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DEPARTMENT OF ELECTRICAL AND ELECTRONIC TECHNOLOGY

ÚSTAV ELEKTROTECHNOLOGIE

DESIGN OF A PHOTOVOLTAIC POWER SYSTEM WITH BATTERY STORAGE FOR HOUSEHOLD PURPOSES IN AREA OF BRNO-MESTO

NÁVRH FOTOVOLTAICKÉ ELEKTRÁRNY S BATERIOVÝM ÚLOŽIŠTĚM PRO DOMÁCNOST V LOKALITĚ BRNO-MĚSTO

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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Bachelor's Thesis

Bachelor's study program **Microelectronics and Technology**

Department of Electrical and Electronic Technology

Student: Martin Vrana ***ID:*** 223377

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TITLE OF THESIS:

Design of a photovoltaic power system with battery storage for household purposes in area of Brno-mesto

INSTRUCTION:

Learn about the principle of photovoltaic process and analyze and analyze the PV technologies used to produce PV cells. Make an analysis of battery storage technologies and according to the parameters of each type of battery focus on the evaluation of the market in the Czech Republic (advantages, subsidies, conditions, legislation). In the practical part of the bachelor thesis, you will then design a PV and battery storage solution for a household in the Brno city area.

RECOMMENDED LITERATURE:

Podle pokynů vedoucího práce.

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Chair of study program board

Abstract

This thesis broadly discusses the individual parts that make up a photovoltaic system, specifically the new and widely available technologies for solar panels, batteries, and inverters. This research is applied in the evaluation of a potential construction plan of both a hybrid and grid tied photovoltaic system for a household located in the district of Brno-Mesto. The focus of each design is a cost-effective solution that utilizes currently available parts on the market, that also covers a significant part of the energy requirements of the household. The cost of each system is subsidized by government grants. The designed grid tied system has a lower price than the hybrid system. It lacks costly battery storage, hence it has a shorter return period of return of six years, compared with seven years for the hybrid system. A hybrid system is advantageous, as it allows for local storage of energy, and provides backup power in the case of a grid blackout. Given that the measurement of energy by the electricity supplier is done by net metering, combined with currently high energy prices, both systems have a relatively short break-even period compared with systems in the past. The choice of system that is installed in the household is up to the client.

Keywords

Photovoltaic cell, photoelectric effect, solar panel, solar energy, semiconductors, PN junction, rechargeable battery, remote area power supply, renewable energy, electrical grid, sustainability, household energy usage, urban planning, engineering economics

Abstrakt

Táto bakalárska práca sa zameriava na rešerš technológií obsiahnutých v návrhu fotovoltického systému, ako sú solárne panely, nabíjateľné akumulátory, a systémy na premenu elektrickej energie. Následne sú tieto informácie využité na návrh hybridného a sieťového fotovoltického systému pre rodinný dom nachádzajúci sa v lokalite Brno-Mesto. Plán realizácie je nájsť cenovo výhodné riešenie s rozumným časom návratnosti, ktoré prevažne pokryje energetický odber domácnosti. Takisto sú náklady každého zo systémov znížene o dostupné štátne dotácie podľa parametrov každej inštalácie. Sieťový systém je lacnejší ako hybridný systém, pretože systém neobsahuje drahé batérie. Preto má nižšiu dobu návratnosti šiestich rokov, v porovnaní so siedmimi rokmi v prípade hybridného systému. Hybridný systém je výhodný, pretože umožňuje lokálne ukladanie energie a poskytuje záložné napájanie v prípade výpadku prúdu. Dodávateľ elektriny umožňuje uložiť prebytočnú energiu vyrobenú systémami do virtuálnej batérie, z ktorej je možné počas roka čerpať v čase nedostatočnej výroby energie. V kombinácii so súčasnými vysokými cenami energie majú oba systémy relatívne krátke obdobie finančného bodu zvratu v porovnaní so systémami v minulosti. Finálny výber typu inštalovaného systému je na klientovi.

Kľúčové slová

Fotovoltický článok, fotoelektrický jav, solárny panel, solárna energia, polovodiče, PN prechod, nabíjateľné batérie, solárny ostrovný systém, obnoviteľné zdroje energie, energetická sústava, udržateľnosť, energetická spotreba domu, strategický plán rozvoja, ekonomika

Rozšírený abstrakt

Jedným z problémov, ktoré musí ľudstvo v budúcnosti vyriešiť, je prechod z používania neobnoviteľných zdrojov energie na obnoviteľné zdroje. Výroba elektrickej energie pomocou fotovoltických panelov predstavuje sľubný zdroj obnoviteľnej energie.

Táto bakalárska práca je zameraná na návrh fotovoltického systému inštalovaného na streche konkrétneho rodinného domu nachádzajúceho sa v mestskej časti Brno-Černovice. Cieľom návrhu je nájsť vhodný systém pre klienta, ktorý by pokryl prevažnú časť energetického dopytu domácnosti. Ďalšou podmienkou je celková cena inštalácie, tak, aby sa investícia vrátila v rozumnom čase.

Práca sa najprv zaoberá dostupnými technológiami fotovoltických článkov a nabíjateľných akumulátorov. Články fungujú na princípe fotovoltického javu [1]. Hlavným materiálom fotovoltických článkov je kremík. Kremíkové fotovoltické články sú v podstate diódy s veľkou plochou prechodu. Dopadajúce svetlo na prechode je premenené na elektrický prúd [2]. Existujú dva hlavné typy kremíkových fotovoltických článkov: monokryštalické a polykryštalické články [2]. Monokryštalické články sa skladajú z jedného súvislého kryštálu kremíka, zatiaľ čo polykryštalické články obsahujú spojené zrná kremíka [2]. Monokryštalické články majú vyššiu efektivitu výroby elektrickej energie v porovnaní s polykryštalickými článkami [2]. Existujú aj novšie typy článkov, ako sú tenkovrstevné články alebo články na báze minerálu perovskitu, tie ale nie sú zatiaľ dostatočne dostupné na trhu [3]. Monokryštalické články sú cenovo výhodné kvôli dobrej dostupnosti na trhu, pretože sú vyrábané vo vysokých množstvách.

Nabíjateľné akumulátory môžu byť využité vo fotovoltickom (FV) systéme na uloženie prebytočne vyrobenej elektrickej energie, ktorá by sa v domácnosti nezužitkovala. Dostupné technológie nabíjateľných batérií zahŕňajú články olovené, na báze NiMH, alebo novšie typy lítium iónových článkov [4]. Každý typ má svoje výhody a nevýhody, ako je napríklad hustota kapacity uloženia elektrickej energie, bezpečnosť a energetická náročnosť výroby [4]. Potenciálny typ použitej akumulátorovej technológie v navrhovanom systéme sú lítium iónové články, pretože sú cenovo dostupné, a tiež sú podporované štátnymi dotáciami [5].

V prípade plánovanej inštalácie na rodinnom dome je možné požiadať o štátnu dotáciu v Českej republike z programu Nová zelená úsporam. Tá ponúka maximálnu dotáciu o výške 200 000 Kč v prípade splnenia pravidiel uvedených vo vyhláške programu. Inštalácia fotovoltického systému je tiež regulovaná legislatívou Českej republiky. Pokiaľ chce klient používať fotovoltický systém prevažne na vlastné účely, je potrebné aby systém neprekročil maximálny inštalovaný výkon 10kW, inak je potrebná licencia od energetického regulačného úradu (Zákon č. 458/2000 Sb. o podmínkách podnikání a o výkonu státní správy v energetických odvětvích a o změně některých zákonů paragraf §3 odsek (3)). FV systém musí byť inštalovaný na streche domu. V inakšom prípade je potrebné stavebné povolenie (Zákon č. 183/2006 Sb. o územním plánování a stavebním řádu (stavební zákon) paragraf §103 odsek e) číslo 9). V prípade predaja energie do siete je potrebné, aby neprekročil mesačný zisk z predaja sumu 30 000 Kč (Zákon č. 586/1992 Sb. o daních z příjmů paragraf §10).

Existujú tri hlavné typy fotovoltických systémov, ktoré sa dajú inštalovať v rodinných domoch. Prvý je systém pripojený priamo na verejnú elektrickú sieť, takzvaný sieťový systém [6]. V tomto prípade je jednosmerný elektrický prúd vyrábaný panelmi premenený na striedavý prúd pomocou meniča. Premenený striedaný elektrický prúd je priamo využitý v danom momente elektrickými spotrebičmi v domácnosti. Prebytok je dodaný a predaný do verejnej elektrickej siete [6]. Tento systém je cenovo najlacnejší, pretože nie je potrebné kupovať drahé batériové úložisko, elektrická sieť vyrovnáva dopyt energie domácnosti. Druhý typ je takzvaný ostrovný systém, pri ktorom je elektrická energia vyrábaná panelmi uložená do batériového úložiska, a následne je využitá v domácnosti premenou na striedavý prúd pomocou meniča pripojeného na batérie [6]. Daný systém je výhodný v prípade nedostupnosti pripojenia k elektrickej sieti, je ale obmedzený na celkové množstvo vyrobenej elektrickej energie. Tretí systém je kombinácia predošlých systémov, takzvaný hybridný systém, ktorý obsahuje pripojenie k elektrickej sieti spolu s batériovým úložiskom [6]. Toto zapojenie maximalizuje využitie vyrobenej elektrickej energie v domácnosti, zároveň ale tiež zaručuje dodávku elektrickej energie v prípade nadmerného odberu [6].

Tým, že sa dom plánovanej inštalácie nachádza v Juhomoravskom kraji v Brne, je podľa dát predpokladaná výroba elektrickej energie fotovoltickým systémom vyššia ako v ostatných častiach Českej republiky [7]. Ročný dopyt elektrickej energie skúmanej domácnosti činí približne 11,3 MWh. Vysoká spotreba je spôsobená inštaláciou elektrického ohrevu vody a kúrenia, čo zapríčiňuje vyššiu spotrebu v zimnom období. Aby bolo možné splniť celkový požadovaný výkon elektrických zariadení, a pokryť vysoký dopyt po elektrickej energii, je predpokladaný potrebný výkon inštalácie približne 7 až 8 kWp. Rozmery rodinného domu boli získané pomocou programu CadMapper a Google Earth [8] [9]. Výsledné merania boli prenesené do 3D modelu domu v programe SketchUp Pro [10]. Plán uloženia panelov bol realizovaný pomocou softvéru PV*SOL premium [11]. Celkový inštalovaný výkon, ktorý sa zmestil na strechu domu bez závažnejšieho zatienenia panelov je 7,63 kWp. Tvar a orientácia strechy komplikuje inštaláciu panelov. Je zložená z horizontálnej časti a šikmej časti pokrytej škridlami, ktorá je orientovaná prevažne na východ. Ďalšou komplikáciou je prítomnosť dvoch komínov na streche. V priebehu dňa vrhajú na významnú časť strechy tieň, čím zmenšujú dostupnú plochu na inštaláciu fotovoltických panelov. Predpokladané hodnoty výroby a spotreby elektrickej energie boli vypočítané pomocou programu PV*SOL premium [11].

V práci sú uvedené vybrané fotovoltické panely, menič, a batériové úložisko dostupné na českom internetovom trhu s najlepším pomerom ceny a potrebných parametrov. Výkon vybraných monokryštalických panelov činí minimálne 300 Wp kvôli vysokému počtu potrebných panelov. Vybraný menič je od firmy SolaX power. Ide o hybridný centrálny menič s maximálnym vstupným jednosmerným výkonom 8 000 W, pretože požadovaný výkon domácnosti je vysoký. Ďalší faktor, ktorý ovplyvňuje výber daného centrálneho meniča, je trojfázový výstup striedavého prúdu meniča, ktorý je potrebný na napájanie elektrického ohrevu vody a kúrenia. Takisto je asymetrický, čo zaručí dodávku elektrickej energie do fázy s vyšším odberom ako v ostatných. Práca porovnáva dva systémy, jeden bez batériového úložiska, a druhý s batériovým úložiskom. V oboch prípadoch je menič rovnaký. Navrhnuté batériové úložisko obsahuje moduly od firmy Pylontech s technológiou článkov $LiFePO_4$ s celkovou kapacitou 12 kWh. Daná kapacita bola zvolená kvôli najlepšiemu pomeru medzi cenou a množstvom ročne uloženej energie.

Do simulačného programu PV*SOL premium boli zadané náklady za každý systém, spolu s cenou elektrickej energie a ročné náklady za distribúciu elektrickej energie. Výsledná finančná analýza ukázala, že systém bez batériového úložiska vyrobí za rok 7 161 kWh a má finančnú návratnosť za päť až šesť rokov. Systém s batériovým úložiskom ročne vyrobí 6 941 kWh, z ktorej časť s veľkostou 2 091 kWh sa uloží do fyzickej batérie, má finančnú návratnosť za šesť až sedem rokov. Prebytočná elektrická energia, ktorá nebola spotrebovaná v jednotlivých fotovoltických systémoch, je uložená do virtuálnej batérie od dodávateľa elektrickej energie E.ON [12]. Ide o spoplatnenú službu, ktorá sleduje množstvo dodanej elektrickej energie do siete za rok. Následne umožňuje bezplatne čerpať zo siete dané množstvo ročne vyrobenej elektrickej energie v inom období [12].

Bibliographic citation

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Author’s Declaration

Author:	*Martin Vrana*
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Paper type:	*Bachelor’s Thesis*
Academic year:	*2021/22*
Topic:	*Design of a photovoltaic power system with battery storage for household purposes in area of Brno-Mesto*

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the project and listed in the comprehensive bibliography at the end of the project.

As the author, I furthermore declare that, with respect to the creation of this paper, I have not infringed any copyright or violated anyone’s personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation S 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll., Section 2, Head VI, Part 4.

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Brno, June 2, 2022 ---------------------------------------

author’s signature

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Brno, June 2, 2022 --

Author’s signature

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INTRODUCTION

With the rapid progress of human innovation comes the rising need for energy. Ever since the start of the industrial revolution, the global demand for energy has been continuously growing, fuelled by the abundant use of non-renewable energy sources, such as coal, oil, and gas. Over time, these energy sources will be depleted. Other problems that have arisen from the use of fossil fuels is the ecological threat of climate change or the economic danger of fuel unavailability and price fluctuations. To combat these problems there have been continuous efforts to switch over to renewable energy sources, such as solar energy collected via photovoltaic cells. The long development history of photovoltaic cells has culminated in the possibility of producing panels with high efficiency, therefore photovoltaic panels became affordable to the general consumer market as a viable source of energy.

This bachelor's thesis focuses on discussing the feasibility of implementing a photovoltaic system in a real household within the district of Brno-Mesto. Hence, the research will examine the theory of generating electrical energy using different types of photovoltaic cells, the possibility of using various battery types to store said generated energy, and the possibility of implementing such a system to a household and connecting it to the power grid. After this the theory delves into the legal side of projecting a photovoltaic system, such as government subsidies and laws.

The practical part of the thesis centres around projecting a building plan of a photovoltaic system for a specified household. The project will be aided with design software aimed at planning photovoltaic installations. The solution will adhere to the specifications required by the client, such as a favourable financial projection, and meeting the building restrictions of the roof.

1. THEORY

1.1 Semiconductors

The photovoltaic effect is based on the theory of semiconductors. Semiconductors are materials, that have the electrical conductivity between that of metals and insulators [13]. The most known intrinsic semiconductors are silicon and germanium, but there are also other types of semiconductors, such as alloyed $A_{III}B_{V}$ semiconductors [14].

Silicon is a group IV element, located just below carbon in the periodic table. This means that it has 4 valence electrons in its atomic state, hence it can form 4 covalent bonds [15]. Pure silicon can form various structures, including a monocrystalline tetrahedral lattice with the same structure as diamond, or a polycrystalline/amorphous structure with irregularities in its lattice [14].

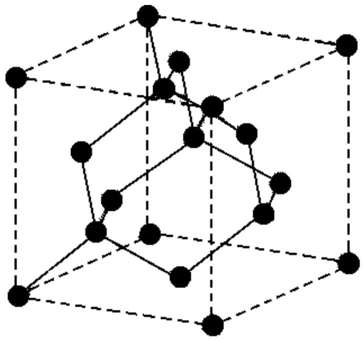

Figure 1.1 Structure of silicon monocrystal with diamond cubic lattice *[14]*

A singular atom of silicon has orbitals within energy shells with discrete energy levels. As the number of atoms of silicon within a defined space increase, the interatomic distances decrease as covalent bonds form within the crystal lattice [13]. As the energy shells of neighbouring atoms start to overlap, the shells in each atom start to split to different energy levels, so that no atom has the same energy arrangement of orbitals [1]. This occurs due to Pauli's exclusion principle, where two electrons in an orbital cannot have the same spin [16]. This creates different energy bands, a valence band bound energetically closer to the nuclei, and a conduction band with a higher energy [14]. The difference between these energy gaps is called the band gap and is responsible for the semiconducting nature of silicon. If a material has a band gap wider than 3 eV, electrons cannot escape the valence band, and therefore the material has no free electrons, it is an insulator [1]. If the energy bands overlap, the material is a metal and the electrons can freely delocalize [13]. The case in-between applies to semiconductors, as only some electrons can jump from the valence band to the conduction band at temperatures above absolute zero [3].

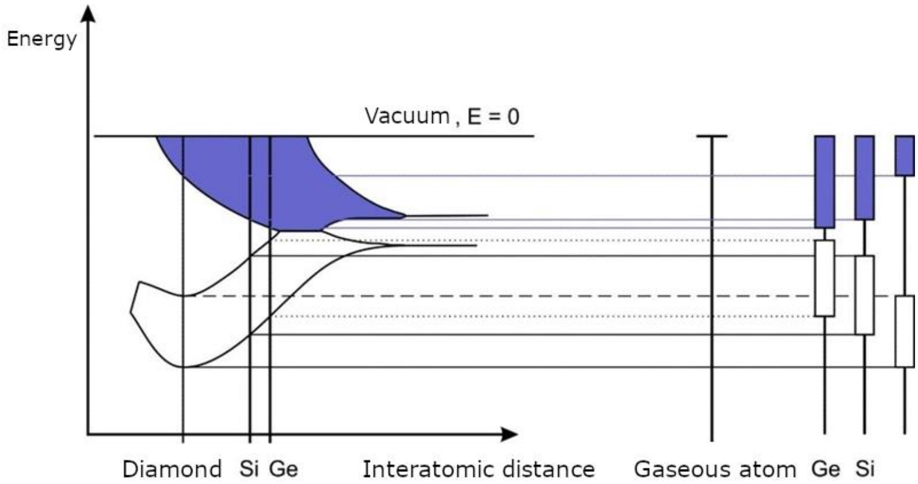

Figure 1.2 Electric band structure of semiconductors *[1]*

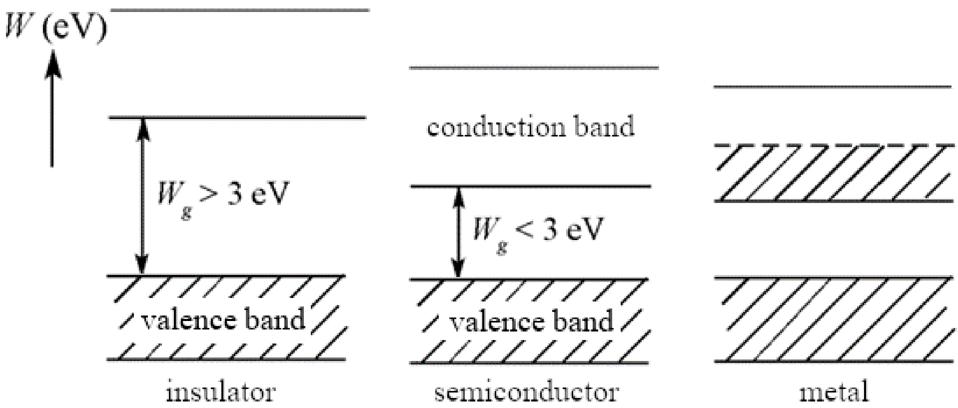

Figure 1.3 Band gap of different materials *[14]*

1.2 Photovoltaic cell model

Pure silicon alone cannot be used in a photovoltaic cell, as the structure that allows for the photovoltaic effect to occur is the semiconductor PN junction [1]. A PN junction emerges when placing two semiconductor materials with different major charge carriers in physical contact [17]. The specific characteristic is the prevalent type of charge carrier present in each semiconductor, either electrons with negative charge, or electron holes with positive charge [6]. The prevalent charge carrier type and concentration in semiconductors is determined by the concentration of dopants, atoms of foreign elements introduced into the crystal lattice [6]. In the case of P type (positive) doped semiconductors the dopant must have one less valence electron than the surrounding atoms, so that when it forms only three covalent bonds, one electron hole is created in the lattice due to the absence of the fourth bonding electron [6]. The opposite applies to N type (negative) doped semiconductors, where the dopant atoms have one excess electron, which is released into the conduction band [3].

Once the P type and N type semiconductors are brought into contact, an exchange of charges occurs, electrons from the N type diffuse into the P type semiconductor and vice versa, causing a neutralization of charge carriers [1]. What is left behind are ionized ions of dopants in their respective regions, and a space charge region forms [14]. This space charge region has an electric field formed by the oppositely charged dopant ions, which causes the diffused charge carriers drift back to their respective type of semiconductor [6]. The diffusion current and drift current equalize, creating a PN junction with no relative charge flow [1]. This equilibrium state is broken only when an external voltage is applied to the PN junction, or when the rate of charge generation on the P-N interface increases [18]. If a photon with sufficient energy hits an electron in the valence band of the semiconductor, the electron gets promoted to an excited state in the conduction band, creating an electron hole in the valence band [3]. If the charge carriers are located at the PN junction, they get separated by the drift current caused by the electric field of the space charge region, causing an increase in electric charge flow [6]. The more light that hits the PN junction, the larger the photocurrent, and hence the larger the current in the attached external load [6]. This is the basis of the photovoltaic effect.

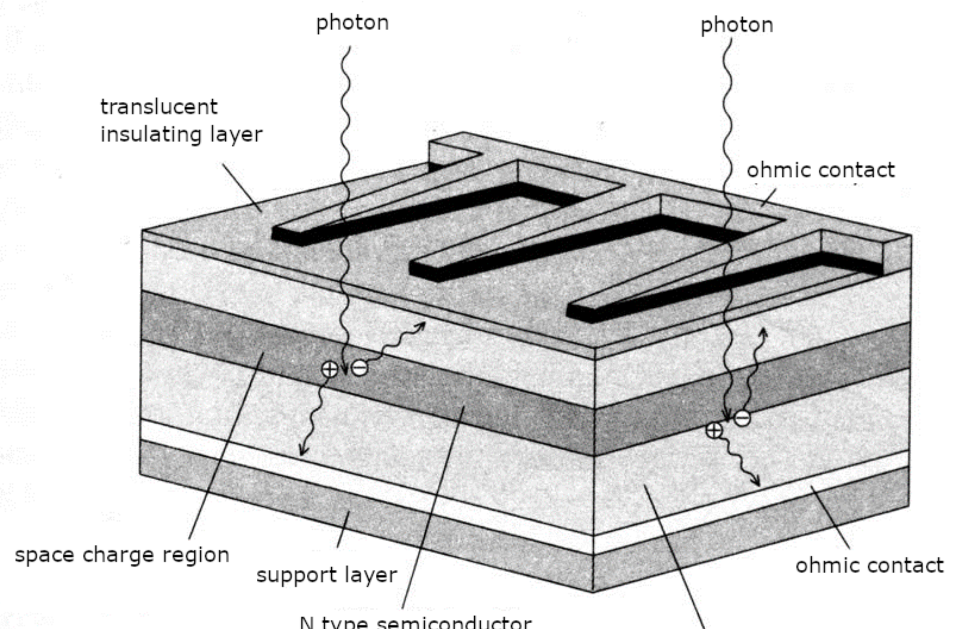

Figure 1.4 Structure of PN junction in a photovoltaic cell *[18]*

If we we're to assume that a photovoltaic cell was ideal, it would convert all light falling onto the PN junction into electric energy. This is not the case with real solar cells, because as with any model of an electric component, there are additional parasitic characteristics that reduce efficiency. One factor is that some generated charge carriers recombine sooner than they can be removed from the PN junction. Another variable is the series and parallel resistance of the different parts of the photovoltaic cell that cause a voltage drop. Because a photovoltaic cell contains a PN junction, it is also a diode, and as such it can also carry current in a forward bias, which reduces the total generated current.

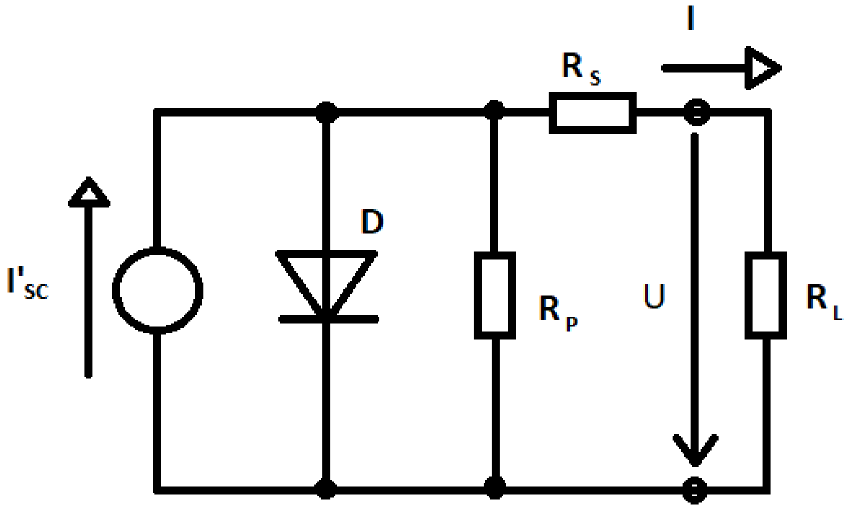

Figure 1.5 Equivalent schematic model of photovoltaic cell *[19]*

The current in the equivalent model of a photovoltaic cell is defined by the following non-linear equation,

$$I = I'_{SC} - I_0\left(e^{\frac{q(IR_S)}{A_0 kT}} - 1\right) - \frac{(U+IR_S)}{R_{Sh}}\ [A], \qquad \textbf{(1.1) [18]}$$

where the total current *I* [A] and voltage *U* [V] on the load resistor R_L [Ω] is the short circuit current I'_{SC} [A] lowered by the current in the forward biased diode and the voltage drop of the parallel resistance R_{Sh} [Ω] and series resistance R_S [Ω]. I_0 [A] is the backward bias current, A_0 is the diode quality factor [-], and *kT* [J] is the product of the Boltzmann constant and absolute temperature.

Due to the inherent flaws, each photovoltaic cell has a maximum power it can generate, P_{MPP} [W], at the maximum power point, MPP,

$$P_{MPP} = U_{MPP} I_{MPP}\ [W], \qquad \textbf{(1.2) [18]}$$

given as the product of the voltage U_{MPP} [V] and current I_{MPP} [A]. The maximum voltage it can generate under no load is given as open circuit voltage U_{OC} [V], and the maximum current when the cell is shorted is I_{SC}[A]. These parameters are usually provided by the manufacturer on the data sheet of a photovoltaic cell or panel.

1.3 Types of photovoltaic panels

A single photovoltaic cell will generate a voltage in the range of millivolts, which is usually not sufficient to be useful in most high-power applications. To mitigate this limitation, multiple photovoltaic cells are connected in series and parallel in a similar fashion to connecting batteries, forming a photovoltaic panel. A major part of the construction of a fully functional panel is the structural assembly, including support materials and the internal electrical connections. This chapter considers materials that make up photovoltaic cells, their individual characteristics, their availability, and scalability of production.

1.3.1 Monocrystalline photovoltaic cells

There are other single PN junction materials with higher solar energy conversion efficiency, such as gallium arsenide and indium phosphide, but their production cost is higher than that of silicon [18]. Advancements in production methods and high demand in silicon based integrated circuits has allowed the large-scale manufacturing of high-quality monocrystalline silicon wafers. As a result of this, it has become more economically viable to use monocrystalline photovoltaic cells, instead of previously cheaper polycrystalline cells, which is reflected by the recent dominant share of global production of monocrystalline cells [20]. Appearance wise a silicon monocrystal has no grain boundaries and has a homogenous structure. This allows for the highest available commercial efficiency of cells at about 22% [2] in comparison to other technologies.

Figure 1.6 Monocrystalline (left) and polycrystalline (right) photovoltaic cell *[2]*

The general production method of monocrystalline cells is similar to that of integrated circuits. A pure silicon ingot is produced with the Czochralski method, which is sliced into wafers with an appropriate width of about 0,5 mm [3]. The roughness of the surface of the cells is increased to increase the absorptive properties of the cell, because inbound light will be reflected at different incidence angles to the panel. After the diffusion of dopants into the wafer and the application of an antireflective layer of titanium oxide, metal contacts are either sputtered or coated onto the surface [18].

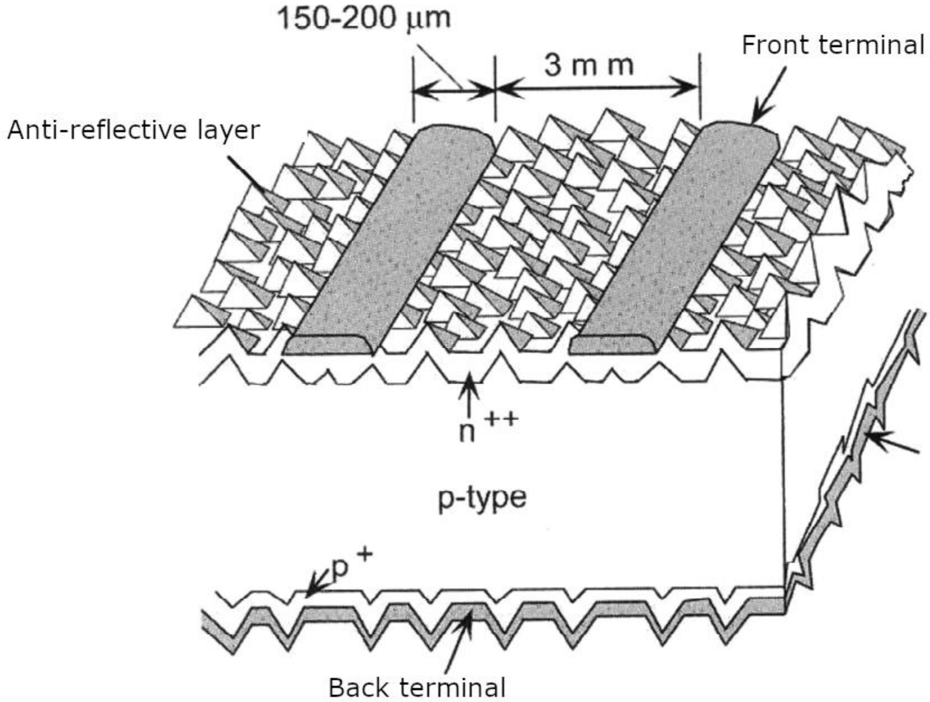

Figure 1.7 Monocrystalline photovoltaic cell structure *[19]*

1.3.2 Polycrystalline photovoltaic cells

In the past polycrystalline cells were more cost effective to produce than monocrystalline cells. The production method was easier to replicate and scale up, as it relied on the deposition of distilled trichlorosilane that formed granular polysilicon with adequate purity [21].

The polysilicon granules are melted in foundries and cast into block moulds, eventually forming a square ingot that is cut into polysilicon wafers [18]. The rest of the production process is akin to the manufacturing of monocrystalline cells, with the addition of an antireflective coating made of titanium oxide that is sputtered on [18]. The lower grade of the crystalline structure causes a lower overall efficiency of about 13% [3].

1.3.3 Thin film photovoltaic cells

Known as the second generation of photovoltaic cell technology, it relies on the thin film deposition of elements and alloys to form a thin photovoltaic film on a substrate, instead of using crystalline silicon [21]. The main advantage over the use of crystalline silicon is the lower production cost, as the deposited material is thin and small in volume. Common thin film materials include amorphous silicon (a-Si), cadmium telluride (Cd-

Te) and copper indium selenide (CIS) [3]. The disadvantage of these types of cells is the lower maximum efficiency of about 10%, and smaller market availability [3].

1.3.4 Perovskite photovoltaic cells

Perovskites are a group of minerals with a common group structure, consisting of a lattice of two different metallic cations and a central anion held together with ionic bonding [21]. When this material is deposited between a hole extracting and electron extracting electrode, the thickness of the perovskite is a couple orders of magnitudes smaller than that of crystalline silicon, allowing for complete light penetration of the solar cell [21]. Recent research has shown that the apparent maximum efficiency of perovskite photovoltaic cells measured in labs is 25,2% [22], and is a promising candidate for a future market dominating photovoltaic cell technology. Given that they are still mainly in the research phase, they are not commercially available yet.

1.4 Batteries

Electrochemical batteries work on the principle of storing chemical potential energy in its electrodes and electrolyte when charged, which is then converted back to electrical energy when an external electrical load is applied to it [23]. There are two types of electric batteries: primary and secondary. Primary batteries are simple galvanic cells made up of two electrodes and an electrolyte, that produce energy without the need to be charged [24]. Their disadvantage is that they are not reusable, and hence are single use only. In comparison, secondary batteries are rechargeable, which means that if an external charging current is applied to them, the drained batteries have their original chemical potential energy restored and can be used again [24]. Rechargeable batteries do not have an infinite life span, meaning that they have a set number of recharge cycles before total degradation. With today’s advancements in battery technologies, they can be used for long enough that they became a viable electrical energy storage medium [25]. This thesis will consider only rechargeable batteries, as they are essential when storing excess electrical energy from photovoltaic panels.

Each rechargeable battery type has a set of characteristics that define their properties. The most essential property is the charge capacity, measured in Amp-hours (Ah) or Watt hours (Wh), which gives the amount of charge over time than can flow out of a battery, before it is completely drained [23]. Another is the energy density of a battery, the total amount of energy in joules stored within a specific volume (volumetric density in J/m^3) or a specific mass (gravimetric density in J/kg or Wh/kg) [26]. The voltage rating of a battery determines the average potential difference it can provide to a load. The voltage range determines the range in which a rechargeable battery safely operates. This is because a fully charged battery has an initial open circuit electromotive force, that drops as a load is applied due to the internal resistance of the cell, and the fact that as it discharges the supplied voltage decreases [23]. The total constant current draw of a battery determines the total discharge time of a cell [23]. In the case of battery systems, it is important to follow the recommended parameters given by the manufacturer, as they allow for the safe and reliable operation of the cells. The parameters are regulated by charge controller circuits, that convert externally supplied power to a suitable voltage and maximum current. They also provide over discharge and over charge protection, keeping the terminal voltage of the batteries within a suitable voltage range [6].

1.5 Types of battery technologies

There are multiple available secondary battery technologies on the market, each with their advantages and disadvantages.

1.5.1 Lead acid batteries

Regarded as the oldest type of rechargeable batteries, they work on the principle of changing the electrode chemistry in redox reactions during a charge or discharge process, similarly to that of primary cells [4]. Both types of electrodes are made from lead metal in the form of paste covered plates that have a high surface area [27]. The chemical reactions occurring at the anode and cathode are different. The electrolyte is highly concentrated sulfuric acid, which also participates in the reactions at both electrodes. The total reversible reaction is described by the following equations:

$$Charging \Leftrightarrow Discharging$$

$$Positive\ electrode:\ PbO_2 + H_2SO_4 + 2H^+ + 2e^- \rightleftharpoons PbSO_4 + 2H_2O, \quad (1.3)\ [28]$$

$$Negative\ electrode:\ Pb + H_2SO_4 \rightleftharpoons PbSO_4 + 2H_2O + 2H^+ + 2e^-, \quad (1.4)\ [28]$$

$$Cell\ reaction:\ Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons PbSO_4 + 2H_2O, \quad (1.5)\ [28]$$

When a lead acid battery is fully discharged, the lead electrodes are covered in lead sulphate. During the charging process lead sulphate is converted to and deposited as lead (IV) oxide at the positive electrode, and at the negative electrode the lead sulphate is directly converted to lead metal. This also restores the sulfuric acid electrolyte. The electrochemical potential of a cell is high due to the large differences in standard electrode potentials of each half cell:

$$E_{cell} = E^0{}_+ - E^0{}_- = \mathrm{E^0}_{\mathrm{PbO_2\,/\,PbSO_4}} - \mathrm{E^0}_{\mathrm{Pb\,/PbSO_4}} = 1{,}685 - (-0{,}356) = 2{,}041\ V, \quad (1.6)\ [27]$$

The construction of a lead acid battery is simple. Multiple lead acid cells are joined together in series to form a battery with a higher voltage, where each electrode is separated by a porous separator that allows for exchange of ions, typically microporous polymers such as polypropylene or polyvinylchloride [4]. The casing is made up of thick polypropylene, that protects the bare cells from damage and the leakage of electrolyte.

For photovoltaic power systems it is important to choose lead acid batteries that are designed for indoor RAPS (remote area power supply) use with continuous power delivery, because they differ from automotive starter batteries. Deep cycle lead acid batteries have thicker electrode plates, which provide a lower but more steady power output [27].

Table 1.1 ***Advantages and disadvantages of lead acid batteries***

Advantages	**Disadvantages**
Lower cost compared to other secondary battery types [29]	Low power density [4]
Availability and easiness of production, easy to recycle [27]	High mass due to the use of liquid electrolyte and high density of lead [27]
Long term durability and reliability [2]	Toxicity of lead and sulphuric acid [27]
Good performance at high or low temperatures [4]	

1.5.2 NiMH batteries

The NiMH battery is a continuation of the early research in rechargeable battery technologies, such as the NiCd batteries [18]. Nickel metal hydride batteries have completely replaced the nickel cadmium batteries because they don't contain toxic cadmium and have a higher energy density [4]. The following reaction takes place at the electrodes of the cell:

$$Charging \Leftrightarrow Discharging$$

$Positive\ electrode$: $NiOOH + H_2O + e^- \rightleftharpoons Ni(OH)_2 + OH^-$, (1.10) [27]

$Negative\ electrode$: $MH + OH^- \rightleftharpoons M + H_2O + e^-$, (1.11) [27]

$Cell\ reaction$: $NiOOH + MH \rightleftharpoons Ni(OH)_2 + M$, (1.12) [27]

The electrolyte in the battery is concentrated potassium hydroxide (KOH) [18]. The M in the reactions represents a metallic alloy, that absorbs hydrogen during the charging phase, forming a metal hydride [29].. Generally, there are two major types of alloys used in NiMH batteries, either rare-earth metals, usually made up of lanthanum and nickel, or alloys consisting of titanium and zirconium [29]. The apparent rarity and cost of these transition elements causes the NiMH battery to be resource intensive for production. Overall, the stability of the reactants and the safe charging reaction makes the NiMH batteries one of the safest types of batteries on the market [30]. In comparison with lithium ions batteries, NiMH batteries can be safely overcharged or drained without significant damage to the cells [30].

Nowadays most NiMH batteries have a small voltage of about 1.2V [18], as the battery is made up of only one cell. The most common size of NiMH batteries are AA cells for portable electronics, although early hybrid vehicles had larger traction batteries with higher voltages [4].

Table 1.2 *Advantages and disadvantages of NiMH batteries*

Advantages	**Disadvantages**
Safe charge and discharge characteristics [30]	Practically replaced by higher energy density Li-ion cells, hence smaller economies of scale advantage [27]
Excellent portability, drop-in replacement for alkaline batteries	Commercially available only in small portable capacities

1.5.3 Lithium-ion batteries

As the name implies, a rechargeable lithium-ion battery does not contain pure lithium metal as the electrode material. It instead relies on the intercalation of lithium ions into the surface structure of the electrodes [31]. Since 1985, the material design of the lithium-ion battery has undergone many iterations, due to the use of different electrode and electrolyte materials [25]. Each new material either increases the reliability of the battery or increases the energy density of each cell. On today’s market there are multiple competing technologies, as they usually have different characteristics and use cases. As a result of the recent global growth in rechargeable battery demand, manufacturers are competing for market share, therefore they are trying to maximize their production scale [25]. Higher availability has lowered the general cost down to affordable levels.

The general reaction that takes place during the charge and discharge cycle is the backwards and forward motion of lithium ions within the electrolyte between the anode and cathode [29]. A common type of lithium-ion cell is made up of lithium cobalt oxide ($LiCoO_2$) as the positive electrode, and graphite as the negative electrode. During the charging process the lithium ions intercalate in the structure of the graphite. The overall reaction doesn’t state the total number of exchanged lithium ions per graphite ring, as lithium ions never change oxidation state, and the total number depends on the concentration of the electrolyte.

$$Discharging \Leftrightarrow Charging$$

$$Positive\ electrode:\ LiCoO_2 \rightleftharpoons Li_{1-x}CoO_2 + xLi^+ + xe^-, \quad (1.13)\ [18]$$

$$Negative\ electrode:\ xLi^- + xe^- + C_6 \rightleftharpoons Li_xC_6\ , \quad (1.14)\ [18]$$

The typical voltage of this cell is about 3,6V [27]. The voltage is so high due to the high oxidation potential of lithium [13] . Low density of lithium salts also contributes to the low density of Li-ion batteries [13].

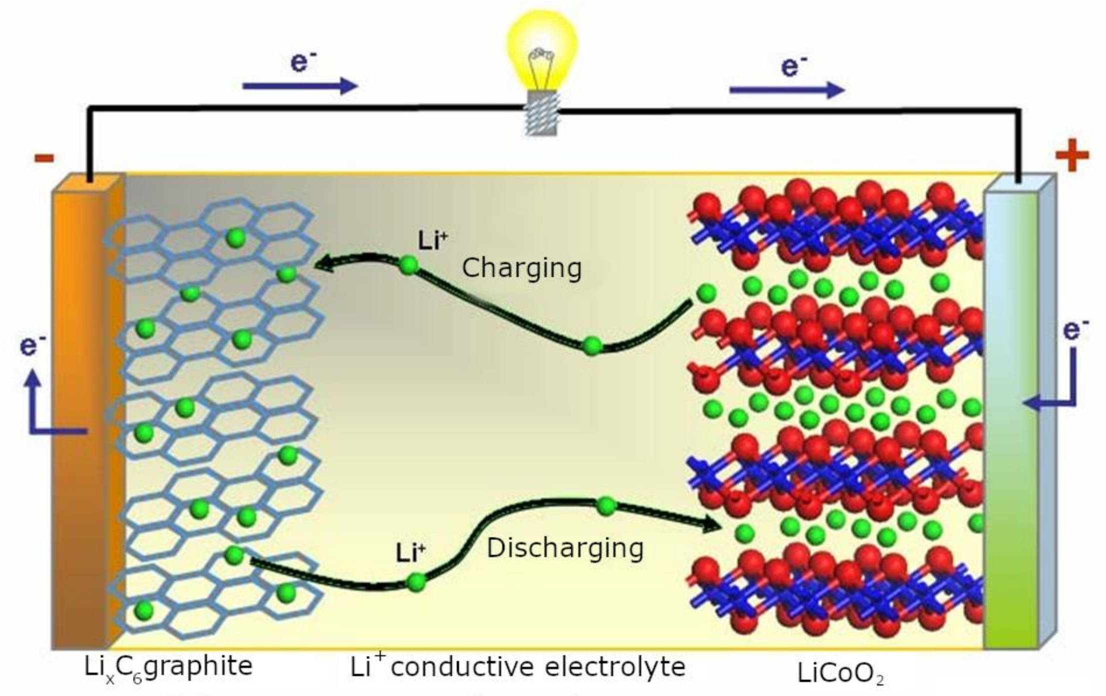

Figure 1.8 Electrode chemistry of $LiCoO_2$ battery during charge/discharge cycle *[18]*

The precise characteristics and parameters of each Li-ion battery type is usually stated in its datasheet. The most common electrode materials are the following.

Table *1.3 Types of common Li-ion battery electrode materials*

Abbreviation	Chemical name	Positive electrode	Negative electrode	Source
LCO	Lithium cobalt oxide	$LiCoO_2$	Graphite	[28]
LMO	Lithium manganese oxide	$LiMn_2O_4$	Graphite	[32]
NMC	Lithium nickel manganese oxide	$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$	Graphite	[32]
NCA	Lithium nickel cobalt aluminium oxide	$LiNiCoAlO_2$	Graphite	[27]
$LiPO_4$	Lithium iron phosphate	$LiFePO_4$	Graphite	[25]
LMO – LT	Lithium manganese oxide – lithium titanate	$LiMn_2O_4$	$Li_4Ti_5O_{12}$	[27]

The most common type of li-ion battery enclosure is a cylindrical cell, that can be spotwelded into large battery packs. There are also other types, such as flat pack batteries intended for small devices, such as smartphones or notebooks. The electrodes are rolled or folded together with separators, and then encased in a metal or plastic cases.

Table ***1.4 Advantages and disadvantages of Li-ion batteries***

Advantages	Disadvantages
Good long-term energy and capacity retention [29]	Lower power density than primary lithium cells [29]
High energy density compared with other competing battery technologies [27]	High power applications require active thermal management [27]
	Higher internal resistance compared to NiMH batteries [29]
	Possibility of thermal runaway and explosion in the case of improper handling [33]
	Difficult to recycle [33]

Table ***1.5 Comparison of discussed battery technologies [27]***

Battery type	**Lead acid**	**NiMH**	**Li-ion**
Typical voltage [V]	2,1	1,2	3,6 – 3,7
Energy density [Wh/kg]	30-50	60-120	100-250
Power density [W/kg]	180	250-1000	250-340
Total recharge cycles [-]	500-800	500-1000	400-1200
Memory effect	No	No	No
Monthly self-discharge rate [%]	3-20	30	5

2. SOLAR RADIATION

Incident solar radiation is the term given to the electromagnetic energy that hits the surface of the earth perpendicularly [34]. The electromagnetic spectrum produced by the sun follows that of a black body with the absolute temperature of about 5800 K [35]. From Wien's law we can calculate that the wavelength of light with maximum intensity in the spectrum is around 500 nm.

$$\lambda_{max} = \frac{2{,}90\times10^{-3}}{T} = \frac{2{,}90\times10^{-3}}{5800} = 5\times10^{-7}[m] \quad (2.1)\ [23]$$

The temperature T is given as absolute in kelvin and λ_{max} is the wavelength of light[m]. This incident light spectrum is not the same as the one that reaches the earth's surface, as the radiation passes though the atmosphere [34]. The radiation intensity, called the solar constant, that enters the earth's atmosphere is 1367 W/m^2 [35]. The solar radiation is scattered or reflected by the atmosphere. Different gasses in the air have different absorption spectra and scatter the light in the process of Rayleigh scattering, that depends on the wavelength of light [36].

$$I_{Rayleigh} \propto \lambda^{-4}\ [W/\,m^2] \quad (2.2)\ [36]$$

Where the λ is the wavelength [m] of light within the spectrum. The longer the wavelength of light, the more it is scattered [36]. Another factor is the air mass index:

$$AM = \frac{1}{cos\theta}\ [-] \quad (2.3)\ [35]$$

It gives a relative number to the absorption of the atmosphere due to the angle of incidence ϑ [°] of light from the normal of the measured surface. As the angle changes the distance the light must travel through the atmosphere also changes [35].

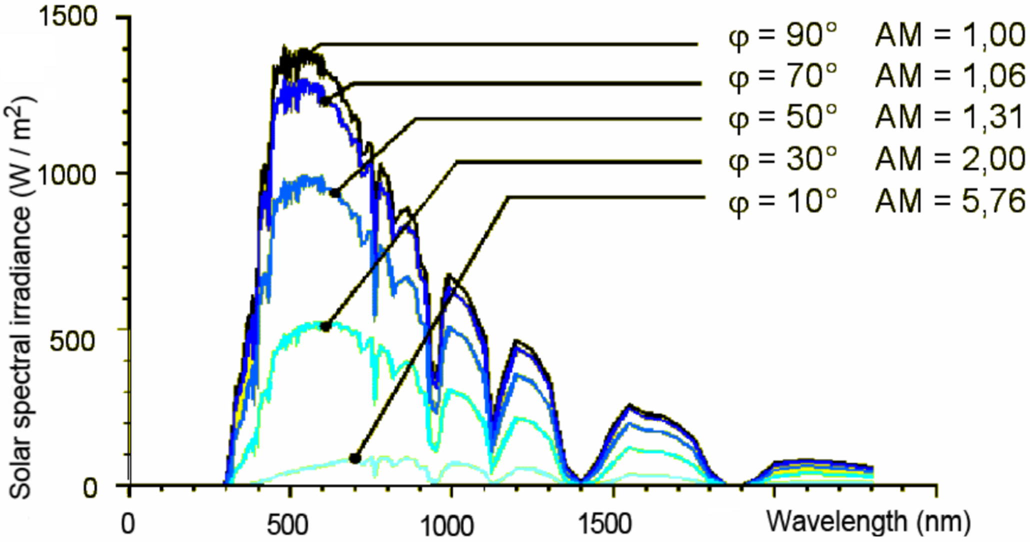

Figure 2.1 Solar *spectrum under different angles of incidence [35]*

Other factors such as cloud coverage and air pollution make the standard global solar irradiance on the surface of the earth 1000 W/m^2, with the air mass index of 1,5 [36]. This value does not include the seasonal changes in irradiance and position on the earth.

The earth orbits the sun in an elliptical orbit with the period of one year [6]. During this orbit the earth rotates around its axis that is tilted at a constant angle of 23,5° [34]. That gives rise to the cyclical nature of seasons, as the tilt towards the sun of the northern or southern hemisphere changes during the year, resulting in alterations in the surface intensity of sunlight across the globe [34]. The positional latitude on earth also affects the total solar energy that falls on a specific area during the year, as the air mass index increases with the angle of incidence [35]. This can be seen on the map of the Czech Republic, where the total incident solar energy decreases with the increase in latitude [7]. Another factor is the geographical landscape of a region, which determines the average annual cloud coverage of the region. Therefore, it is more efficient to have a photovoltaic system in the South Moravian region. The angle of the installed photovoltaic panels determines how much energy can be produced throughout the year in a specific area, as the angle of incidence of the solar radiation changes, therefore it is crucial to find the optimal angle.

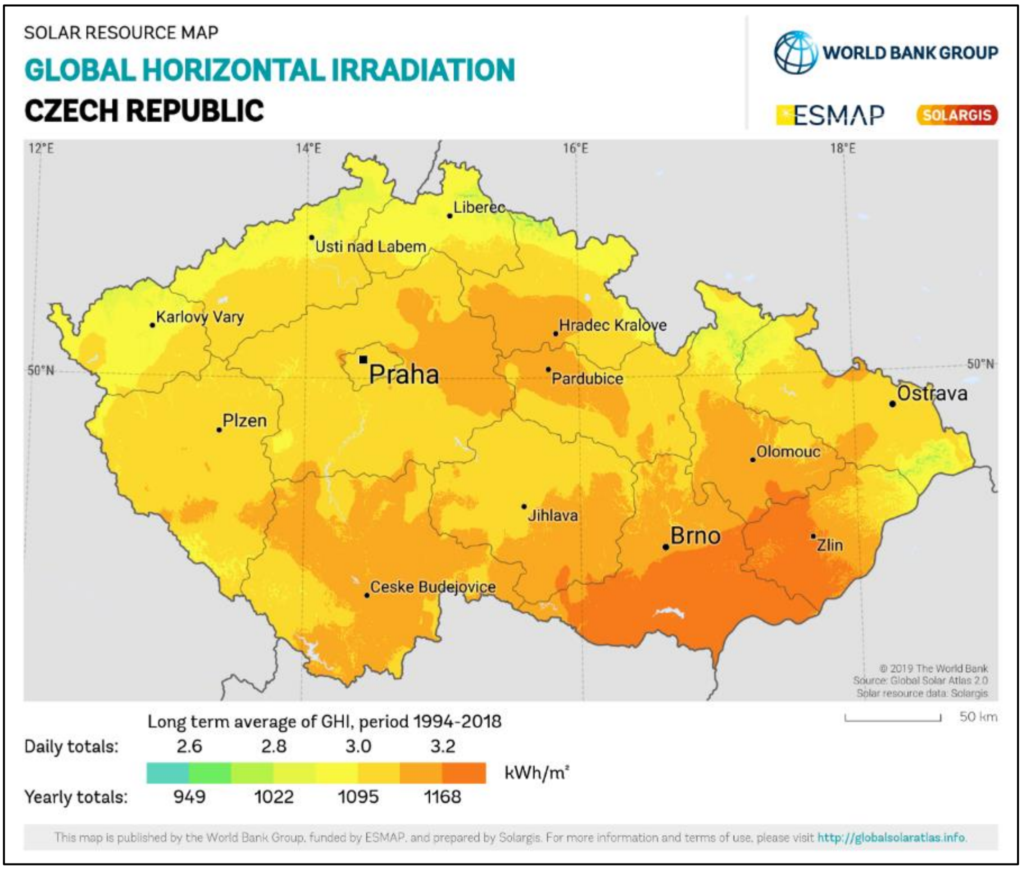

Figure 2.2 Average annual solar irradiation map of the Czech Republic *[7]*

3. PHOTOVOLTAIC SYSTEM TYPES

3.1 System types

The three main types of photovoltaic systems are the following, each having a different application with set parameters. The total scale of the system depends on the demands of the investor, either if they want to maximize energy production, or they just want to meet the energy demand of a building [2].

3.1.1 On grid system

This system relies on connecting the solar panels directly to an inverter combined with a DC-to-DC converter. The direct current generated by the panels is converted to alternating current (230V at 50 Hz in the European Union) at the maximum power point of the panels [6]. The inverter is then connected to the household distribution board, that is connected to the public electricity grid [19]. The metering box of the energy supplier monitors the net consumption of electricity, recording if the appliances in the house use energy from the panels or the grid, or that the panels produce and supply excess energy to the grid [37]. It is the easiest system to implement because the cost and the use of an energy storage system is mitigated by the grid acting as a balancing energy source [38]. The main disadvantage is the reliance on the grid. In the case of a blackout the system will not function. Energy price fluctuations can also make the system economically obsolete, with low buyback prices and high energy prices for the draw of electricity from the grid.

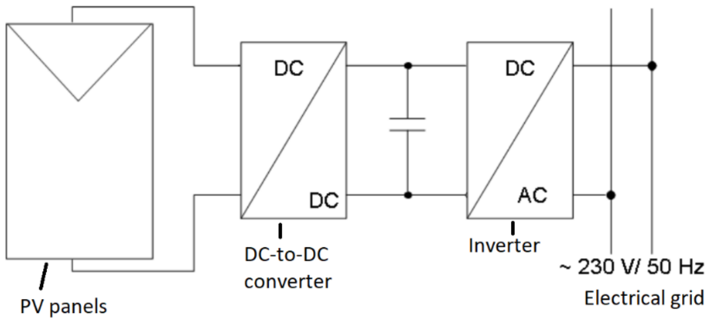

Figure 3.1 On grid PV system components *[35]*

3.1.2 Off-grid system with battery storage

In the case that a building is remote and has no access to the electric grid, the only option is local electricity generation and storage. The PV panels are connected to a DC-to-DC converter or a charge controller with maximum power point tracking that is connected to a battery bank [35]. The DC converter is connected to the inverter that distributes the AC electricity via the electrical installation in the building [35]. The advantage is that the system is self-reliant and has no monthly energy payments. It is limited by the total energy produced by the PV panels and the deliverable continuous maximum power.

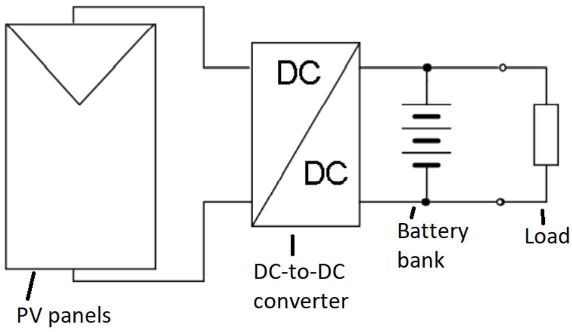

Figure 3.2 Off-grid PV system components *[35]*

3.1.3 Hybrid grid connected system

A hybrid system combines the on grid system with local energy storage in batteries, where a charge controller is placed between the panels and the inverter [19]. It allows for the storage of energy in times of excess power generation without sending it and selling it off to the electric grid and allows for the utilization of energy locally in times of no or low energy production [35]. If the energy requirements by the household exceed the total produced by the PV system, more energy can be drawn from the grid. This makes the system flexible for the variations of daily energy generation due to seasonal changes and secures the building against power outages.

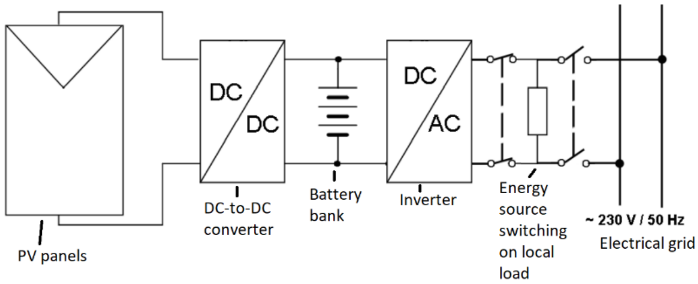

Figure 3.3 Hybrid PV system components *[35]*

3.2 Inverters

The main component of a photovoltaic systems is the inverter, as it transforms direct current into alternating current, which can then be used by all household appliances. The underlying electronics of an inverter are usually a H bridge that produces a pulse width modulated signal that is filtered with a low pass filter at the output [6]. If the input DC voltage doesn’t meet the input range of the inverter, it can be stepped up or down with a buck or boost converter [6]. Depending on the system type there are multiple variants. They can either output single phase or three phase alternating current [37].

3.2.1 Central inverter

The easiest, very reliable, and most cost-effective solution for small scale PV systems, as all the panels are interconnected via series and parallel connections to a central inverter [6]. The price of a central inverter is comparatively lower compared with string and micro inverters, as there are no duplicate functional power electronics blocks [6]. The drawbacks include the increased danger due to collectively higher direct current voltages produced by the panels, and higher losses due to conversion inefficiencies at higher voltages [6]. It is required that the direct current wiring meet strict parameters for good electrical isolation and electrical distribution to the inverter [38]. Another flaw are mismatch losses, as interconnected photovoltaic panels will have variations in energy production but are forced to all work at the same maximum power point [39].

3.2.2 Micro inverter

A micro inverter is a device that attaches close to one photovoltaic panel or is directly integrated into a panel [40]. It converts direct current into alternating current at a power in the range of hundreds of watts, which is distributed by the local AC wiring instead of dedicated DC wiring [39]. It also has a MPPT unit to track the attached PV panel, which allows for the greatest power utilization in the PV system, even with system mismatch [6]. The disadvantage is that monitoring of the system is more complex, as additional wiring is required for communication with the micro inverters [39].

3.2.3 String inverter

Combines the features of central and micro inverters, as independent strings of PV panels are connected to individual string inverters, which have joined outputs at the AC side [40]. This type of inverter should be considered if the cost is between the other inverter types, and if panel power production matching is of greater importance than ease of installation.

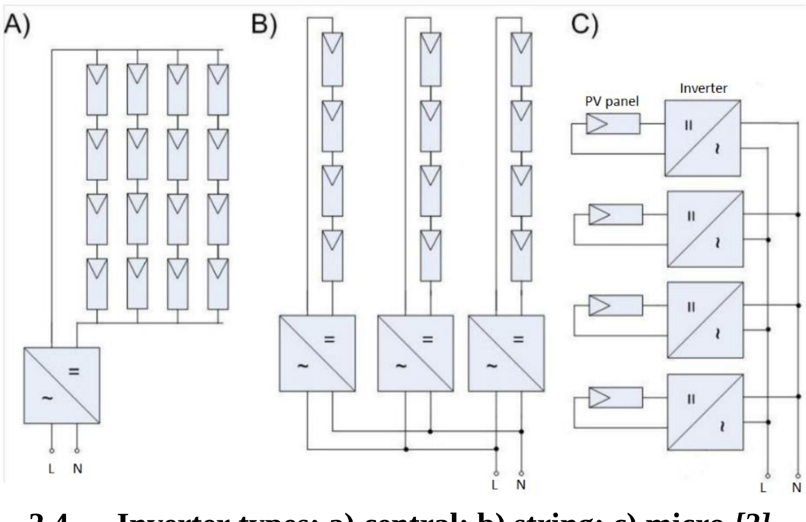

Figure 3.4 Inverter types; a) central; b) string; c) micro *[2]*

4. LEGISLATION IN THE CZECH REPUBLIC

4.1 Building and operation permissions

To build and operate a private photovoltaic system in a household, it is required to follow local planning and taxation laws.

Table ***4.1 Laws in the Czech Republic that apply to photovoltaic systems [41] [42]***

Act No. 458/2000 Coll. on the energy law
Act No. 180/2005 Coll. on the support of electricity produced from renewable energy sources
Decree No. 475/2005 Coll. provisional decree of the act on the support of the use of renewable energy resources
Decree No. 364/2007 Coll. amendment to the decree No. 475/2005
Decree No. 150/2007 Coll. on the regulation of prices in the energy sectors
Decree No. 51/2006 Coll. on the conditions of connecting to the electricity system
Act No. 183/2006 Coll. on spatial planning and building regulations (Building Act)
Act No. 91/2005 Coll. on the energy law
Act No. 586/1992 Coll. on income taxes

Under Czech law as stated by Act No. 183/2006 Coll. on spatial planning and building regulations (Building Act) in §103 paragraph e) point 9 it is not necessary to apply for planning permission for a photovoltaic system if the total installed power doesn’t exceed 20 kW. Act No. 458/2000 Coll. on business conditions and the performance of state administration in the energy sectors and on the amendment of certain laws states under §3 paragraph (3) that it is also not necessary to apply for a license issued by the Energy Regulatory Authority to conduct business on the energy market in the Czech Republic if the installed power doesn’t exceed 10 kW. Act No. 586/1992 Coll. on income taxes states under §10 that if the personal income obtained from the sale of excess energy produced by a photovoltaic system doesn’t exceed a personal income of 30 000 Kč, no income tax applies to it. The price of the sale of excess energy depends on the legal agreement set by the local energy provider.

4.2 Subsidies

Given that the design of the investigated photovoltaic system applies to a residential household, the rules for the application of Czech government grants are given in the document “Závazné pokyny pro žadatele a příjemce podpory programu Nová zelená úsporám v rámci Národního plánu obnovy pro rodinné domy“ [5]. This document defines the different energy saving, utilization and generation methods implemented in a newly built household. The grants apply after the date of 21.9.2021 and are currently active at the time of writing. The section C.3 states the rules for the financial support of photovoltaic systems, requiring that:

- It is a new installation for a residential house placed on the building itself [5]
- PV installation is interconnected with the AC distribution network in the household [5]
- The generated electrical energy is primarily utilized by the household [5]
- It is connected to the public electrical distribution grid [5]
- The installation has a maximum power of 10 kWp [5]
- The inverters have a minimum efficiency of 95%, and have a maximum power point tracking system with a minimum efficiency of 98% [5]
- Follows the standards EN 50549-1:2019 and 2016/631 set by the European commission [5]
- Minimum efficiency of panels at 1000 W/m^2 and 25°C is 18% for monocrystalline silicon panels and 12% for amorphous silicon panels [5]
- The battery capacity is defined by the value stated by the manufacturer under a constant discharge current over 10 hours [5]
- The minimum battery capacity is numerically equal to or maximally double the installed photovoltaic power in kWh. Batteries based on lead acid or NiMH technology are not subsidized [5]

The maximum allowed grant for one household is 200 000 Kč [5] and is calculated from the parameters given in table 5.2. Given a specific calculated grant bracket, the total grant size cannot exceed 50% of the total cost of installation and is hence decreased to match this criterion [5].

Table ***4.2 Grant allocation parameters [5]***

Installed parts of the photovoltaic system	**Grant amount [Kč]**
Installation with a minimal power of 2 kWp	40 000
Installation with a minimal power of 2 kWp with a hybrid inverter	60 000
Installation with a minimal power of 2 kWp with an installation of an efficient water heater	100 000
For every additionally installed 1 kWp of solar panels over 2kWp	10 000
For every additionally installed 1 kWh of lithium ion technology based battery capacity	10 000

5. CASE STUDY INFORMATION

5.1 PV*SOL premium

PV*SOL is a suite of programs developed by Valentin Software GmbH. Specifically, the program PV*SOL premium allows for the complete planning and simulation of a photovoltaic system of any size [11]. The program contains the following tools:

- Specifying the location of the planned installation, allowing for the exact simulation of the solar irradiation of the desired building
- 3D modelling utility to place the photovoltaic panels on an imported model of the investigated building, with predictive simulation of panel shading and optimal panel installation
- A database of photovoltaic panels, inverters, and battery systems, that can be picked and implemented in the simulation of the system
- Energy usage profile definition from a database, depending on the electrical loads present in the household
- Automatic cost and break-even analysis
- Predictive annual simulation of photovoltaic energy production with 1 minute time interval precision

This program was chosen, as it allowed for complete customization of the input parameters and was intuitive to use.

5.2 Geographical data

The specific assignment in this thesis applies to a real residential house located in the city district of Brno-Černovice. It is a three-story residential house, where the third floor has a slanted tiled roof on only one side, the rest is made up of horizontal flat sheet metal. The tilted roof is oriented NEE at a bearing of about 80° from the north. This means that there is no part of the roof that is titled directly towards the south, which complicates installation.

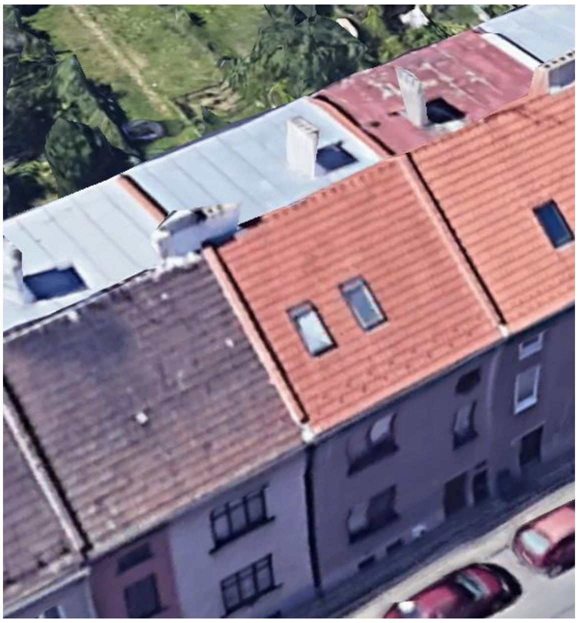

Figure 5.1 3D model of the residential house on Google Earth *[8]*

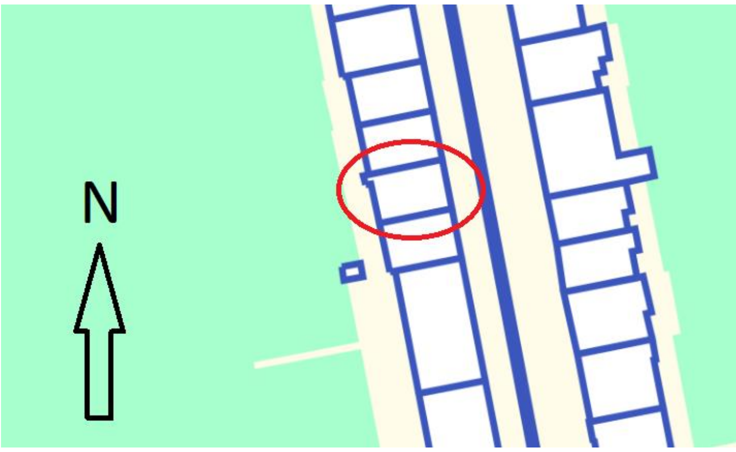

Figure 5.2 2D view of the geographical location of the household *[9]*

The floor dimensions of the house were retrieved from the online utility CadMapper [9]. The dimensions of the roof were triangulated and measured from 3D models available on Google Earth [8]. Acquired measurements were then used to produce a full 3D model of the building in Sketchup Pro [10].

It is impossible to completely cover the roof due to two structural incompatibilities. First one is a narrow, slanted section on the other side of the tiled roof that is too small for PV installation. The second element are two chimneys located on the horizontal part of the roof, which drop a shadow on anything that is north from them.

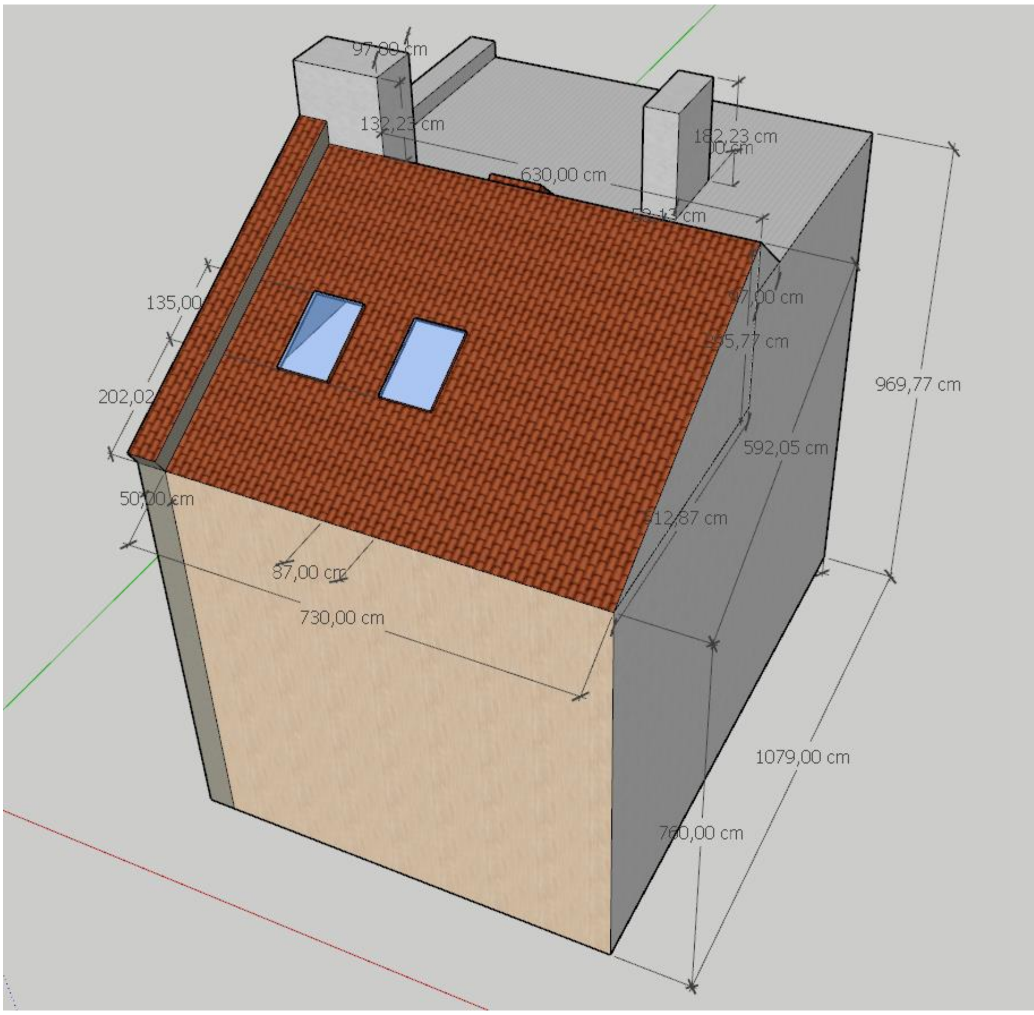

Figure 5.3 3D model approximation of the household in Sketchup Pro *[10]*

5.3 Energy usage

The total yearly energy usage was retrieved from the yearly billing documentation from the electricity supplier. The data was provided both in terms of years and irregular payment periods.

Table *5.1 Yearly energy draw of building*

Time frame	**Annual energy use [MWh]**
10/2016-10/2017	3,864
10/2017-10/2018	4,047
10/2018-10/2019	3,972
10/2019-10/2020	5,918
10/2020-10/2021	11,291

The yearly energy usage stayed relatively constant from 2016 to 2019, until the energy usage drastically increased due to the installation of a new electric water and air heating system in 2020. Energy demand of the household is expected to remain at around 11,3 MWh per year, unless other drastic changes to demand occur, such as the theoretical scenario of an increase in use due to the home charging of a new electric vehicle. The total maximum power draw of the household is estimated using data from average residential households with common appliances, and the included electric air and water heater. To fully utilize the energy generated by the PV system, it might be necessary to have a timer on the appliances that have the highest power draw during the peak generation hours and limit the power draw. Another factor that affects the system design, is that the electric heater uses three phase AC, which can be supplied by only a three-phase inverter. Therefore, the PV system will utilize a high power central three phase inverter, that has more than one MPPT tracker, and can also be hybrid in the case of battery energy storage. Precise power draw cannot be estimated, but the energy profile of the household in PV*SOL Premium was chosen to reflect the following data.

Table 5.2 *Power draw of appliances in average household [43]*

Appliance	**Power draw [W]**
LCD TV	100
Computer Monitor	30
Desktop Computer	450
Dishwasher	1500
Fridge / Freezer	400
Electric stove	2000
Front Load Washing Machine	2200
Home Internet Router	15
20 x LED Light Bulb	200
Microwave	2500
Total	9395

Table 5.3 *Parameters of IVT AIR X 130 air heater and AirModul 9E9 water heater [44]*

Part	IVT AIR X 130	IVT AirModul
Maximum heating power	13 kW	9 kW
Electric supply	400 V, 3N, AC, 50 Hz	-
EU energy rating	A++	A++

The precise energy profile of the household is unavailable, as the distributor offers monitoring only on a per month basis. Hence the selected energy profile for the household was chosen from a database in PV*SOL Premium, that includes the energy draw of a typical two-person household with a child, and a domestic electric space and water heater [11]. The total energy draw of this model is 11415 kWh [11], which is within a small margin of error compared with the real measured value of 11291 kWh. The projected peak power load is around 15 kW, but for most of the year average peak power draw is about 6 kW [11]. This is the power delivery that the utilized inverter must achieve, additional spikes in demand will be covered by the grid.

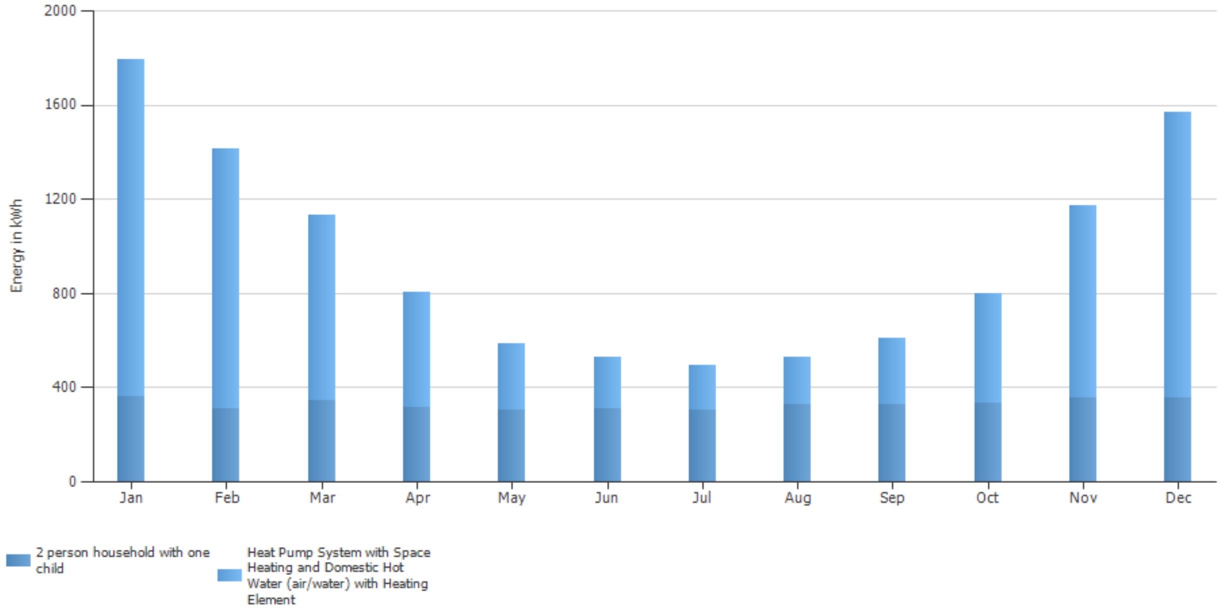

Figure 5.4 Modelled energy profile of the investigated household *[11]*

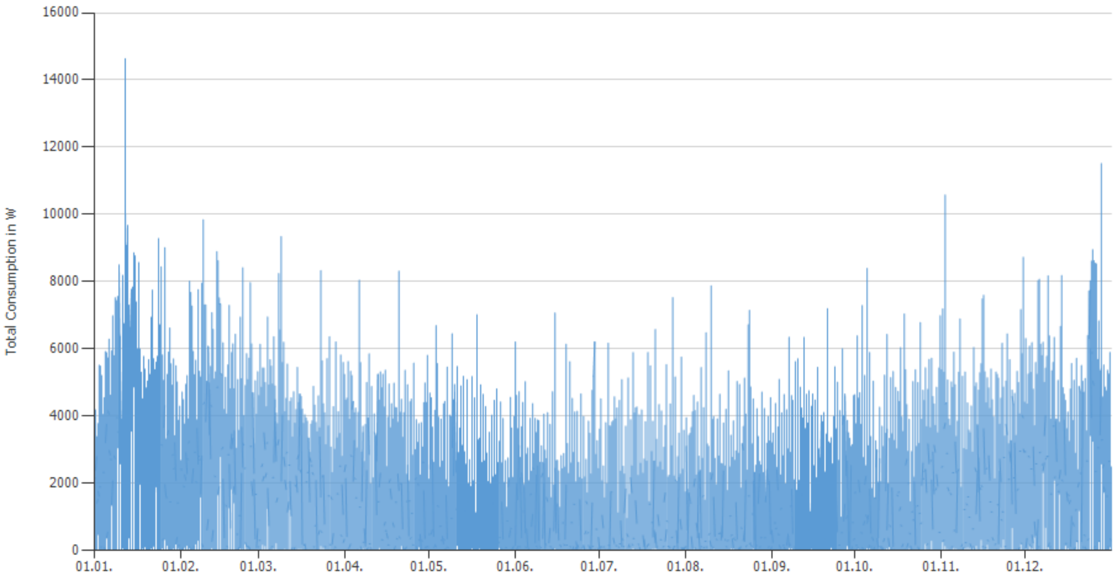

Figure 5.5 Modelled power draw of the investigated household *[11]*

6. INSTALLATION PLAN AND COST ANALYSIS

The chosen parts included in this thesis were sourced from internet retailers located in the Czech Republic. They were chosen based on their current stock availability and on the best price to performance ratio in their respective class.

6.1 Panels

Due to the current global semiconductor shortage in 2021 and 2022, it is more difficult to find photovoltaic panels. Hence the only type that will be considered are monocrystalline silicon photovoltaic cells, as they have the highest efficiency rating on the market and are comparatively cost competitive with polycrystalline silicon panels. The total power draw of the household is relatively high; therefore, the chosen panels have a power rating of over 300 Wp. Having larger panels cuts down on the total mounting and wiring hardware as a smaller number of panels is needed. The chosen inverter can also handle higher voltages produced by such panels. The panels also fulfil the requirements stated in chapter 4, that to receive a subsidy the efficiency of the monocrystalline silicon cells be at least 18% [5]. The chosen panels are from the company LONGi solar, as they have a wide selection of panels with a large range of power ratings and are present in the PV*SOL premium database. They also guarantee a -0,55% annual reduction in the maximum power output of the panels over a 25-year period [45]. The provided information by the manufacturer is given at standard testing conditions, meaning an irradiance value of 1000 W/m^2, cell temperature of 25°C, and a spectral value of AM 1,5 [45].

Table 6.1 ***Datasheet information for 455 Wp photovoltaic panel [45]***

Model number	LR-72HPH-455M
Operational temperature [°C]	-40 ~ +85
Maximum power [W]	455
Open circuit voltage [V]	49,5
Short circuit current [A]	11,66
Voltage at maximum power [V]	41,7
Current at maximum power [A]	10,92
Surface area [m^2]	2,173
Module efficiency [%]	20,9

Table 6.2 ***Datasheet information for 375 Wp photovoltaic panel [46]***

Model number	LR-60HIH-375M
Operational temperature [°C]	-40 ~ +85
Maximum power [W]	375
Open circuit voltage [V]	41,1
Short circuit current [A]	11,60
Voltage at maximum power [V]	34,6
Current at maximum power [A]	10,84
Surface area [m^2]	1,822
Module efficiency [%]	20,6

The roof is made up of two sides. Roof side 1 is pitched towards the east, and roof side 2 is horizontal. I chose to install only 455 Wp panels on roof side 1, as there is enough space to pack them without leaving unfilled gaps. On roof side 2 the panels are only 375 Wp. This is because they are mounted at an optimal angle of 14,90° calculated by PV*SOL premium, meaning that there must be spacing gaps to prevent shading. Hence it is best to have narrower and smaller panels. Optimal packing of panels was done through trial and error, guided by panel shading simulation in PV*SOL premium. Additionally, roof side 2 has the panels turned directly south to maximize energy production. The chosen panel installation also maximizes energy production early in the morning. Roof side 1 is tilted at the rising sun, allowing for the residents to mainly utilize locally generated electricity in the morning hours.

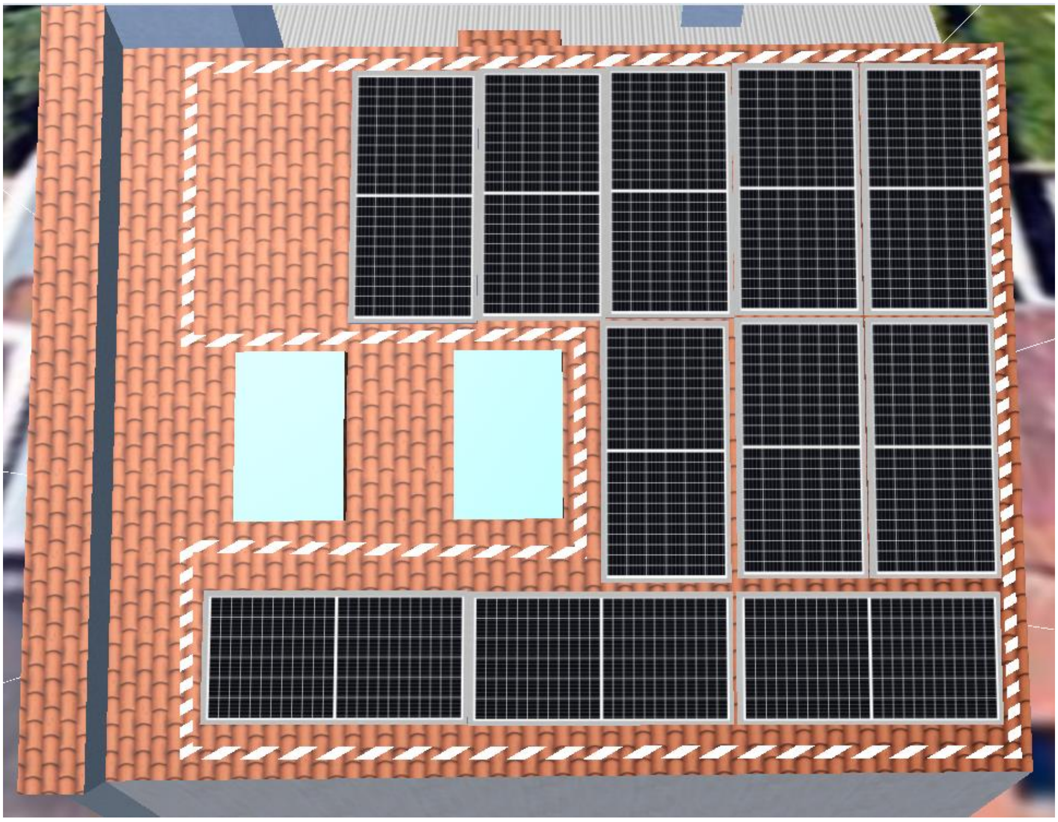

Figure ***6.1 Installed panels on roof side 1*** **[11]**

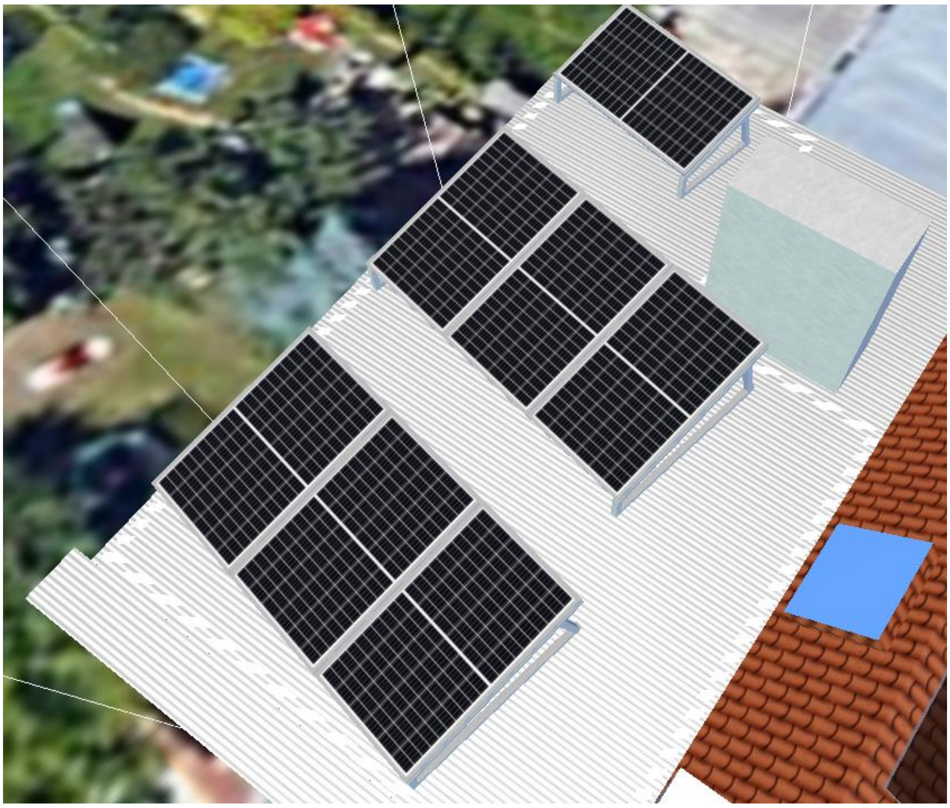

Figure 6.2 Installed panels on roof side 2 ***[11]***

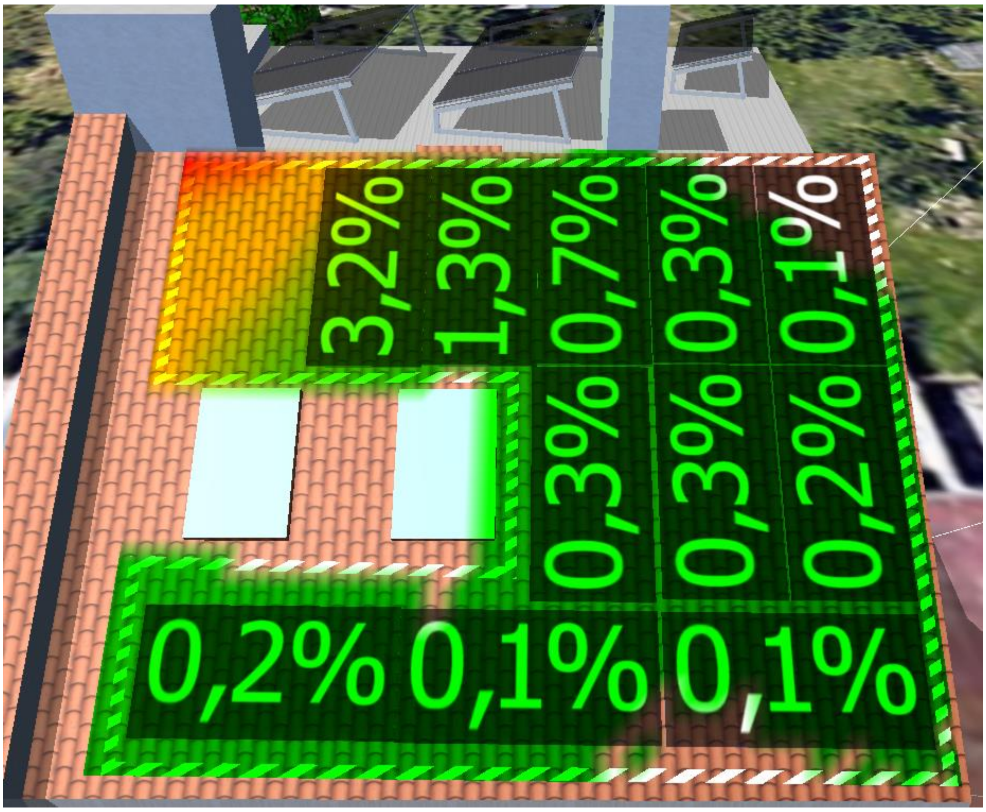

Figure 6.3 Shading of panels on roof side 1 ***[11]***

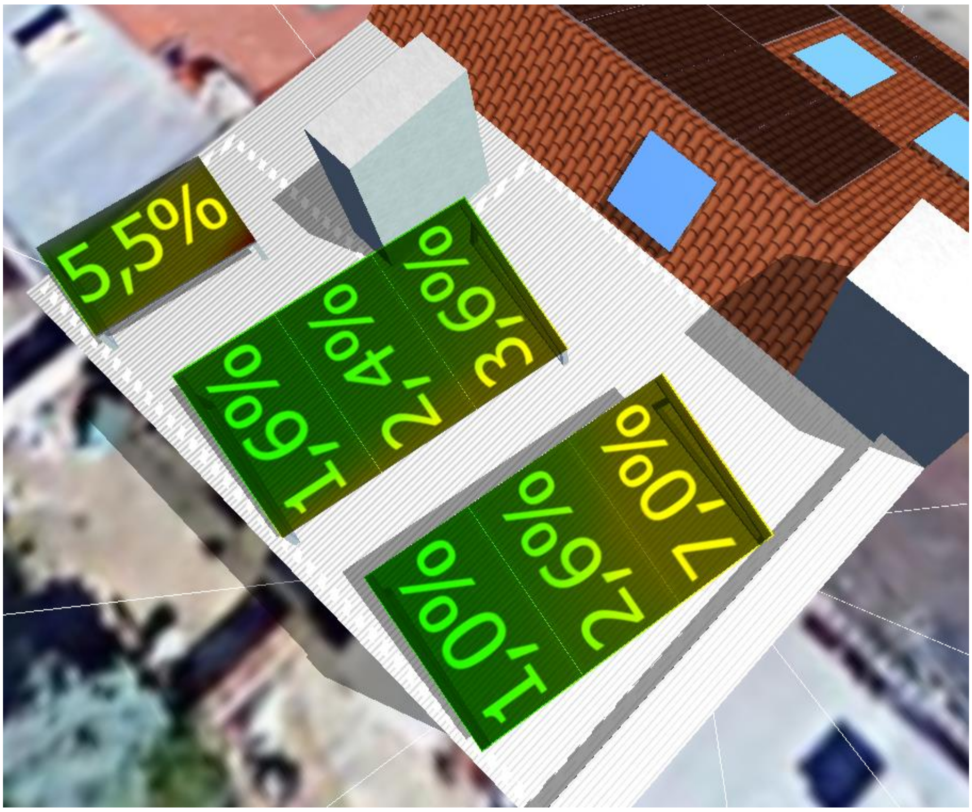

Figure 6.4 Shading of panels on roof side 2 ***[11]***

The total number of 455 Wp panels installed on roof side 1 is eleven adding up to a total power of 5,005 kWp, and roof side 2 has seven 375 Wp panels with a total power of 2,625 kWp. The complete maximum photovoltaic power of the system is 7,630 kWp, a value below the threshold of 10 kWp stated in Act No. 458/2000 Coll. §3 paragraph (3). Additional panels could be added to the system, as there is space, but it would decrease the overall efficiency of the system. The regions left unpopulated are highly shaded by the chimneys located on the roof, which would otherwise cause losses due to uneven shading of panels and disrupt the maximum power point tracking. Some of the panels are already partially shaded in the simulations, with the highest shading percentage occurring on roof side 2. The panels closest to the chimneys have shading values of 7,0% and 5,5%, which is not ideal, but it does not majorly disrupt power generation, as they are only shaded during specific times of the day.

6.2 Inverter and battery system

Because the electric air and water heater require three-phase AC, the only type of inverter that is considered for the system is a central three phase inverter. As stated in chapter four, the maximum allowed wattage of a residential PV system is 10 kWp. The power rating of the inverter must be lower than this, so the chosen inverters have a reasonable maximum AC power delivery of 6-7 kW. This should meet the electricity demand of the customer if the power draw is reasonably managed. To provide a fair comparison, this thesis compares two photovoltaic systems. An on grid system and a hybrid system with battery storage. The results of the simulation in PV*SOL premium will determine, whether it is effective to implement a battery storage solution with a reasonable cost return period.

Another factor that complicates the design of the photovoltaic system is the way electricity consumption is metered in the Czech Republic. As stated in Decree No. 359/2020 Coll. about the measurement of electricity, § 11 paragraph (3), electric energy consumption is measured separately for each phase. This means, that if a three-phase inverter delivers power evenly to all phases, a load that is applied to only one phase will not draw the total power provided by the photovoltaic system, but instead will partially be supplied by the grid and PV system [47]. This means that the household will pay the energy provider for the distribution and usage of energy that the PV system could otherwise cover with no additional costs [47]. Therefore, it is required that the three-phase inverter is asymmetric and can deliver power to each phase respectively as is required by the applied loads. The selection of available asymmetric inverters on the market is not large, and they usually come at a higher price compared with symmetric inverters [47].

To make the comparison of a hybrid and on grid system less confusing, the chosen inverter will be the same for both cases. It is an asymmetric hybrid three-phase inverter, meaning that it has an integrated battery charge controller [48]. It works both in the case that the battery is connected, or absent. The inverter is by the company SolaX power, as it is available for purchase in Czechia, and it supports a wide variety of battery systems, provided that the inverter specifications are met by the battery system.

Figure 6.5 Hybrid asymmetric inverter Solax X3-Hybrid-6.0T *[49]*

Table *6.3 Datasheet information for* Solax X3-Hybrid-6.0T *[49]*

Model number	X3-Hybrid-6.0T
Operational temperature [°C]	-25 ~ +60
IP rating [-]	IP65
Maximum recommended DC power [W]	8000
Maximum DC voltage [V]	1000
Maximum input current [A]	11/11
Maximum short circuit current [A]	14/14
MPPT voltage range (full load) [V]	280-800
Number of MPP trackers [-]	2
Strings per MPP tracker	1
Nominal AC power [VA]	6000
Maximum AC power [VA]	6000
Rated grid voltage (AC voltage range) [V]	400(360 to 440)
Rated grid frequency [Hz]	50/60
Battery voltage range [V]	170-500
Maximum battery charging/discharging power [W]	8000
MPPT efficiency [%]	99.9
Euro efficiency [%]	97.0
Maximum efficiency [%]	97.8

The efficiency ratings of the inverter meet the requirements for the subsidies [5]. The inclusion of two MPP string trackers allows to separate the PV system into two panel strings in series, where one will be located on the tiled roof side 1, and the other will be located on the horizontal sheet metal covered part of the roof side 2.

The battery technology that was chosen is lithium ion, because it is the only battery type subsidized by the Nová zelená úsporám program [5]. $LiFePO_4$ batteries also offer higher volumetric and gravimetric energy density compared with lead acid batteries, so it can be easily installed in a small space in the building [27]. Another requirement is that the battery bank needs to be easily modular, so the capacity can be adjusted to suite the installed photovoltaic system, without excess unused capacity. If the client desires to modify the system in the future, they can add additional battery modules later. The chosen battery modules are by the company Pylon Technologies, Co. Ltd. Each individual Pylontech US2000C Plus module is connected in series with other modules [50]. The advantages of these modules are the compatibility with the Solax X3-Hybrid-6.0T inverter, low cost compared with other readymade solutions on the market that are not customizable, and the inclusion of an integrated battery management system on each module [50].

Figure 6.6 Pylontech US2000 Plus 48V 50Ah 2,4kWh battery module *[50]*

Table *6.4 Datasheet information for* Pylontech US2000 Plus 48V 50Ah 2,4kWh *[50]*

Model number	Pylontech US2000 Plus
Nominal Voltage [V]	48
Nominal Capacity [Wh]	2400
Usable Capacity [Wh]	2280
Discharge Voltage [V]	44.5 ~ 53.5
Charge Voltage [V]	52.5 ~ 53.5
Charge / Discharge Current [A]	25 (recommended)
	50 (Maximum time 60 s)
	90 (Peak time 15 s)
Design life	15+ Years (25℃)
Cycle life	>6000 (25℃)
Working Temperature [℃]	0~50
Single series string quantity [-]	16

It is stated by the manufacturer that the battery modules have a projected life span of at least 15 years [50]. This is based on the calculation, that the regular depth of discharge of cells is 90% over a maximum number of 6000 cycles [50]. If we take the worst-case scenario, where the batteries are discharged daily by 90%, the life span comes out to 16,4 years before major deterioration of cells. This means, that the cost return period for a hybrid system must be less than 15 years, as otherwise the batteries would deteriorate before they would be paid off by the cost of energy savings.

The batteries can be stacked on top of each other without mounting, but for a more reliable installation, it is better to have them installed in a server rack. The market offers differently sized racks based on the total number of modules installed in the battery bank. The chosen rack is the Pylontech box 22U, which offers space for five Pylontech US2000C Plus units [51].

Figure 6.7 Pylontech box 22U *[51]*

6.3 Energy metering

In an ideal situation, all the energy produced by a photovoltaic system would be consumed locally by the household. This is not the case, as the household will have a varying energy demand throughout the day, compared with the sinusoidal power output of the photovoltaic system over the course of the day. Hence, excess photovoltaic energy will either have to be wasted, or be delivered to the electrical grid. Given that the household is located in the South Moravian region, the local energy distributor E.ON does not buy excess energy at a given market price, but instead provides net metering in the form of a virtual battery [12]. The premise is that instead of requiring a physical battery bank for the system, the excess energy is delivered to the electric grid, where it is utilized [12]. This grid feed in is metered on the energy meter of the household [12]. In the situation that the photovoltaic system cannot provide enough power to the household, energy will be drawn from the electric grid at zero market cost from the total delivered earlier. The energy supply and demand are tallied over the course of a year, allowing the household to draw excess energy generated in the summer during the winter months, when the production capacity is lower [12]. The only cost of this virtual battery are monthly subscription payments depending on the total energy that was delivered to the grid, and distribution fees for the delivery of energy from the grid, as those are separate from the market price of energy [12]. The subscription costs are summarized in the table below.

Table ***6.5 Monthly subscription fees for a virtual battery by E.ON [12]***

Virtual battery capacity [MWh]	Cost in Kč including VAT per month
1	49
2	99
3	149
4	199
4 +	499

The only requirements set by the distribution company E.ON are:

- The customer must sign a contract with E.ON about the installation of a photovoltaic system connected to the grid with a maximum installed power of 10kWp and must fulfil the requirements set by the grant program Nová Zelená Úsporám [12]
- The customer must have a valid contract for the supply of electric energy from E.ON [12]
- The household must be connected to the internet to verify the energy consumption data [12]

6.4 Simulation results

6.4.1 On grid system

By letting the software PV*SOL premium simulate the system with the chosen parts, panel placement and household energy demand profile on a minute precision scale, the following data was acquired. The total energy that was generated by the panels was 7161 kWh. Because there is no energy storage in batteries, only 2704 kWh was utilized by the household, and 4457 kWh was sent to the grid [11]. The total percentage of locally utilized photovoltaic energy was 23,7%, which is not a problem, as the virtual battery increases this share to 62,6%. The only downside of a virtual battery is that the grid does not supply fully renewable energy, but instead the mixture of energy from fossil fuels, nuclear and some renewable energy. In addition, the total stored energy in the virtual battery is over 4 MWh, which means that the monthly cost of energy storage is in the highest bracket, at 499 Kč per month [12].

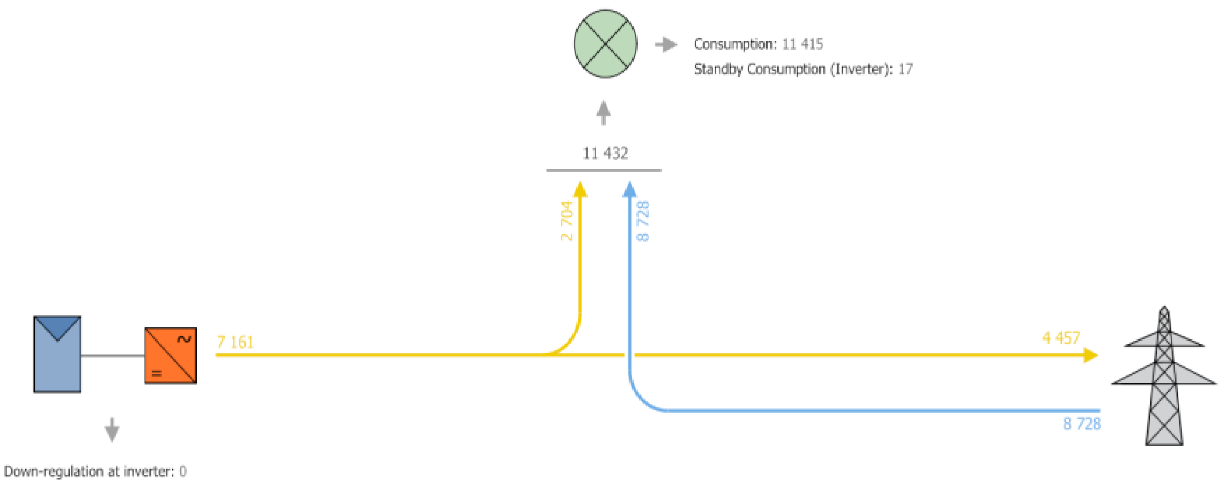

Figure 6.8 Energy flow graph of the on grid system in PV*SOL premium *[11]*

Table *6.6 Performance of panels on roof side 1 [11]*

PV Generator Output [kWp]	5,01
PV Generator Surface [m²]	23,91
Global Radiation at the Module [kWh/m²]	1004,1
Global Radiation on Module without reflection [kWh/m²]	1009,24
Performance Ratio (PR) [%]	90,33
PV Generator Energy (AC grid) [kWh/Year]	4566,14

Table ***6.7 Performance of panels on roof side 2 [11]***

Spec. Annual Yield [kWh/kWp]	912,31
Spec. Annual Yield [kWh/kWp]	912,31
PV Generator Output [kWp]	2,62
PV Generator Surface [m²]	12,75
Global Radiation at the Module [kWh/m²]	1226,01
Global Radiation on Module without reflection [kWh/m²]	1232,83
Performance Ratio (PR) [%]	80,18
PV Generator Energy (AC grid) [kWh/Year]	2595,18
Spec. Annual Yield [kWh/kWp]	988,64

The additional data acquired from the simulation is the total annual yield from panels on each side of the roof. On roof side 1 where the panels are facing east, the total yield is 912,31 kWh/kWp per year, which is less than the panels on roof side 2 with the annual yield of 988,64 kWh/kWp. This confirms the expectation, that the panels with the more optimal bearing towards the south will be more efficient. Also, the panels are placed, so that they are not majorly affected by shading caused by interfering objects. The total energy draw of 11415 kWh would not be possible to cover with a larger photovoltaic system, as the yield ratio shows us, that we would need a system with a peak power output higher than 10kWp, which is not permitted by the Energy Regulatory Authority under Act No. 458/2000 Coll. on business conditions and the performance of state administration in the energy sectors and on the amendment of certain laws §3 paragraph (3) and the energy distributor [12].

6.4.2 Hybrid system

Unfortunately, the database in PV*SOL premium does not contain the Pylontech US2000 Plus battery modules. This is not a major problem, as it instead has battery modules directly from SolaX power, that form a battery bank with similar specifications. The batteries from SolaX power were not used in the official design of the system, as they are not available on the market in the Czech Republic. The T3.0 battery modules by SolaX power are based on the same $LiFePO_4$ technology as Pylontech US2000 Plus, and have a capacity of about 3,0 kWh per module, instead of 2,4 kWh as US2000 Plus [11]. The total battery bank of four T3.0 modules is 12,3 kWh, which is close enough to five modules of US2000 Plus adding up to 12 kWh, or a 2,5% difference in capacity [11]. This difference is negligible, as above 12 kWh the total storage capability of the battery bank plateaus, gradually increasing the cost per unit energy stored. This is shown in the following graph, where each point represents a different capacity of SolaX power battery banks with total achieved storage capacity per annum, that was run in the PV*SOL premium simulation. Hence, the final chosen capacity of the battery bank in the hybrid photovoltaic system was 12,3 kWh.

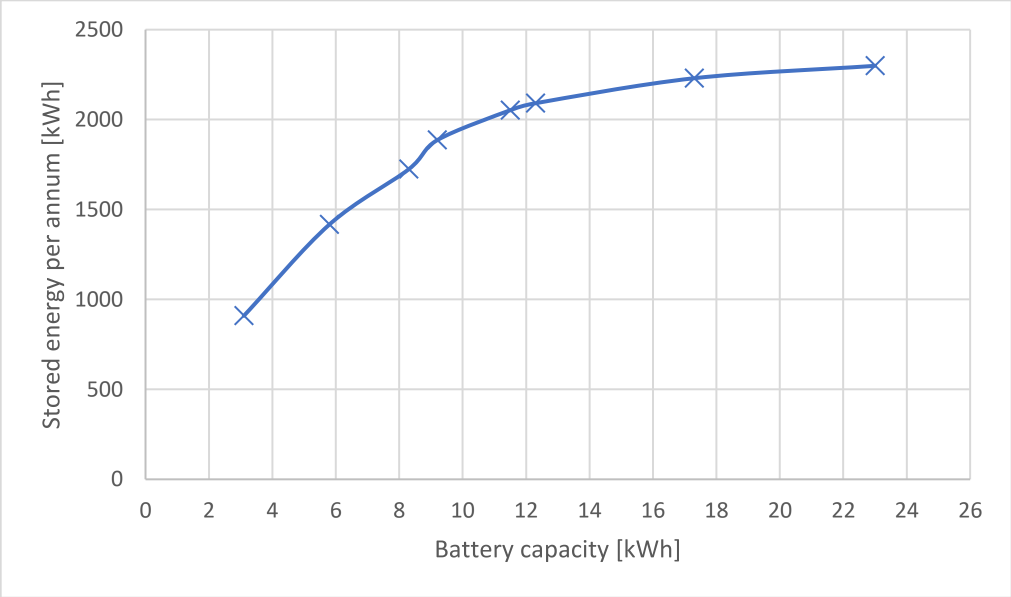

Figure 6.9 Energy stored per annum compared with battery bank capacity *[11]*

We can observe that the total energy that is utilized locally by the household is higher than in the case of the on grid system, up to 4650 kWh. The total energy produced by the photovoltaic system is lower in the hybrid system, as there are losses of about 144 kWh in the charge and discharge cycles of the battery bank. Therefore, with the excess energy stored in the virtual battery the photovoltaic system covers 60,8% of the household energy demand. The size of the required virtual battery falls to the 3 MWh bracket, with a monthly cost of 149 Kč [12]. The placement of the panels is the same as before.

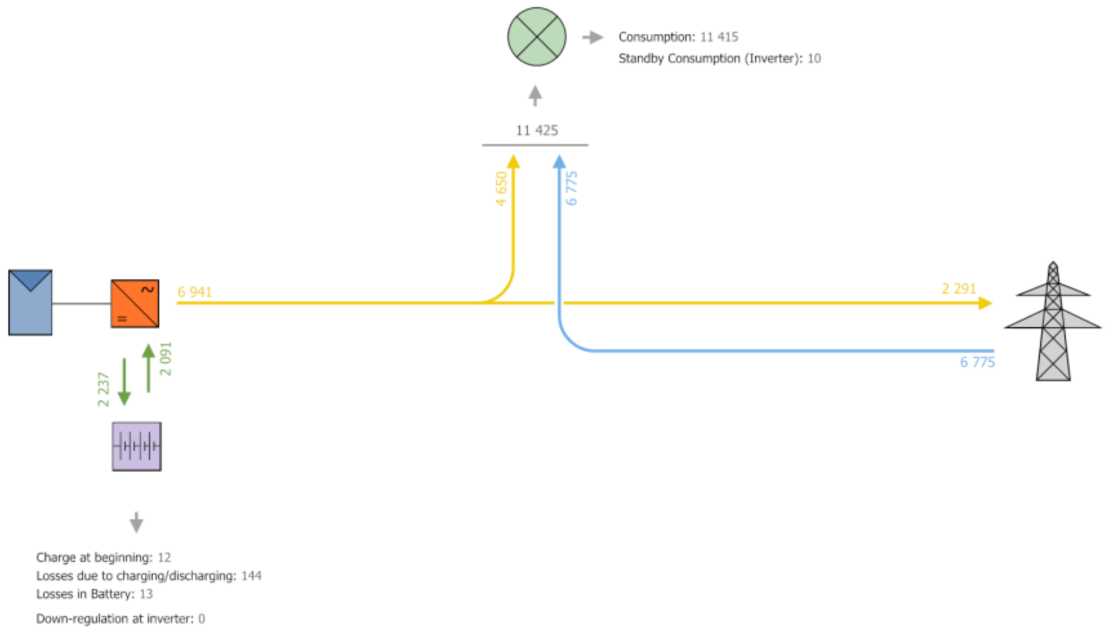

Figure 6.10 Energy flow graph of hybrid system in PV*SOL premium *[11]*

Table *6.8 Performance of panels on roof side 1 [11]*

PV Generator Output [kWp]	5,00
PV Generator Surface [m²]	23,91
Global Radiation at the Module [kWh/m²]	1004,10
Global Radiation on Module without reflection [kWh/m²]	1009,24
Performance Ratio (PR) [%]	87,56
PV Generator Energy (AC grid) [kWh/Year]	4426,09
Spec. Annual Yield [kWh/kWp]	884,33

Table *6.9 Performance of panels on roof side 2 [11]*

PV Generator Output [kWp]	2,62
PV Generator Surface [m²]	12,75
Global Radiation at the Module [kWh/m²]	1226,01
Global Radiation on Module without reflection [kWh/m²]	1232,83
Performance Ratio (PR) [%]	77,70
PV Generator Energy (AC grid) [kWh/Year]	2514,82
Spec. Annual Yield [kWh/kWp]	958,03

6.5 Cost projection and break-even analysis

The total cost of each system determines the return period, alongside current energy prices. Additional costs include the cost of installation and mounting material cost. Wiring cost includes the cost of string diodes, fuses, DC circuit breakers and surge protectors. The installation would be done by an appointed professional company; therefore, it is difficult to estimate the total cost and the data is only informational. It will be included in the final cost projection, but they are only rough estimates chosen subjectively. The electrician responsible for the installation would need to be certified to install photovoltaic systems in order to receive the grants under the Nová zelená úsporám program [52] [5]. Also, under ČSN 33 1500 it is required that the photovoltaic system is inspected by a qualified professional at least every four years, as it is an electrical installation producing power that is exposed to the elements [53].

Table ***6.10 Estimated installation and additional material cost***

Installation work cost	20000 Kč
Panel mounting hardware cost	25000 Kč
Wiring cost	20000 Kč
Total additional cost	65000 Kč

Electrical energy price is determined by the energy distributor. It consists of distribution fees and spot market prices per unit energy in kWh. The household is under the D 57d distribution rate (given in the energy payment invoice), as it utilizes direct electric air and water heating, meaning that it has a higher than average energy draw [54]. This allows for the use of low rate and high-rate energy tariffs, depending on the time of day when the electricity is drawn [54]. If the energy is drawn during off peak periods, like during the night, the distributor charges a lower spot market price per kWh [54]. The ratio of high rate and low rate draw is given in the energy payment invoice. PV*SOL premium does not support inputting a two rate energy tariff, hence an average energy cost has to be calculated. The price of energy per kWp for each rate was set by E.ON on 1.4. 2022 [55]. The estimated inflation of energy costs was set at 2% per year, as it is unclear how the market will evolve in the future with the current global events.

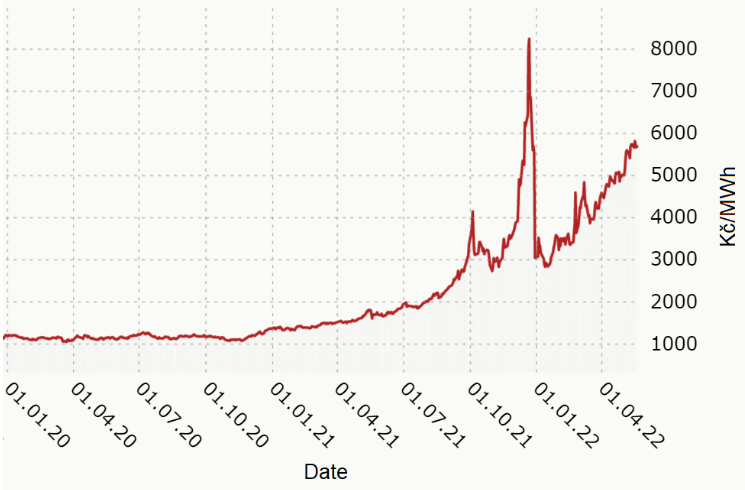

Figure 6.11 Price of energy in Kč/MWh by E.ON over last three years *[56]*

Table *6.11 Energy tariff prices for D 57d [55]*

Tariff	[MWh]	[%]	[Kč/MWh] [55]
High	6,311	0,559	5936,00
Low	4,980	0,441	5754,00

$$Average\ tariff = 0{,}559 \cdot 5936{,}00 + 0{,}441 \cdot 5754{,}00 = 5855{,}73\ Kč/MWh \quad (6.1)$$

6.5.1 On grid photovoltaic system cost projection

The total net cost of the on grid system is calculated from the combined cost of materials and installation, alongside the subsidies.

Table *6.12 Cost of parts of the on grid photovoltaic system including VAT*

Manufacturer	Name of part	Number of elements [-]	Date of availability	Cost per unit [Kč]	Total cost [Kč]	Source
LONGI Solar	LR4-72 HPH 455 M G2	11	05.04.2022	5738,00	63118,00	[57]
LONGI Solar	LR4-72 HPH 375 M G3	7	05.04.2022	4692,00	32844,00	[58]
Solax Power Co. , Ltd.	X3-6.0-T	1	05.04.2022	56685,00	56685,00	[49]

Table 6.13 *Total maximum subsidy for the on grid photovoltaic system [5]*

Type of subsidy	Eligible units	Subsidy per unit [Kč]	Total [Kč]
Installation with a minimal power of 2 kWp	1,00	40000,00	40000,00
For every additionally installed 1 kWp of solar panels over 2kWp	5,00	10000,00	50000,00

The total maximum subsidy does not include the bracket for including a hybrid inverter in the system, as there are no batteries installed, which disqualifies the inverter.

Table 6.14 *Net cost of the on grid photovoltaic system including VAT*

Total cost of parts [Kč]	152647,00
Total additional costs [Kč]	65000,00
Total cost of system [Kč]	217647,00
50% of total cost of system [Kč]	108823,50
Total maximum subsidy [Kč]	90000,00
Applicable subsidy for system [Kč]	90000,00
Net cost including VAT [Kč]	127647,00

The total annual fees were calculated by taking fixed monthly payments for the parameters of the household, and annual distribution fees that apply to the 8,728 MWh drawn both from the virtual battery and the additional grid demand.

Table 6.15 *Annual fees for distribution and related costs including VAT [55] [12]*

Fee	**Monthly cost [Kč]**	**Annual cost [Kč]**
Fixed monthly utility fee	96,00 + 5,00	1212,00
Virtual battery service 4+ MWh	499,00	5988,00
Fee for main circuit breaker over 3 × 20 A and up to 3 × 25 A	387,00	4644,00
Fee for the support of renewable energy sources	-	5219,34
Distribution fee	-	2291,42
Annual total	**-**	**19354,76**

The resulting graphs show that the photovoltaic system decreases the energy demand from April to September to levels below the electricity demand of the household, causing the cost of electricity to go to negative numbers, as excess energy is stored in the virtual battery. During the winter months the costs savings are insignificant, as the energy production decreases to below 400 kWh per month from October until February.

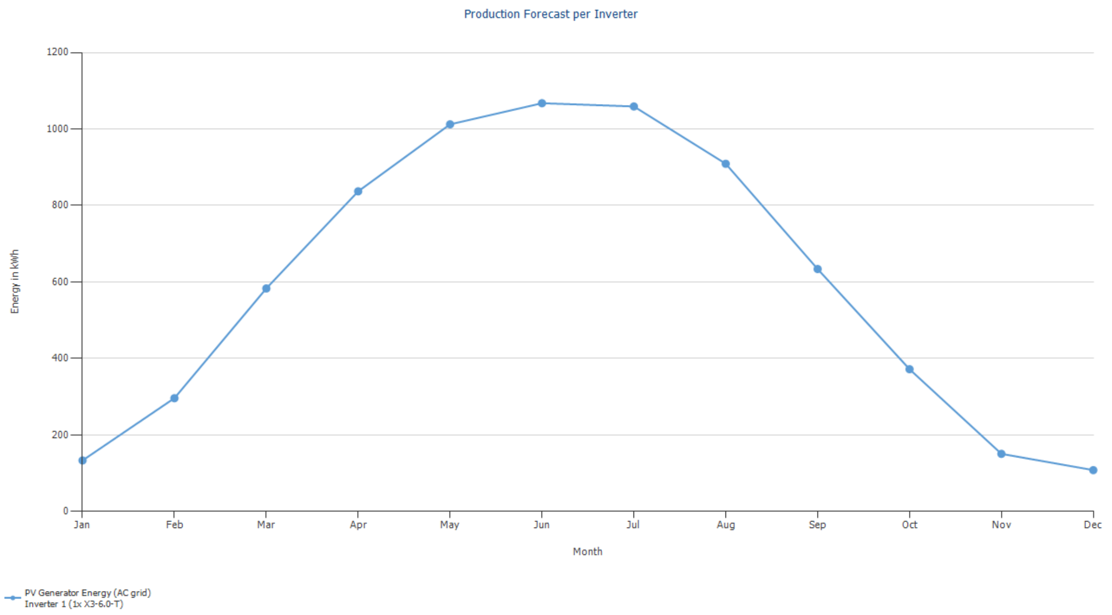

Figure 6.12 Production forecast of on grid system in PV*SOL premium *[11]*

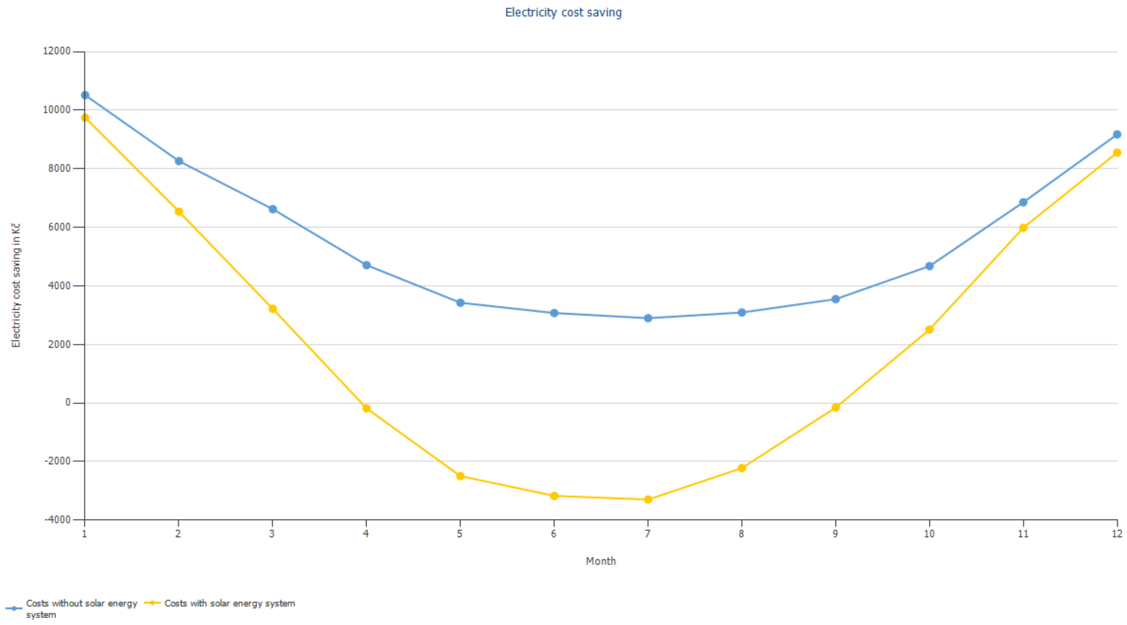

Figure 6.13 Electricity cost savings of on grid system in PV*SOL premium *[11]*

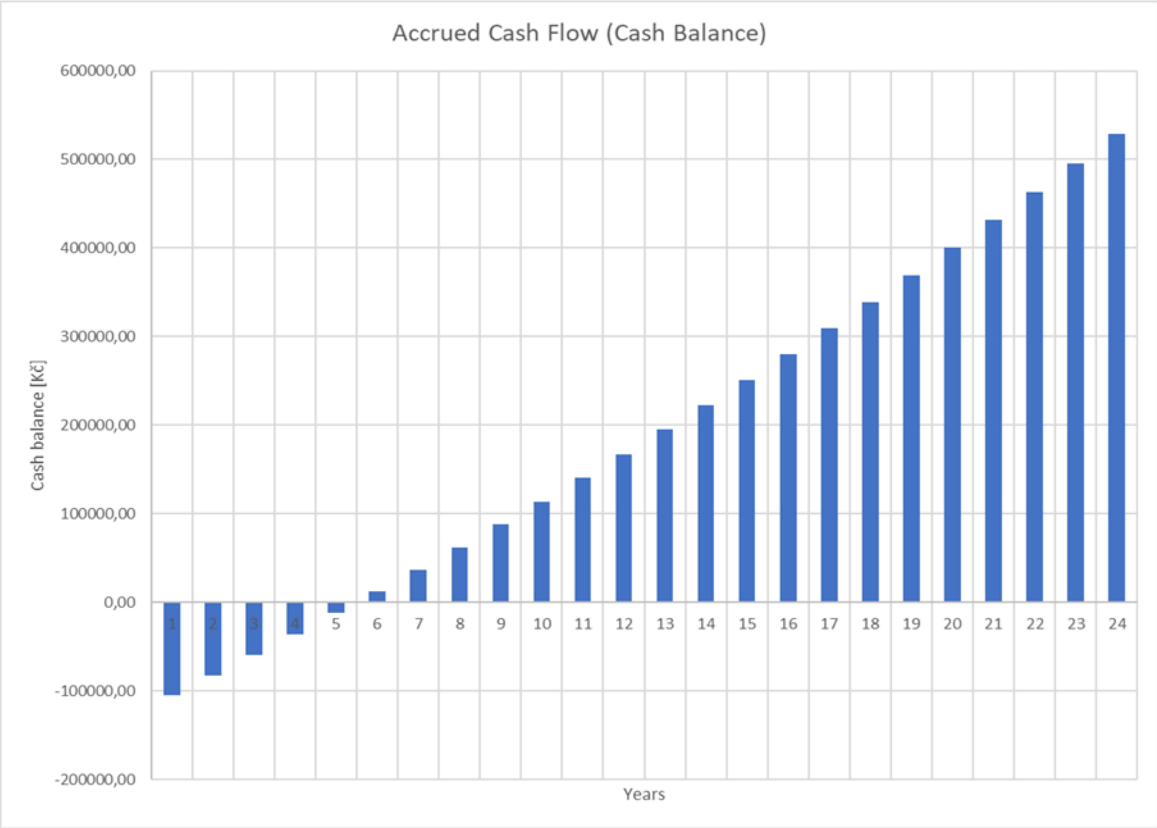

Figure 6.14 Accrued cash flow of on grid system in PV*SOL premium *[11]*

The accrued cash flow generated by the savings from the on grid photovoltaic system shows, that the break even point of the system is at around the five to six year mark. This is appealing, as the return on investment is relatively short. This prediction might be different, as the real system and household will have varying efficiencies compared with the model. The return period is currently also low due to the currently high energy prices, that might rebound to lower levels in the future. The inflation of energy prices is difficult to predict, hence it would be ideal to repeat the analysis over the course of the lifetime of this on grid photovoltaic system. The total predicted savings over the expected 24 year lifespan of the system is about 528309,95 Kč.

6.5.2 Hybrid photovoltaic system cost projection

The parts used in the hybrid system are the same as in the on grid system, except for the inclusion of the battery bank. This adds an additional major cost.

Table ***6.16 Cost of parts of the hybrid photovoltaic system including VAT***

Manufacturer	Name of part	Number of elements [-]	Date of availability	Cost per unit [Kč]	Total cost [Kč]	Source
LONGI Solar	LR4-72 HPH 455 M G2	11	05.04.2022	5738,00	63118,00	[57]
LONGI Solar	LR4-72 HPH 375 M G3	7	05.04.2022	4692,00	32844,00	[58]
Solax Power Co. , Ltd.	X3-6.0-T	1	05.04.2022	56685,00	56685,00	[49]
Pylontech	Pylontech kabinet rack 22U	1	05.04.2022	8640,00	8640,00	[51]
Pylontech	Pylontech US2000C Plus 48V 50Ah 2,4kWh CANBUS	5	05.04.2022	30320,00	151600,00	[50]
Pylontech	Battery to inverter cables	1	05.04.2022	1222,00	1222,00	[59]

Table ***6.17 Total maximum subsidy for the hybrid photovoltaic system [5]***

Type of subsidy	Eligible units	Subsidy per unit [Kč]	Total [Kč]
Installation with a minimal power of 2 kWp with a hybrid inverter	1	60000,00	60000
For every additionally installed 1 kWp of solar panels over 2kWp	5	10000,00	50000
For every additionally installed 1 kWh of lithium ion technology based battery capacity	9	10000,00	90000

The total cost of the system is lower than double that of the total maximum applicable subsidy, therefore the subsidy has to be lowered to 50% of the system cost.

Table ***6.18 Net cost of the hybrid photovoltaic system including VAT***

Total cost of parts [Kč]	314109,00
Total additional costs [Kč]	65000,00
Total cost of system [Kč]	379109,00
50% of total cost of system [Kč]	189554,50
Total maximum subsidy [Kč]	200000,00
Applicable subsidy for system [Kč]	189554,50
Net cost including VAT [Kč]	189554,50

The use of a physical battery lowers the total fees associated with energy distribution from the total virtual battery and grid draw of 6,775 MWh, decreasing the annual fees to 13480,57 Kč.

Table ***6.19 Annual fees for distribution and related costs including VAT [55] [12]***

Fee	**Monthly cost [Kč]**	**Annual cost [Kč]**
Fixed monthly utility fee	96,00 + 5,00	1212,00
Virtual battery service 3 MWh	149,00	1788,00
Fee for main circuit breaker over 3 × 20 A and up to 3 × 25 A	387,00	4644,00
Fee for the support of renewable energy sources	-	4057,89
Distribution fee	-	1778,68
Annual total	**-**	**13480,57**

The total energy produced by the hybrid system is almost the same as in the case of the on grid system, with an excess of energy produced between April and September, and the production falling below 400 kWh per month from October until February.

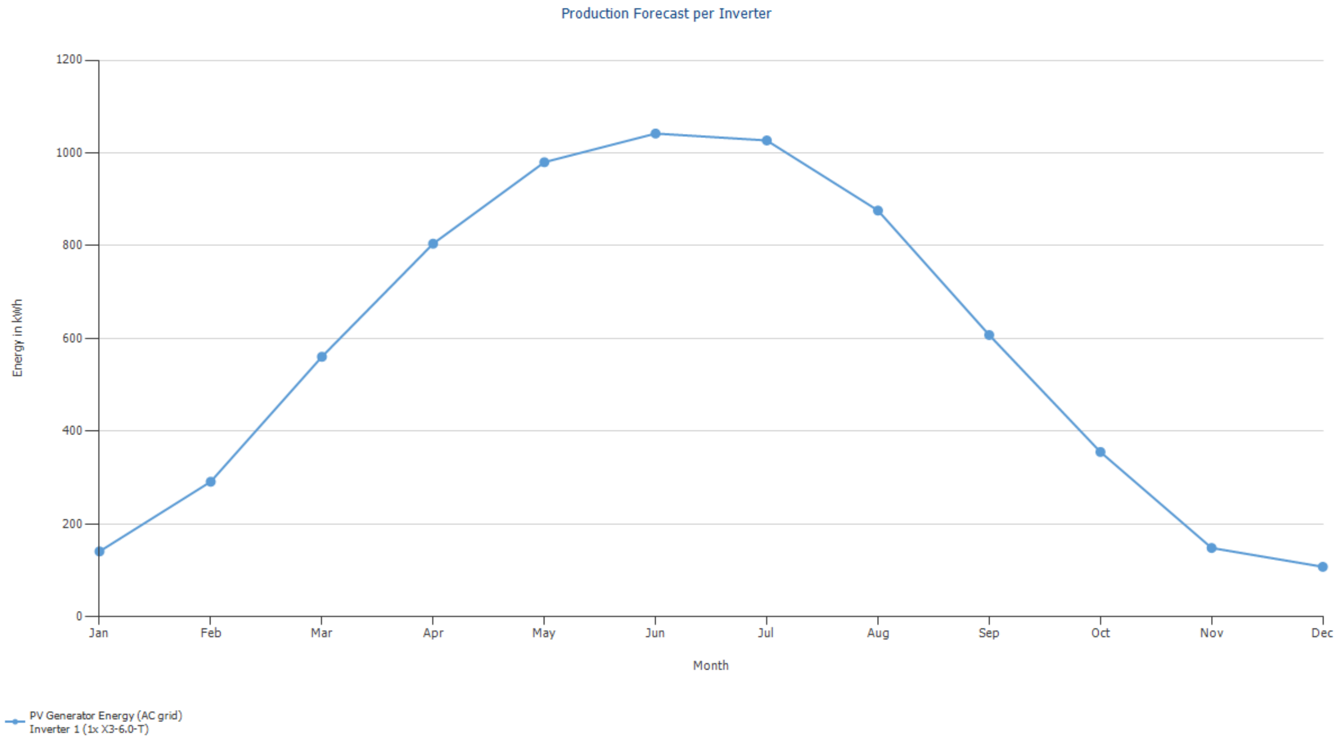

Figure 6.15 Production forecast of hybrid system in PV*SOL premium *[11]*

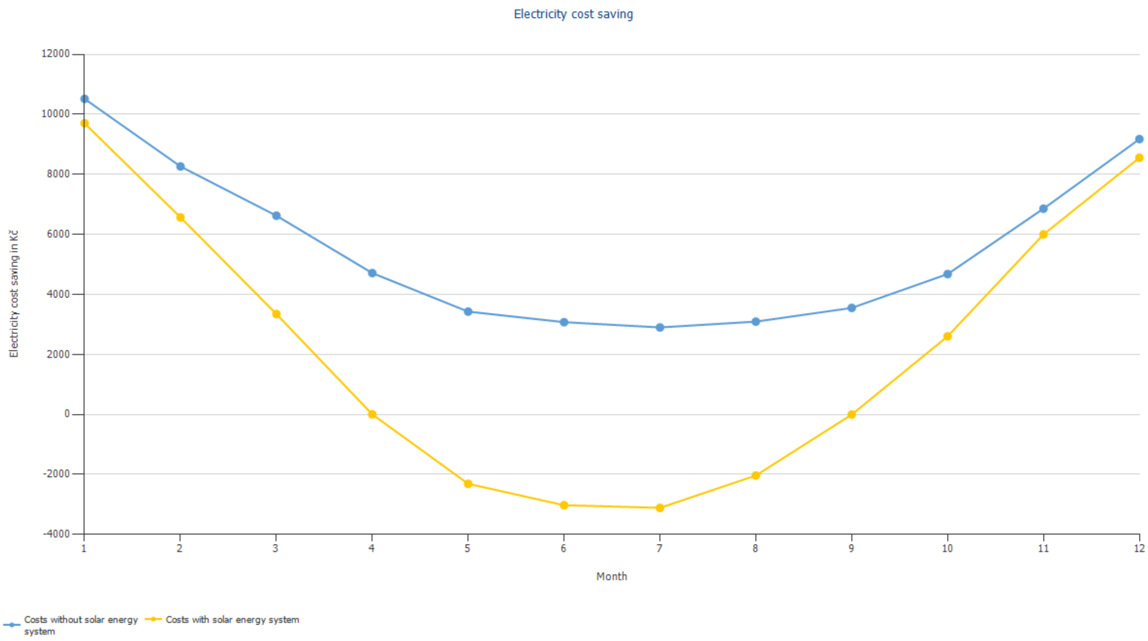

Figure 6.16 Electricity cost savings of hybrid system in PV*SOL premium *[11]*

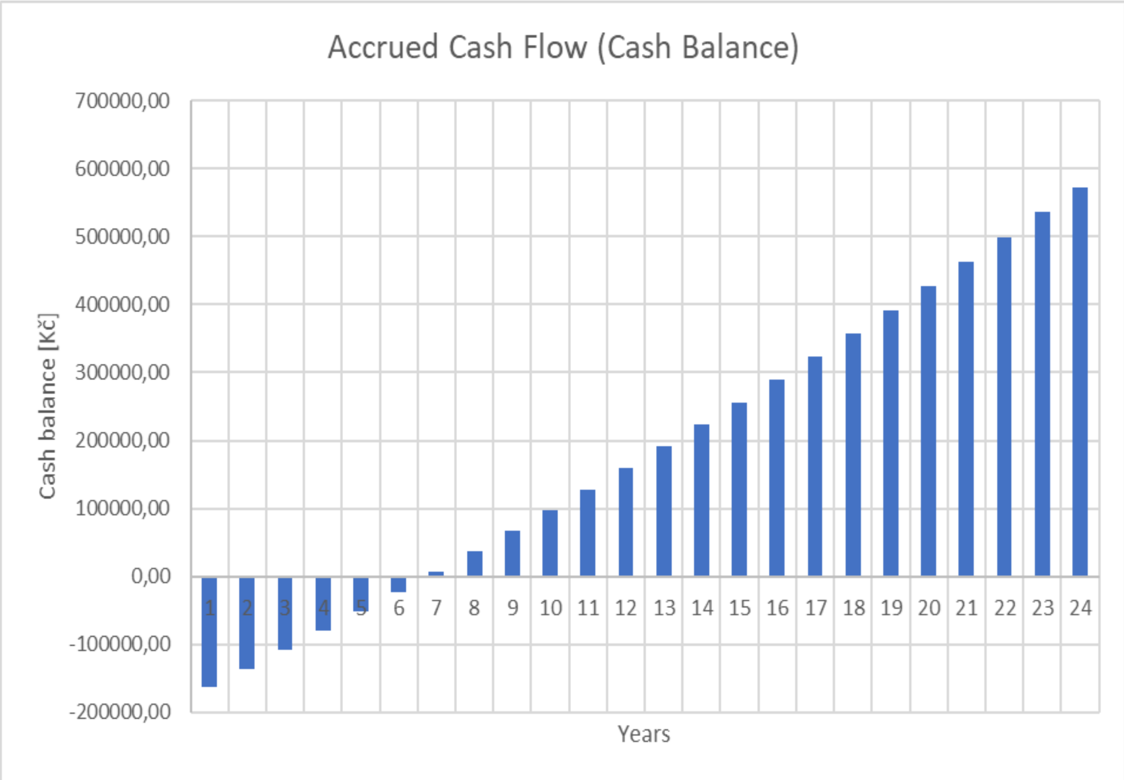

Figure 6.17 Accrued cash flow of hybrid system in PV*SOL premium *[11]*

The predicted accrued cash flow indicates that the return period of the system is between six to seven years, which is astonishingly close to the results of the on grid system. Even if the additional cost of a physical battery bank is high, it is offset by the currently high subsidies, high energy prices, and major savings from lower annual distribution fees. Given that the predicted lifespan of the batteries is about 15 years [50], this low return period makes the physical battery bank a viable option, as there is a 8 year period where the physical battery bank reduces costs beyond its purchase price. The battery bank might have a longer lifespan, allowing the system to operate for the predicted 24 years, in which the total monetary savings could reach about 572679,25 Kč.

6.5.3 Replacement of parts

As is the case with almost any electrical system, maintenance of the photovoltaic system will be required. The panels are rated to have a warranty of 25 years [46] [45], which means they shouldn't need to be replaced due to degradation, and hence affect the predicted cost analysis. The parts that are more prone to break and degrade are the inverter and the battery bank. The inverter has a claimed 10 year extended warranty [49], and the batteries have a predicted design lifetime of 15 years [50]. By using the same parts for replacements with the same price, the cost analysis for each type of system is the following.

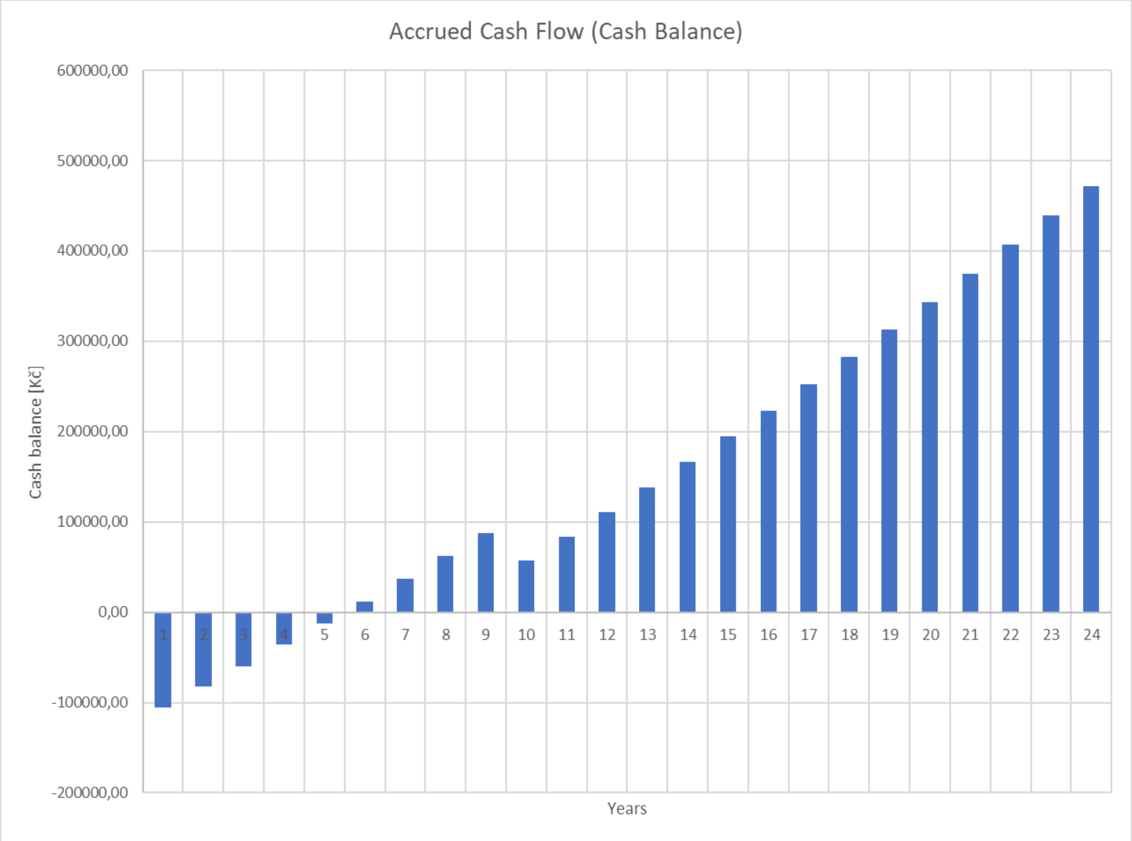

Figure 6.18 Accrued cash flow of on grid system in PV*SOL premium with replaced inverter *[11]*

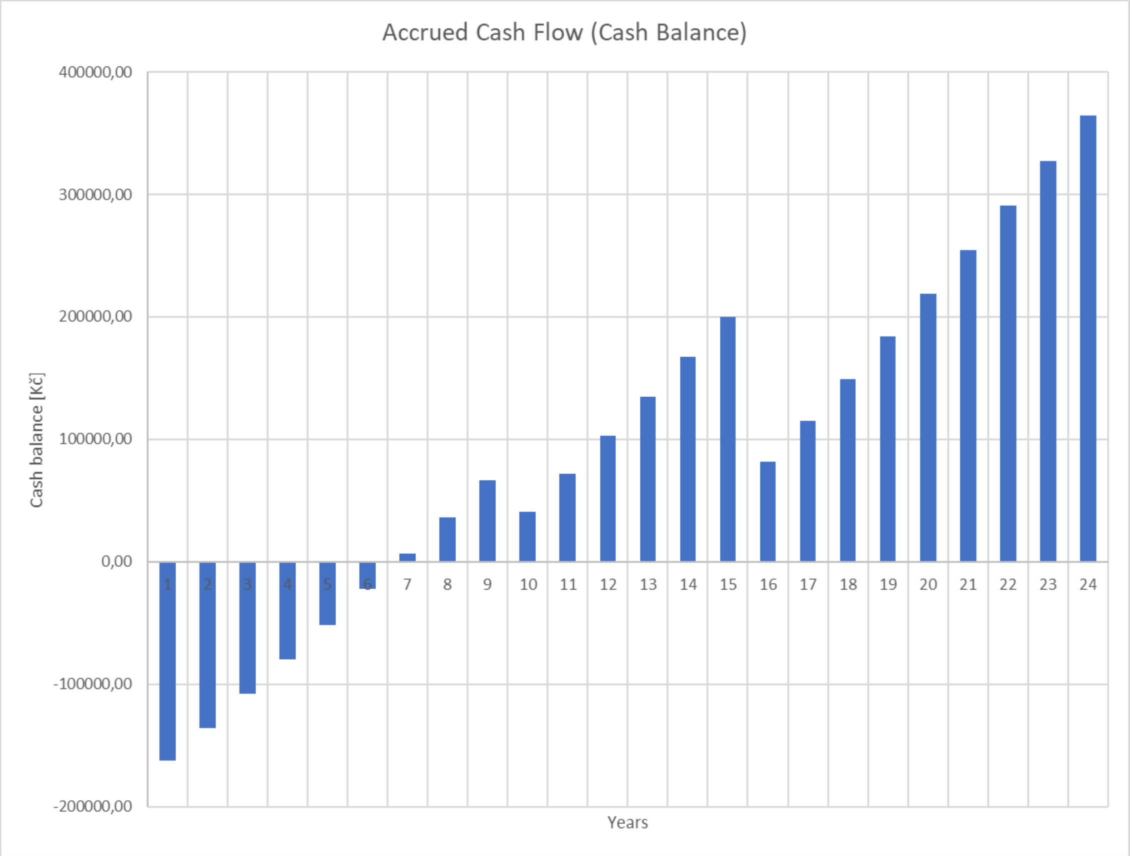

Figure 6.19 Accrued cash flow of hybrid system in PV*SOL premium with replaced inverter and battery bank *[11]*

We can observe, that even if we replace the theoretically dysfunctional or inefficient parts, the breakeven point remains at the same period for both systems. This prediction does not consider the reduction or increase in price of parts over time, or the use of more efficient technologies for both the inverter and the battery bank.

CONCLUSION

This bachelor's thesis focused on the research of available photovoltaic and battery technologies on the market, and their application in an affordable residential photovoltaic system. Photovoltaic panels are starting to get widespread adoption in the energy market due to progress made in material processing and large-scale production of solar cells. The main material used in photovoltaic cells is still silicon, as it is widely available due to the market overlap with integrated circuit production. Other photovoltaic technologies, such as thin film materials and perovskite layers are still commercially unviable, even if their efficiency is higher than that of monocrystalline silicon cells. Battery technologies are also advancing quickly, given the recent push in the development of lithium-ion cells. Comparing the three discussed technologies, (lead-acid, NiMH and lithium-ion) lithium-ion cells offer the best parameters in terms of energy capacity, cost, and availability with the other two technologies. Lithium-ion battery storage is also advantageous for a household PV system, because it is the only technology that is subsidized by the government in the Czech Republic under the Nová zelená úsporám program. The program has other additional parameters that need to be met to receive a subsidy, alongside legislation issued by the Energy Regulatory Authority for the personal production of electrical energy. The practical part of the thesis is focused on designing a suitable photovoltaic system for a client in a household located in Brno-Mesto, Czech Republic. Satellite imagery shows that the South Moravian region is suitable for installing a photovoltaic system, as it receives the highest amount of incident solar energy per m^2 in the entire country. The residential building had a few specific parameters that complicated planning. First was the unusual shape of the roof, where none of the sides faced South, which reduces energy production potential, and the presence of chimneys that reduced the available area for photovoltaic panel installation. The total power that was possible to be installed without shading the panels by more than 10% was 7,63 kWp, of which 5,01 kWp was installed on one side of the roof facing east, and 2,62 kWp was installed facing the south. The second factor was a comparatively high electrical energy demand, as the building had a newly installed electric air and water heater. Electrical energy demand data of the household shows it is 11,291 MWh per year. A comparison was made between the design of a on grid a hybrid photovoltaic system, as each type has its advantages and disadvantages. Potential parts of each system were researched on the commercial market on the internet that would satisfy the needs of the customer, both in terms of total cost and technical parameters. The chosen battery bank size for the hybrid system was chosen to be 12,3 kWh, as it offers the highest capacity before diminishing cost returns. Both systems were simulated in PV*SOL premium software to estimate the total energy produced by the installed panels, and to predict the cost projection with current energy prices. The energy metering was set so that net excess energy produced by each system would be stored in a virtual battery, offered by the energy distribution company E.ON as an annual subscription service. The results of the simulation show, that the on grid system can produce 7161 kWh over the year, whilst the hybrid system can produce 6941 kWh, of which 2091 kWh is stored in the battery bank annually. Excess unused energy was stored and utilized in the virtual battery. The return period of the on grid system came down to five to six years, which is almost the same as in the case of the hybrid system with a return period of six to seven years. This means that both systems would be viable. The factors that make the hybrid system more preferable are that it is future proof in the case that the virtual battery service gets discontinued by E.ON, or in the case of upgrading a purely on grid system the cost of the additional battery is not subsidized later. The choice of system is up to the client, depending on if they have sufficient starting funds for the hybrid system, and if they have enough space in their household to install the battery bank.

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SYMBOLS AND ABBREVIATIONS

Abbreviations:

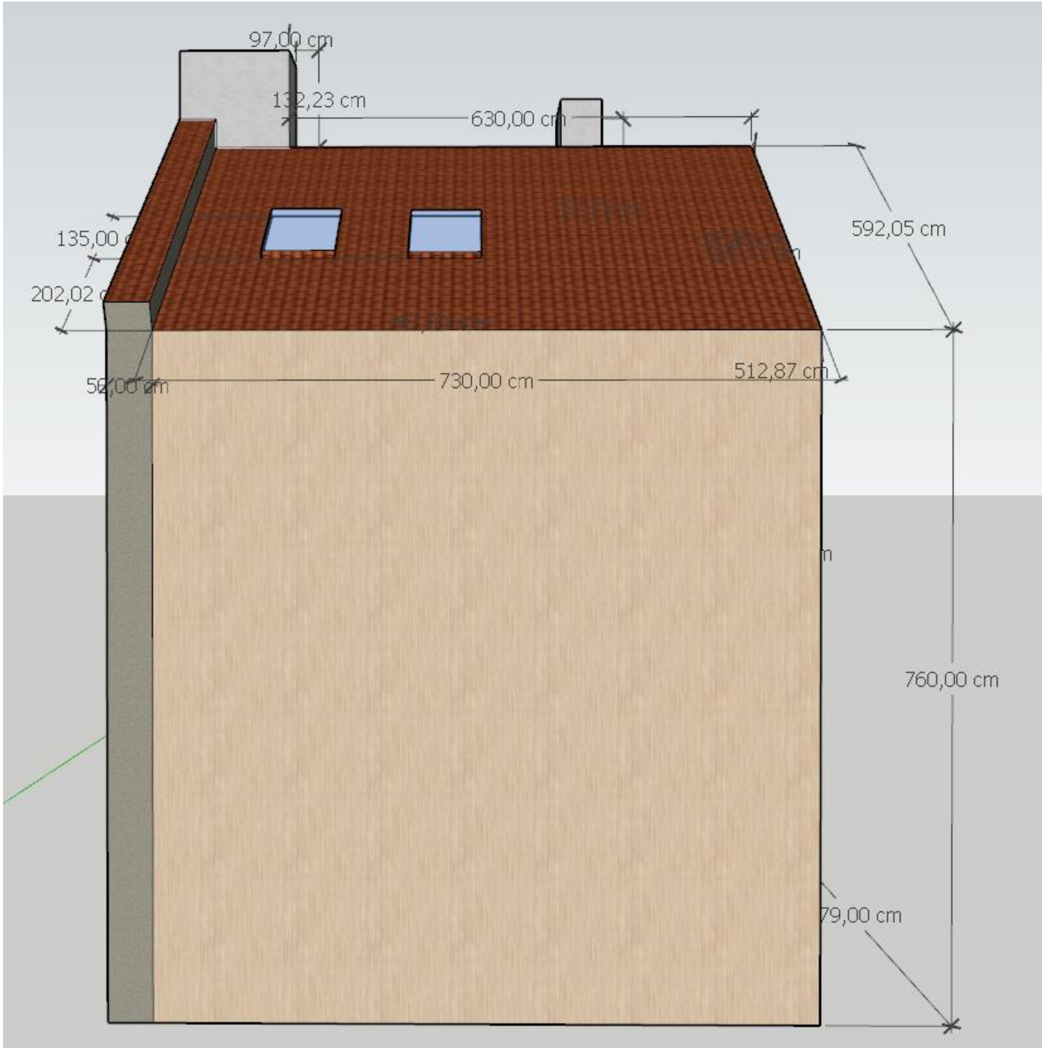
FEEC	Faculty of Electrical Engineering and Communications
BUT	Brno University of Technology
$A_{III}B_{V}$	Mixed group 3 and group 5 semiconductor
PV	photovoltaic
eV	electron volts
P	positive
N	negative
MPP	maximum power point
MPPT	maximum power point tracking
a-Si	amporphous silicon
Cd-Te	cadmium telluride
Ah	amp hours
Wh	watt hours
RAPS	remote area power supply
VRLA	valve regulated lead acid battery
NiMH	nickel metal hydride
NiCd	nickel cadmium
LCO	Lithium cobalt oxide
LMO	Lithium manganese oxide
NMC	Lithium nickel manganese oxide
NCA	Lithium nickel cobalt aluminium oxide
LiPO4	Lithium iron phosphate
LMO – LT	Lithium manganese oxide – lithium titanate
AC	alternating current
DC	direct current
NEE	north east east

Symbols:

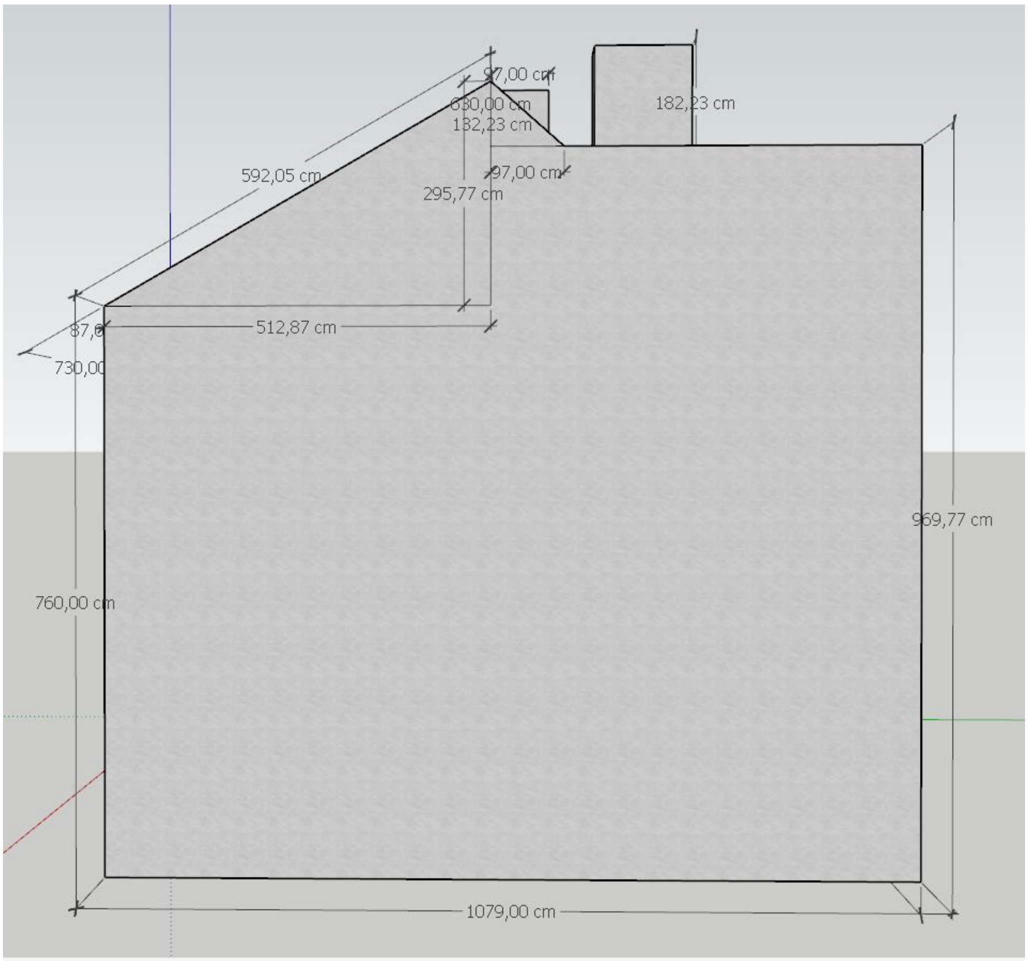
U	*voltage*	*(V)*
I	*current*	*(A)*
R_L	*load resistance*	*(Ω)*
I'_{SC}	*short circuit current*	*(A)*
R_{Sh}	*parallel resistance of photovoltaic cell*	*(Ω)*
R_S	*series resistance of photovoltaic cell*	*(Ω)*
A_0	*diode quality factor*	*(-)*
kT	*energy coefficient*	*(J)*
P_{MPP}	*maximum power of photovoltaic cell*	*(W)*
I_{MPP}	*maximum power point current of PV cell*	*(A)*
U_{MPP}	*maximum power point voltage of PV cell*	*(A)*
U_{OC}	*open circuit voltage of photovoltaic cell*	*(V)*
I_{SC}	*short circuit current of photovoltaic cell*	*(A)*
λ_{max}	*maximum intensity wavelength of light*	*(m)*
T	*absolute temperature*	*(K)*
I	*intensity*	*(W/m^2)*
Θ	*angle*	*(°)*
AM	*air mass index*	*(-)*

LIST OF APPENDICES

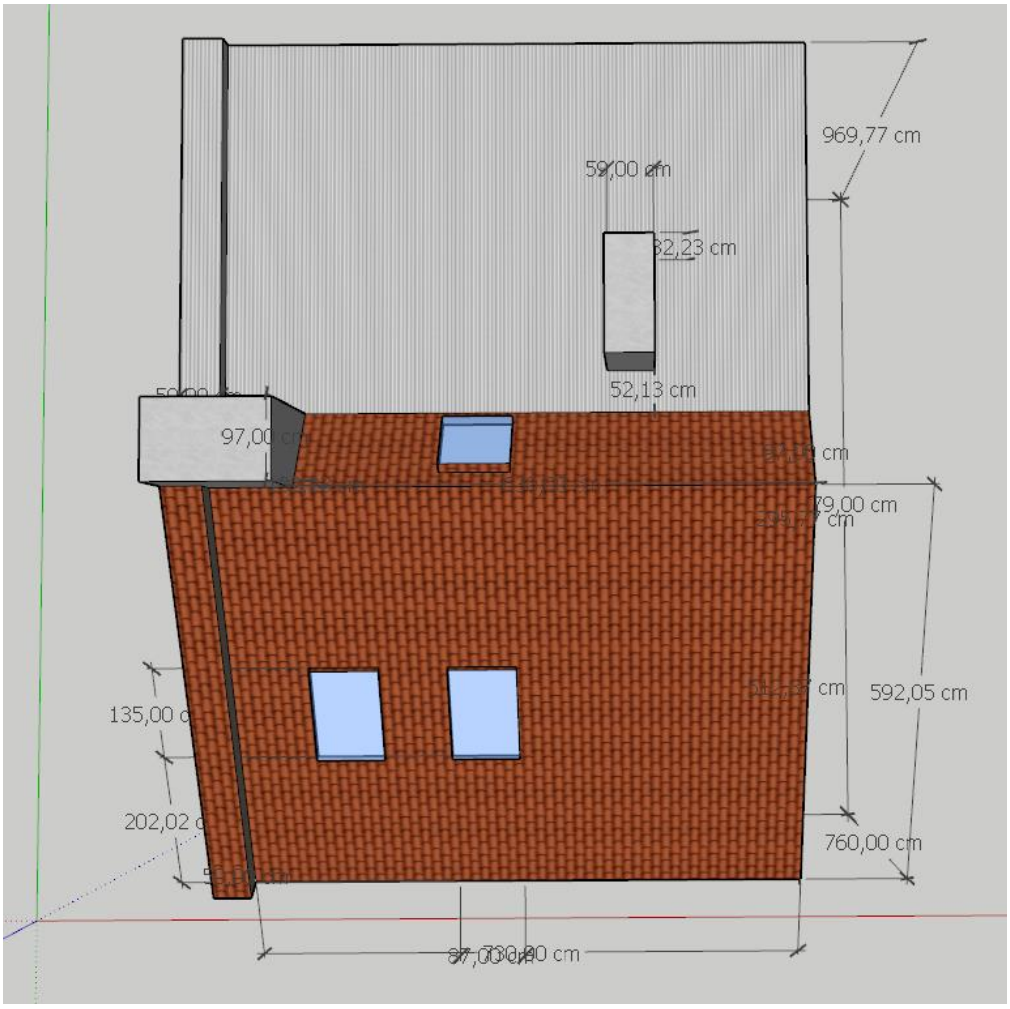
A.1 Dimensions of the household – front [10]



A.2 Dimensions of the household – side [10]



A.3 Dimensions of the household – top [10]



A.4 On grid system data export [11]

Project Overview [11]

Figure: Overview Image, 3D Design

PV System [11]

3D, Grid-connected PV System with Electrical Appliances and Battery Systems

Climate Data	Brno, CZE (1996 - 2015)
Values source	Meteonorm 8.1
PV Generator Output	7,63 kWp
PV Generator Surface	36,7 m²
Number of PV Modules	18
Number of Inverters	1
No. of battery systems	1

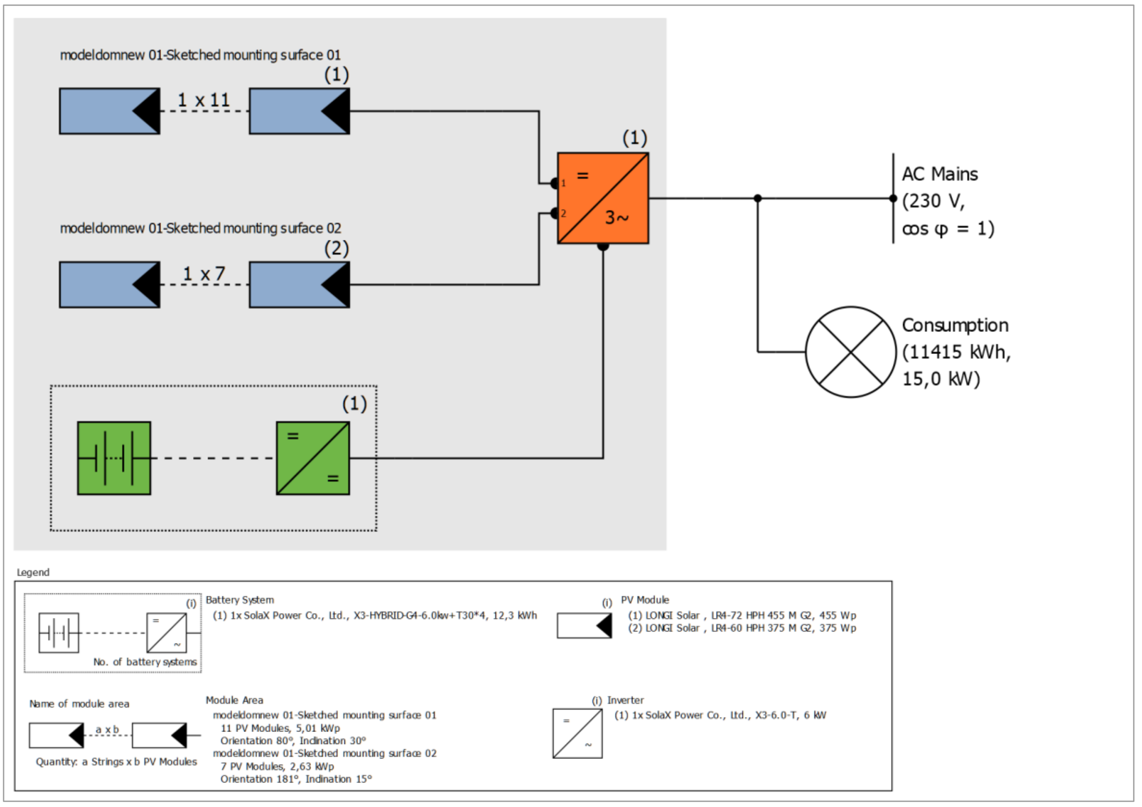


Figure: Schematic diagram

Production Forecast [11]

Production Forecast		
PV Generator Output	7,63	kWp
Spec. Annual Yield	927,00	kWh/kWp
Performance Ratio (PR)	85,31	%
Yield Reduction due to Shading	6,2	%/Year
PV Generator Energy (AC grid) with battery	6 938	kWh/Year
Down-regulation at Feed-in Point	0	kWh/Year
CO_2 Emissions avoided	3 182	kg / year
Level of Self-sufficiency	40,7	%

Financial Analysis [11]

Your Gain		
Total investment costs	379 109,00	Kč
Internal Rate of Return (IRR)	16,11	%
Amortization Period	6,8	Years
Electricity Production Costs	3,3977	Kč/kWh
Energy Balance/Feed-in Concept	Net-Metering	

A.5 Hybrid system data export [11]

Project Overview [11]

Figure: Overview Image, 3D Design

PV System [11]

3D, Grid-connected PV System with Electrical Appliances		
Climate Data	Brno, CZE (1996 - 2015)	
Values source	Meteonorm 8.1	
PV Generator Output	7,63	kWp
PV Generator Surface	36,7	m²
Number of PV Modules	18	
Number of Inverters	1	

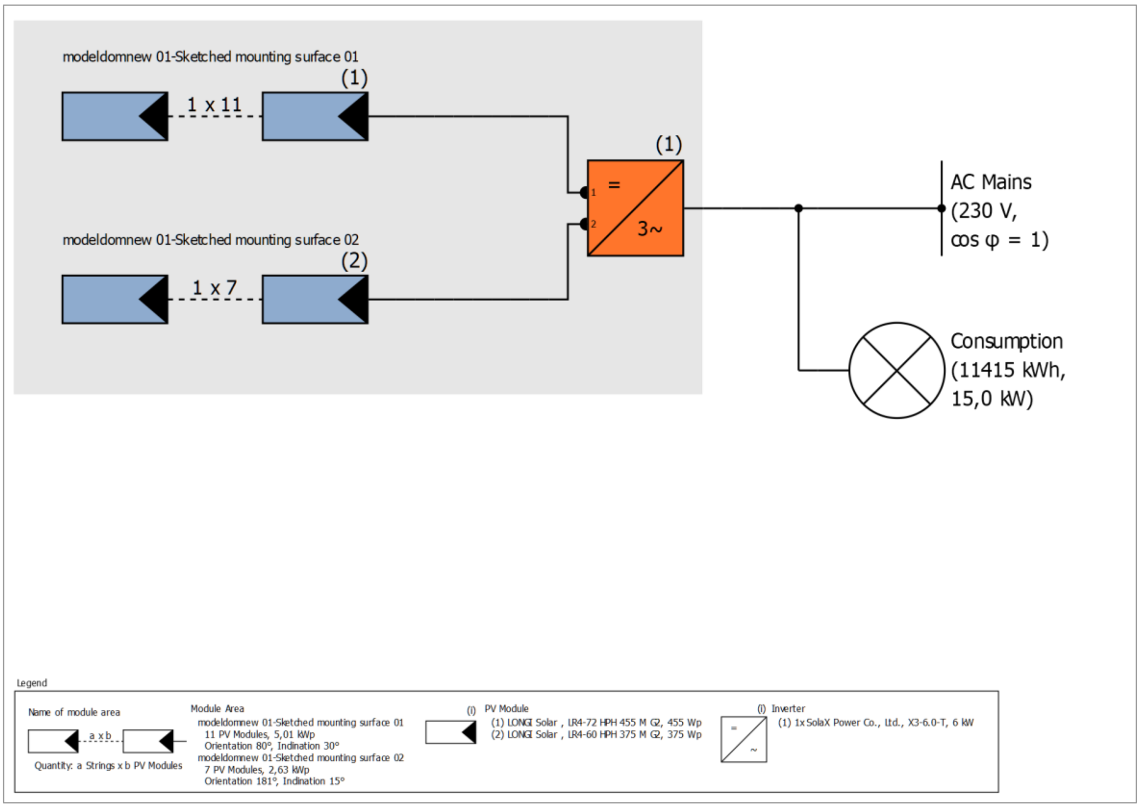


Figure: Schematic diagram

Production Forecast [11]

Production Forecast	
PV Generator Output	7,63 kWp
Spec. Annual Yield	935,98 kWh/kWp
Performance Ratio (PR)	86,13 %
Yield Reduction due to Shading	6,0 %/Year
PV Generator Energy (AC grid)	7 159 kWh/Year
Down-regulation at Feed-in Point	0 kWh/Year
CO_2 Emissions avoided	3 357 kg / year
Level of Self-sufficiency	23,7 %

Financial Analysis [11]

Your Gain		
Total investment costs	217 647,00	Kč
Internal Rate of Return (IRR)	19,98	%
Amortization Period	5,5	Years
Electricity Production Costs	3,8447	Kč/kWh
Energy Balance/Feed-in Concept	Net-Metering	