor, Jakub Holovský, for all of his guidance and help, which made this work possible. A big thanks to my friends Lamia and Keresha, who were there to provide me with encouragement when I needed it the most. And a special thanks to my friend Abdulrahman, for all of his help and motivation, that greatly helped me through my last three years of university studies. Finally, last but not the least, I would like to give my heartfelt thanks to my father, mother and sister for their unconditional support in my journey, without which I would not be where I am today. I am especially thankful to my sister Sravani, who made me feel at home in Czech Republic.

List of abbreviations and keywords

1. **PV:** Photovoltaic
2. **IRP:** Integrated Resource Plan (A country's electricity capacity plan- indicating the country's electricity demand, how it will be supplied and the costs related)
3. **CSP:** Concentrated Solar Power (Technology that uses mirrors or lenses to generate solar power)
4. **OECD:** Organisation for Economic Co-operation and Development
5. **PV*SOL:** Design and simulation software of a PV system
6. **PV system:** A system installed with photovoltaic modules, that use the photovoltaic effect to generate electricity from sunlight.
7. **Daily excess energy:** The generated PV energy not used directly by the consumption of electrical appliances in the house.
8. **Consumption profile:** The data containing electricity consumption values per unit time, compiled for over a period of time (per minute/hour/day/year), e.g. a consumption profile for household electrical appliances or hot water.
9. **Electric boiler:** Uses electricity to heat water by converting electrical energy to thermal energy.
10. **Low and high tariff:** Price of consumption of electricity. Prices set by the electricity provider. During low tariff hours, a lower price is charged than during high tariff hours.

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Chapter 1: Introduction

1.1. Description of goals and presentation of topics

The topic as per topic registration is as follows: "Simulation of PV system with accumulation into hot water"

The objective of this Bachelor's thesis is to analyse the solutions to excess PV energy generated by a household PV system, namely for the purpose of heating water. This work will consist of approaching the objective in three ways- using the software tool PV*SOL, a case study and a mathematical approach. Each of the three approaches provide different information that allow us to perform certain tasks and lead us to compare two possible solutions: the solution with one boiler and the solution with two boilers in series.

The first part of the thesis (chapters 3 to 5), focuses on the goal to create an electricity and water consumption profile for a PV installed house and calculate the available daily excess PV energy. This is accomplished by first, using the software tool PV*SOL for the design and simulation of the PV system of the house in consideration. PV*SOL is used to perform two main tasks: to obtain the minutely generated data of the PV system and provide an overview of the financial savings analysis. We then proceed to calculate the daily excess PV energy available.

The second part of the thesis (chapter 7), focuses on the analysis of the excess PV energy for water heating, comparing it to the water consumption profile, for the two solutions. We first look at a case study approach for the two solutions by analysing a few theoretical cases that are evaluated by set of priorities. Then a second, alternative approach- a mathematical approach to the two solutions is presented. Which is analysed by looking at two negative evaluation criteria. The results of the case study approach and the mathematical approach are then compared for the two solutions.

1.2. Motivation

The motivation for working on this thesis, was to gain the knowledge of how household PV systems work with regards to the consumption demand and managing the excess energy generated. This thesis focuses on a system based in Czech Republic, but I hoped to explore how this knowledge can be useful in the case of my home country South Africa; where currently, there is a huge reliance on coal powered electricity. I believe the negative impacts of this reliance are too great and that the option of household PV systems should be more widely encouraged. Not only to manage the current energy crisis, but to also contribute to the need for a more sustainable environment for the future.

Chapter 2: An introductory review of the state of South Africa's electricity

A short review of the energy crisis in South Africa is presented as an addition to the motivation of this thesis. This section explores a few points of reasoning behind why I believe there is a need for more households in South Africa to be encouraged to shift to household PV systems. The objective of this thesis is to analyse the PV system performance for a house based in Czech Republic, namely the analysis of solutions to the excess PV energy by heating water. However, I believe the knowledge gained through the tasks performed can be investigated in the future for how it would apply or differ in solutions for South African households.

2.1. The current energy crisis in South Africa

In South Africa, CO_2 emissions and air pollution is a major, growing concern. In the 2019 data provided by OECD (Organisation for Economic Co-operation and Development), South Africa ranked 12th globally in CO_2 emissions, at 479 MtCO$_2$ (Million Metric Tonnes). [1]

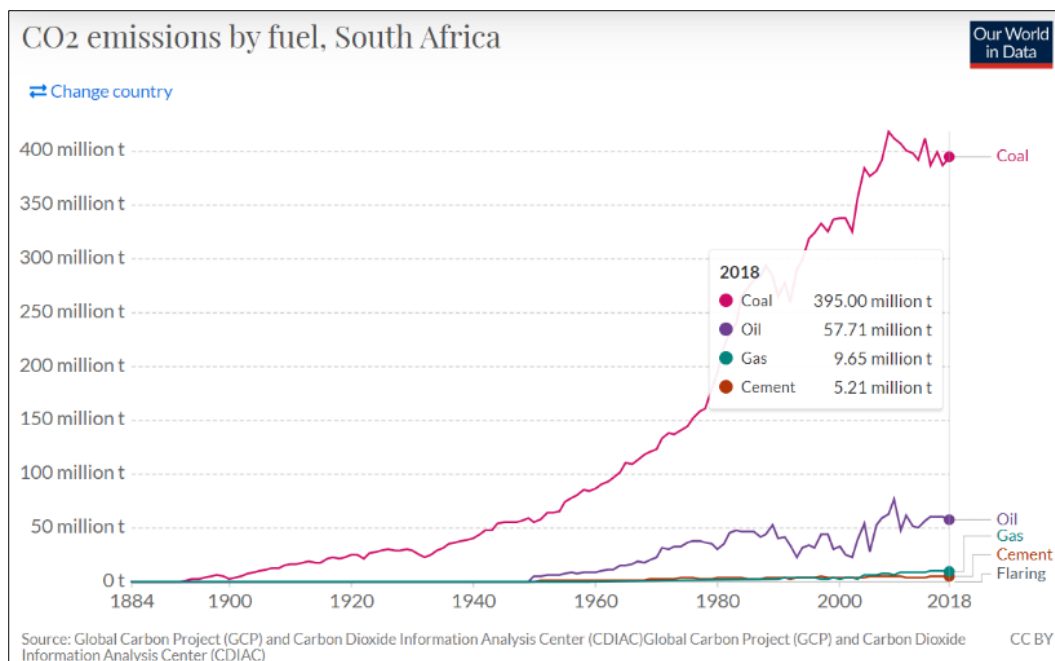*Figure 1: CO$_2$ emissions by fuel in South Africa for years 1884-2018*

Due to South Africa's heavy reliance on fossil fuels as a primary energy source, specifically coal, it sits on a high rank globally for greenhouse gases and CO_2 emissions. Coal can basically be singled out as the single-most impactful cause for these statistics, as about 88% - 90% of South Africa's electricity was produced from coal in 2018. [2]

This reliance on coal and coal mining processes is not expected to decrease for another two decades. One of the main reasons being an extreme lack of alternate energy source to replace coal. In the present time, more than ever, I believe a drive towards solar technology in the form of PV systems, for household solutions, is required. The major energy crisis in South Africa can linked to Eskom. Eskom is the primary electricity public supply utility in South Africa and the company uses over 90 million tonnes of coal annually, producing up to 90% of its electricity using coal fired power stations. [3]

There are numerous problems Eskom is currently facing- a huge debt crisis and the severe maintenance issues of their facilities- resulting in constant load shedding (electricity blackouts) throughout the country during peak demand periods as well as normal periods. The position Eskom holds in South Africa with regards to coal and it's usage is described by Eskom:

"*South Africa produces an average of 224 million tons of marketable coal annually, making it the fifth largest coal producing country in the world. 25% of our production is exported internationally, making South Africa the third largest coal exporting country. The remainder of South Africa's coal production feeds the various local industries, with 53% used for electricity generation. The key role played by our coal reserves in the economy is illustrated by the fact that Eskom is the 7th largest electricity generator in the world, and Sasol the largest coal-to-chemicals producer.*" [3]

Another growing concern is South Africa's poor air quality- due to air pollution exposure and effects. Which is attributed directly to greenhouse gases emissions. Fine particulate matter known as PM2.5 is an air pollutant that presents the greatest risk to health. Causing severe health problems as when inhaled, it is capable of causing serious respiratory illnesses and cardiovascular diseases. [4]

Data from OECD (Organisation for Economic Co-operation and Development) measures these effects using estimates of the "Value of a Statistical Life" (VSL) and the number of premature deaths attributed to ambient particulate matter. South Africa is estimated to have had 436 mortality per 1000 inhabitants in 2018. Ranking at first place compared to the G7 countries like US, Germany, Italy and Japan, and ranking at sixth compared to the G20 countries, falling just behind the highest polluted countries like China, India and Saudi Arabia. The figures below showing this comparison. [4]

Air pollution exposure — Exposure to PM2.5, Micrograms per cubic metre, 2010 – 2019

Source: Air quality and health: Exposure to PM2.5 fine particles - countries and regions

Show: Chart | Map | Table | fullscreen | share | download ▼ | My pinboard ▼

Location ▾	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
South Africa	29.37	29.39	29.06	28.64	28.83	29.03	28.49	28.58	28.44	28.33
Italy	20.09	21.19	18.64	17.91	16.91	17.81	15.56	15.87	16.03	15.85
OECD - Total	15.67	16.23	15.24	15.28	14.80	14.76	14.04	14.01	14.06	13.93
Japan	11.72	12.88	13.32	13.58	13.92	13.60	13.54	13.76	13.66	13.65
Germany	16.25	15.74	13.95	13.72	12.37	12.86	11.90	12.01	12.05	11.93
France	14.86	14.78	13.53	13.45	11.51	12.23	11.44	11.39	11.49	11.37
United Kingdom	12.39	12.95	11.39	11.37	10.83	10.32	10.15	10.29	10.10	10.02
United States	9.23	9.27	8.88	8.65	8.45	8.18	7.39	7.76	7.79	7.68
Canada	7.90	7.35	7.61	7.28	7.50	7.28	6.21	7.28	7.07	7.09

Figure 2: South Africa and G7 Country rankings for Air pollution exposure

2.2. Household PV (photovoltaic) systems

The term 'photovoltaics' refers to the process of direct conversion of sunlight into electric energy. And photovoltaics as an energy source provides an alternative to the coal power generated electricity. Some of the main advantages of photovoltaics include: they are a renewable energy source, that are almost free from any emissions and few if any, environmental or hazards. They are also naturally occurring in nature, i.e. no direct fuel costs and the energy is essentially inexhaustible.

Some of the disadvantages to name are: a large scale implementation of this technology or even other renewable energies in a country, require large amount of investment costs. The energy densities where a sufficient amount of energy can be used are small in many areas. And the biggest disadvantage to mention, would be the varying energy supply- to ensure there is a supply of energy regardless of the time of day or year. The energy from photovoltaics is especially effected by this as the generated electricity directly depends on the available sunlight and weather conditions. Therefore, back-up power stations are required to ensure a constant power supply. [5]

However, a small scale installation, namely, a household photovoltaic system can provide a solution that allows people to lower their dependence on the grid. Household photovoltaic systems allow users to produce their own power for household electrical consumption needs through a photovoltaic system installation.

The basic component of a photovoltaic plant being the solar or photovoltaic cell- semiconductors that consist of Silicon in most cases. A small voltage is generated in a single cell through the photovoltaic effect, and, in order to achieve a usable voltage, many of these cells are switched together in series in a solar or photovoltaic module. Several of the solar modules are connected in series into a string, what we call solar panels. [5]

A typical structure of a household photovoltaic plant consists of these strings placed on the roof, connected to an inverter. The inverter converts the direct current delivered by the modules to alternating current for household electricity use. Some other components include: A mounting surface for the PV modules, charge controllers (for stand-alone PV systems) and cables. Based on where this system is installed and the priorities of the users, three main types of PV systems can be installed [6]:

1. Stand-alone or off-grid PV systems- rely on solar power only and a load, or they can include batteries for energy storage.

2. Hybrid PV systems- Combine PV modules with a complementary electricity generation method like gas or wind generators. Their purpose is to optimize the different methods of generation and typically require more sophisticated controls than stand-alone or off-grid systems.

3. Grid-connected PV systems- Are connected to the electricity supply grid via inverters. The principle being that an oversupply or excess PV electricity is transported to the grid and the grid in turn supplies the house with electricity during periods when sufficient PV power was not generated.

Of main interest to us, is the grid-connected PV system which is the type of house that was analysed in this thesis.

When there is an excess PV energy generation, there are some solutions that can provide usage for this energy [6]:

- Selling the excess energy to the electricity grid: In countries where the government has in place schemes, electricity can be sold to the grid for a price. The offered prices being the deciding factor in whether or not it is profitable. In the case of Czech Republic, this is not a financially profitable option, which is explained in chapter 6 of this thesis. Also in the case of South Africa, it is not a viable option for many households, which is explained later in this chapter.

- Storage of energy into batteries: For short to medium-term usage, batteries are the most common storage technology. Lead acid or Lithium ion are rechargeable batteries that are typical examples that are used. When batteries are used, charge controllers are included, which disconnect the batteries from the PV modules when they are fully charged or may disconnect the load to prevent the batteries from being discharged below a certain limit. Some of the main advantages of this option include:
  - ➢ Increasing self-consumption of generated solar power.
  - ➢ Excess PV power stored is available at use any time, during day or night. And, for batteries that are installed with a blackout protection, they can also be used in times of electricity outages.
  - ➢ Some companies may offer a cost-effective installation of the batteries at the same time as PV module installation.

  Some of the disadvantages include: It is not a long-term environment friendly option and they are still an expensive solution compared to a solution, for example, to use excess PV energy for water heating through boilers.

- Water heating solution: (Considering the excess after consumption of household electrical appliances excluding the electric boilers) Excess PV power can be used to heat water for consumption, acting as a thermal storage. The advantages of this choice include:
  - ➢ A more cheaper option to that of batteries.
  - ➢ An ease way of storage of energy.
  - ➢ For a high water consumption profile of a house throughout the year, it is the most beneficial choice.
  - ➢ A sustainable form of usage.

  Some of the disadvantages include: There will be losses in energy and the excess PV energy can only be used for water heating.

The is the solution of interest to us, as the objective of this thesis is to analyse such a system performance for the case of a single boiler and two boilers in series.

2.3. PV potential and barriers in South Africa

There is great potential for Solar energy technologies in South Africa. Being one of the sunniest countries all year round- it receives about 2500 hours of sunlight annually and up to 8-10 hours of daily sunshine in many regions. According to the report by GET.invest (European programme that aims at mobilising investments in decentralised renewable energy projects):

"SETRM(The Solar Energy Technology Roadmap) estimated that 40 GW of Solar PV and 30GW of CSP can be developed in South Africa by 2050. Currently contracted capacity, anticipated to be installed by 2021, amounts to 2,321 MW for solar PV and 600 MW for CSP. The IRP 2016 envisions 17,600 MW of CSP and solar PV generation by 2050, in addition to the already contracted capacity."[7]

However, there are many barriers for South Africa to transition into successful green energy country- The debt crisis of Eskom and the political stance the government takes on Eskom in the public eye, are some of the causes halting the progress towards other energy alternative sources [8].

To gain an overview on specifically the solution of household PV systems, an interview was conducted with Mr. Jacque Fernihough from BushPower- a household solar systems installation company in South Africa. The following points summarise the main topics that were discussed [9] :

- The current electricity situation in South Africa is quite unstable, when asked about the main causes, the following response was received,
  "With Eskom, the government controlled provider of electricity, having a huge maintenance backlog. As such, the infrastructure is not coping with increased demand." [9]
- The cost of solar installations is the main factor that is stopping people from choosing the household PV option.
- The main barriers for a transition into green energy include corruption within Eskom that is slowing down the transition, according to Mr. Jacque Fernihough,
  "Rules around whether households can feed into the grid, also need to change. Doing so will encourage households to install more solar than they need, and in doing so, be able to feed excess into the grid, and get paid for it." [9]
- With regards to the grid feed-in tariffs, it is currently not a viable option in South Africa for many households, the motivation to shift to solar is low, but in the next 5-10 years, Mr. Jacque Fernihough expects that there will be an increase in solar solutions in South Africa.
  "Many towns and cities still do not allow feeding into the grid, and if they do, they make it very difficult to apply to do so. Also, the rate they offer does not make it attractive for households to install more than they need."[9]

For current households in South Africa with PV installations, the option of batteries is the popular choice for usage of excess PV energy, as it provides power for times of load shedding- the periodic electricity outages from Eskom. A future investigation can be conducted, for the possibility of extending

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the analysis that was performed in this thesis for a household PV system in Czech Republic, to the case of South African households.

Chapter 3: Analysis of a household PV system in Czech Republic

This chapter introduces the first approach of using the PV*SOL software simulation tool in order to achieve the objective. This software was used to accomplish two main goals- to obtain the generated minutely data of PV energy and for analysing the financial savings, which is presented in chapter 6.

3.1. Location and PV system characteristics

Before we created our project for simulation in PV*SOL, we needed some details about the house and its current PV installation characteristics. The house that the software was used on is Mr Jakub Holovský's residential home located in Revnice, Na Výšině 978, Czech Republic, coordinates: 49.9º N-14.2º E.
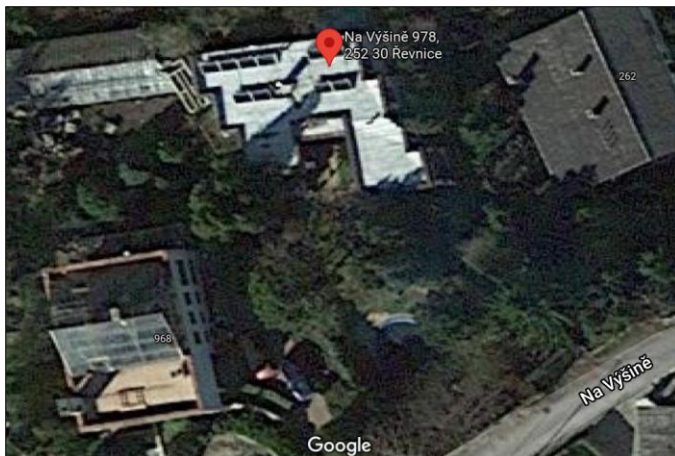

Figure 3: Aerial view image of the house located in Revnice

The house is installed with the PV system with the solar panels mounted on the roof.

Figure 4: Installed solar panels on the roof of the house

The physical and electrical characteristics of the installed PV system:

Number of modules	10
Power of single module	325 Wp
Total power of PV system (all modules)	3.25 kWp
Azimuth angle (module aligned with azimuth of house)	173° (South-South East)
Angle of the structure	30°
Inverter model	GoodWe 3000NS, power: 3 kW

Table 1: Physical and electrical characteristics of the installed PV system

Parameters of installed PV modules:

Manufacturer	Jinko Solar
Model	Jinko solar cheetah perk, JKM325M-60V
Efficiency	19.48%
Power	325 Wp

Table 2: Electrical parameters of the installed PV modules

Using the information of the location of our home and the physical/electrical characteristics of our PV system, we were able to build the model in the software.

3.2 Design of the PV system

After defining the starting details in a new project, the main parameters for the design of the model of a PV system are the "Consumption and thermal system" [10] and "3D Design" [11]. A summary of the steps that were followed in these two parts of the design process is presented in this section. Once all the parameters of the design were defined, a simulation of the PV system behaviour was performed.

3.2.1. Consumption and thermal system

A consumption profile, which is the annual electricity consumption for our house, can either be selected from the database where there are templates available or we can provide our own data if we have it.
In our case, own data of the consumption profile was imported. How this data was obtained is explained in chapter 4, section 4.3, where we look at the creation of the consumption profile of the household electrical appliances.
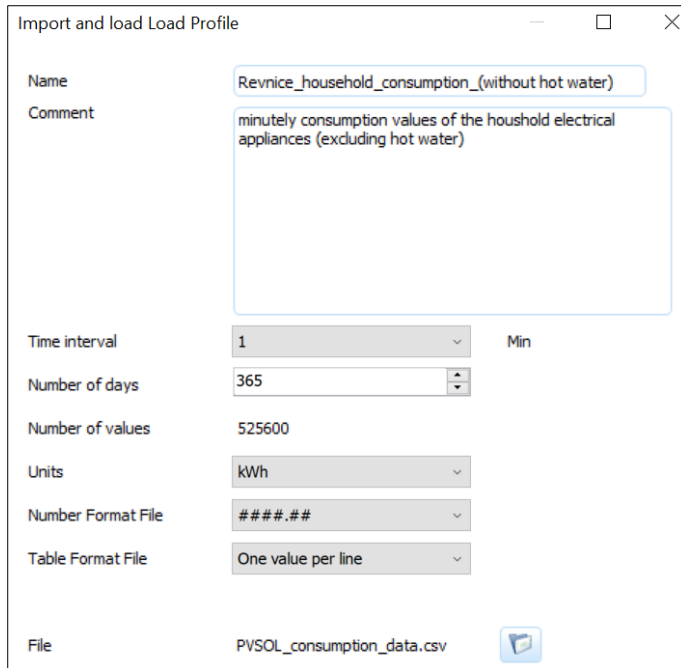
Figure 5: Defining our own consumption profile in PV*SOL

After adding the consumption details, we have the "Thermal system" in the software [12] . Here, we can choose if we have a heating system, hot water system or both in the house. In our case, we have only the hot water system with some storage tank specifications.

Energy for the hot water consumption is extracted from the storage tank (boiler). It is also here that thermal losses occur, and they depend mainly on the height, thickness of insulation and temperature of storage environment to name a few parameters.

The heating element is of the 'variable' type with maximum power of 2 [kW] and uses the excess energy in the PV system to heat water stored in the storage tank. The annual hot water demand is also included. This value comes directly from the water heating demand that is explained in chapter 5, where the water consumption profile was created.

Note however, that this value is only an annual consumption value based on a profile pre-defined profile in the PV*SOL software, and only for a single boiler. The software doesn't allow simulation with two boilers. Therefore, the calculations and analysis considering the hot water consumption profile and excess PV energy are performed outside of the PV*SOL software, in MS Excel, for the cases of a single boiler and two boilers. This is presented in chapters 4-5, 7.

The consumption (household electrical appliances without hot water) for the year is displayed after our defined profile is imported:
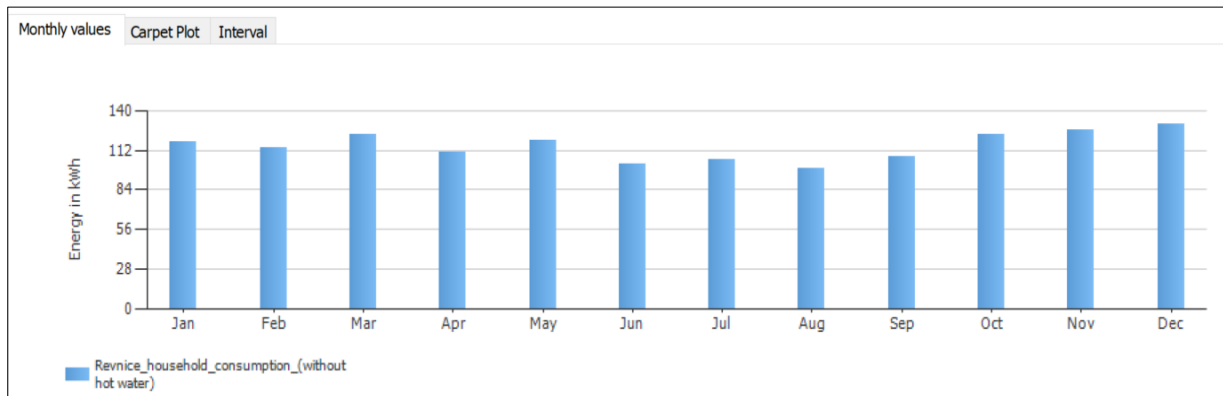
Figure 6: Annual household consumption (excluding hot water consumption)

3.2.2. Model of the house

The design of the model of the house is started by selecting "3D Design→ Edit". Once selected, the model of the house and the installed PV module configuration can designed in the 3D editor environment of the software [11]. The simulation of the PV system behaviour was performed after these tasks were completed.

The points below summarise the main steps that were followed when the model was created:

- Placement of appropriate dimensions of objects such as buildings, trees, chimney/vents on the roof surface etc., was done in the "Terrain view" and "Object view" options on the main taskbar.
- The selection of our installed PV modules, by searching the manufacturer and the product version was performed in the "Module configuration" option. Checking the "Also products that are no longer available" allows us to choose products for the simulation that are no longer in use.
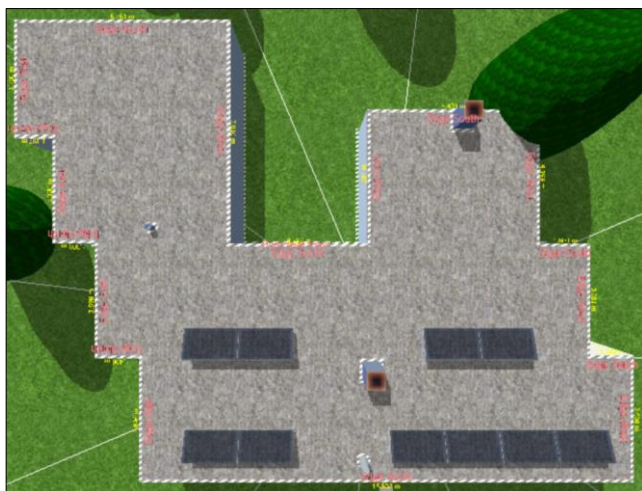
*Figure 7: Adding chimneys and vents onto the roof in 'Object View' of PV*SOL*

Double clicking on our modules shows us additional information including the module basic data, electrical data and other characteristics. Important information like the I/V characteristics at STC and at various irradiances (the rate at which radiant energy is incident on per unit area) can also be seen.

Figure 8: I/V Characteristics of our module in the additional information screen

- The type of module placement, in our case, is by module mounting on the roof surface. The mounting angle and other parameters were defined in the "Module Mounting → Assembly System" option.
- The last step of the building of our module was the selection of the inverter. This was done in the "Module Configuration → configure all unconfigured Modules → select inverter configuration" option. Similarly to the selection of the PV modules, the manufacturer and the product version were searched in the database. The "Show Inverter" displays the inverter product information, and other additional information like the electrical data, MPP Tracker and other data.

After confirming our choices and leaving the 3-D environment, the data was saved to our project for simulation.
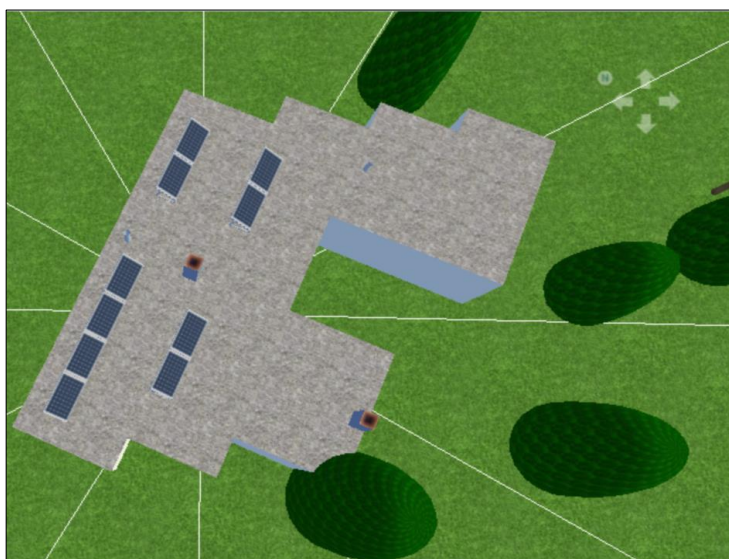
Figure 9: Terrain view of our final 3-D model

3.3 Simulation

After entering our project, consumption data and designing the 3D model of the house, the final step was to simulate the behaviour of the PV system. This is done by selecting the "Results" option on the main taskbar (Note, the options "Cables", "Plans and Parts" are not used). For precise simulation results, the "1 minute" option of "Time step of simulation" was chosen when the project data was entered.

An overview of the simulation results:

PV System

PV Generator Output	3.3 kWp
Spec. Annual Yield	987.37 kWh/kWp
Performance Ratio (PR)	82.2 %
Yield Reduction due to Shading	5.3 %/Year
PV Generator Energy (AC grid)	3,216 kWh/Year
Direct Own Use	503 kWh/Year
Heating element	1,023 kWh/Year
Down-regulation at Feed-in Point	1,690 kWh/Year
Grid Feed-in	0 kWh/Year
Own Power Consumption	47.3 %
CO$_2$ Emissions avoided	911 kg / year

PV Generator Energy (AC grid)

Legend: Direct Own Use, Heating element, Down-regulation at Feed-in Point, Grid Feed-in

Appliances

Appliances	1,379 kWh/Year
Standby Consumption (Inverter)	7 kWh/Year
Heating element	1,023 kWh/Year
Total Consumption	2,410 kWh/Year
covered by PV power	1,526 kWh/Year
covered by grid	883 kWh/Year
Solar Fraction	63.3 %

Total Consumption

Legend: covered by PV power, covered by grid

Thermal system

Hot water demand	1,834 kWh/Year
Thermal losses	341 kWh/Year
Total heat demand	2,175 kWh/Year
covered by boiler	1,151 kWh/Year
covered by heating element (solar)	1,023 kWh/Year
Solar Fraction (Thermal system)	47.1 %
CO$_2$ Emissions avoided	235 kg / year

Total heat demand

Legend: covered by boiler, covered by heating element (solar)

The results of the simulation provide many details and values. Some of the important results of interest to us are:

The *"PV generator energy (AC grid)"* value of 3216 [kWh], is the annual PV energy our system generated after the inverter converted it to AC. This is the simulated total value by PV*SOL. However, we note that the actual value measured of the generated PV energy for the year was lower than this simulated value. This will be explained more in detail in chapter 4, when the calculations for excess energy are performed using these simulated generation values, but they were rescaled for accuracy.

And of this 3216 [kWh] generated, 1963 [kWh] was used for consumption of our own appliances ("*heating element*" of 1023 [kWh] and *"Direct own use"* of 503 [kWh]) which amounts to about 47.3% usage for self-consumption. The remaining 53% is not sold to the grid as it is not a profitable option, as explained in chapter 6. Therefore, we instead aim to maximise this excess PV energy for self-consumption. Of the three possible solutions for usage of this excess PV energy as mentioned in chapter 2, section 2.3, our usage is for heating of water.

Another value of interest could be the *"solar fraction"* value (not shown in the overview above) of 63% which provides insight on the level of self-sufficiency of our system- the ratio of amount of energy for consumption provided by the PV system (1526 [kWh]) to the required (2410 [kWh]).

The graph below shows the distribution of PV energy usage over the course of the year.
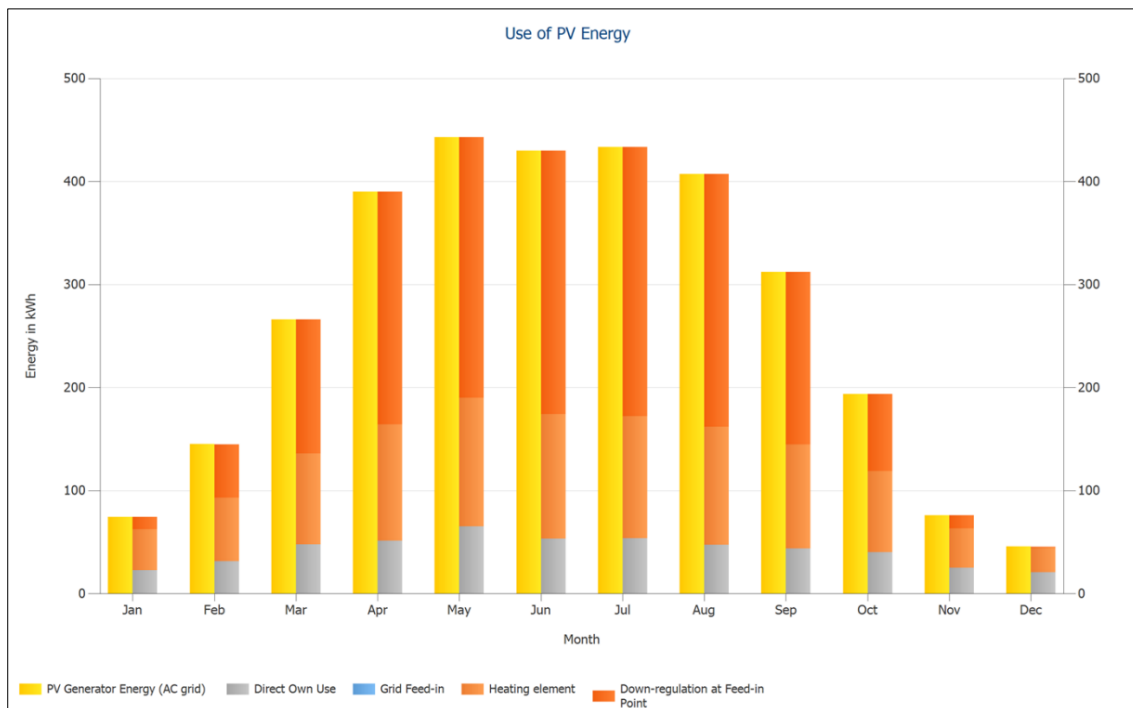

Figure 10: Distribution of PV energy usage over a year

Still on the "Presentation" tab, the final step is to export the minutely generated PV energy values from PV*SOL after the simulation. This data, exported in .csv format, will be used to perform the rest of the calculations on MS Excel.

Chapter 4: Daily excess energy based on consumption profile

In this chapter, we create the electricity consumption profile of Mr Holovský's house. Which is the profile of the amount of electricity used by the household appliances in a day (not including the consumption of hot water). Based on this consumption profile, the daily excess PV energy was then calculated. The daily excess PV energy refers to the energy not directly used by household electrical appliances.

The reason we analyse the daily excess energy is not because there is a problem to secure hot water for the house, as we always have the grid to supply the heating required. But the point is that if we generate electricity by the PV system, we cannot practically supply this to the grid (technically it is possible, but economically, it is not a viable option as the cost for which we sell to the grid is not profitable, as explained in chapter 6).

As such, for the purpose of our analysis, we considered the connection to the electrical grid to be essentially a one-way flow- from the grid to our house. To meet our priority of consuming everything that is in excess for personal use, the basic rule we follow is to match our consumption to the production for our own use as much as possible.

4.1. Tools for measurement and analysis

In the first step before proceeding with the calculations, we need the information of the electrical connection scheme of the PV system, grid and the household appliances as well as the consumption data.

From the scheme shown below, we note the following main components and details:

- We have a 3 phase grid connection; first and second phase have installed wattmeters (let measuring meters from top to bottom be labelled as meter A,B,C)
- SEMS Portal website connected to inverter (GW3000-NS)- measuring generated electricity from our PV modules and supplied into first phase.
- Meter A: measures consumption of the house on the first phase (excess into pool filter is not measured).
- Meter B: measures consumption by preheat boiler from first phase (120l).
- Meter C: measures consumption in second boiler from second phase (125l).

- Solid state relay connected before the preheat boiler.
- Flowmeter connected between second boiler and preheat boiler.
- Wattmeters (meters A,B,C) and flowmeters connected to Energomonitor.
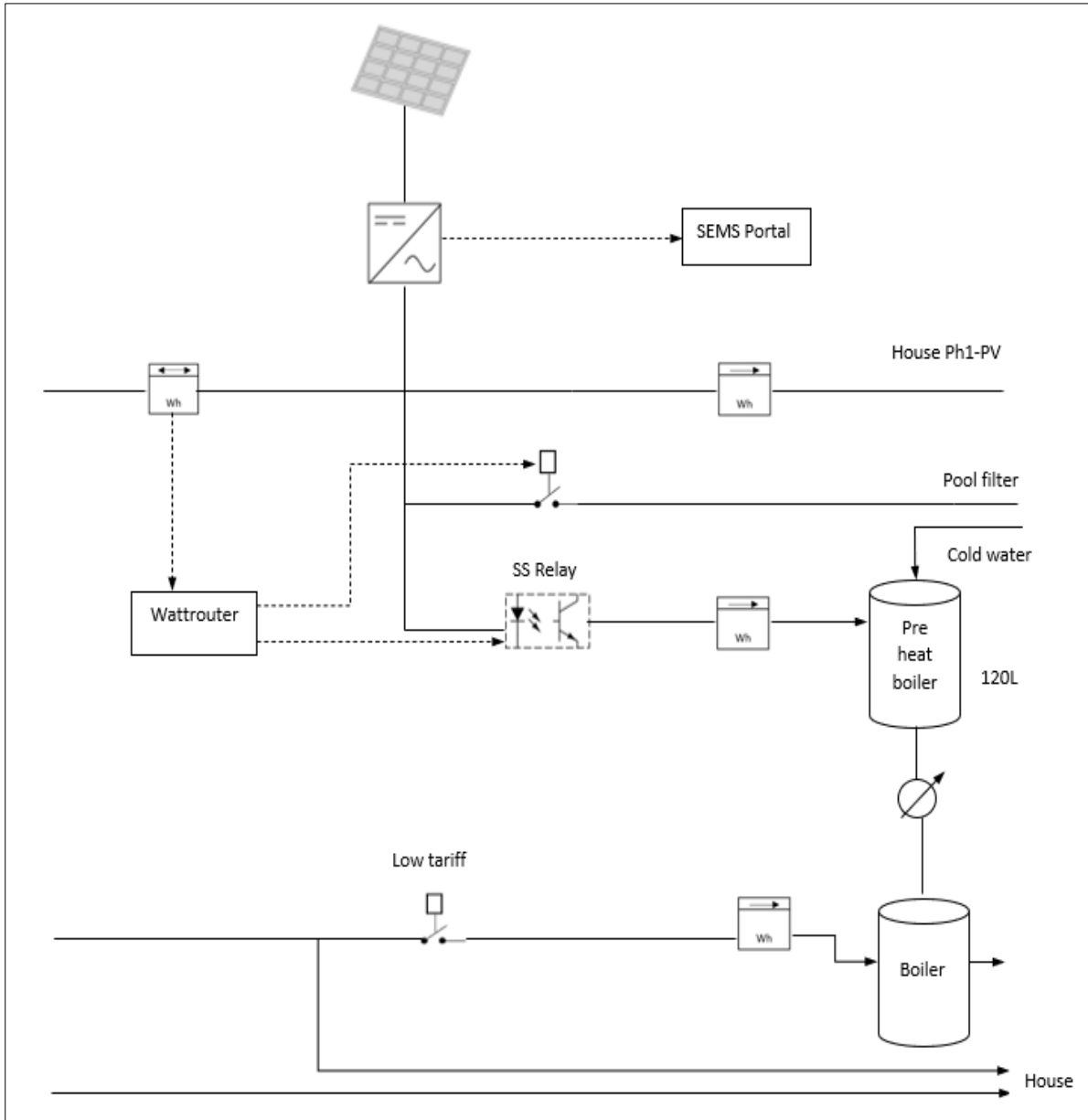
Figure 11: Measurement scheme of the house electrical and PV system

We note that for the analysis in this project, the pool filter is essentially not considered in calculations. This is because, the meter A is measuring the consumption of the house except the boilers and pool filter; and meters B and C are measuring only the consumption of the boilers. Meter A gives us information about the consumption of the household electrical appliances and the sum of the meters B and C gives us the knowledge of the hot water energy demand. This information is sufficient for our objective and analysis.

The generated minutely data taken from PV*SOL are the simulated values that will be rescaled to the real generation values (obtained from <u>SEMS Portal</u>- website connected to inverter installed in the house). The reason for this is that when we calculate daily excess energy, we need to know the exact matching between generation and consumption, so we need the lowest possible time-step, and we are not able to extract minutely values of real PV generation. Hence the calculations with the rescaled simulated values will be performed.

The tools that were used to obtain the data and perform calculations:

- <u>SEMS Portal:</u> Website that provides the data for generated electricity by our PV system modules; done via the GOODWE inverter connected to the website.
- <u>Energomonitor:</u> Website that provides the data about electricity consumption of our house; obtained by wattmeters installed in all the phases.
- <u>PV*SOL</u> (alternatively to SEMS Portal): the software can also provide the values of generated electricity by our PV system modules via simulation.
- <u>MS (Microsoft) Excel</u>: the websites and the software above usually export data in .csv or .xlsx format- so MS Excel was used to compile, calculate and analyse the data as well as to generate graphs.

4.2. Generated electricity

The first step in our calculations was to obtain the values for electricity generated from our PV system. This can be done in two ways- using the simulated values from PV*SOL software or taking the data from the inverter connected to website SEMS Portal.

If the second option of collecting data from the SEMS Portal website is chosen, the website provides you the information for generated values for any date. Logging in to the site and choosing our plant, we see the welcome screen that displays data for that day. The smallest resolution we can obtain is the total values for a day for a year. By selecting the document button next to the date, we see the screen for various reports we can export (see figure below).
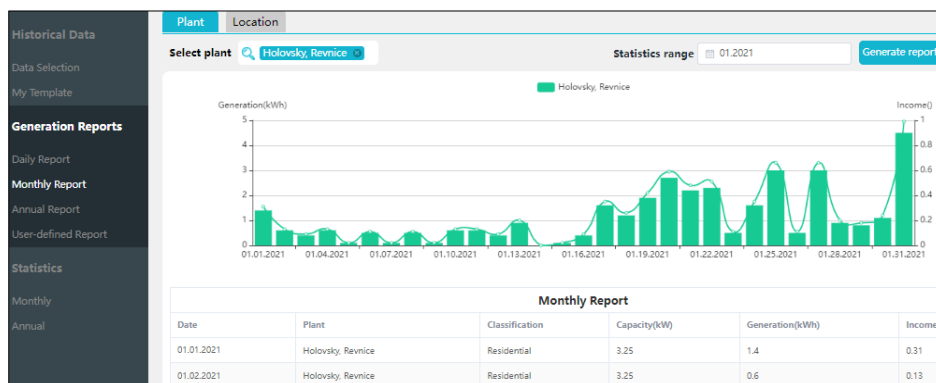

Figure 12: Exporting data from the SEMS Portal website

We can export the type of data we would like- daily, monthly, yearly etc. The smallest resolution available on the website, is the 24 hour total value for a day, for everyday of a month. For the "Monthly report" under the "Generation Report" option, choosing the month under the "statistics range" option provided the total daily generated electricity values in [kWh] for every day of that month. The figure above shows the monthly report for January 2021. Exporting the data results in a .csv format, allows us to open the values in MS Excel.

However, for our analysis as we mentioned before, we are concerned with the "daily" excess, so we would like to place our focus on a single day. As such, even though the SEMS Portal website can provide the exact total generation values for a day it cannot provide it for hourly, or minutely. Therefore, for precise analysis, we use the PV*SOL data from simulation results in chapter 3, which provided the simulated minutely values.

For the year 2021(Jan-Nov), the SEMS Portal data generation data showed that the actually generated PV energy was lower than the simulated values from PV*SOL. As such, before using the minutely data from PV*SOL in calculations, they were rescaled with the correct ratio to match the generation total from SEMS Portal (note: the total value is taken from last year: 2773.2 [kWh], because we have the whole year total and it could be said it would be similar to the total of 2021, seeing as Jan-Nov 2021 total was around 2636.2 [kWh]).

The graphs below show an example of the generated PV energy after rescaling the minutely simulated values, for 20th June, a typical summer day and 30th January, a typical winter day. The difference between a typical summer and winter day can be seen. On a clear, sunny summer day, we experience a full day of generation from morning to evening. Whereas for a cloudy, winter day, there is significantly lower amount of generated PV, with almost all of the generation occurring for just a few hours around noon.
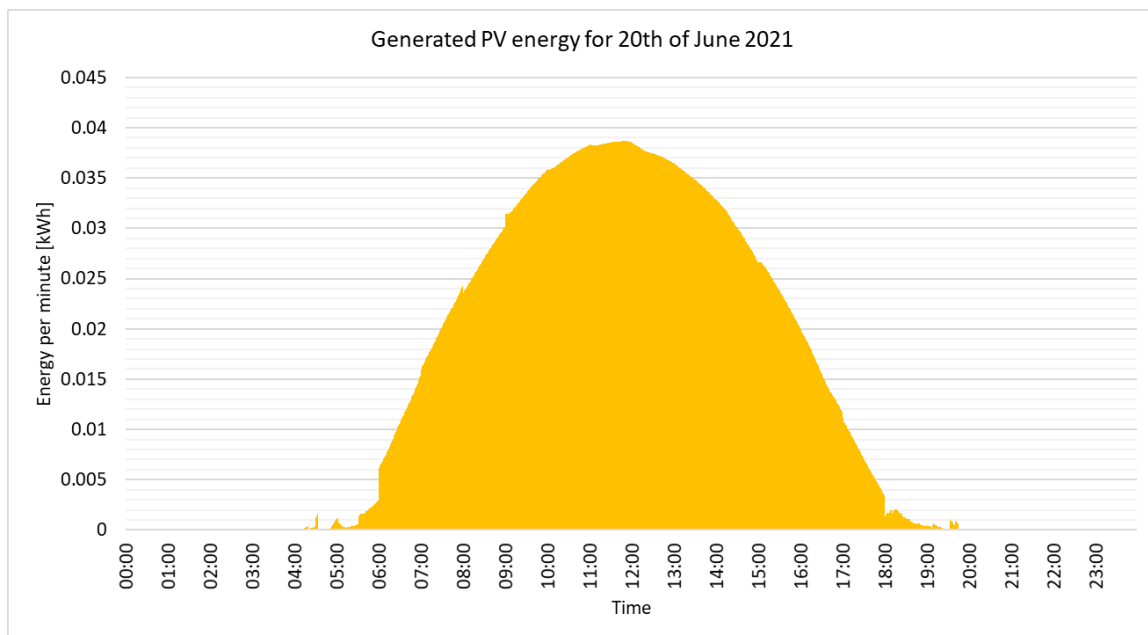
Figure 13: Generated PV energy on 20.06.2021
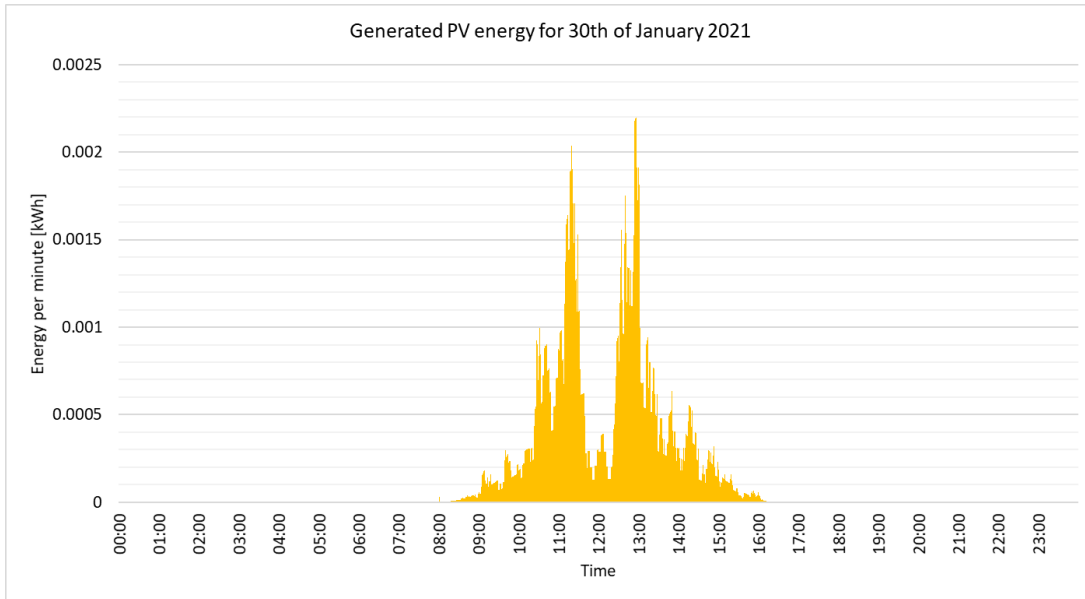
Figure 14: Generated PV energy on 30.01.2021

4.3. Electricity consumption

According to our connection scheme, we consider that our main consumption for the house is measured through meter B, phase 1 with PV. In order to see the data for our consumption, we use the website Energomonitor, which gives us the electricity consumption data in all phases where wattmeters were installed as well as information about water consumption.
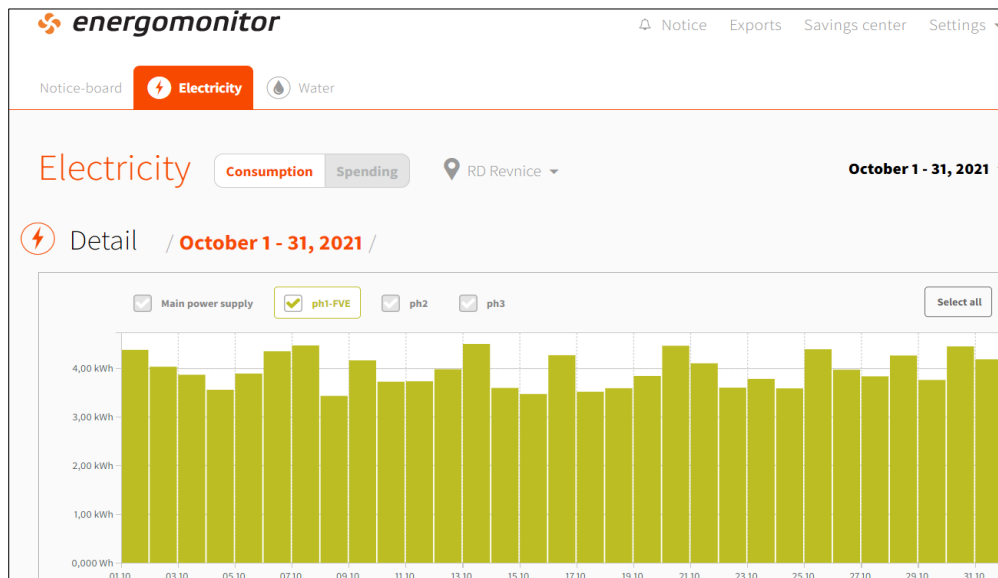
Figure 15: Electricity consumption data screen on the website Energomonitor

We are concerned with the total consumption of our house by the electrical appliances, excluding hot water. For precise analysis we need the minutely values per day. Similarly to how we obtained the data of the electricity generated, here we do the same by selecting the option of "Exports" and then choosing the time step and date range for which we would like to collect data. In our case, we chose the "no aggregation" option that provides the smallest scale of data possible which is minutely consumption. The time period specified was 01.01.2021 to 30.11.2021 (the latest measured values available at the time of this project).

After specifying these details, we can export the values in .csv format to continue our calculation process. Note: the website is not able to provide the huge yearly/minutely data at once. Data needs to be requested in smaller chunks, e.g. a month at a time maximum, and then compiled to form the full year profile.

The figure below is a snapshot of the data that was exported to the Excel sheet for the month October 2021. The highlighted (blue, orange, green) columns correspond to values for wattmeter A-phase 1 with PV, wattmeter B-phase 1 and wattmeter C-phase 2, respectively. The dates and times in (yy-mm-dd hh:mm:ss) format are given in the first column.

Figure 16: Snapshot of data extracted from Energomonitor on MS Excel

4.4. Calculated daily excess energy

After obtaining the daily values of generated energy simulated by PV*SOL (rescaled according to data from SEMS Portal) and the daily consumption values from Energomonitor, the daily excess energy values are calculated. In the next chapter we create the hot water consumption profile and compare it to the daily excess energy profile for the year.

The calculation was done with minutely values, as the difference between minutely generation and consumption. There will be days when the consumption values are higher and in this case, there is essentially no excess available (the calculated excess energy is a negative value, so we compute it as 0 excess energy available). This would be the case for example, on a cloudy day in winter, when it is possible that we have essentially little to no generation of PV energy or all of the PV energy was used by consumption of the house electrical appliances.

The graph below shows this excess energy per minute for 20th January 2021. Similarly, the calculation was performed for the whole year.
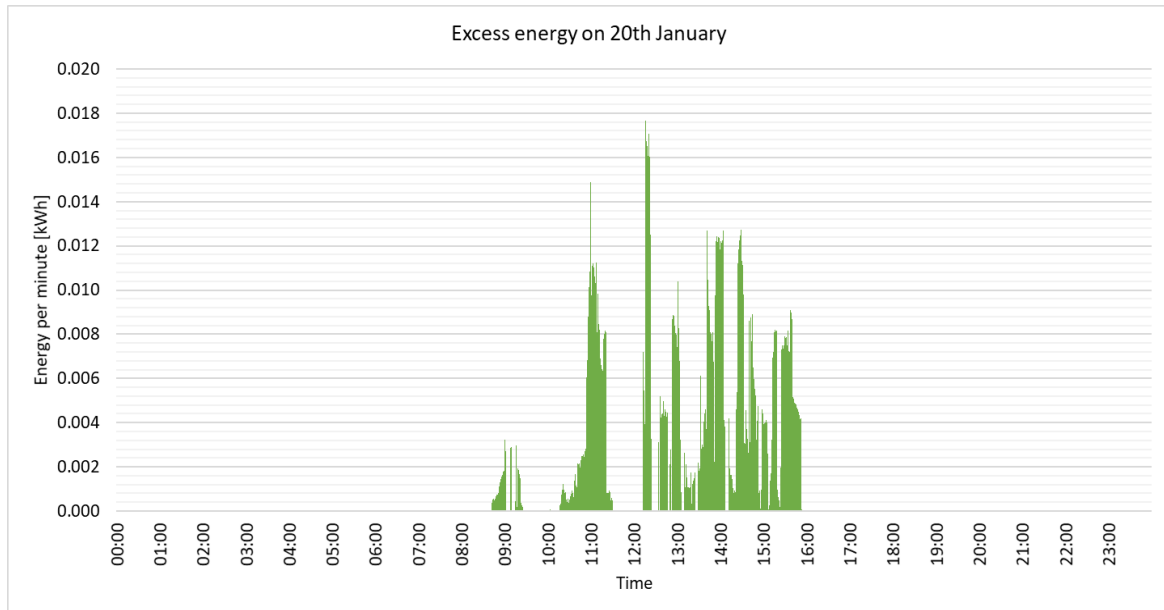
Figure 17: Excess energy on 20.01.2021

The generated PV electricity data was extracted from 01.01.2021 to 30.11.2021, as that is as further as the data that was available at the time of this project. For generated PV energy, we may take the previous year's values for December. However, the same can't be done for the consumption values as the connection scheme for the house was changed from January 1st 2021, and the way we are measuring consumption is not the same as last year. Therefore, in this project the yearly data for 2021 from January to November was considered.

The daily excess values were calculated minutely. However, in chapter 7, when the system performance with a single boiler and two boilers in series is analysed, the summed minutely to hourly values of the excess and consumption were considered for convenience in calculations.

The graphs showing the excess energy calculated for the months of February and June 2021 are attached in the appendix.

Chapter 5: Daily excess energy and hot water consumption profile

In this chapter, a hot water consumption profile of the house is created. This is then compared to the daily excess energy profile created in the previous chapter. The data for the hot water consumption was taken from Energomonitor, where we looked at the minutely data for the period of January-November 2021.

The current configuration of the house, for the hot water heating system, consists of two boilers. The first one being the pre-heat boiler with a capacity of 120l and the second one with a capacity of 125l. And as previously mentioned, the pre-heat boiler is supplied with excess energy from the PV system, with its consumption being measured by the second wattmeter B. And the consumption of the second boiler is measured by the third wattmeter C, connected to phase 2. The second boiler provides hot water connected to the bathroom.

In order to build our hot water consumption profile, i.e. the hot water demand for our house, specifically, the consumption measured through wattmeters B and C was used- the sum of the two values of consumption measured by meter B and C. The monthly values of the heating demand are more or less the same for the course of the year as seen below:
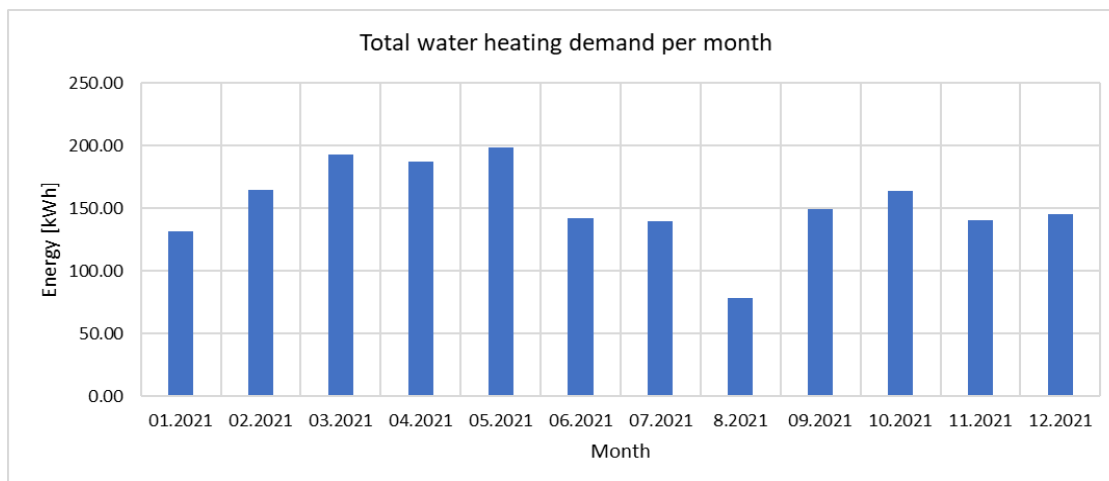
Figure 18: Hot water consumption profile for the year

There was a lower hot water demand measured in August are there was a holiday period of 2 weeks when no consumption of hot water occurred.

Shown below is an example day, the 8th of July's excess energy vs heating demand. This is the minutely data shown, of the calculated excess and water heating demand. In this case, there was an abundance of excess PV energy due to the sun shining all day. However it can also been seen that during many hours in the afternoon, our consumption is much lower than excess, and any energy not used to heat water is essentially lost. This is an example of a typical peak summer day where a lot of hot water is not needed or used during the day.
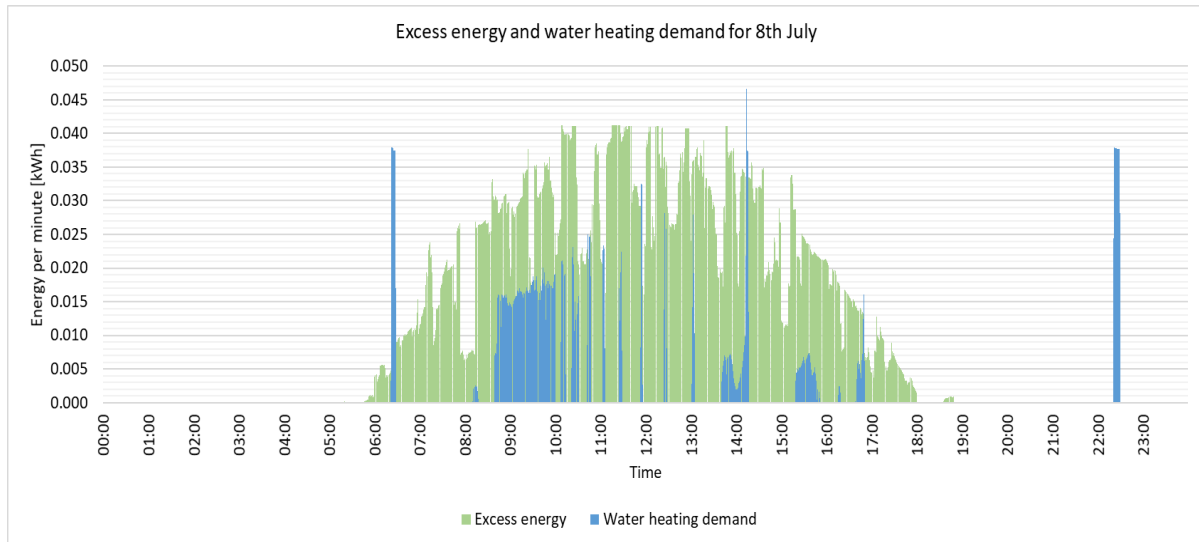
Figure 19: Excess energy in comparison to the hot water demand on 08.07.2021

In contrast, the graph below shows the comparison for the 17th February, and the February of 2021 being one of the coldest ones in Czech Republic in the last 5 years. It's can be seen that during many hours of the day, there is essentially no excess PV energy available. As it's a typical cold winter day, we have high hot water demands with several peaks during the day, mostly early morning and the night time. In this case, it is possible that we encounter situations of discomfort where there is a hot water demand but the boiler is empty. In such cases, a back-up heating is relied on to meet the demand.
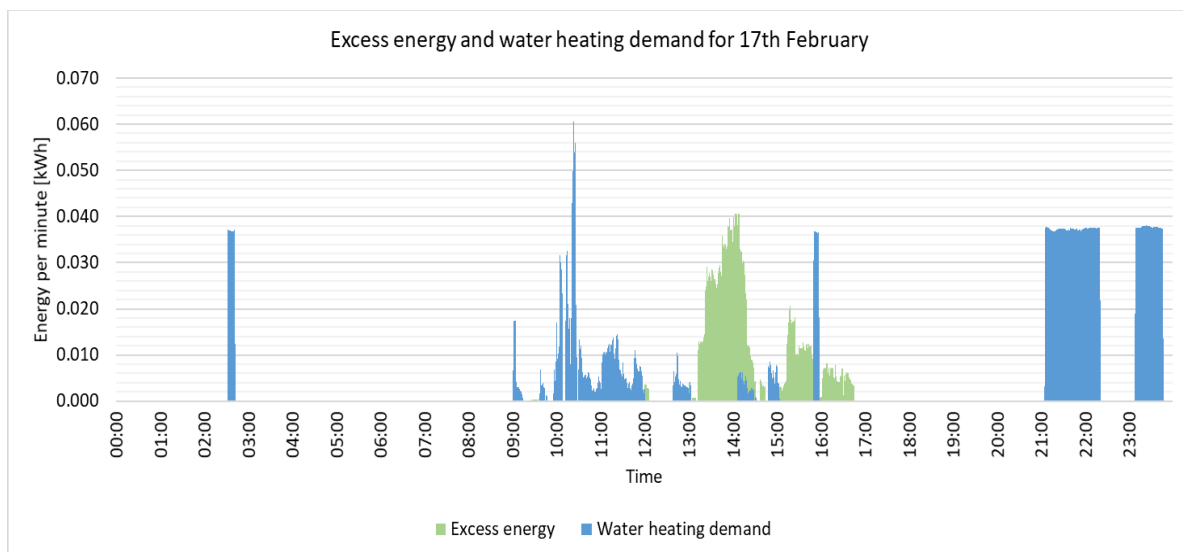
Figure 20: Excess energy in comparison to the hot water demand on 17.02.2021

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In chapter 7 of the thesis, this excess PV energy and hot water consumption profile, were analysed further, and two solutions were presented- the solution with a single boiler and two boilers connected in series. With two main approaches that were analysed for how the excess PV energy available and the hot water demand can be managed.

Chapter 6: Financial savings for a given type of electricity tariff

6.1. Feed-in tariffs in Czech Republic

Feed-in tariffs are defined usually by law, that distributors have to buy electricity from producers (our household PV generation) when we have a grid-connected system. In the past, it was a popular choice of setup: The generated electricity was supplied to the grid and the energy that was required was bought back. It was a profitable situation as the cost at selling electricity was less than the cost at which it was bought [13].
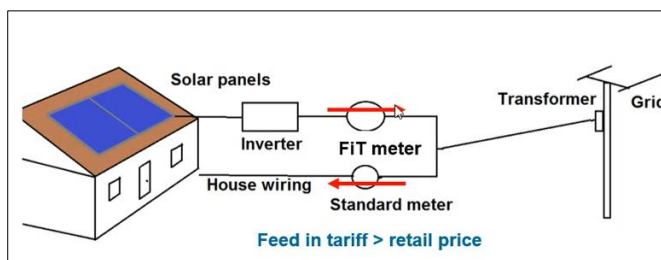
Figure 21: A profitable grid-connected system, feed-in tariff > retail price of electricity [14]

But right now, the feed-in tariffs don't work in favour of household consumers. The feed-in tariff scheme was essentially fully banned for new PV installations starting from 2014 [15], [16] In the past they were subsidized but in the current situation there are so subsidizes for feeding in to the grid. The price offered for feeding in is very low (~ 0.3 [CZK/kWh]) and the retail price of bought electricity is much higher than what we gain if we sell [13]. As such, it is no longer profitable to feed-in to the grid.
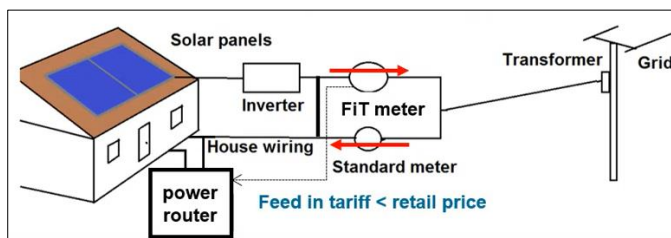
Figure 22: An unprofitable grid-connected system, feed-in tariff < retail price of electricity [14]

Therefore, by having a small household PV system it is still possible to supply and buy from the grid, but the objective is to minimize the amount sold to grid and maximise the energy for self-consumption in our house., i.e. having a system controlling the flow and regulating the heating of the boiler. This is case with our house, with heating of the boilers. The wattrouter measures the energy selling into grid and regulates the appliances in the house to prevent the overflow of energy into grid.

Shown below is the energy flow graph obtained from the PV*SOL simulation. This graph can show a useful summary of the energy generated and where it is used. However, important to note is that the PV*SOL software shows the simulation results for the case of consumption with electrical appliances and a single boiler. It is not able to simulate the two boiler configuration and we are not able to input the minutely hot water consumption data into the software either, but only the annual hot water requirement. For a more detailed analysis, the calculations would need to be performed outside of the software using another tool like MS Excel.

The energy flow graph shows that of the 3216 [kWh] of energy generated, 503 [kWh] is supplied for our own consumption of electrical appliances and 1023 [kWh] for hot water. And for the purpose of this project, as said before the feed-in energy of 1690 [kWh] supplied to grid would essentially be considered a loss, which is about 53%.
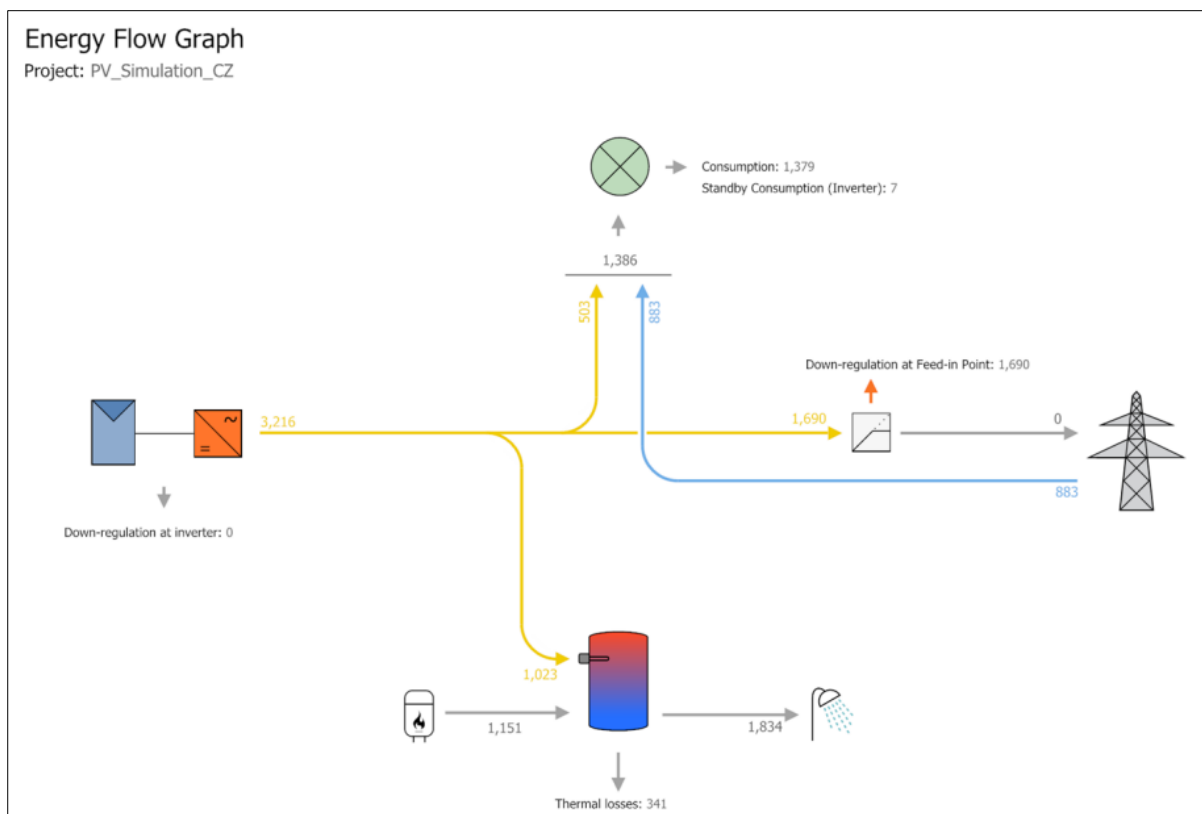
*Figure 23: Energy flow graph from the simulation results in PV*SOL*

6.2. Financial Savings in PV*SOL

It is possible to see the impact on financial savings due to any investments, feed-in tariffs, and from-grid tariffs using the available tool, "Financial savings" in the PV*SOL software.

Our current tariff offered by the distributer is the D35d type.
The rates are as follows: 3.776 [Kč/kWh] for high tariff and 2.762 [Kč/kWh] in low tariff.
With relatively long low tariff hours: from 10:00-17:00 and 21:00-06:00, because historically electrical heating was used.

There is also a more common type D25d offered which more correctly corresponds to the situation with only a boiler, excluding the electrical heating. The low tariff times applicable are: 01:00-06:00 and 14:00-17:00. This tariff was used for the analysis.

Under the "financial savings" option of the main task bar, a summary of the steps that were followed is given below [17]:

1. The investment after subsidy for the house is 147800 CZK and interest on capital of 2%. This was added under the "Financial analysis parameters".
2. "Economic Parameters→Energy Balance/Feed-in Concept → Surplus feed-in" was chosen. The feed-in tariff rate applicable was entered in the "Applied Feed-in Tariffs". A new tariff scheme was manually created as data for Czech Republic was not available in the database.
3. Next, the tariff rated applicable from grid was defined. Once again, we created a new entry as our tariffs were not available in software, choosing "From grid tariff → Select → New".
   The important parameters are the tariff periods, namely defining the low/high tariff periods:
   - With two number of chronologically different tariff periods:

Figure 24: Creating the low tariff and high definitions

   - In the final step, in the table visible under "Tariff period definition a", we set the times when the different tariffs apply. The columns display the times and rows the months. The dark orange showing high tariff times and the light yellow the low tariff in the figure below.

Figure 25: Setting the different tariff times definition

4. Under the "Energy price for natuarl gas", the low tariff electricity price was used 2.762 [CZK/kWh], as the alternative to PV energy is heating water by low tariff. (Note: the inflation rate for energy price was also added at 4%) [18]

Once the "Results" or "Presentation" options are chosen on the software's main task bar, the financial savings are also calculated.

Remuneration and Savings	
Total Payment from Utility in First Year	0 ₹/Year
First year savings	7,367 ₹/Year
First year savings (Energy from Grid)	4,542 ₹/Year
First year savings (Thermal system)	2,826 ₹/Year
CZ_from_grid_tariff (Example)	
Energy Price Low Tariff	3 ₹/kWh
Saving Low Tariff	424 ₹/Year
Energy Price High Tariff	4 ₹/kWh
Saving High Tariff	1,291 ₹/Year
Inflation Rate for Energy Price	4 %/Year

Figure 26: Results after simulation of financial savings pt.1
(Note: the currency is in [CZK], the symbol was defaulted to the one shown above in the image; prices of low tariff and high tariff are shown after rounding here even though calculation is done with exact values)

The accrued cash flow for the 26th year for a 25 year assessment period is also presented. The full cash flow table is attached in the appendix.

Economic Parameters	
Return on Assets	5.67 %
Accrued Cash Flow (Cash Balance)	94,137 ₹
Amortization Period	17.4 Years
Electricity Production Costs	2.29 ₹/kWh
Payment Overview	
Specific Investment Costs	0 ₹/kWp
Investment Costs	0 ₹
One-off Payments	1,47,800 ₹
Incoming Subsidies	0 ₹
Annual Costs	0 ₹/Year
Other Revenue or Savings	0 ₹/Year

Figure 27: Results after simulation of financial savings pt.2

Important to note is that the PV*SOL software shows the calculation results for the idealized case of a boiler backed up by a gas stove and the gas price is set here as a price of low tariff. So that the situation of backing up by high tariff never happens in this PV*SOL simulation. Also, because the gas stove can provide very quick heating when necessary, it means that the situations of "discomfort" also never happen. But as mentioned before, it cannot simulate the case for the real measured consumption and it cannot simulate the case of two boilers in series. Therefore, for a more detailed analysis and also for the case of two boilers, the calculations should be performed outside the software using a different tool like MS Excel.

Chapter 7: System performance with one boiler and two boilers in series.

In this final chapter, our aim is to analyse the system performance for the two solutions for the usage of excess PV energy- heating of water with one boiler and two boilers connected in series.

We know that for our current configuration, we do not sell any excess energy left after consumption of the house (electrical appliances without hot water boilers) to the grid. Our objective was set, to instead use it for consumption of water heating. In this chapter, we explore more closely some of the main situations that can occur during our hot water consumption in relation to: the generated PV energy, the excess energy, effect of having a back-up heating source, the possible issues that can arise and the different tariff rates that apply for these cases.

There are two approaches we followed for this analysis: first, a case study and second, a mathematical approach. Each approach was started by looking at the solution of one boiler first, and then expanded to the analysis that considered a solution with two boilers.

7.1. Analysis by case study

The system performance is analysed first as a case study describing five theoretical cases that can occur. Listed below are example cases of the different days we might encounter, with regards to the available sunshine for the particular day and the water heating demand.

1) A typical summer day, with sunshine all day, the main consumption is in the evening or early morning. We consider the boiler to be empty in the morning (filled with cold water).

2) Same situation to case 1) but the sun doesn't shine all day, the morning may start off sunny but the afternoon gets cloudy- we have to rely on a back-up heating turned on at 16:00. So that until 18:00 the boiler is refilled.

3) Same situation to case 2) but the morning starts off cloudy and then proceeds to get sunny in afternoon. So the back-up that is turned on at 16:00 is essentially not used as the sun is still shining. After sometime, around 18:00, the sun is no longer shining and the back-up continues to 20:00.

4) Morning is cloudy, same as case 3). This time we want to use water during the day for example because there are holidays and people stay at home.
5) The sunshine conditions are ideal, but considering the water consumption, on the first day, all consumption happens in the morning and the next day, all the consumption happens in the evening.

Then we define three priorities that our system would need to be evaluated by for maximum usage of PV energy:

1) The first priority is that the boiler has to be able to accept energy from the PV system. In other words, the water in the first boiler has to be cold in the morning. For the case of two boilers, the pre-heat boiler would need to be empty in the morning.

2) The second priority is that hot water has to be available for the users any time during the day.

3) The third priority is that back-up heating should be switched on when the low-tariff rates apply.

7.1.1. System with one boiler

We consider a single boiler with capacity 120l connected to the PV system and directly to the bathroom for supplying hot water. In this configuration, the cold water entering the boiler is heated by the excess energy from PV system and when there is a consumption, hot water is directly taken from this boiler.

The following situations can be expected for the solution with a single boiler:

For case no. 1), any remaining hot water from the day before, is used early in the morning, so we consider the boiler is full of cold water afterwards. When the sun starts to shine, the boiler is able to accept the maximum excess PV energy to heat water throughout the day (for example, from around 06:00-17:00). When there is a main consumption in the evening, the boiler is filled with hot water and the back-up heating is not necessary. In this ideal case, the solution with a single boiler works perfectly.

However, this won't always be the scenario as seen from cases 2) - 4). In these cases , there needs to be a back-up heating option that provides the required hot water demand, because sun does not shine the whole day. A situation of "discomfort" from here onwards, refers to the situation when hot water is not available for use if there is a demand from the user.

For case no. 2) similarly to case no. 1), when the sun starts shining the boiler accepts the maximum excess PV energy in the morning, and the boiler is filled till some time. Then, it starts getting cloudy (for example, from around 12:00), with little or no excess PV energy available for the rest of the day. When there is a main consumption in the evening or night, the user would experience a situation of discomfort, therefore this situation is avoided by switching on back-up around 16:00, continuing till 18:00 till when the boiler is refilled. In this way, possible discomfort during the day is avoided. However, starting from 18:00, the high tariff hours apply, so if back-up hours are continued, we see that in this case, it will be during high tariff hours.

For case no. 3), similarly to case no.2), except the morning is cloudy and there is little to no excess PV energy available until the afternoon, which lead to possible situations of discomfort in the morning hours, until the sun starts to shine sometime in the afternoon, continuing till the evening (for example, from around 12:00-18:00). The back-up heating is switched on at 16:00 but is essentially not used as the boiler is full from the afternoon's sunny condition, and the main consumption in the evening is covered. However, as the sun stops shining around 18:00 and the back-up heating is continued till 20:00, three hours of high tariff are used. So in this case, we can see that it's possible we encounter situations of discomfort as the boiler is filled late, as well as back-up during high tariff hours.

For case no. 4), similarly to case no. 3), There is little to no excess PV energy available in the morning hours as it is cloudy until afternoon (for example, 12:00 onwards) when there is an increase in excess PV energy. But since it is a holiday, people may stay at home, with demand for hot water during the day (for example, from 10:00-14:00) when the boiler is not full due to the cloudy conditions. The back-up is only switched on in the evening at 16:00. Therefore, in this case, during the day, users will experience situations of discomfort, with hot water only available for use in the evening. And for continued back-up from 18:00 onward, it will be in high tariff.

For case no. 5), the first day starts off with the consumption of any remaining hot water early in the morning, so we consider the boiler to be full of cold water afterwards. Then, the suns shines the whole day and the boiler accepts maximum PV energy, filling the boiler, with no consumption the rest of the day, it remains full for the next day morning as well. For the second day, there is no consumption till the evening, and the boiler is still full to meet the water heating demand. So in this case, there are no situations of discomfort encountered and high tariff back-up not required either, however, every two days the boiler is not able to accept any excess PV energy as it is full of hot water.

7.1.2. System with two boilers

Now we consider two boilers in series connected in our system. Let the first be the pre-heat boiler of 120l capacity connected to the PV system and the second be the 125l boiler connected to the grid and the bathroom. The connection to the grid ensuring that there is always hot water available for consumption regardless of PV energy supply and energy from the first boiler.

The pre-heat boiler receives cold water and is heated by the energy from the PV system. The second boiler connected only to the grid will always have hot water ready for consumption regardless of conditions. But when there is a usage of hot water, water flows from the first to the second. In the ideal case, the temperature of water entering our second boiler should be sufficient enough for use, so no heating in second boiler is necessary. So ideally the setpoint temperature of boiler 1 > setpoint temperature in boiler 2. And in the case that this is not true, i.e. it has not been heating to the required temperature in the pre-heat boiler by the PV system, the second boiler needs to perform this task itself.

The following situations can be expected for the solution with two boilers:

For case no. 1): Consider the pre-heat boiler is full of cold water in the morning and the second boiler has some starting energy. As there is a full day of sunshine, the pre-heat boiler is able to accept maximum usage of the excess PV energy, filling the boiler until evening. When a main consumption occurs in the evening, hot water is available for use from the second boiler, and the water entering from the pre-heat boiler heated to the required temperature, and is available during the whole day. In this ideal case, the solution of the two boilers works perfectly.

However, as with the solution with one boiler, there will be some days that are not the ideal case. As seen listed in cases 2)-5). However, for the solution with two boilers, the first pre-heat boiler essentially acts a storage of PV energy with no back-up. And we expect the second boiler to manage any situations of discomfort without requiring back-up in high tariff hours, so we consider the traditional case with back-up on for only low tariff hours. The cases in this scenario are explored below:

For case no. 2), similar to case no.1) As the sun starts to shine in the morning, the pre-heat boiler is filled with maximum excess PV energy. As there is no consumption till the evening, the pre-heat boiler remains full until afternoon, and when it starts to get cloudy, there excess PV energy is no longer stored for the rest of the day. When the main consumption occurs in the evening, hot water flows from the second boiler, and back-up in high tariff won't be required as the low tariff back-up in the second boiler during the day ensures there is hot water is available throughout the day. So in this case, there is no discomfort encountered and high tariff back-up not required.

For case no.3), similarly to case no.2), Except the pre-heat boiler remains empty till the afternoon as there is little to no storage of excess PV energy until the sun starts shining in the afternoon. During these morning hours, the second boiler with back-up in low tariff manages any discomfort. This continues till the afternoon and when the pre-heat boiler starts to receive excess PV it becomes filled once again, and the main consumption in the evening is covered. In this case as well, there is no discomfort encountered throughout the day and high tariff back-up is not required.

For case no.4), similar to case no.3), Except the main consumption occurs during the day as people are at home for the holiday. The same scenario as case no.3) applies, where there is no storage of PV energy in the pre-heat boiler until the afternoon, but the consumption is covered by the second boiler which is backed-up in low tariff during the day. In this way, situations of discomfort are avoided. And once again, the pre-heat boiler starts to fill from the afternoon till evening. In this case, situations of discomfort throughout the day are avoided and back-up in high tariff is not required.

For case no. 5) similarly to the solution with a single boiler, on the first day, considering the pre-heat boiler is full of cold water in the morning, it accepts maximum PV energy throughout the day and the second boiler has some starting energy. It is an ideal case of sunshine all day, and with no consumption the rest of the day, the pre-heat boiler remains full till the next day morning. There is no consumption till the evening of the second day, by when it is covered by the second boiler. So in this case, there are no situations of discomfort encountered throughout the day and no requirement for high tariff back-up either, however, every two days the pre-boiler is not able to accept any excess PV energy as it is full of hot water.

We see that for the cases 1) and 5) the solution with two boilers does not bring any advantage, but for the cases 2) – 4) the solution with two boilers is always better.

In the next section, a mathematical approach is presented to explore both solutions more exactly, as we account for impacts of starting energy in both solutions and the flow of heat from the pre-heat boiler to the second boiler for the solution of two boilers.

7.2. Analysis by mathematical approach

For the two solutions of a single boiler and two boilers, alternatively to case study approach, we now use a mathematical approach and apply two (negative) criteria for analysis:

1) The count of energy (hours of operation) spent in high tariff hours for realizing the back-up heating.
2) The count of conflicts with water consumption that arise when a user wants to use hot water, but the boiler is empty, a situation referred to as "discomfort".

The common type of tariff D25d is used for purpose of this analysis, which corresponds to the situation with only a boiler excluding space heating, with tariff rates:
- 2.762 Kč/kWh in low tariff
- 3.776 Kč/kWh for high tariff
- Low tariff times applicable: 01:00-06:00 and 14:00-17:00.

For the convivence of calculations in this section, the minutely values for the year summed to hourly values were used.

7.2.1. System with one boiler

For a single boiler of capacity 120l, and for heating from 15°C (cold water) to 75°C (hot water):

From the Law of Thermodynamics, $c = \frac{Q}{m\Delta T} \Rightarrow Q = cm\Delta T$ [J]

Given water heating capacity $c = 4186 \left[\frac{J}{°Cl}\right]$ and $1[J] = \frac{1}{3600000}$ [kWh],

The heat energy needed to heat m in l of 120l from 15° to 75°:

$Q = 30139200$ [J] ≈ 8.372 [kWh]

Therefore, for a single boiler at full capacity of 8.372 kWh, consider a back-up heating source of 2 kW.

Consider also a self-discharging value of the boiler, as we want to account for the impact of the starting energy in our boiler at later times. The exact calculation of the discharging is complex, but it can be approximated as follows: this value will depend on the temperature of the boiler, and the temperature of the boiler is proportional to the energy. Therefore, setting this constant to a low value at the beginning like 0.1 [kW/kWh], it will be multiplied by the energy (in kWh) in the boiler to give the value of discharging power.

We perform analysis and calculation of the count of hours spent in in "discomfort" and high tariff back-up as follows:

1) Given the starting energy (energy value in boiler at the end of previous hour), for the current hour, the excess power, consumption and self-discharging, we calculate the energy in the first boiler. This can be considered as an 'Auxiliary' value, before the check for negative values.

   In mathematical notation:

$$A = E_{t-1} + (X_t - C_t - S \cdot E_{t-1} + B_t) \cdot 1 hour$$

$$E_t = \begin{cases} A & for \ A \geq 0 \\ 0 & for \ A < 0 \end{cases}$$

Where,

$A = $ Auxiliary value

$E_t = $ Energy stored in boiler at time t

$X_t = $ Excess power at time t

$C_t = $ Consumption at time t

$S = $ Self-discharging constant

$B_t = $ Back-up power at time t

2) We account for cases of discomfort by checking if the calculated energy in the boiler for the hour is positive. If not, we denote it as 1. Implying that for this hour, the boiler has no energy if hot water is required.

$$D = \begin{cases} 0 & for \ A \geq 0 \\ 1 & for \ A < 0 \end{cases}$$

$D = $ discomfort count.

3) This value in boiler changes once again when the back-up is switched on. During these hours, we check if the energy in the boiler is less than boiler capacity, then the back-up power is added to existing value. Otherwise, it implies there is an excess of energy beyond the capacity of the boiler and back-up is essentially not used, so the energy value is denoted the maximum of boiler capacity.

$$B = \begin{cases} 1 \ for \ (A < (Q - B_t) \ and \ t \in \langle t_1 \ ... \ t_2 \rangle) \\ 0 \ \ otherwise \end{cases}$$

$t_1 = $ Starting hour of back-up

$t_2 = $ Ending hour of back-up

$B = $ Back-up count

4) The count of hours of back-up in low/high tariff is checked as: in the hours when we have an overlap of back-up heating being on and the corresponding tariff hours. However, a particular tariff back-up is only applied if the energy in boiler was less than capacity. Otherwise the back-up power was essentially not used so it not counted.

$$L = \begin{cases} 1 & for \ (B = 1 \ and \ t \in \langle 02\text{:}00..06\text{:}00 \rangle \cup \langle 14\text{:}00..17\text{:}00 \rangle \ ) \\ 0 & otherwise \end{cases}$$

L = Low tariff count

$$H = \begin{cases} 1 & for \ (B = 1 \ and \ t \in \ \langle 07\text{:}00..13\text{:}00 \rangle \cup \langle 18\text{:}00..01\text{:}00 \rangle) \\ 0 & otherwise \end{cases}$$

H = High tariff count

This analysis was then applied to the calculations for a year for the solution of one boiler. This was done in MS Excel, with the hourly values starting from the first hour of the year in January and ending at the last hour in November.

Two scenarios were analysed:

1) Consider back-up switched on from 14:00-18:00.
2) Consider back-up switched on from 16:00-20:00.

A comparison of these two scenarios is then presented- how the count of hours of discomfort and count of back-up in high tariff varied with the varying times of back-up heating.

For both scenarios, we considered a back-up heating of 2 [kW] and the self-discharging constant of 0.1 [kW/kWh]. We set the starting energy for the beginning of the year (energy in the boiler at end of the 23rd hour on 31.12.2020) to 1 [kWh].

The table below shows the results that were obtained, with daily totals summed into a monthly summary for the year, solution with 1 boiler:

Month (2021)	Count of hours of discomfort		Count of hours of high tariff back-up	
	Back-up: 14:00-18:00	Back-up: 16:00-20:00	Back-up: 14:00-18:00	Back-up: 16:00-20:00
January	46	43	9	68
February	48	48	7	55
March	43	50	11	52
April	22	25	3	25
May	21	24	5	33
June	5	1	2	20
July	2	1	1	16
August	8	8	3	21
September	18	21	5	41
October	43	54	12	61
November	44	35	13	74
Total:	**300**	**310**	**71**	**466**

Table 3: Results of analysis by mathematical approach- solution with one boiler

From the results above, it can be seen that for both scenarios, the discomfort count is similar while there was a significant difference in the high tariff hours used.

The figures below show the distribution, most of the discomfort occurs in the winter months (October-March). This is expected as there is drop in excess PV energy during these cloudy, winter months. The count then reducing as spring approaches, with the summer months seeing little to no hours of discomfort.
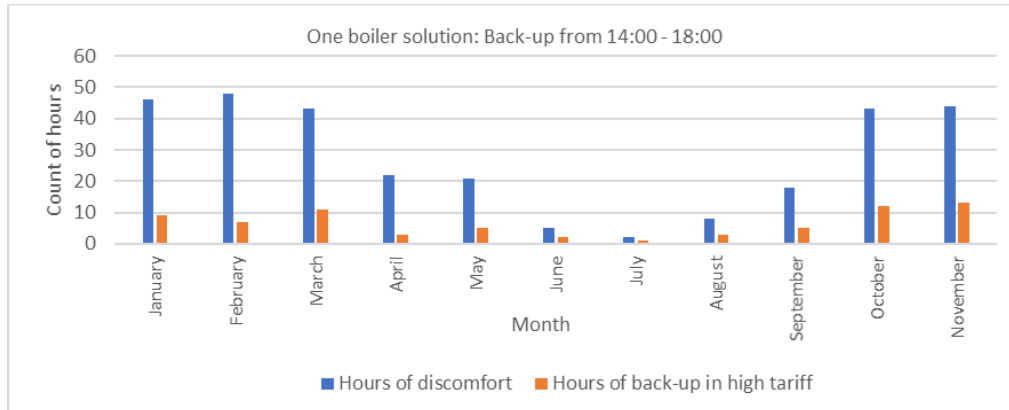
Figure 28: Count of discomfort and high tariff back-up, one boiler- scenario no.1
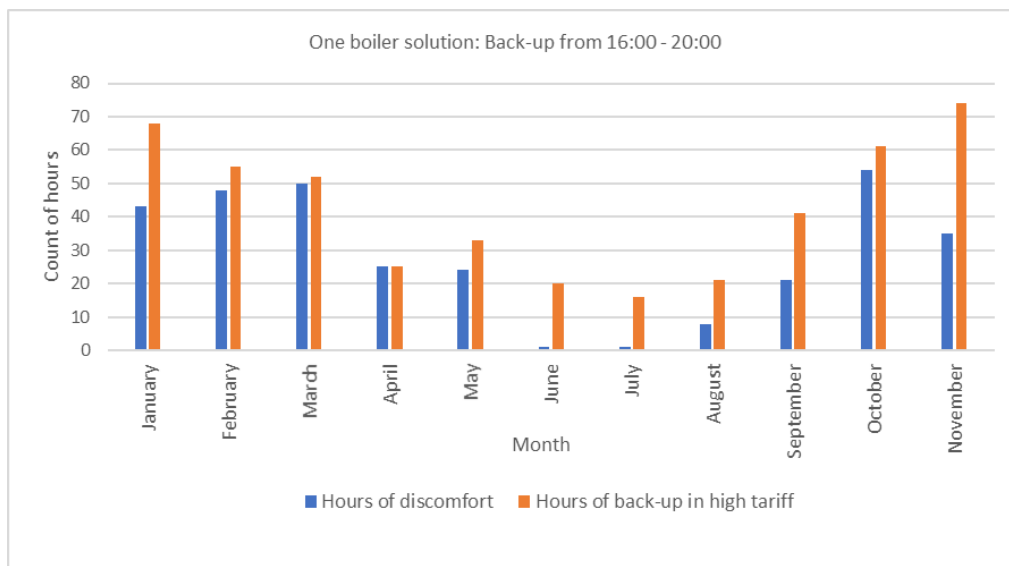
Figure 29: Count of discomfort and high tariff back-up, one boiler- scenario no.2

For back-up considered from 14:00-18:00, four hours are available in low tariff and just one in high tariff. Of the 334 hours available in high tariff for the year, 21% usage occurred. Additionally, there were 888 hours backed-up in low tariff, with a 66.5% usage.

Whereas if we consider back-up from 16:00-20:00, two hours are available in low tariff with three in high tariff per day. Of the 1002 hours available in high tariff for the year, 47% usage occurred. With 540 hours of back-up in low tariff hours (81% usage).

Therefore, it can be seen that for a similar count of discomfort, having back-up considered from evening to night, 16:00-20:00, we spend significantly more hours in high tariff. Our priority would be to have as little discomfort as possible, so the option of back-up considered from late afternoon to evening, 14:00-16:00, is a better solution in terms of both, a lower discomfort count and lower count of high tariff hours.

7.2.2. System with two boilers

We now consider the mathematical approach for the solution of two boilers in series. Our aim was to again, evaluate the two criteria- the hours of discomfort and the hours spent in high tariff back-up.

For the case of two boilers, one with capacity of 120l and the other 125l respectively, similarly as calculated for the case of one boiler, for water heating from 15°(cold water) to 75°(hot water):

Given water heating capacity $c = 4186 \left[\frac{J}{°Cl}\right]$ and $1[J] = \frac{1}{3600000}[kWh]$,

$$c = \frac{Q}{m\Delta T} \Rightarrow Q = cm\Delta T \ [J]$$

The energy needed at full capacity for first boiler would be, $Q(1) = 30139200[J] \approx 8.372 \ [kWh]$

The energy needed at full capacity for first boiler would be, $Q(2) = 31395000 \ [J] \approx 8.72 \ [kWh]$

The main difference between the solution with single and two boilers would now be flow of heat from the first to the second boiler. And in order to determine the energy in boiler 1 and boiler 2 at any given time t, we account for this term.

For any given time t [hour], we know the consumption, we take the same amount of water from boiler 2 as from boiler 1. But, we are not measuring the volume of water, only the energy. And as such, we have the information of energy we extracted, and we know there is a relation between the volume of water and the energy, and to determine the energy in the respective boilers, the following steps would be followed,:

1) Re- calculate consumption in boiler 2 into volume.
2) This volume will be the same in boiler 1.
3) The value is then re-calculated into energy in boiler 1.

This re-calculation however requires for us to know the temperature of the water, which we do not measure. And essentially these re-calculations will be different in boiler 1 and boiler 2 because they're at different temperatures. However, we do have the information of the heat energy accumulated and we can use the fact that the ratio of temperatures is proportional to the ratio of energies.

Let energy of boiler 2: $E(2) = m_2 c \Delta T_2$

and energy of boiler 1: $E(1) = m_1 c \Delta T_1$

Then, $\frac{E(1)}{E(2)} = \frac{m_1 c \Delta T_1}{m_2 c \Delta T_2}$ and for $m_2 = m_1$, $\Rightarrow \frac{E(1)}{E(2)} \propto \frac{\Delta T_1}{\Delta T_2}$

This ratio of energies will then be multiplied by the consumption, and the term subtracted from the energy in boiler 1 and added to boiler 2.

Note that this temperature scale is a 'rescaled' scale (%), so 0% relative corresponds to 15°C and 100% relative corresponds to 75°C.

Therefore a full boiler filled with cold water at 15°C, corresponds to the case of 0% energy and 0% relative temperature.

When adding the term Consumption $* \left(\frac{E(1)}{E(2)} \right)$ it is possible that $E(2) = 0$, which leads to a division by 0. This case is handled, as there is no consumption. This corresponds to a situation of discomfort when boiler is empty and this situation is assumes that the user waives the hot water demand at that moment.

We perform the analysis and calculation of the energy in two boilers, count of discomfort hours and count of back-up in high tariff as follows:

1) Similarly to the case of one boiler, given the excess power that feeds directly into boiler 1 and the consumption, self-discharging for the current time t, we calculate the energy in boiler 1. The negative values are accounted for in the same way, using 'Auxiliary' value A.

   The difference to the situation with single boiler is the addition of the heat flow term, the consumption multiplied by the ratio of energies. Additionally, we keep in mind that the self-discharging values are also dependant on the temperature of the boiler, and in turn the energy. The self-discharging value set at the beginning is multiplied by this value.

   Let:

   $A_t(1) =$ Auxiliary value for boiler 1

   $A_t(2) =$ Auxiliary value for boiler 2

   $E_t(1) =$ Energy in boiler 1 at time t

   $E_t(2) =$ Energy in boiler 2 at time t

   $X_t =$ Excess power at time t

   $C_t =$ Consumption at time t

   $S(1) =$ self-discharging constant in boiler 1

$S(2) = $ self-discharging constant in boiler 2

$B_t = $ Back-up power at time t

Then, energy in boiler 1:

If $E(2)_{t-1} > 0$:

$$A_t(1) = E_{t-1}(1) + \left(X_t - S(1) \cdot E_{t-1}(1) - C_t \cdot \frac{E_{t-1}(1)}{E_{t-1}(2)}\right) \cdot 1hour$$

$$E_t(1) = \begin{cases} A_t(1) \ for \ A_t(1) \geq 0 \\ 0 \ for \ A_t(1) < 0 \end{cases}$$

Else:

$$A_t(1) = E_{t-1}(1) + (X_t - S(1) \cdot E_{t-1}(1)) \cdot 1hour$$

$$E_t(1) = \begin{cases} A_t(1) \ for \ A_t(1) \geq 0 \\ 0 \ for \ A_t(1) < 0 \end{cases}$$

Energy in boiler 2:

If $E(2)_{t-1} > 0$:

$$A_t(2) = E_{t-1}(2) + \left(-C_t - S(2) \cdot E_{t-1}(2) + C_t \cdot \frac{E_{t-1}(1)}{E_{t-1}(2)} + B_t\right) \cdot 1hour$$

$$E_t(2) = \begin{cases} A_t(2) \ for \ A_t(2) \geq 0 \\ 0 \ for \ A_t(2) < 0 \end{cases}$$

Else:

$$A_t(2) = E_{t-1}(2) + (-S(2) \cdot E_{t-1}(2) + B_t) \cdot 1hour$$

$$E_t(2) = \begin{cases} A_t(2) \ for \ A_t(2) \geq 0 \\ 0 \ for \ A_t(2) < 0 \end{cases}$$

(Note: the back-up B_t will be added to boiler 2 depending on conditions, explained below)

2) The value of energy in boiler 2 changes once again, when the back-up is turned on. During these hours, we check if the energy in the boiler 2 is less than capacity, then the back-up power is added to existing value. Otherwise, it implies there is an excess of energy beyond the capacity of the boiler and back-up is essentially not used, so the energy value is denoted the maximum of boiler capacity.

$$B = \begin{cases} 1 \; for \; (A_t(2) < (Q2 - B_t) \; and \; t \in \langle t_1 \dots t_2 \rangle \\ 0 \; otherwise \end{cases}$$

$t_1 =$ Starting hour of back-up

$t_2 =$ Ending hour of back-up

$B =$ back-up count

Then, for $t \in \langle t_1 \dots t_2 \rangle$ according to check above (after accounting for discomfort):

(i) $If \; 0 \le A_t(2) < (Q2 - B_t): E_t(2) = A_t(2) + B_t$
(ii) $If \; A_t(2) < 0: E_t(2) = B_t$
(iii) $Else \; A_t(2) > (Q2 - B_t): E_t(2) = (Q2) \cdot 1hour$

3) We account for the cases of "discomfort" in the same way as before, checking if the calculated energy in the boiler 2 for the hour is positive or 0. If not, we denote it as 1. Implying that for this hour, boiler 2 has no energy if there is a consumption requirement.

$$D = \begin{cases} 0 \; for \; A_t(2) \ge 0 \\ 1 \; for \; A_t(2) < 0 \end{cases}$$

$D =$ Discomfort count

4) The count of hours of back-up in low/high tariff spent in boiler 2, is calculated in a similar as way in the case of one boiler:

$$L = \begin{cases} 1 \; for \; (B = 1 \; and \; t \in \langle 02{:}00..06{:}00 \rangle \cup \langle 14{:}00..17{:}00 \rangle \;) \\ 0 \; otherwise \end{cases}$$

$L =$ Low tariff count

$$H = \begin{cases} 1 \; for \; (B = 1 \; and \; t \in \; \langle 07{:}00..13{:}00 \rangle \cup \langle 18{:}00..01{:}00 \rangle \\ 0 \; otherwise \end{cases}$$

$H =$ High tariff count

The analysis was then applied to the calculations for a year for the solution of two boilers. Similarly to before, the calculations were done in MS Excel, with the hourly values starting from the first hour of the year in January and ending at the last hour in November.

For the solution with two boilers, the scenario of the back-up only during the low tariff hours was analysed. As mentioned before, the first boiler acts as storage of PV energy with no back-up. We expect the second boiler working traditionally with only low tariff hours back-up to be sufficient in managing any discomfort that may occur.

For the calculations, a back-up heating of 2 [kW] was considered and the self-discharging value set at 0.1 [kW/kWh] at the beginning for both boilers. The starting energy at the beginning of the year (23rd hour of 31.12.2020) for the boilers was set as 1 [kWh] for boiler 1 and 4 [kWh] for boiler 2.

The table below shows the results that were obtained, with daily totals summed into a monthly summary for the year, for solution with two boilers (by definition high tariff back-up is zero here):

Month (2021)	Count of discomfort
January	3
February	2
March	2
April	1
May	1
June	0
July	0
August	0
September	1
October	2
November	2
Total	**14**

Table 4: Results of analysis by mathematical approach- solution with two boilers in series

We can observe that for this solution, there were little to no hours spent in discomfort, with 0 high tariff hours, which is the ideal case. The few hours spent in discomfort occurred mostly during the winter months with the summer months having none. An additional hour of back-up maybe added and analysed to see if it's possible to eliminate the discomfort hours, however, this is not very beneficial as the discomfort count is not significant enough to increase our hours of high tariff back-up.

Shown below are calculations for a few example days for the two boilers solution:

1) The first example below is of a sunny day in summer, 24th June 2021. It can be seen that there was PV energy generation from morning to evening, with excess PV energy available (around 06:00 to 17:00) and main consumption was early in the morning hours and a little in the evening.
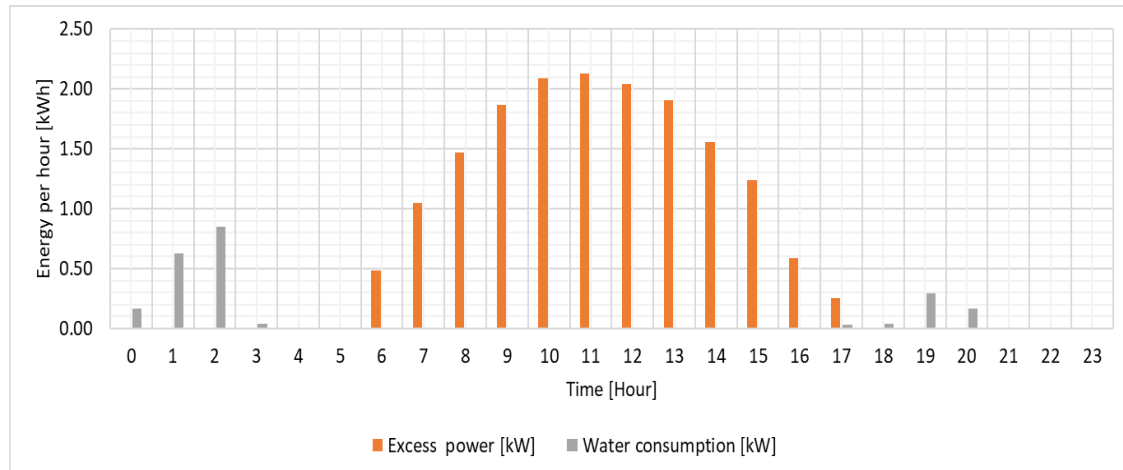
Figure 30: Excess energy and hot water demand on 24.06.2021

The figure below showing the distribution of the energy in the boilers for the 24 hour period. The day started with 1.4 [kWh] for the pre-heat boiler and 3.4 [kWh] for the second boiler. The steady accumulation of energy in boiler 1 can be seen starting from 06:00 onwards as there is excess PV energy available throughout the day.

Figure 31: Distribution of energies in boiler 1 and boiler 2 on 24.06.2021

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2) The second example is of the 5th of January. A typical winter day when it was possibly cloudy the whole day, leading to little or no excess PV energy for usage of water heating. we have to rely on back-up heating for hot water consumption the whole day. With individual consumption peaks early in the morning, and once at night.

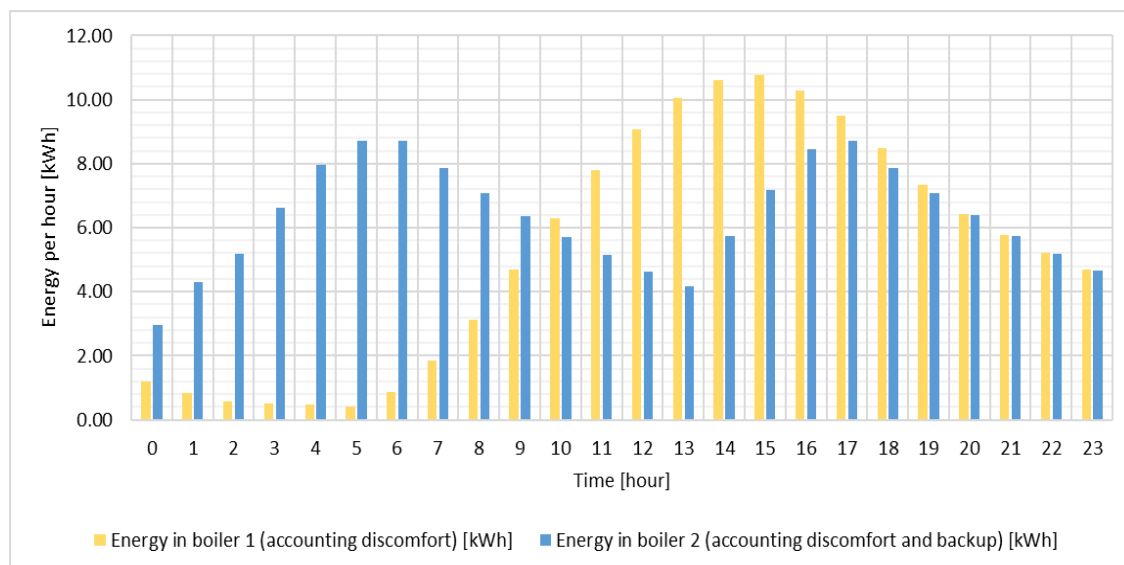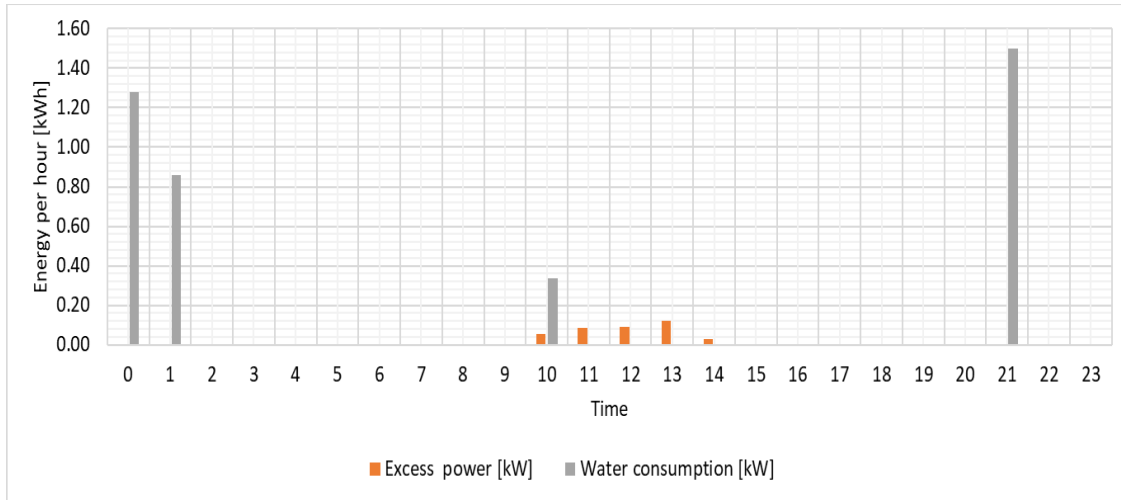*Figure 32: Excess energy and hot water demand on 05.01.2021*

It can be seen from the figure below that energy in the boiler 1 has practically no accumulation throughout the day. We rely on low tariff back-up heating in the second boiler for the whole day.
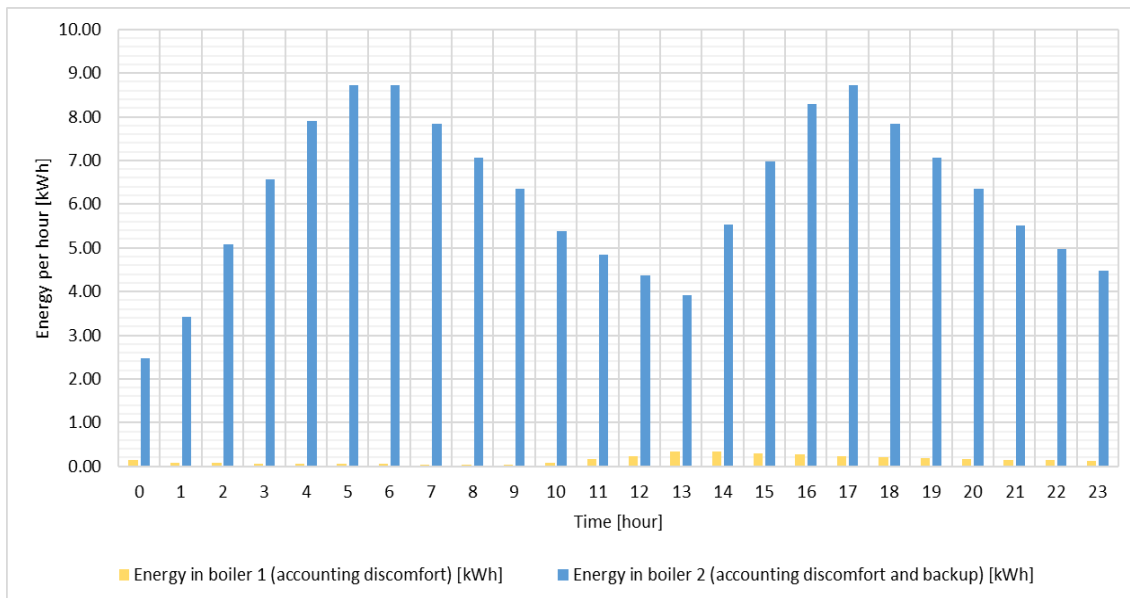

Figure 33: Distribution of energies in boiler 1 and boiler 2 on 05.01.2021

7.3. Additional observations and future considerations

The system performance was analysed in the two approaches as presented above, for the solution of one and two boilers. In this way, it is possible to extend the analysis for any system given the starting parameters of the boilers, the information about the excess PV energy and heating demand, for a particular time period.

Listed below are some additional observations and a few points that can be considered for future improvements in analysis:

- The discomfort hours occur mainly on days with little to no excess PV energy available for that particular hour, but we have a high consumption demand, for example, early winter mornings.

- The starting energy of boiler 1 (in both solutions, the single boiler or two boilers) effects the maximum usage of excess PV energy for the day. Ideally, it would have cold water in the morning (close to 0 energy). In summer, this value maybe higher than in winter due to a higher accumulation during a previous sunny day and no consumption during the evening or night. And for an accurate analysis, the mathematical approach should be applied on consecutive days.

- To counter the effect of starting energy throughout the day, the self-discharging value was introduced. This value was approximated to be proportional to a base value set at the beginning, multiplied by the energy in the boiler. However, increasing this value by the order of 10s of Watts in some cases, greatly impacts the calculated energy in the boiler, by decreasing it. Therefore, for more accurate calculations, a more precise value should be considered.

Chapter 8: Conclusion

The objective of this thesis was to analyse the PV system performance for two solutions- single boiler and two boilers in series, for usage of the daily excess PV energy by self-consumption of hot water. In the first part of this thesis, the software PV*SOL was used to simulate the system performance for a house located in Czech Republic. A daily excess PV energy and hot water consumption profile were then created.

In the second part of this thesis, given the information about calculated excess PV energy and the hot water demand, the objective was approached in two different ways. The case study approach found that for a study of 5 cases, the solution with two boilers in series provided a better solution in 3/5 cases, in terms of discomfort and high tariff back-up hours encountered. The solution with a single boiler encountered discomfort when the boiler became full too late or when there was a fluctuation of sunlight during the day. The solution with two boilers was always better in handling these situations with no discomfort or a high tariff back-up requirement.

The mathematical approach was evaluated with two negative criteria. The analysis was performed for the solution of one boiler with two scenarios of when the back-up is considered switched on. It was found that switching on the back-up from 14:00-18:00 was a significantly better solution than evening, (18:00-20:00). For a similar count of discomfort hours, the earlier back-up times avoided many hours of high tariff back-up. However, the solution with two boilers provided better results than both scenarios for one boiler. With the traditional low tariff back-up only, almost no hours of discomfort were encountered and 0 hours of high tariff back-up required.

Therefore, through both approaches, it was found that the PV system performance with two boilers, the first boiler acting as a pre-heat boiler for storage of excess PV energy, was the better solution. Possible future improvements in analysis could include: considering additional evaluation criteria for the mathematical approach, a more precise self-discharging of the boilers and working with minutely data instead of hourly data.

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10. Appendix

Appendix 1:

Result of the financial savings simulation in PV*SOL. The full cash flow table for a period of assessment of 25 years.

Cash flow

Cashflow Table

	Year 1	Year 2	Year 3	Year 4	Year 5
One-off Payments	₹ -1,47,800.00	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00
Savings on energy costs	₹ 7,223.01	₹ 7,364.64	₹ 7,509.04	₹ 7,656.28	₹ 7,806.40
Annual Cash Flow	**₹ -1,40,576.99**	**₹ 7,364.64**	**₹ 7,509.04**	**₹ 7,656.28**	**₹ 7,806.40**
Accrued Cash Flow (Cash Balance)	₹ -1,40,576.99	₹ -1,33,212.36	₹ -1,25,703.32	₹ -1,18,047.04	₹ -1,10,240.64

	Year 6	Year 7	Year 8	Year 9	Year 10
One-off Payments	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00
Savings on energy costs	₹ 7,959.47	₹ 8,115.53	₹ 8,274.66	₹ 8,436.91	₹ 8,602.34
Annual Cash Flow	**₹ 7,959.47**	**₹ 8,115.53**	**₹ 8,274.66**	**₹ 8,436.91**	**₹ 8,602.34**
Accrued Cash Flow (Cash Balance)	₹ -1,02,281.17	₹ -94,165.64	₹ -85,890.98	₹ -77,454.07	₹ -68,851.73

	Year 11	Year 12	Year 13	Year 14	Year 15
One-off Payments	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00
Savings on energy costs	₹ 8,771.01	₹ 8,942.99	₹ 9,118.35	₹ 9,297.14	₹ 9,479.43
Annual Cash Flow	**₹ 8,771.01**	**₹ 8,942.99**	**₹ 9,118.35**	**₹ 9,297.14**	**₹ 9,479.43**
Accrued Cash Flow (Cash Balance)	₹ -60,080.71	₹ -51,137.72	₹ -42,019.38	₹ -32,722.24	₹ -23,242.80

	Year 16	Year 17	Year 18	Year 19	Year 20
One-off Payments	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00
Savings on energy costs	₹ 9,665.31	₹ 9,854.82	₹ 10,048.05	₹ 10,245.08	₹ 10,445.96
Annual Cash Flow	**₹ 9,665.31**	**₹ 9,854.82**	**₹ 10,048.05**	**₹ 10,245.08**	**₹ 10,445.96**
Accrued Cash Flow (Cash Balance)	₹ -13,577.50	₹ -3,722.68	₹ 6,325.37	₹ 16,570.45	₹ 27,016.41

	Year 21	Year 22	Year 23	Year 24	Year 25
One-off Payments	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00	₹ 0.00
Savings on energy costs	₹ 10,650.78	₹ 10,859.62	₹ 11,072.55	₹ 11,289.66	₹ 11,511.03
Annual Cash Flow	**₹ 10,650.78**	**₹ 10,859.62**	**₹ 11,072.55**	**₹ 11,289.66**	**₹ 11,511.03**
Accrued Cash Flow (Cash Balance)	₹ 37,667.19	₹ 48,526.81	₹ 59,599.36	₹ 70,889.02	₹ 82,400.05

	Year 26
One-off Payments	₹ 0.00
Savings on energy costs	₹ 11,736.73
Annual Cash Flow	**₹ 11,736.73**
Accrued Cash Flow (Cash Balance)	₹ 94,136.78

(Note: the currency is in [CZK], the symbol was defaulted to the one shown above in the image; Prices of low tariff and high tariff are shown after rounding here even though the calculation is done with exact values)

Appendix 2:

Daily excess energy values, shown in <u>Energy per minute [kWh],</u> for the month of February 2021.
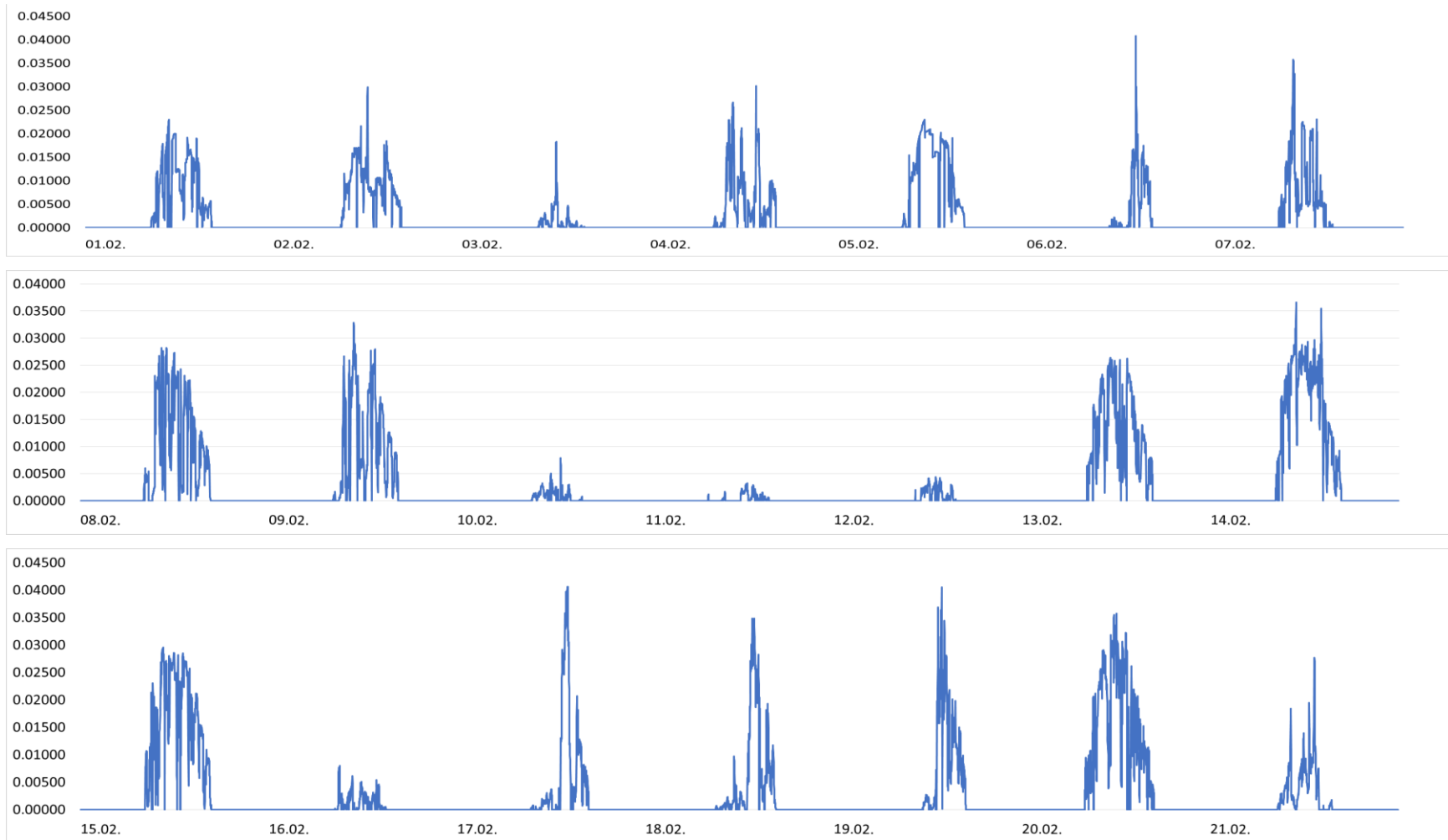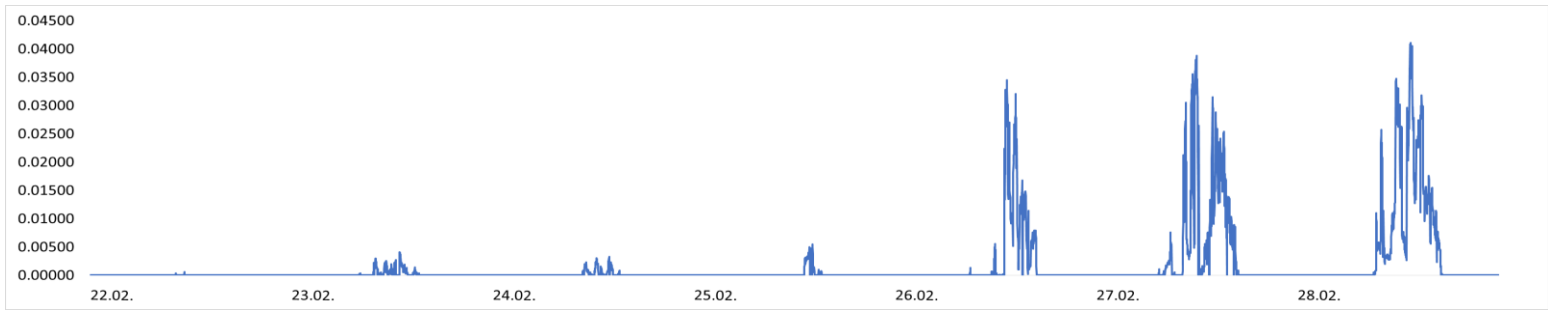
Appendix 3:

Daily excess energy values, shown in <u>Energy per minute [kWh],</u> for the month of June 2021: