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Федеральное государственное автономное образовательное учреждение
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**«НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ»
/ NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY**

Институт – Энергетический / Institute – Power Supply
Направление подготовки – Электроэнергетика / Direction – Electric Power
Магистерская программа – Оптимизация развивающихся систем электроснабжения / MA Course – Optimization of developing power supply systems
Кафедра – Электроснабжения промышленных предприятий / Department – Industrial Electric Power Supply

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ / MASTER'S THESIS

Тема работы / Theme
«Анализ возможностей использования солнечной энергии в Чешской Республике»
«Design of Residential Photovoltaic System»

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Томск / Tomsk – 2016

Министерство образования и науки Российской Федерации
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Институт Энергетический
Направление подготовки (специальность) 13.04.02 – «Электроэнергетика и электротехника»
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УТВЕРЖДАЮ:
Зав. кафедрой
________ ________ ____________
(Подпись) (Дата) (Ф.И.О.)

ЗАДАНИЕ
на выполнение выпускной квалификационной работы

В форме:

Магистерской диссертации

(бакалаврской работы, дипломного проекта/работы, магистерской диссертации)

Студенту:

Группа	**ФИО**
5АМ3И	Давид Воборжил / David Vobořil

Тема работы:

Анализ возможностей использования солнечной энергии в Чешской Республике Design of Residential Photovoltaic System	
Утверждена приказом директора (дата, номер)	№ 10120/с от 25.12.2015

Срок сдачи студентом выполненной работы:	27.04.2016

ТЕХНИЧЕСКОЕ ЗАДАНИЕ:

Исходные данные к работе *(наименование объекта исследования или проектирования; производительность или нагрузка; режим работы (непрерывный, периодический, циклический и т. д.); вид сырья или материал изделия; требования к продукту, изделию или процессу; особые требования к особенностям*	Объект исследования: Жилой дом, расположенный в деревне Стеблова в предместьях города Пардубица, в Чешской Республике. Фотоэлектрическая система с накопителем и без электроснабжения частного дома. Цель работы: Спроектировать фотоэлектрическую станцию для частного дома находящегося в Чешской Респубике.

функционирования (эксплуатации) объекта или изделия в плане безопасности эксплуатации, влияния на окружающую среду, энергозатрат; экономический анализ и т. д.).	
Перечень подлежащих исследованию, проектированию и разработке вопросов *(аналитический обзор по литературным источникам с целью выяснения достижений мировой науки техники в рассматриваемой области; постановка задачи исследования, проектирования, конструирования; содержание процедуры исследования, проектирования, конструирования; обсуждение результатов выполненной работы; наименование дополнительных разделов, подлежащих разработке; заключение по работе).*	- Аналитический обзор фотоэлектрических станций. Их основные компоненты, составляющие и их параметры, влияющие на выработку электрической энергии. - Постановка задачи проектирования: разработка и проектирование системы электроснабжения с источниками питания от фотоэлектрической станции; - Исследование ветрового и солнечного потенциала в Ческой Республике; - Расчет нагрузок жилого дома; - Выбор структурной схемы и подбор основного оборудования для электростанции, экономическая оценка целесообразности проекта; - Заключение по работе.
Перечень графического материала *(с точным указанием обязательных чертежей)*	Презентация в формате ppt, pdf.

Консультанты по разделам выпускной квалификационной работы

(с указанием разделов)

Раздел	Консультант
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«Социальная ответственность»	Сумарокова Людмила Петровна / Sumarokova Lyudmila

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Tomsk Polytechnic University

Energy Institute

Design of Residential Photovoltaic System

Diploma Thesis

Study Programme:

Studijní obor: Elektrotechnika a management

Supervisor: Ludmila Petrovna Sumarokova

David Vobořil

2016

Declaration

I hereby declare that I elaborated this diploma thesis independently in its entirety. I have acknowledged all the sources of information.

In Prague……………………… ………………………………...

David Vobořil

Аннотация

Ключевые слова

ABSTRACT

The objective of this Diploma thesis is to design a photovoltaic system for a specific family house located in the Czech Republic.
The theoretical part is focused on the basic info about the photovoltaic system components and their parameters which affect the system power production.

The practical part is dedicated to the actual design of the photovoltaic system, it introduces several suitable variants of the system, calculates its energy generation and compares it to the house power consumption in 15-minute intervals of average day for each month. In the end the work briefly presents the economic evaluation of the designed systems.

KEY WORDS

decentralized power source, renewable energy source, residential power system, photovoltaic system,

ABBREVIATIONS

AC	Alternating Current
CHMI	Czech Hydrometeorlogical Institute
DC	Direct Current
HDO	Mass Remote Control (from ‘Hromadné dálkové ovládání’)
INOCT	‘Installed’ Nominal Operating Cell Temperature
IRR	Internal Rate of Return
MPPT	Maximum Power Point Tracking
NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value
NZÚ	Czech subsidy program (from ‘Nová zelená úsporám’)
PV	Photovoltaic
PVGIS	Online PV system yield calculator
STC	Standard Test Conditions

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Introduction

The photovoltaic (PV) systems nowadays play an important role in the Europe's energy sector transition towards low emission future. The reason for this action is to limit the global warming by limiting the mean global temperature rise to 2°C above pre-industrial levels. To achieve this, one of the objective of European Union is to cover 20% of the final energy consumption from renewable energy sources by 2020. [1] Each member country, including the Czech Republic, has committed to reaching its own goal according to the possibilities of the country with respect to its current renewable energy generation and its potential. The Czech Republic has committed to achieve 13% of renewable energy share in gross final consumption. To achieve its objective, each EU country has adopted a *National renewable energy action plan* which specifies the actions intended to take to meet the targets. The *National renewable energy action plan* of the Czech Republic [2] from 2012 has set the target of renewable energy share in gross final consumption to 14% by 2020. While the Czech Republic has already in 2015 exceeded its target, the new action plan is supposed to raise the target to 15,9%. One of the measures to achieve this goal is introduction of new subsidy program *Nová zelená úsporám* which brings financial subsidies to, among other, photovoltaic power plants on roofs of family house.

This work deals with the design of photovoltaic system for the specific family house in the Czech Republic. In the first part the location specifics and its suitability for installing PV system is presented. It describes the subsidy program in the Czech Republic which applies to the installations of PV systems from 2016 along with all the requirements which need to be met to comply with the program.

The next part is dedicated to the family house intended for installation of the system. It presents local irradiance and temperature conditions along with the house power consumption and used appliances. Moreover, it optimizes the house power consumption to achieve the highest possible direct usage of the energy produced by the PV system.

Furthermore, the work presents the various components necessary for building a safe, reliable and efficient photovoltaic system. The main components of PV systems are described along with their main characteristics which effect the behavior and energy generation of the system during changing conditions. The important part which the work also deals with, are the specifics of components which need to be borne in mind in order to ensure their safe and reliable operation when being connected to form the PV system. The work also presents necessary protection and connecting elements of the system.

Finally, several variants of the PV systems are designed for the family house according to its specifics. For each of this systems, all the components are chosen. Using the information presented in previous chapters, the energy generation of the presented systems is calculated and compared to the house power consumption in 15-minute intervals for average working and weekend day of each month. In the end, the work briefly presents the economic evaluation of the system variants over their lifetime. The more in-depth economic evaluation is part of the Czech thesis which builds on the conclusions from this work.

1. Conditions for PV Systems in Czech Republic

1.1 Weather Conditions

There are two major weather aspects affecting the output power of the PV system, solar irradiance and air temperature. The Czech Republic is an inland country located in temperate latitudes of the northern hemisphere. The climate of the Czech Republic can be described as mild but variable locally and throughout the year. The climate of various regions of the country is significantly different, the main sources of these differences are, among others, altitude, wind flow, pressure distribution and the inclination of surfaces.

1.1.1 Solar Irradiance

"Solar irradiance (or irradiation) is the power per unit area (usually W/m2) produced by the Sun in the form of electromagnetic radiation." [3] In the Figure 1 the yearly sum of global irradiance on optimally inclined south oriented PV module in Europe is presented. Using the information presented in the figure, it is possible to compare the values for the considered location with other parts of Europe. The yearly sum of global irradiance for Czech Republic is between 1200 and 1300kWh/m^2. To obtain the same amount of irradiance as in the most suitable places in the South of Europe the area almost twice as big is needed. It is necessary to add that places with solar irradiance of that high values as 2200kWh/m2 and more, are located on the very South of Spain, Italy and Turkey. Most of the South counties are in the range of 1600 to 1900kWh/m^2 of yearly sum of global irradiation, which is still 30-46% more than in the considered location. The annual amount of sunshine hours in the Czech Republic ranges from 1331 to 1844 hours according to the Czech Hydrometeorological Institute (CHMI). This observation signalizes that the considered area isn't the most suitable for installing PV modules but there's one more aspect which plays a significant role in the amount of power which can be harvested from the sun using PV system, the air temperature.

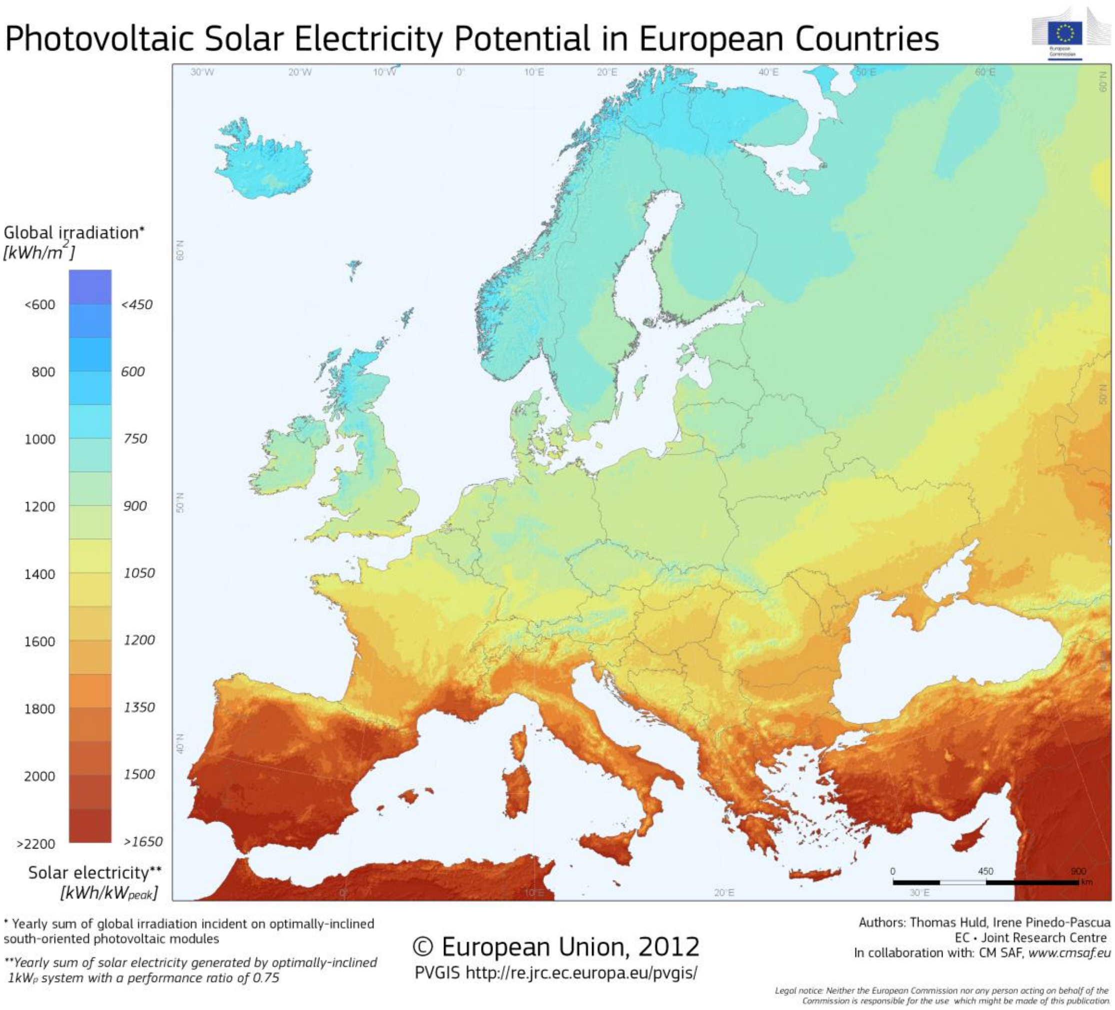


Figure 1 | Solar Irradiation and solar electricity potential. Source: PVGIS

1.1.2 AIR TEMPERATURE

High air temperature negatively affects the operational temperature of the PV systems by reducing the efficiency of energy conversion of the PV modules.

The average air temperature values for the whole Europe are presented in Figure 2 and Figure 3. Temperature during winter (represented by January in Figure 2) and summer (July in Figure 3) in the Czech Republic are significantly lower compared to the Southern countries. The lower temperature reduces the difference in power outputs between the considered locations and the locations more suitable for installing PV systems in terms of the amount of solar irradiance.

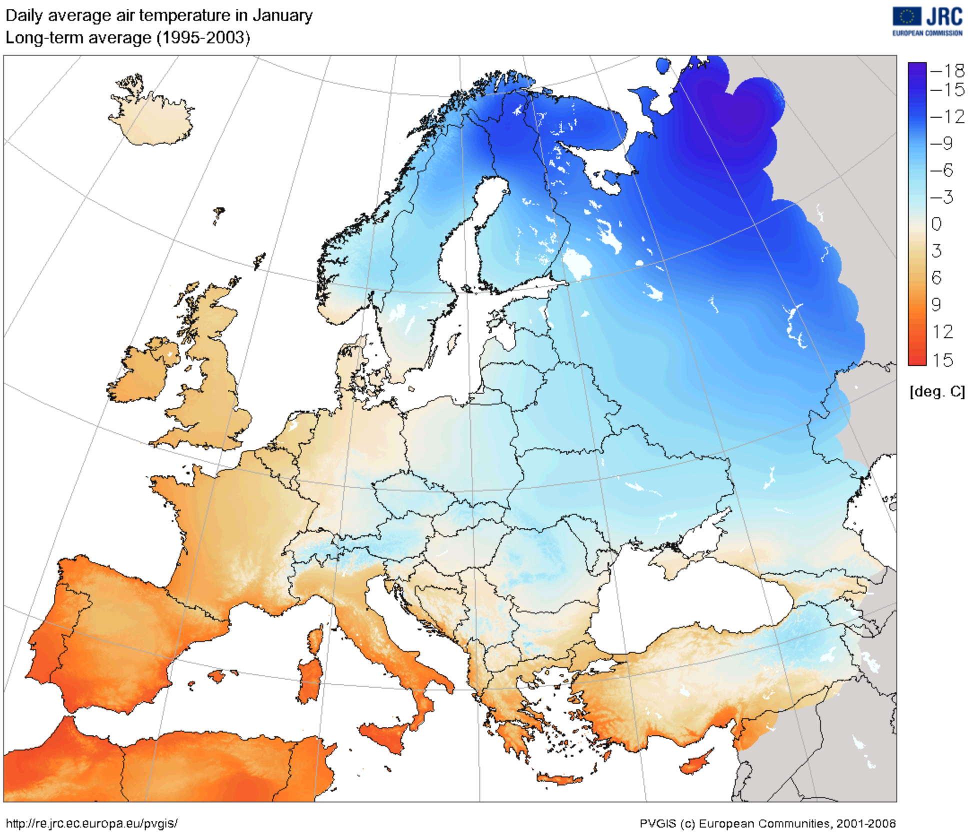


Figure 2 | Daily average air temperature in January. Source: PVGIS

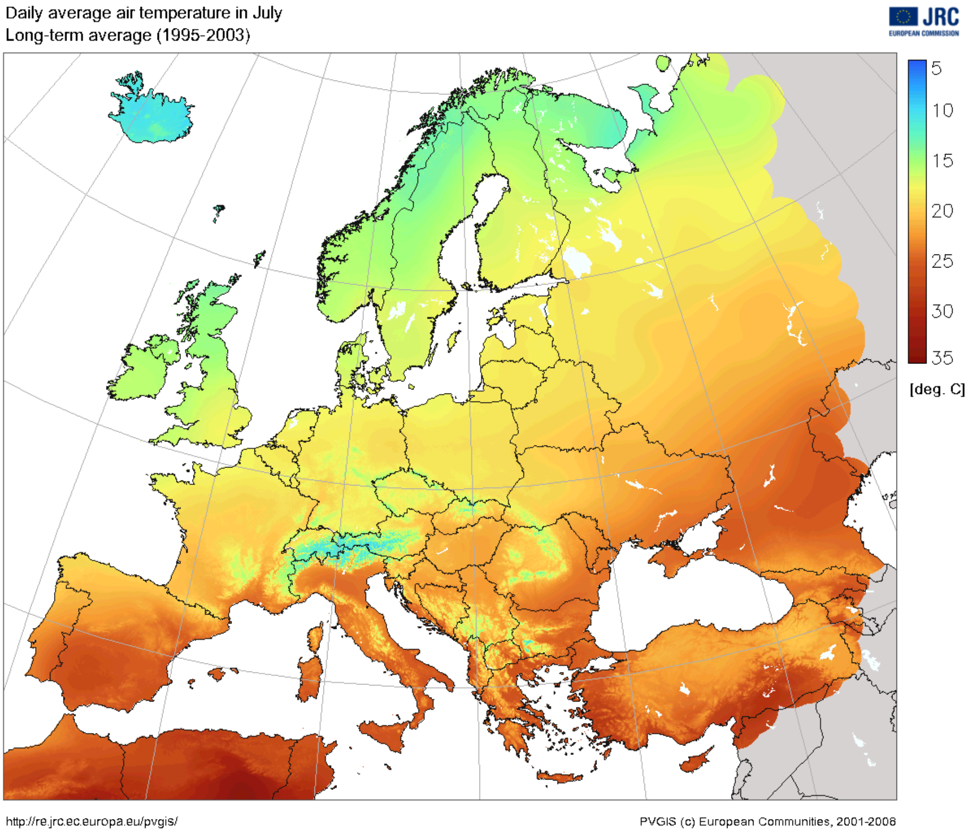


Figure 3 | Daily average air temperature in July. Source: PVGIS

1.2 SUBSIDY PROGRAM

The considered project is subject to the subsidy program *Nová zelená úsporám (New Green to Savings)*, namely the subsidy category C - *Efficient use of energy resources*, sub-category C.3 *Installation of solar thermal and photovoltaic systems*. The objective of the program is to improve the environment in the Czech Republic by reducing greenhouse gas emissions through the improved energy efficiency of buildings, the support of residential development with very low energy performance and the efficient use of energy sources. All the information about the subsidy program is available in [4].

1.2.1 GENERAL REQUIREMENTS FOR GRANTING THE SUBSIDY

From the basic requirements which need to be fulfilled in order to be granted the financial subsidy, only the requirements which are directly tied to the considered variants of the photovoltaic system in this work are described in this chapter.

- The considered object for installation of the PV system must meet the definition of “family house” prior to the installation of the system (in the default state) and after completing the installation.
- The financial subsidy may be provided only to the measures implemented which weren’t subject to earlier subsidy from state budget or other public sources.
- Only one application can be applied per object (family house), the application may include a combination of measures from multiple sub-categories of the subsidy program.
- In case the applicant does not use the products and materials for the installed systems listed in the *List of products and technologies*, he is required to prove the technical characteristics of the products and materials upon completion of the applied measure.
- The amount of financial subsidy for one applicant is limited to a maximum value of 5 million CZK.
- The applicant is required to provide expert technical supervision of implementing the system.

1.2.2 THE SPECIFIC REQUIREMENTS OF THE SUBSIDY CATEGORY C

Eligible applicants are owners or constructors of houses, physical or legal persons. Applying is possible before, during or after completion of the implementation of subsidized measures. Subsidy is in a form of fixed monetary amount and depends on the type of the implemented PV system, the total amount to one application is limited to a maximum of 50% of properly documented eligible expenses, which include "expenses directly related to the supply and installation of supported measures into the building". [4]

- The subsidy for PV systems applies to the systems connected to the distribution grid after 1. 1. 2016.
- Applying to the subsidy program is possible only once for each house for the duration of the program. The exception is a combination of system for hot water (C3.1 / C3.2 / C3.3), with a PV system with accumulation to the batteries (C3.5 / C3.6).

In the following table a list of maximum amount of subsidy for each type of system is presented. The amount of subsidy is applicable only up to the 50% of the total expenses.

Subsidy Category	System Type	Amount of Subsidy [CZK]
C.3.3	Solar PV system for direct water heating	35 000
C.3.4	Solar PV system without electricity accumulation with accumulation of surplus energy into heat and with energy usage over 1 700 kWh.year^{-1}	55 000
C.3.5	Solar PV system with electricity accumulation and energy usage over 1 700kWh.year^{-1}	70 000
C.3.6	Solar PV system with electricity accumulation and energy usage over 3 000kWh.year^{-1}	100 000

Table 1 | Maximum amount of subsidy according to the type of system. Source: novazelenausporam.cz

In order to be granted the subsidy, the system needs to comply with requirements dependent on the type of the system. For each system the requirements are as follows:

C.3.3 - Solar PV system for direct water heating

- PV system equipped with technology for efficient optimization according to the load (e.g. MTTP)
- the efficiency under standard test conditions (STC) at least 15% for mono- and polycrystalline modules and 10% for thin film amorphous modules
- the system must not be connected to the distribution grid
- the coverage of hot water consumption of at least 50%
- hot water storage tank with minimal volume of 45l per 1kWp installed capacity of the PV system

Requirements for the subcategory of PV systems connected to the distribution grid (C.3.4, C.3.5 a C.3.6).

- installed capacity of maximum 10kWp
- System connected to the distribution grid
- inverter with minimal 94% Euro efficiency and technology for Maximum Power Point Tracking (MPPT) with minimal adaptation efficiency of 98%
- the efficiency under standard test conditions (STC) at least 15% for mono- and polycrystalline modules and 10% for thin film amorphous modules
- utilization rate of generated electricity to cover consumption at the place of production of at least 70% of the total theoretical yield of the system which takes into account the climate conditions, characteristics of the PV modules, including orientation, distribution losses, inverter and other components parameters – determined by exact calculation according to the simplified equation (1.1)

$$Q_{PV,total} = P_{inst} \bullet 1000 \qquad \text{[kWh/rok]} \qquad (1.1)$$

- device for optimization of self-consumption of produced energy – automatic system management according to the current energy production and consumption with priority to use the produced energy for actual power consumption and accumulation of surplus energy

C.3.4 - Solar PV system without electricity accumulation with accumulation of surplus energy into heat and with energy usage ≥ 1 700 kWh per year

- mandatory accumulation of surplus energy into hot water
- the volume of the hot water tank or storage tank of 80 liters per 1kWp of installed capacity of the PV system

C.3.5 - Solar PV system with electricity accumulation and with energy usage ≥ 1 700 kWh per year

- mandatory accumulation of surplus energy into batteries
- battery energy storage capacity of at least 1,75 kWh per 1kWp of installed capacity of the PV system

C.3.6 - Solar PV system with electricity accumulation and energy usage ≥ 3 000 kWh per year

- mandatory accumulation of surplus energy into batteries
- battery energy storage capacity of at least 1,75 kWh per 1kWp of installed capacity of the PV system

1.2.3 *Accumulation System Requirements*

The additional document to the subsidy program published in February 2016 specifies, among other, the requirements for batteries and hot water storage. Certain restrictions are established in order to ensure that only batteries suitable for the PV systems are used.

Batteries

It is not permitted to use nickel-cadmium (Ni-Cd) and all lead-based “start-up” batteries. The document also emphasizes that in the system design the manufacturer recommended depth of discharge should be considered in order to maintain the battery service life and therefore the sustainability of the project. In case of using “modern technology batteries allowing high amount of deep discharge cycles without a significant loss of capacity” it is possible to reduce the minimum limit for marginal battery capacity to 1,25 kWh/kWp. Appropriate battery technologies are lithium based batteries, such as lithium-ion, LiFePO4, LiFeYPO. The lowered limit cannot be applied to lead-based batteries, including gel, AGM and traction acid battery types, Ni-MH and Ni-Fe. [5]

Hot Water Storage

In case the minimum hot water storage volume requirements in subcategory C.4 are significantly higher than volume necessary for hot water usage according to number of household members and hot water applicable standards, the limit can be lowered according to the requirements of the standard but not lower than 120 liters. The requirement of minimum 70% usage of produced energy by the PV system has to be fulfilled. [5]

2. OBJECT SPECIFICATIONS

In this chapter, the information about the house, its power consumption, location and weather conditions are introduced. While designing residential power supply system, knowing all these information is crucial for choosing the correct system components and accurate economical evaluation of the system.

The considered object is newly reconstructed family house located in village Stéblová in the outskirts of Pardubice, city in the Czech Republic. The reconstruction began in 2012 and the last significant interior changes were made in November 2015. The house is insulated with polystyrene with thickness of 140cm. The usable floor area of the house is 138m^2 of which 96m^2 is living area. The living area contains 4 rooms and a kitchen connected to a dining room. Furthermore, the house includes four rooms in the partly underground cellar area of around 42m^2 which are used as a storage space and technical room with boiler pumps and switchboard. The house is regularly inhabited by two persons, both of them are working full-time, therefore their presence is limited only to the weekends and evenings of working days.

Figure 4 | Location of village Stéblová is highlighted by the red marker. Source: Google Maps

2.1.1 SOLAR IRRADIATION

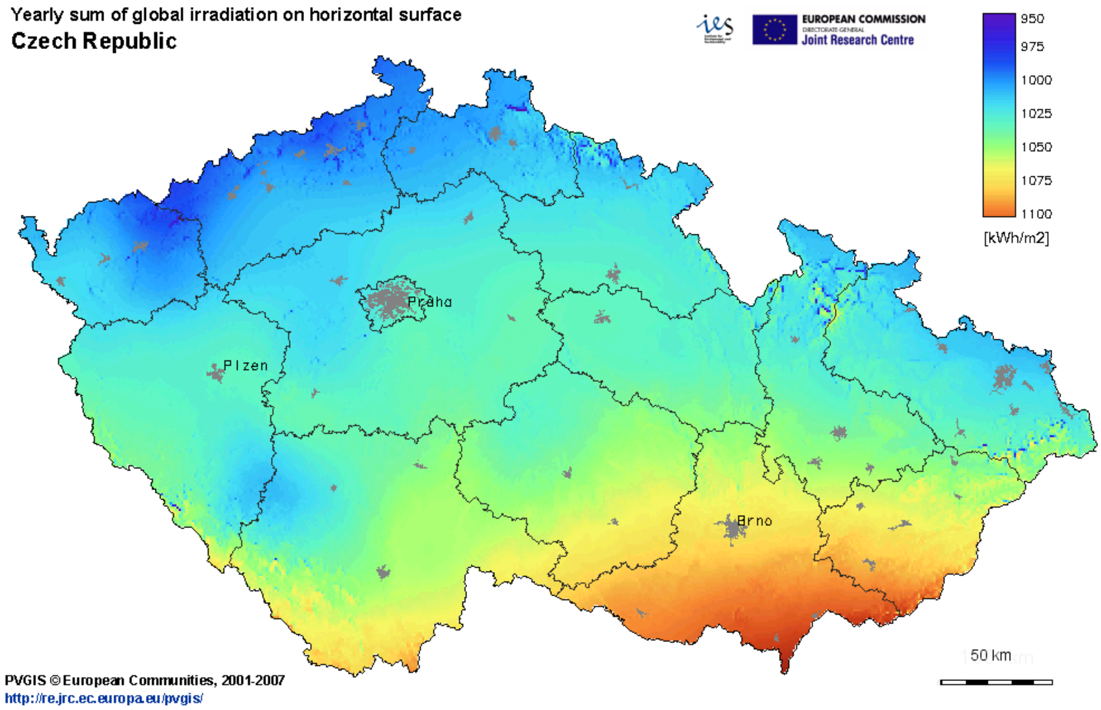
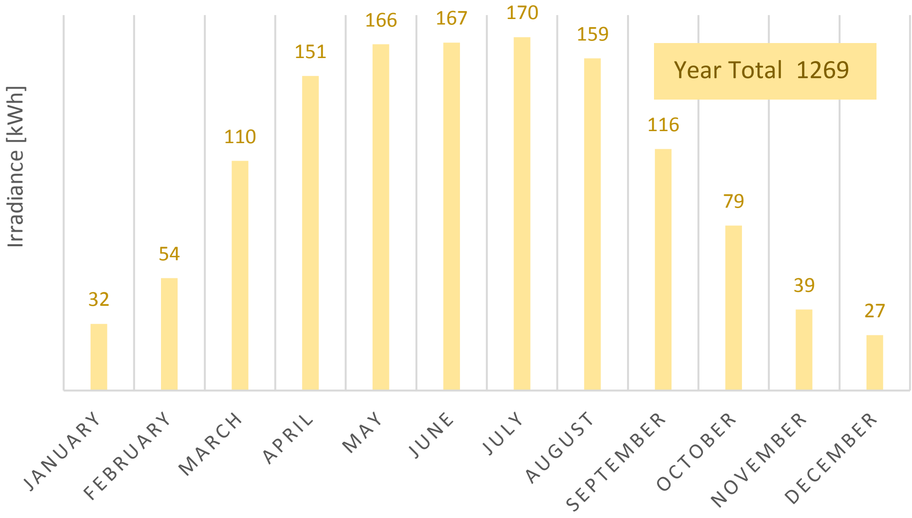


Figure 5 | Yearly sum of incident irradiation on horizontal surface in Czech Republic. Source: PVGIS

As shown in the Figure 5, the yearly sum of irradiation for the considered location is around average for the Czech Republic. The irradiation data were obtained as a long-term average for 15-minute intervals for average day of each month for azimuth of 20° and inclination of 30°. The data were obtained from PVGIS database and are presented in Appendix 1. The average monthly irradiance sums are presented in the following table.



Graph 1 | Average monthly irradiance (surface with 20° azimuth and 30° inclination)

2.1.2 *TEMPERATURE*

The daily temperature profile estimation, needed for the estimation of PV system temperature losses during the day, is carried out according to the Formula 2.1. With this method, it is possible to estimate the temperature at any time of the day using the minimum and maximum daily temperature.

It assumes that the daily temperature profile might be described using three different cosine functions for three periods of the day:

- from midnight to sunrise (t_{dawn}),
- from sunrise to time of peak temperature (t_{peak}),
- from t_{peak} to midnight. [6]

The resulting temperature profiles for average day in January and June are presented in Graph 2 and Graph 3.

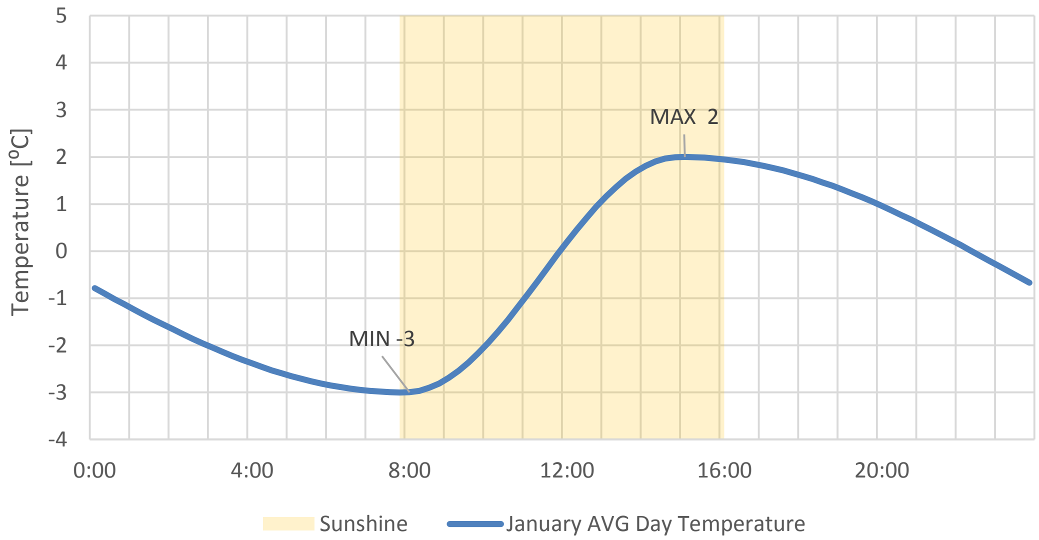
$$T(t) = T_m - T_a \cdot \cos\left(\frac{\pi \cdot (t_{dawn} - t)}{(24 + t_{dawn} - t_{peak})}\right) \qquad \text{for } 0 < t < t_{dawn} \qquad [^0C]$$

$$T(t) = T_m - T_a \cdot \cos\left(\frac{\pi \cdot (t_{peak} - t)}{t_{peak} - t_{dawn})}\right) \qquad \text{for } t_{dawn} < t < t_{peak} \qquad [^0C] \qquad (2.1)$$

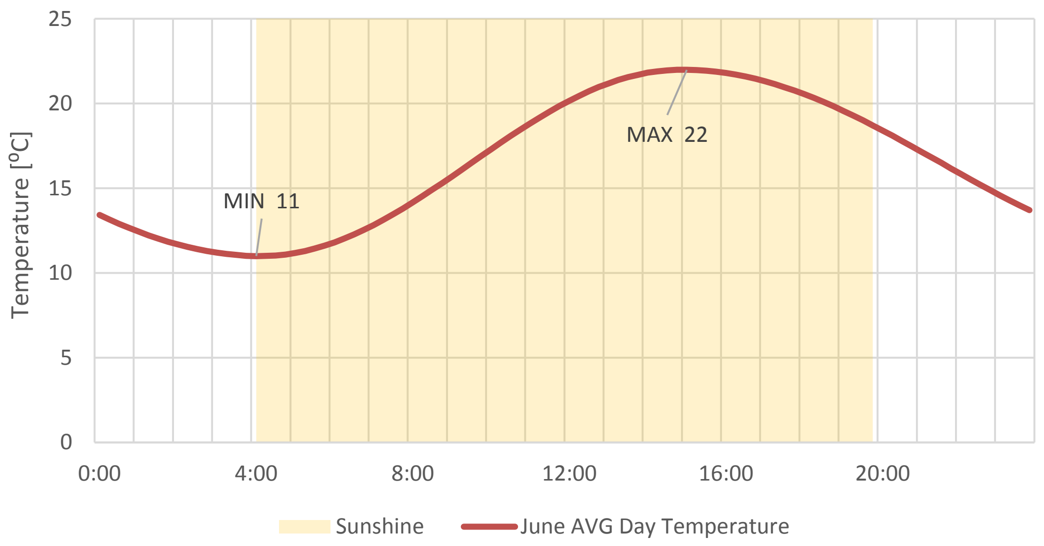
$$T(t) = T_m - T_a \cdot \cos\left(\frac{\pi \cdot (24 + t_{dawn} - t)}{(24 + t_{dawn} - t_{peak})}\right) \qquad \text{for } t_{peak} < t < 24 \qquad [^0C]$$

where

where	T(t)	temperature at time t
	T_m	mean daily temperature, $T_m = \frac{(T_{min}+T_{max})}{2}$
	T_a	amplitude of daily temperature variation, $T_a = \frac{(T_{max}-T_{min})}{2}$
	t_{dawn}	time of dawn
	t_{peak}	time of peak temperature, t_{peak}= 15 h



Graph 2 | Estimated daily temperature profile for average day in January



Graph 3 | Estimated daily temperature profile for average day in June

2.2 House Appliances

As part of the reconstruction, all of the appliances were replaced with the high efficient ones. The lighting is mostly provided by the LED light sources. The list of devices and appliances is given in the table below. The house is fully electrified, electricity is used for cooking, water heating, cooling of the house and partially for its heating as well.

	Appliance	Brand	Product name	Energy Class	Power Consumption [W]	Max Power Cons. [W]	Voltage [V]	Fuse Current [A]
	TV	Panasonic	TX-47AS740E	A++	48		230	
	Microwave oven	Siemens	HF25G5L2		900/1300 (gril)	1990	230	10
	Oven	Siemens	HB63AB521	A		3650	230	16
	Induction hob	Electrolux	EHL7640FOK		2300/3200	7400	230	
	Cooker hood	Electrolux	EFC90244x	E	120		230	5
	Refrigerator	Siemens	KG49EAI40	A+++	176 kWh (p.a.)		230	10
	Washing machine	AEG	Lavamat 86560TL	A++	2200		230	
	Pump -lower water				1000			
	Pump - well				1000			
	Waterworks				1500			
	A/C unit living room	Toshiba		A+ to A++	1440			
	A/C unit (2x) kitchen, bedroom	Toshiba		A+ to A++	575			
HDO	**Electric boiler**	Dražice	OKHE 125	B	2000		230	
HDO	**Heating (currently not being used)**				7500			

Table 2 | House appliances

2.3 Power Consumption

The measuring of power consumption is held continuously in 15-minutes intervals. The power consumption data for years 2014 and 2015 were obtained from the distributor. In this chapter the monthly and daily consumption in selected periods is analyzed. In the power consumption the type and efficiency of the appliances used is reflected as well as the number of people being present, the duration of their presence and their habits. The total power consumption in 2014 was approximately 3,5 MWh, in 2015 3,8 MWh.

The provider of the electricity is ČEZ Distribuce, the tariff used is D45d for direct heating. The reserved power is 3×25A. In the Czech Republic the special system for mass consumer consumption control - HDO (Mass Remote Control) is used by electricity distributors to actively control the consumption. For this purpose special tariffs with two rates of power prices (tariffs) are used. As a result, consumers benefit from lower electricity prices, while distributors and grid operators from the ability to control the load.

HDO Switching Times	
Working Days	Weekends
00:00-00:45	00:00-01:35
01:45-08:40	02:30-03:30
09:40-12:35	04:30-11:00
13:30-18:25	12:00-18:25
19:24-24:00	19:25-24:00

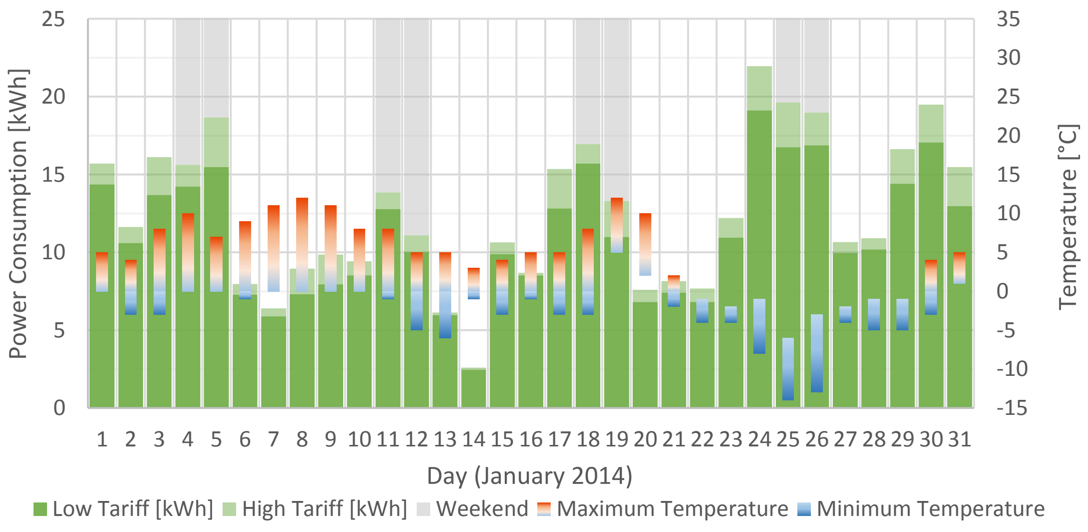
Table 3 | HDO switching times

2.3.1 *January Consumption*

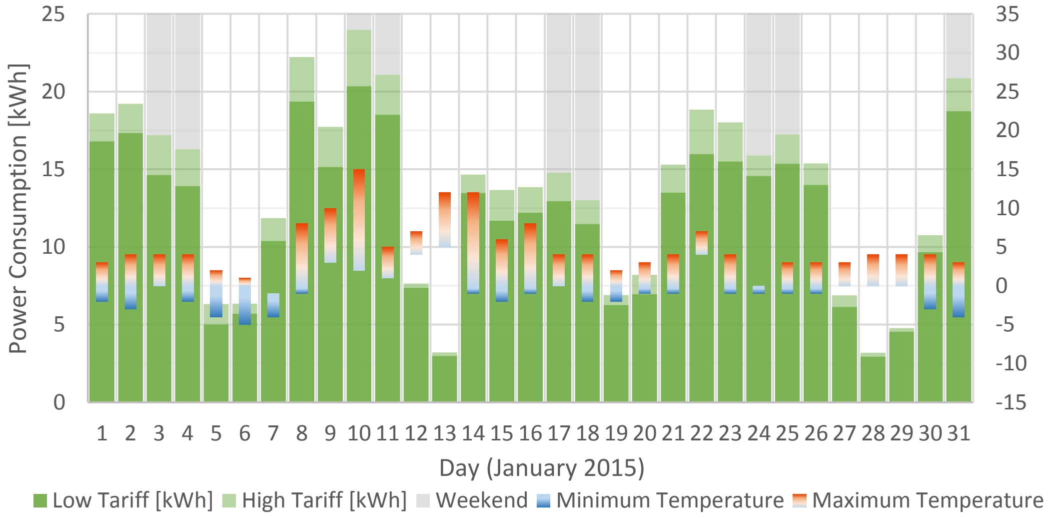
For more in-depth analysis the Consumption in High and Low Tariff along with minimal and maximal temperature for each day in January 2014 and 2015 is presented in the following table and graphs.

Day	Month	Day of the Week (2014)	Temperature [°C] min (2014)	Temperature [°C] max (2014)	High Tariff [kWh] (2014)	Low Tariff [kWh] (2014)	Consumption [kWh] (2014)	Day of the Week (2015)	Temperature [°C] min (2015)	Temperature [°C] max (2015)	High Tariff [kWh] (2015)	Low Tariff [kWh] (2015)	Consumption [kWh] (2015)
1	1	3	0	5	1,342	14,363	15,705	4	-2	3	1,791	16,805	18,596
2	1	4	-3	4	1,042	10,594	11,636	5	-3	4	1,893	17,33	19,223
3	1	5	-3	8	2,419	13,688	16,107	6	0	4	2,554	14,637	17,191
4	1	6	0	10	1,396	14,225	15,621	7	-2	4	2,374	13,923	16,297
5	1	7	0	7	3,203	15,472	18,675	1	-4	2	1,328	5,001	6,329
6	1	1	-1	9	0,678	7,282	7,96	2	-5	1	0,65	5,698	6,348
7	1	2	0	11	0,51	5,884	6,394	3	-4	-1	1,466	10,397	11,863
8	1	3	0	12	1,652	7,297	8,949	4	-1	8	2,872	19,357	22,229
9	1	4	0	11	1,904	7,95	9,854	5	3	10	2,564	15,158	17,722
10	1	5	0	8	0,899	8,52	9,419	6	2	15	3,625	20,348	23,973
11	1	6	-1	8	1,077	12,785	13,862	7	1	5	2,577	18,513	21,09
12	1	7	-5	5	1,073	10,026	11,099	1	4	7	0,267	7,387	7,654
13	1	1	-6	5	0,16	5,968	6,128	2	5	12	0,235	2,986	3,221
14	1	2	-1	3	0,144	2,454	2,598	3	-1	12	1,189	13,478	14,667
15	1	3	-3	4	0,748	9,89	10,638	4	-2	6	1,982	11,682	13,664
16	1	4	-1	5	0,168	8,524	8,692	5	-1	8	1,651	12,201	13,852
17	1	5	-3	5	2,543	12,817	15,36	6	0	4	1,819	12,953	14,772
18	1	6	-3	8	1,241	15,712	16,953	7	-2	4	1,519	11,491	13,01
19	1	7	5	12	2,313	10,985	13,298	1	-2	2	0,621	6,274	6,895
20	1	1	2	10	0,775	6,817	7,592	2	-1	3	1,25	6,959	8,209
21	1	2	-2	2	0,736	7,412	8,148	3	-1	4	1,799	13,502	15,301
22	1	3	-4	-1	0,864	6,82	7,684	4	4	7	2,858	15,976	18,834
23	1	4	-4	-2	1,24	10,958	12,198	5	-1	4	2,507	15,504	18,011
24	1	5	-8	-1	2,86	19,11	21,97	6	-1	0	1,322	14,571	15,893
25	1	6	-14	-6	2,882	16,754	19,636	7	-1	3	1,877	15,357	17,234
26	1	7	-13	-3	2,089	16,879	18,968	1	-1	3	1,378	14,008	15,386
27	1	1	-4	-2	0,698	9,963	10,661	2	0	3	0,751	6,14	6,891
28	1	2	-5	-1	0,731	10,181	10,912	3	0	4	0,243	2,954	3,197
29	1	3	-5	-1	2,225	14,408	16,633	4	0	4	0,241	4,545	4,786
30	1	4	-3	4	2,427	17,055	19,482	5	-3	4	1,102	9,661	10,763
31	1	5	1	5	2,503	12,965	15,468	6	-4	3	2,132	18,739	20,871

Table 4 | Power consumption January 2014, 2015



Graph 4 | Daily consumption, minimum and maximum temperature, January 2014



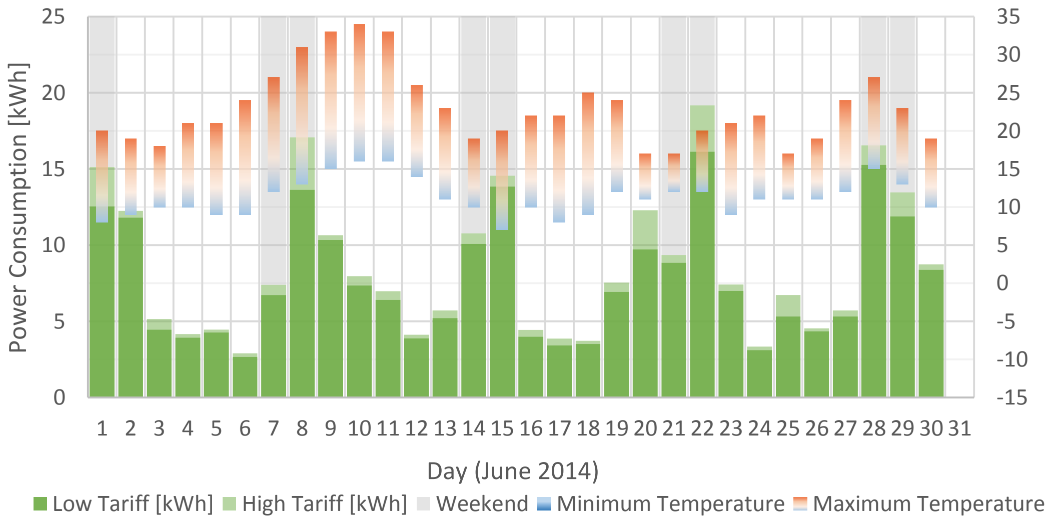
Graph 5 | Daily consumption, minimum and maximum temperature, January 2015

The graphs of daily consumption in January show that consumption during the weeks always grows towards the end of the week. This phenomenon is caused due to the accumulation of heat in central heating circuit after using the wood stove at the weekends along with increased time of presence of persons occupying the house. In 2014 indirect dependence of power consumption on the outdoor temperature can be seen. In the fourth week during the prolonged period of low temperatures the consumption slightly rose, that might be caused by using the air-conditioning for additional heating. Interesting fact is, that the consumption in 2014 fell to its monthly minimum and in 2015 to its second monthly minimum both the second January Tuesday. Furthermore, in 2014 the lowest year consumption was recorded at this day. Total consumption in January 2014 reached 388,3 kWh, in 2015 424,0 kWh, an increase of 9,2%. According to the Czech Hydrometeorological Institute, the average temperature in Pardubice region in January was 1,4°C in 2014 and 2,3°C. in 2015

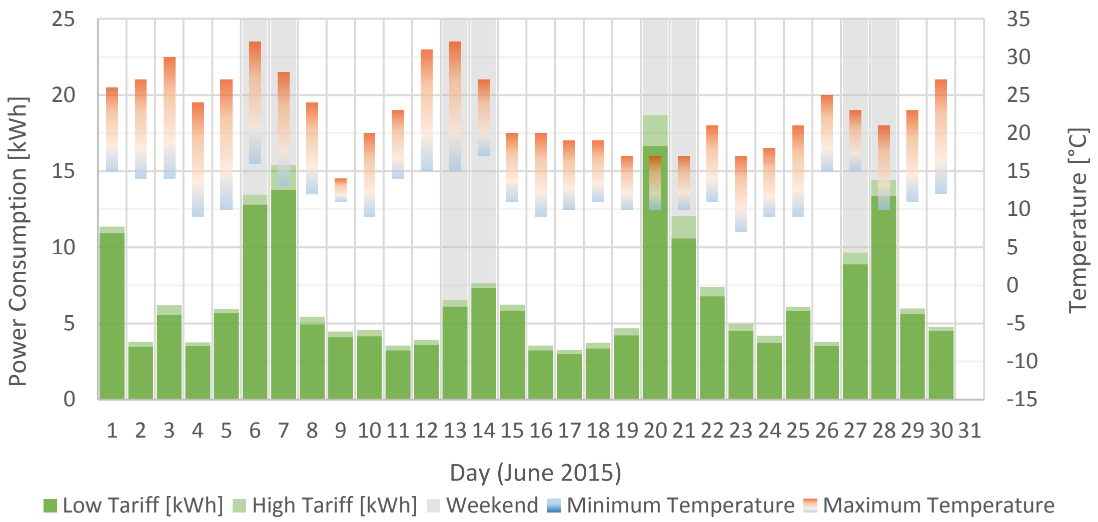
2.3.2 *June Consumption*

Day	Month	2014 Day of the Week	2014 Temperature [°C] min	2014 Temperature [°C] max	2014 High Tariff [kWh]	2014 Low Tariff [kWh]	2014 Consumption [kWh]	2015 Day of the Week	2015 Temperature [°C] min	2015 Temperature [°C] max	2015 High Tariff [kWh]	2015 Low Tariff [kWh]	2015 Consumption [kWh]
1	6	7	8	20	2,578	12,54	15,118	1	15	26	0,44	10,92	11,36
2	6	1	9	19	0,431	11,809	12,24	2	14	27	0,35	3,45	3,8
3	6	2	10	18	0,693	4,46	5,153	3	14	30	0,65	5,54	6,19
4	6	3	10	21	0,221	3,935	4,156	4	9	24	0,26	3,5	3,76
5	6	4	9	21	0,199	4,258	4,457	5	10	27	0,27	5,67	5,94
6	6	5	9	24	0,227	2,674	2,901	6	16	32	0,66	12,8	13,46
7	6	6	12	27	0,663	6,726	7,389	7	13	28	1,64	13,77	15,41
8	6	7	13	31	3,451	13,634	17,085	1	12	24	0,52	4,92	5,44
9	6	1	15	33	0,31	10,34	10,65	2	11	14	0,39	4,08	4,47
10	6	2	16	34	0,606	7,36	7,966	3	9	20	0,43	4,15	4,58
11	6	3	16	33	0,574	6,409	6,983	4	14	23	0,33	3,22	3,55
12	6	4	14	26	0,222	3,896	4,118	5	15	31	0,32	3,58	3,9
13	6	5	11	23	0,503	5,221	5,724	6	15	32	0,43	6,11	6,54
14	6	6	10	19	0,682	10,095	10,777	7	17	27	0,32	7,32	7,64
15	6	7	7	20	0,716	13,837	14,553	1	11	20	0,39	5,84	6,23
16	6	1	10	22	0,439	3,987	4,426	2	9	20	0,32	3,23	3,55
17	6	2	8	22	0,436	3,436	3,872	3	10	19	0,28	2,97	3,25
18	6	3	9	25	0,217	3,505	3,722	4	11	19	0,37	3,36	3,73
19	6	4	12	24	0,617	6,932	7,549	5	10	17	0,46	4,21	4,67
20	6	5	11	17	2,573	9,72	12,293	6	10	17	2,04	16,65	18,69
21	6	6	12	17	0,512	8,844	9,356	7	10	17	1,47	10,57	12,04
22	6	7	12	20	3,034	16,144	19,178	1	11	21	0,63	6,78	7,41
23	6	1	9	21	0,42	6,994	7,414	2	7	17	0,48	4,48	4,96
24	6	2	11	22	0,219	3,117	3,336	3	9	18	0,48	3,71	4,19
25	6	3	11	17	1,389	5,328	6,717	4	9	21	0,26	5,82	6,08
26	6	4	11	19	0,206	4,342	4,548	5	15	25	0,28	3,52	3,8
27	6	5	12	24	0,392	5,316	5,708	6	15	23	0,79	8,87	9,66
28	6	6	15	27	1,291	15,274	16,565	7	10	21	1,06	13,37	14,43
29	6	7	13	23	1,572	11,889	13,461	1	11	23	0,38	5,6	5,98
30	6	1	10	19	0,348	8,39	8,738	2	12	27	0,28	4,49	4,77
0	0	0			0	0	0	0			0	0	0

Table 5 | Power consumption June 2014, 2015



Graph 6 | Daily consumption, minimum and maximum temperature, June 2014

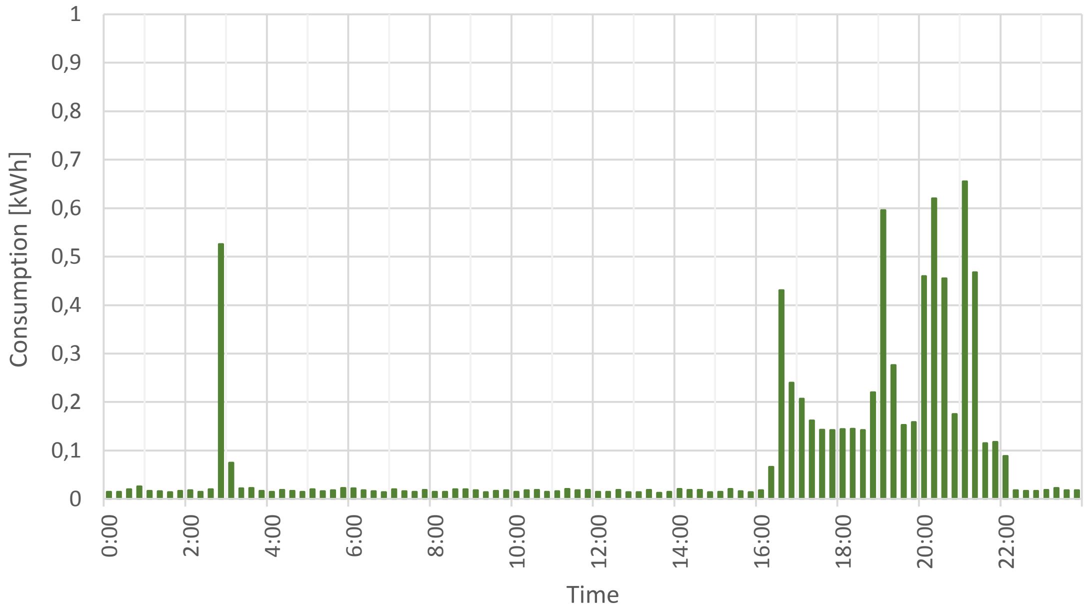


Graph 7 | Daily consumption, minimum and maximum temperature, June 2015

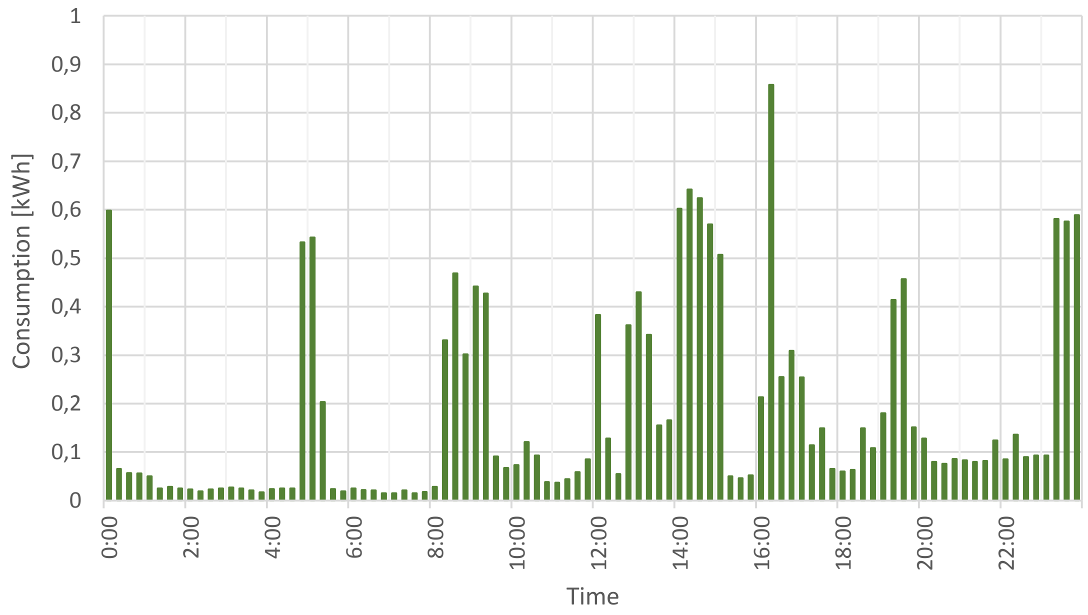
In June the working days can be clearly distinguished from the weekends by the daily power consumption. While during the working days the power consumption reaches the levels around 5 kWh, during the weekends it is regularly in the 10-15 kWh range. The increase in consumption between 9th and 11th day of the month in 2014 suggests that the high temperatures might have caused that the air-conditioning was used for cooling purposes. Total consumption in June 2014 was 256,2 kWh, in 2015 209,5 kWh, which is a decrease of 18,2%. According to the Czech Hydrometeorological Institute, the average temperature in the Pardubice region for the month of June was 15.9°C in 2014 and 16.2°C in 2015.

2.3.3 *DAILY DIAGRAMS*

Thanks to the power consumption measurements provided in 15-minute intervals, the intraday power consumption analysis might be carried out.

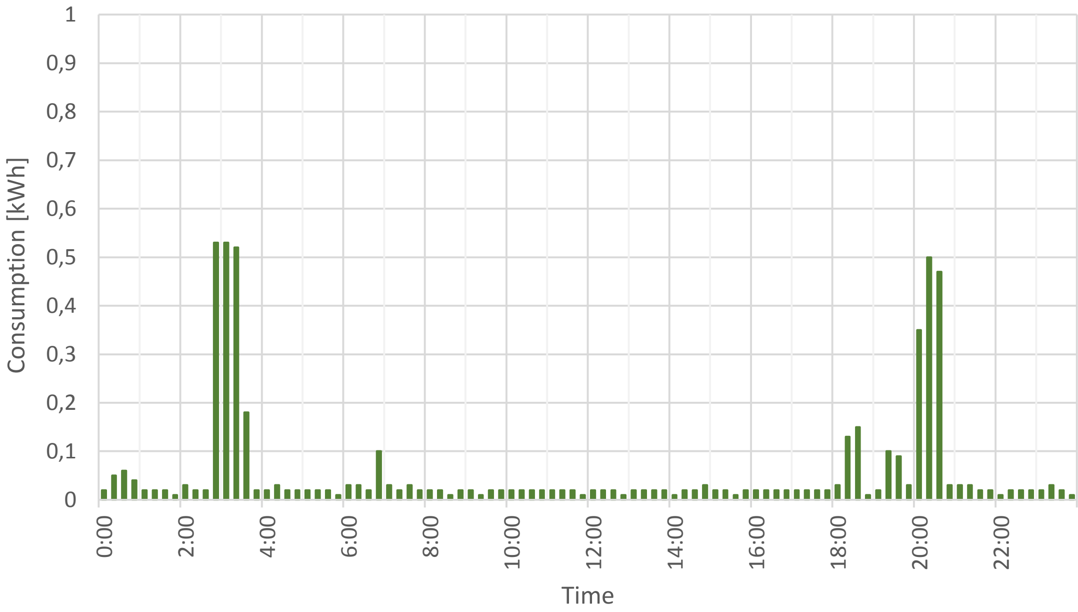


Graph 8 | Diagram of intraday consumption, Tuesday 20. 1. 2014

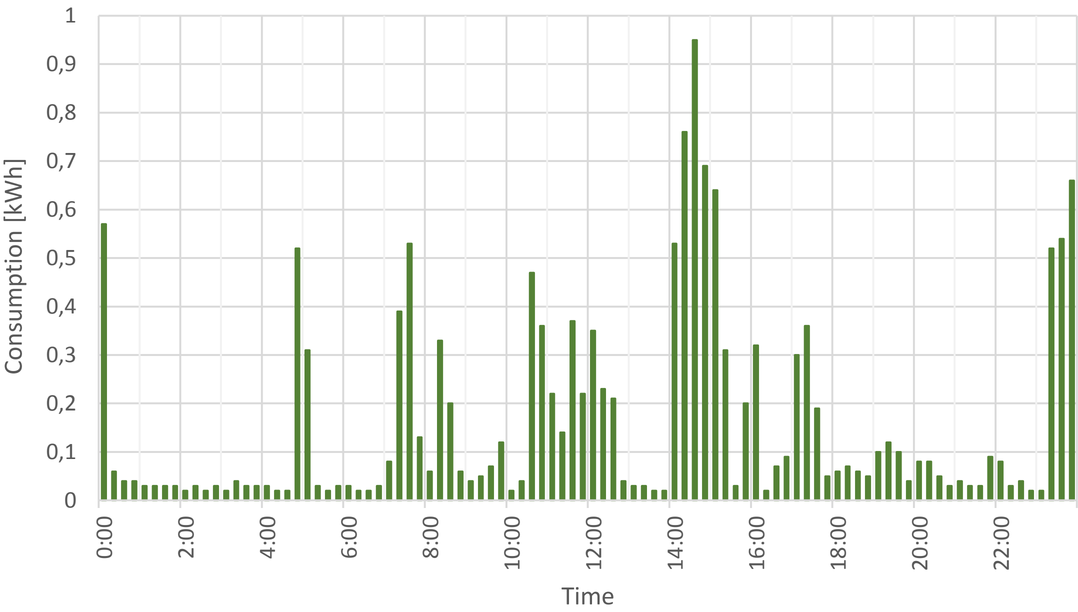


Graph 9 | Diagram of intraday consumption, Saturday 25. 1. 2014

On Graph 8 and Graph 9 a comparison between consumption during the winter working day and the weekend day in January 2015 can be seen. During the working day, power consumption is only limited to the water heating controlled by the HDO system and time when residents are present which is usually in the evening. During the weekend days the power consumption characteristics is substantially different as the residents are mostly present during the whole day.



Graph 10 | Diagram of intraday consumption, Monday 8th June 2014



Graph 11 | Diagram of intraday consumption, Sunday 7th June 2014

The Graph 10 and Graph 11 show power consumption during the summer working and weekend day in June. The consumption is similar in its amplitude and time distribution to what can be seen in the previous two graphs for winter season.

2.4 Heating and Cooling

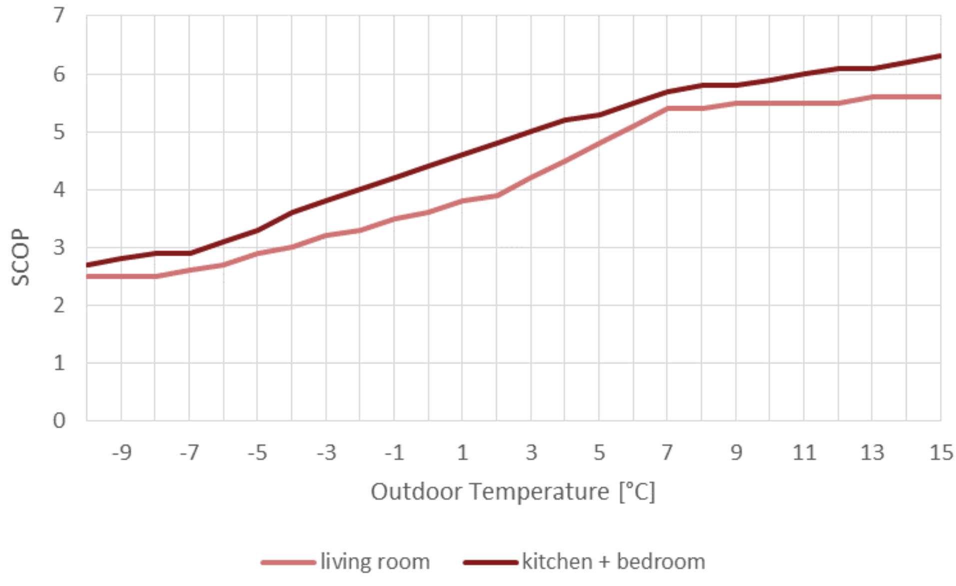
On the weekends the heating of the house is usually provided by a wood stove in which firewood is used. The stove is located in the living room and is equipped with a heat exchanger through which the water in the central heating circuit is heated. During the week, the air-conditioning unit is used to keep temperature at 19°C and used for heating to higher temperatures when the residents are present. The house is equipped with two outside air-conditioning units. The multi-split outdoor unit is connected to the two wall mounted indoor units in kitchen and bedroom. The other outside unit is connected to the floor mounted unit in the living room.

Air-conditioning Units								
Location		Type	Heating			Cooling		
			COP [W/W]	Output Power [kW]	Power Consumption [kW]	EER [W/W]	Output Power [kW]	Power Consumption [kW]
kitchen + bedroom	outside multi-split unit	Toshiba RAS-M18UAV-E	4,71	5,6	1,19	3,61	5,2	1,44
	2 inside wall mounted units	Toshiba RAS-M10SKV-E		0,7-5,2	0,02		1,1-3,2	0,02
living room	outside unit	Toshiba RAS-10SAV2-E	4,27	3,2	0,725	4,2	2,5	0,575
	inside floor mounted unit	Toshiba RAS-B10UFV-E		0,9-4,8	0,025		1,1-3,1	0,02

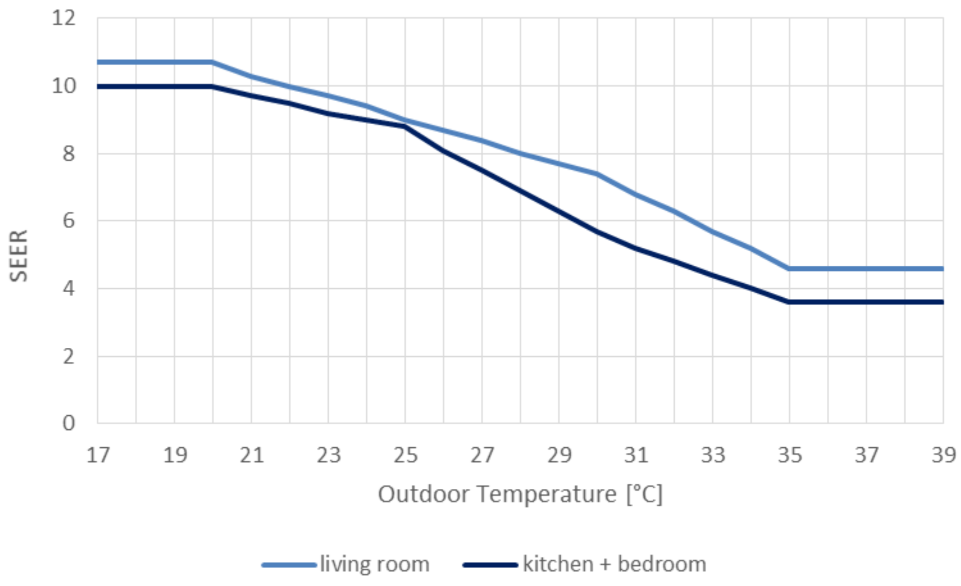
Table 6 | Air-conditioning Units

To describe the air conditioning heating and cooling efficiency the manufacturers were until 2013 using a nominal ratio for heating (COP – known as Coefficient of Performance) and nominal ratio for cooling (EER – Energy Efficiency Ratio). These values are presented in the data sheet of the air conditioning units and can be seen in Table 6. The nominal efficiency indicates how efficient the air conditioning unit is when operating at full load in nominal conditions. Due to the fact that these conditions aren't often achieved, the more accurate description of the air conditioning efficiency was introduced – the Seasonal Coefficient of Performance (SCOP) for heating and Seasonal Energy Efficiency Ratio (SEER) for cooling. It gives a more accurate measure of the efficiency because it indicates how efficient the operation of the air conditioning unit is over an entire cooling or heating season. [7]

Toshiba, the manufacturer of the used air conditioning units, provides an online tool [8] which allows to obtain SCOP and SEER coefficients for specific combinations of outside and inside units dependent on temperature. Both coefficients are presented in Graph 12 and Graph 13.



Graph 12 | SCOP coefficient for used air conditioning units

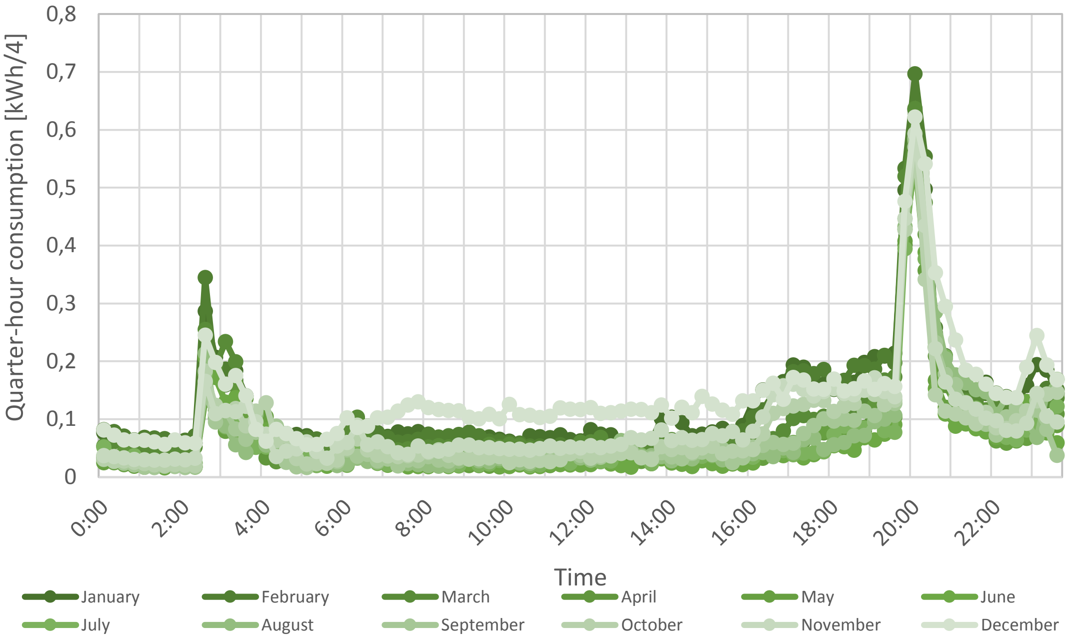


Graph 13 | SEER coefficient for used air conditioning units

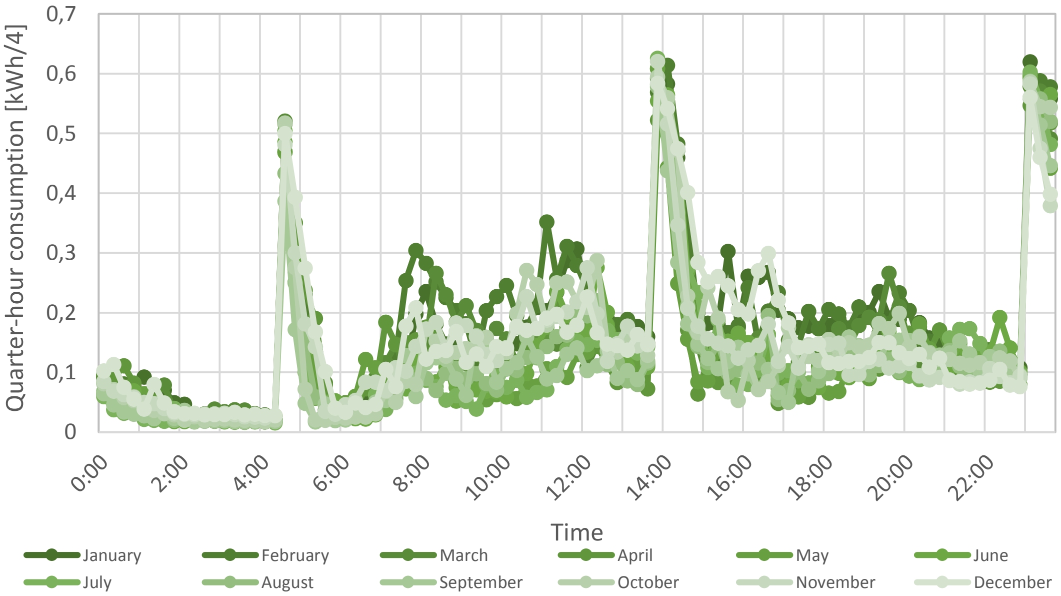
2.5 Water Heating

The preparation of hot water is provided by an electric boiler with power of 2kW. The water is stored in an insulated enamel-lined steel tank with capacity of 125 liters. The heating is controlled by thermostat with the ability to set the desired temperature in the range of 5-74°C. The optimal temperature suggested by the manufacturer (ECO mode) is 60°C. However, to provide sufficient amount of hot water the thermostat is being set to 67°C. The duration of water heating from 10 to 60°C declared by the manufacturer is 3,6 hours. The heater is connected to the Mass Remote Control (HDO) and therefore the heating only occurs at a time of reduced power rates.

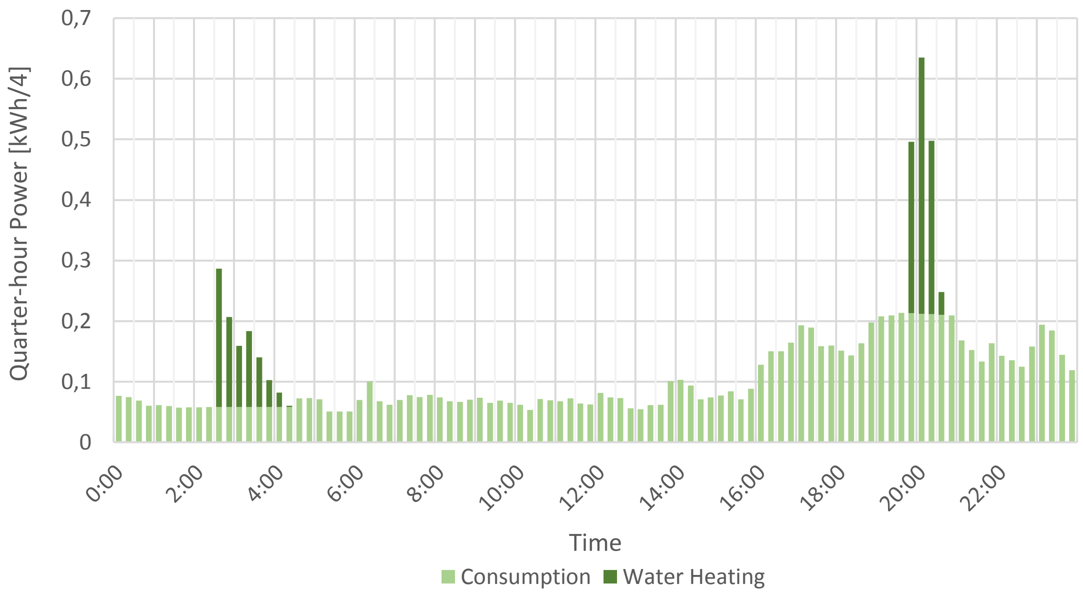
The power consumption for water heating was estimated from the average day power consumption diagrams for each month according to the HDO switching on times. The exact switching times which are the same throughout the year and differ for working and weekend can be seen in Graph 14 and Graph 15. Therefore, to obtain the consumption for water heating, the repetitive consumption peaks were subtracted from the consumption characteristics. It is assumed that the consumption for other purposes than water heating has during the peaks a linear characteristic. The power consumption with distinct consumption for water at working day in January is shown in Graph 16. From the presented data in Table 7 it can be seen that the consumption for water heating during the average weekend days is at least double the consumption during the average working days. In total, consumption for water heating during the weekends accounts for 441kWh, whereas during the working days for 407kWh.



Graph 14 | Average working day power consumption for each month



Graph 15 | Average weekend day power consumption for each month



Graph 16 | Power consumption of average working day in January

Water heating consumption		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Working day	kWh	1,78	1,96	1,97	1,66	1,66	1,99	1,51	1,63	1,71	1,76	1,66	1,78
Weekend	kWh	4,17	4,50	4,04	4,11	3,70	4,17	3,94	3,71	3,09	3,75	3,54	4,07

Table 7 | Water heating consumption for average day in each month

2.6 Solid Fuels Consumption

As a fuel for the wood stove, oak and beech firewood in form of split logs is used. It is being purchased early enough to be stored in the shed next to the house for around a year to dry out. During the heating season 2014/2015[1] was according to the estimation of the residents burned around 5 square meters of stacked split logs of beech and oak firewood. The wood is being purchased for a price of 1 000CZK/m^3. Supplier unfortunately doesn't provide the wood specifics as calorific value and water content. Therefore, average values are used. After being kept under a roof, the wood reduces its water content to 20% in a half a year to a one year. [9] It is estimated that half of the wood is oak wood and the other half beech wood.

Using the calorific value for oak wood of 15,9MJ/kg and its specific weight of 480kg per square meter of stacked split logs and 15,5MJ/kg and 469kg/m(s)^3 for beech wood

[1] heating season in the Czech Republic lasts according to the czech standards from September to May

respectively, the calorific value in kWh per square meter of stacked split logs is calculated. Taking into account the amount of the wood burned during 2014/2015 winter, all together the 10 348kWh of heat was produced. The nominal efficiency of the wood stove is 85%, considering that it usually doesn't operate at its peak efficiency, the expert estimation of Ekowatt company for the real efficiency is around 75%. Therefore, the heat effectively used for heating is around 7760 kWh per the 2014/2015 winter. [10]

In the Czech Republic a special measure is used to determine the need of heating for each month of heating season. It also allows to compare the amount of heat needed to an average values. This measure uses so called "heating degrees". The amount of heating degrees for each month is calculated according to the following formula. [11]

$$\mathrm{D}(22) = (22 - \mathrm{T}13) \cdot \mathrm{N}13 \qquad [-] \qquad (2.2)$$

where	D(22)	amount of heating degrees for indoor tepmperature of 22°C
	N13	the amount of days with temperature lower than 13°C (average temperature for opening and closing the heat supply, according to the Czech standard n. 194/2007)
	T13	average temperature of the days with lower temperature than 13°C

The heating degree values for the 2014/2015 heating season and an average heating season are obtained from the online heating degrees calculator of TZB-info website. [10] Using the obtained values, the 2014/2015 heating season is compared to an average heating season. Therefore, the amount of heat needed for the house heating during an average heating season is obtained.

The heating degrees for the indoor temperature of 22 °C, average temperatures for the 2014/2015 heating season and an average heating season can be seen in Table 8. The heat from the wood is recalculated to individual months of an average heating season using the heat degrees.

Heating season	2014/2015				Average season			
heating to 22°C	Average Temp [°C]	Heating days	Heating degrees	Heat from wood [kWh]	Average Temp [°C]	Heating days	Heating degrees	Heat from wood [kWh]
January	2,3	31	611	1315,1	-0,5	31	709,3	1526,6
February	1,4	28	577,2	1242,3	0,4	29	614,3	1322,2
March	5,4	31	515,6	1109,7	4	31	539,7	1161,6
April	9,1	27	355,8	765,8	9,5	30	382,6	823,5
May	13,5	21	176,4	379,7	13,5	8	73,1	157,3
June					16,5			
July					19			
August					19			
September	15,4	7	66,2	142,5	14,5	3	27,5	59,2
October	10,7	22	272,7	586,9	10,5	31	381,3	820,7
November	7,3	30	440,1	947,2	5	30	527,7	1135,8
December	2,9	31	591	1272,0	1	31	653,6	1406,7
Year avg/total	**7,56**		**3606**	**7761,2**	**9,37**		**3909,1**	**8413,6**

Table 8 | Calorific value of firewood calculation

2.7 Area for Solar Modules Placement

The basic prerequisite of effective utilization of the solar system is suitable orientation and inclination of the surface for placement of the PV modules alongside with the least possible amount of shading. Part of the roof has ideal parameters for installing the modules. It is oriented towards South with azimuth of approximately 20° (South 0°, West 90°) and inclination of 30°. The roof surface is made out of fiber cement tiles. The plan and the measurements of the part of the roof oriented towards South can be seen in the following figure.

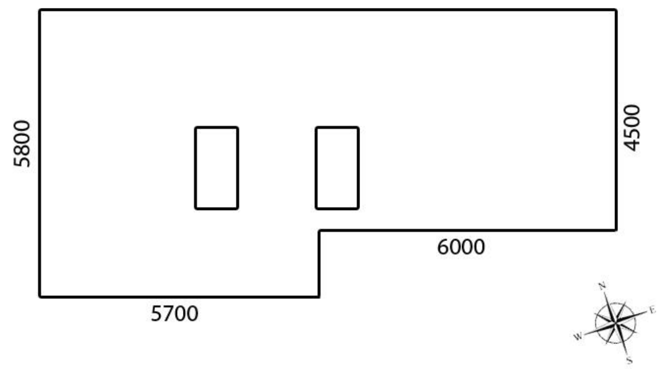


Figure 6 | The plan of the part of the roof situated to the South

3. Components of PV System

Having knowledge of the various PV system components and their operating principles is crucial for choosing the correct type and set of parameters of each component. This chapter provides information about PV components available as well as basic characteristics of their operation and its effect on the whole system.

3.1 PV system types

The components needed for safe, reliable and efficient operation of a PV system are dependent on the operational mode of the whole system. There are two basic types of photovoltaic systems regarding its operational mode which are suitable to be implemented on the roof of a family house:

- Off-grid standalone systems. This type of system is totally independent and supplies all the required energy. The excess solar energy is stored in batteries to be used during time with not enough solar irradiation. It usually includes backup electricity source such as diesel generator for longer periods of not sufficient irradiation. These systems are suitable for places with no access to the power network or with electricity prices high enough for the system to be profitable, which is not the case of the family house considered in this work. Therefore, these systems won't be mentioned in this work.
- On-grid systems work in parallel with the power network and provide savings of power supply costs. In most cases they don't use batteries due to their high prices. This system is also suitable for the considered family house.

3.2 PV Module

Direct conversion of sunlight into DC electricity is provided by a PV cell. Numerous PV cells are electrically connected in series and parallel circuits to form a PV module or panel[2] with desired voltage, currents and power levels. The The standard panel usually has 36 or 72 cells connected in series to produce voltage high enough to charge 12V, resp. 24V battery. With an individual cell having voltage of just under 0,6V the

[2] According to [4], terms *module* and *panel* are often used interchangeably. According to the American *National Electric Code*, a *panel* is technically a group of *modules*.

operating voltage of the series connection at maximum power is about 18V for 36 cells and 36V for 72 cells. The PV modules use a protective laminate sealing to protect the cells against degradation from environmental factors and weather.

3.2.1 PV CELL TECHNOLOGIES

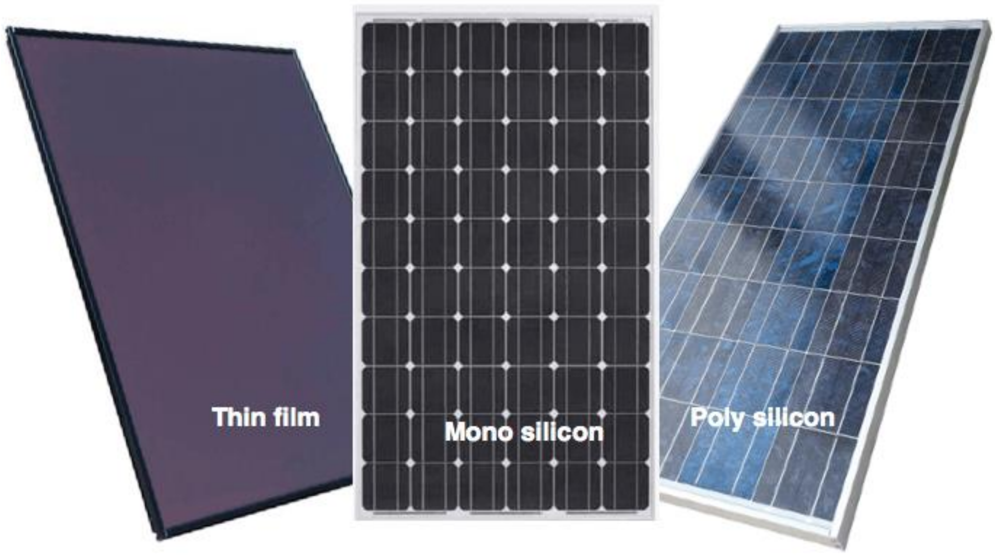


Figure 7 | Monocrystalline, polycrystalline and thin-film PV module. Author: Luke Boyden

PV Cells are made from semiconductor materials, the most common semiconductor used is silicon. There are, however, more methods to produce silicon cells and the differences among them along with the possibility to use other types of semiconductors vastly affect the performance and price of PV modules.

MONOCRYSTALLINE SILICON

Monocrystalline silicon solar cells are the most efficient due to the usage of very pure silicon. On the other hand, they are generally the most expensive, due to the difficult and precise manufacturing process. The cells are produced by slicing pure crystalline silicon ingot into wafers. The ingot is made by Czochralski process during which a single silicon seed crystal is placed in a crucible of molten silicon and then drawn out slowly while being rotated. [12] [13]

Panasonic claims in its statement, that in 2014 it has produced monocrystalline cell with efficiency of 25,6%. A year later it has announced commercial-sized prototype module created out of those cells with a world-record conversion efficiency of 22,5 %.

The results of the test were confirmed by the renowned Japanese National Institute of Advanced Industrial Science and Technology (AIST). [14]

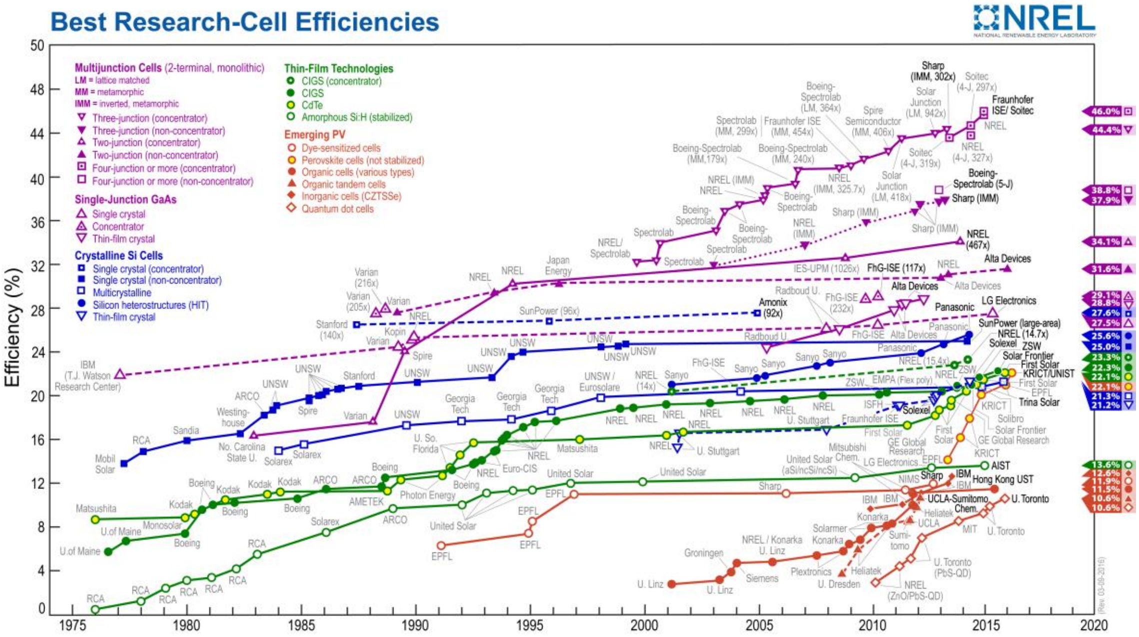
Polycrystalline Silicon

Polycrystalline silicon cells, also referred to as multicrystalline silicon cells, are less efficient and also less expensive to produce compared to monocrystalline cells. They are made from many small silicon crystals rather than single crystal ingot. This technology is the most frequently used in PV systems.

Thin-film Technology

The least expensive and also the least efficient of the mentioned technologies is the thin-film technology. The thin-film cells are, however, less susceptible to low light conditions and shading, and have better temperature coefficient. High worldwide demand for affordable PV technologies led to increasing interest in thin-film solar cells. Thin-film cells are being more frequently used in buildings and solar-powered gadgets as calculators and watches. The most common materials are amorphous silicon (a-Si), copper indium (gallium) diselenide (CIS, CIGS) and cadmium telluride (CdTe). This material can be coated on nearly any shape and size, offering a wide variety of applications.

The most efficient research solar cells manufactured to date can be seen in the Graph 17. However, the solar cells used for commercially available modules usually don’t reach efficiencies this high.



Graph 17 | Most efficient research solar cells to date. Source: NREL

3.2.2 PV Module Performance

The performance of PV module is rated according to its maximum DC power output in Wp (Watt-peaks). The power output depends on the surface area and type of the solar cells in the module and is laboratory tested under Standard Test Conditions (STC), which are 1000 W/m^2 of incident solar irradiance, cell or module temperature of 25 ± 2 °C and air mass of 1,5. Modules used in today’s PV systems are typically rated between 100 and 300 Wp. [13]

Module Efficiency

The efficiency of solar module indicates which portion of the incoming solar irradiance is converted to electric power on the output of the PV module. The nominal efficiency found on the data sheets of PV modules is specified under STC. It can be calculated according to the following formula.

$$\eta = \frac{P_{max}}{A} \quad [\%] \qquad (3.1)$$

where P_{max} maximum (peak) power of the module

A module surface area

The module efficiency is dependent on irradiance level and temperature. The approximate efficiency for crystalline silicon cells at specific irradiation and constant temperature can be calculated according to the following formula. [15]

$$\eta(G) \approx \eta_n \left[1 + 0{,}04 \cdot \ln(\frac{G_i}{A \cdot 1000})\right] \qquad [\%] \qquad (3.2)$$

where η_n module nominal efficiency

G_i instantaneous solar Irradiance

A module surface area

and 1000 represents an irradiation of $1000 W/m^2$

Moreover, the PV module efficiency of crystalline solar cells decreases with increasing temperature. Therefore, crystalline modules achieve their greatest efficiency at low temperatures. The efficiency at specific temperature and constant irradiance is calculated according to the following formula.

$$\eta(T) \approx \eta_n[1 - k_T \cdot (25°C - T_{cell})] \qquad [\%] \qquad (3.3)$$

where T_{cell} cell temperature

k_T power temperature coefficient (negative value)

The power temperature coefficient can be found on the data sheet of the PV module and the value for crystalline silicon panels is approximately -0,45%/°C. For amorphous panels the efficiency actually rises at low irradiance, the power temperature coefficient might be up to +1,4%/°C. [15]

The combination of the mentioned effects can be calculated according to the Formula 3.4.

$$\eta(G,T) = \eta_n[1 + 0{,}04 \cdot \ln(s)] \cdot [1 - k_T \cdot (25°C - T_{cell})] \qquad [V] \qquad (3.4)$$

PVGIS Efficiency calculation

A different approach to determine the PV module efficiency is taken in an online PV performance calculator PVGIS. This approach, however, needs very detailed PV module specifications or experimental data. Therefore, it will be only briefly presented in this work.

The efficiency dependent on irradiance and temperature is calculated according to the Formula 3.5. [16]

$$\eta_{PVGIS}(G,T) = \eta_n \cdot \eta_{rel}(G,T) \quad [\%] \quad (3.5)$$

where η_n PV module nominal efficiency

$\eta_{rel}(G,T)$ relative efficiency according to the irradiance G and temperature T

The relative efficiency is then calculated according to the following formula.

$$\eta_{rel}(G,T) = 1 + k_1 \ln(G') + k_2(\ln(G'))^2 + (T_{cell} - 25)[k_3 + k_4 \ln(G') + k_5 \ln(G')] + k_6(T_{cell} - 25)^2 \quad [-] \quad (3.6)$$

where $k_1 - k_6$ coefficients describing the irradiance and temperature dependence

G' $\frac{G}{1000}$

The coefficients k_1 to k_6 need to be obtained from detailed PV module specifications (such as ideal diode thermal voltage, PV cells series resistance, ideality factor, etc.). These values are however usually not specified on module data sheet. More precise method is to obtain the coefficients experimentally.

The coefficient values presented in [17] for a mainstream multi-crystalline silicon module can be seen in the following table.

Coefficient	k1	k2	k3	k4	k5	k6
	-0,01	-0,027	-0,0041	-0,000021	-0,0001	-0,000003

Table 9 | PVGIS efficiency calculation coefficients

Operating Temperature

The cell/module operating temperature is estimated according to the ambient temperature and the incident irradiance. [6]

$$T_{cell} = T_{amb} + (\text{INOCT} - 20) \cdot \frac{G_i}{800} \qquad [V] \qquad (3.7)$$

where	T_{cell}	cell temperature
	INOCT	installed normal operating cell temperature
	G_i	instantaneous incident solar irradiance
	T_{amb}	ambient temperature

This estimation might be inaccurate especially at higher temperatures due to the increased heat convection which is not considered in this formula. Therefore, the estimated temperature might be higher than the actual cell temperature.

The INOCT or 'installed' nominal operating cell temperature is cell temperature based on nominal operating cell temperature (which can be found in module data sheet) adapted to the mounting configuration of the PV module. [18] The estimated INOCT value according to the mounting configuration can be seen in Table 10. For the direct roof mounting the NOCT should be raised by 18^{0}C. The standoff values in centimeters were calculated from the original values in inches and represent the gap between the roof and the PV modules corresponding to a certain temperature raise.

Mounting	INOCT Value
Rack Mount	INOCT = NOCT - 3^{o}C
Direct Mount	INOCT = NOCT + 18^{o}C
Standoff	INOCT = NOCT + X^{o}C
-in cm	**X**
2,54	11
7,62	2
15,24	-1

Table 10 | INOCT estimation according to the mounting configuration of the PV modules. Source: Fuentes, Martin K., A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays

PVGIS Operating Temperature

The PVGIS calculator uses different approach to the cell temperature calculation. [16] Instead of PV module data sheet values it uses laboratory tested and literature based temperature coefficient.

$$T_{cell} = T_{amb} + k_T \cdot \text{G} \quad [V] \quad (3.8)$$

where k_T temperature coefficient

= 0,035°C/(W/m^2) for free standing modules – laboratory tested

= 0,05°C/(W/m^2) for building integrated modules - literature

Performance Characteristics

Output characteristics for a PV module is represented by a Power and a I-V curve (Figure 8). It represents the current and voltage dependency under STC conditions.

- The **open circuit voltage (V_{oc})** is the maximum voltage of the module when no current is being drawn from the module. It is used to determine the maximum circuit voltage.
- The **short circuit current (I_{sc})** is the maximum current output of a module which occurs when the panel is short circuited. It is used to determine maximum available circuit currents and size overcurrent protection devices and system conductors.
- The **maximum power point (MPP)** indicates the maximum power output of PV module and is given by the product of the maximum power voltage (V_{mp}) and the maximum power current (I_{mp}).

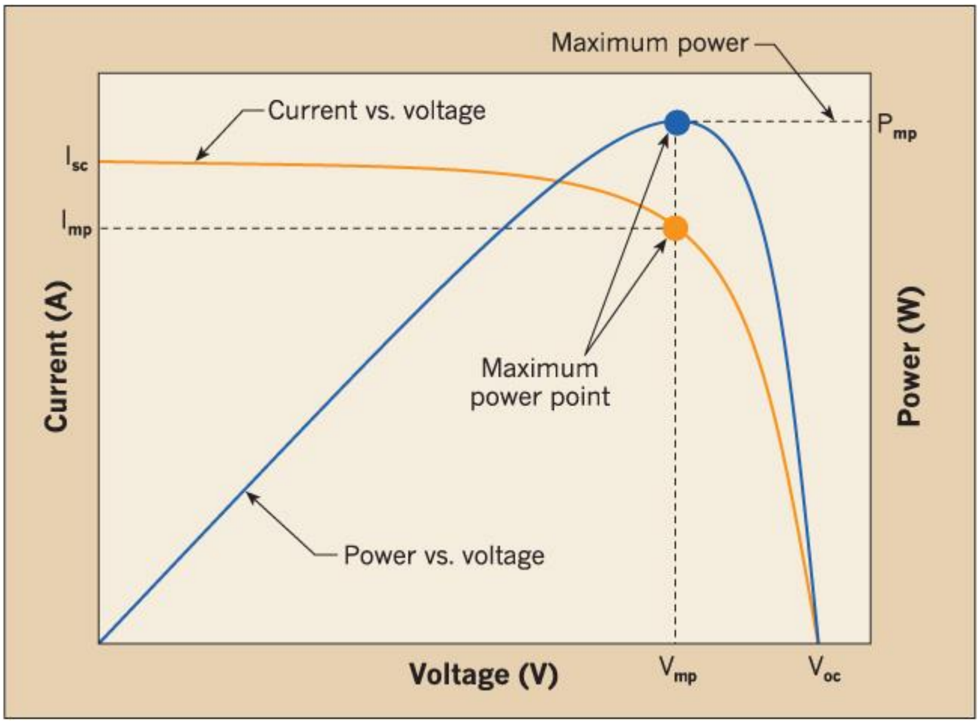


Figure 8 | PV module I-V and P-V curve. Source: Electrical Construction & Maintenance website

IRRADIANCE AND TEMPERATURE DEPENDENCY

The modules rarely operate under STC conditions. The electrical output vary depending on temperature and irradiance. The irradiance changes affect mostly the module current since it's directly dependent on the irradiance. On the other hand, the voltage changes of single PV module are only minor. However, since the PV generators usually consist of a number of modules, the voltage change might be significant.

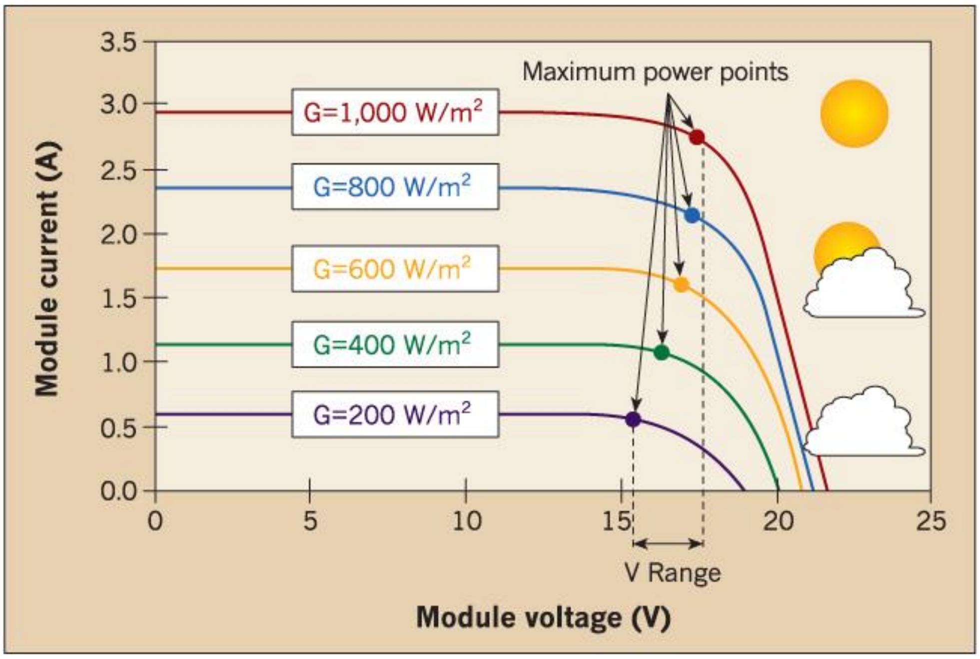


Figure 9 | PV module (50W) I-V curve irradiance dependency. Source: Electrical Construction & Maintenance website

The Figure 9 shows the irradiance dependency of single 50W PV module I-V curve. While with the change of irradiance between 200 and 1000 watts per square meter the module current change is directly dependent, the voltage change is only around 15 % and is usually neglected in the calculations. From the information above, the formula for short-circuit current as a function of irradiance can be formed.

$$\frac{I_{SC}(G)}{I_{SC}(G_{STC})} = \frac{G}{G_{STC}} \qquad [-] \qquad (3.9)$$

where G_{STC} equal 1000 W/m²

$I_{SC}(G_{STC})$ short-circuit current at standard test conditions, available on data sheet

The module voltage is significantly affected by the module temperature. The lower the temperature, the higher the voltage and vice versa. The change of the module voltage determines the minimum and maximum voltage of the PV array and therefore it shouldn't be neglected while designing the entire PV system. Especially with several modules connected in series. The current increases only slightly with increasing temperature. In the summer the power output might be 35% less at high temperatures than under STC. In order to minimize this loss, the PV modules should be installed in a way which allows them to dissipate heat easily.

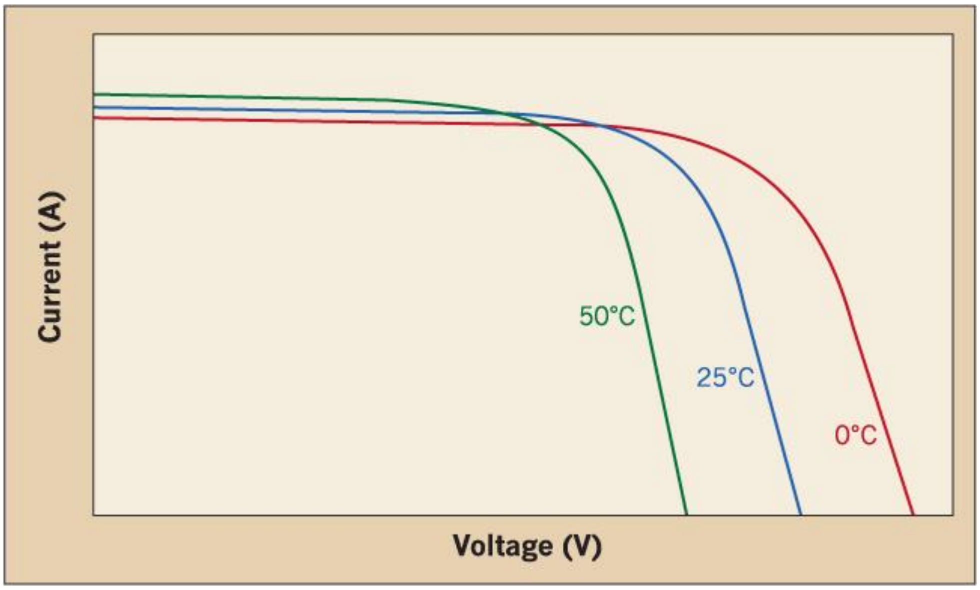


Figure 10 | PV module I-V curve temperature dependency. Source: Electrical Construction & Maintenance website

The module data sheets usually provide information about current and voltage temperature dependency in form of voltage and current temperature coefficients as percentage of mV or mA per °C. Typical values for crystalline modules are shown in the Table 11. The percentage of change refers to the value at STC.

Temperature Coefficient	Crystalline Silicon Modules	High Performance Modules
Open-circuit Voltage	-0,3 to -0,55%/°C	-0,25 to -0,29%/°C
Short-circuit Current	+0,02 to +0,08%/°C	+0,02 to +0,04%/°C
MPP Power	-0,37 to -0,52%/°C	-0,30 to -0,38%/°C

Table 11 | Temperature coefficients for crystalline modules. Source: Planning & Installing Photovoltaics Systems

Knowing the open-circuit voltage temperature coefficient, the open-circuit voltage at specific cell temperature can be calculated according to the following formula.

$$\frac{\Delta V_{OC}}{\Delta T} = k_{T,Voc} \qquad [\%/K] \quad (3.10)$$

where $\Delta V_{OC} = V_{OC}(T_{cell}) - V_{OC}(T_{STC})$

$\Delta T = T_{cell} - T_{STC}$

$k_{T,Voc}$ temperature coefficient for open-circuit voltage

$T_{STC} = 25°C$

The open-circuit voltage at a particular temperature is calculated according to the Formula 3.11.

$$V_{OC}(T) = V_{OC}(T_{STC}) + (T_{cell} - T_{STC})(V_{OC}(T_{STC}) \cdot k_{T,Voc}) \qquad [V] \quad (3.11)$$

Fill factor

The fill factor of a PV cell/module is a quotient of maximum power output and theoretical maximum power which is a product of short-circuit current and open-circuit voltage. For crystalline solar cells/modules, the filling factor is around 0,75, for amorphous modules around 0,5-0,7. [15]

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} = \frac{P_{MPP}}{V_{OC} \cdot I_{SC}} \qquad [-] \quad (3.12)$$

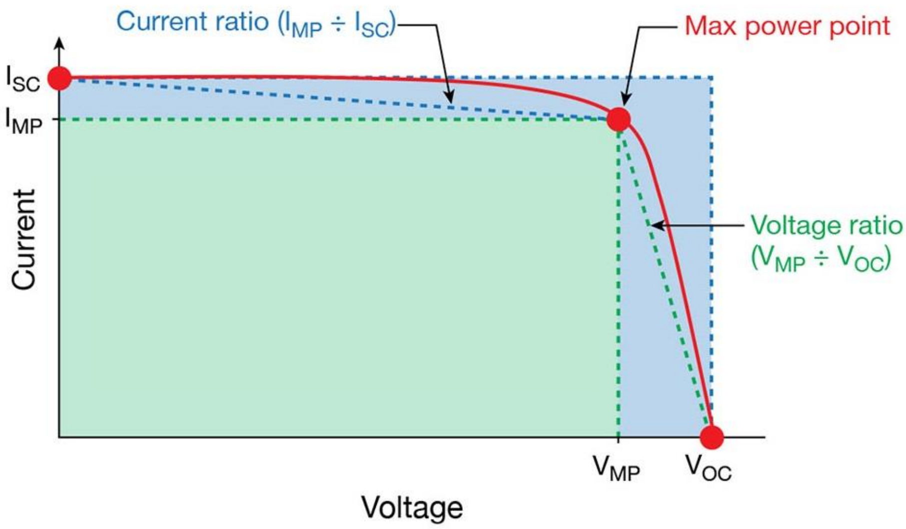


Figure 11 | Fill factor of PV cell/module. Source: Solmetric

Shading

If a single solar cell is shaded it doesn't generate any current. Instead, it becomes an electricity load and current produced from other illuminated solar cells in series combination is then driven through the shaded cell. This current is converted into heat. If the current is high enough, the shaded solar cell can heat up to an extent that causes the cell to be damaged. This situation can be prevented with connecting a forward-biased bypass diode in parallel to the cell. This bypass diode then prevents the current to flow through the shaded cell. Ideally, if every cell in PV module has its own bypass diode, the shading tolerance would be the highest. In practice, however, bypass diodes are usually connected across 18 to 20 solar cells, due to manufacturing reasons. Hence, modules with 36 cells connected in series have two bypass diodes. The bypass diode then, with one cell being shaded, causes all bypassed cells connected in series to this cell to be out of operation. The bypass diodes are usually housed in the module junction box.

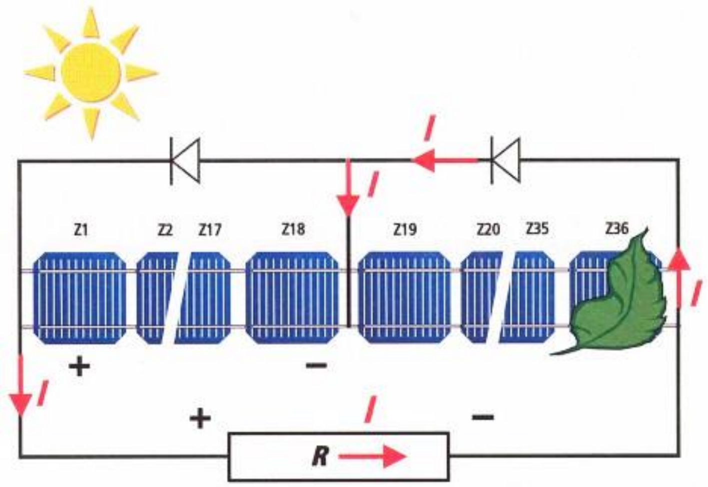


Figure 12 | Shaded solar cell with bypass diode. Source: R. Haselhuhn

3.2.3 *Interconnection of PV Modules*

PV modules are connected in series (string) and parallel combination to form a PV array, or PV generator, of desired voltage, current and power levels. The number of modules connected in series determines the PV generator output voltage which is the sum of voltages of all connected modules. The current of the string is determined by the lowest output current of any module in the string. The parallel connection of strings then determines the output current of the PV generator and it is again sum of currents of all strings connected, the output voltage is equal to the lowest string voltage. Hence, to avoid power loss, only the same type of modules should be connected.

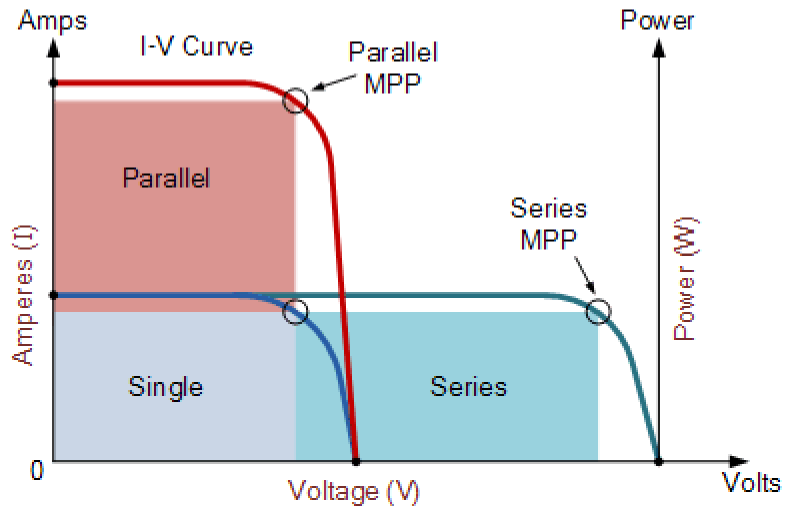


Figure 13| I-V curve of series and parallel combination of PV modules. Source: alternative-energy-tutorials.com

3.3 Inverters

Figure 14 | PV inverters. Source: clean energy reviwes

The inverter converts DC power produced by the PV generator into AC power that can be used to power the appliances. PV systems of power up to 5kWp are generally built as single-phased systems [15], where the single-phase inverter is connected to one phase of the house power grid. With larger systems the three-phased inverters or multiple single phased inverters are used to connect the PV generator to the three-phase supply system.

Almost all inverter manufacturers offer directly integrated data capture functions either as standard or an optional add-on. The data can be either shown directly on the inverter display or sent to a PC. This enables monitoring and evaluation of the PV system. The usually measured data cover following values:

- input: voltage, current, power
- output: voltage, current, power, frequency
- inverter operating time
- volume of generated energy
- device status and faults

3.3.1 *GRID-CONNECTED INVERTERS*

In grid-connected PV systems the inverter is connected to the utility distribution grid. This allows the surplus power generated by the PV generator to be fed into the utility power grid and on the other hand, when the power is needed it can be drawn from the utility grid.

3.3.2 *MPP TRACKER*

In order to use the most of the electricity generated, the inverter shall work in the maximum power point (MPP) of the PV generator. As mentioned in Chapter 3.2.2, the MPP changes according to irradiance and temperature. Therefore inverters are equipped with MPP Trackers (MPPT) which uses electronic circuits to adjust the output voltage of the PV generator to correspond to the voltage at the MPP. The MPP Tracker is essentially an electronically controlled DC converter. [15]

3.3.3 *INVERTOR PERFORMANCE*

As well as other components of the system, the invertor works with certain efficiency. The efficiency describes the losses caused by current conversion, transformer (in inverters which are equipped with transformer) and the power switching devices.

Conversion efficiency

The conversion efficiency describes the losses caused by converting DC current to AC current. The conversion efficiency is highly dependent on the input power. It is also dependent on the inverter's input voltage. However, this effect isn't as significant.

$$\eta_{con} = \frac{P_{AC,input\ real}}{P_{DC.input\ real}} \qquad [\%] \qquad (3.13)$$

Tracking efficiency

The quality of the inverter MPP Tracker adjustment is dependent on the speed of the tracking, which affects whether the irradiance peaks of short duration can be utilized.

$$\eta_{TR} = \frac{P_{DC,inst,input,real}}{P_{PV.inst,max}} \qquad [-] \qquad (3.14)$$

where $P_{DC,inst,input,real}$ instantaneous real input power

$P_{PV.inst,max}$ maximum instantaneous PV generator power

Static efficiency

Static efficiency is the product of conversion and tracking efficiency. The efficiency stated as the nominal efficiency on the invertor data sheet usually only represents the efficiency during operation in the invertor's nominal range. In many cases the maximum efficiency is also stated, it usually represents efficiency during partial (50-80%) load of the inverter. However, the inverter usually operates in lower load range and different voltage level. Therefore, efficiency characteristic curves provide better picture of actual operating efficiency.

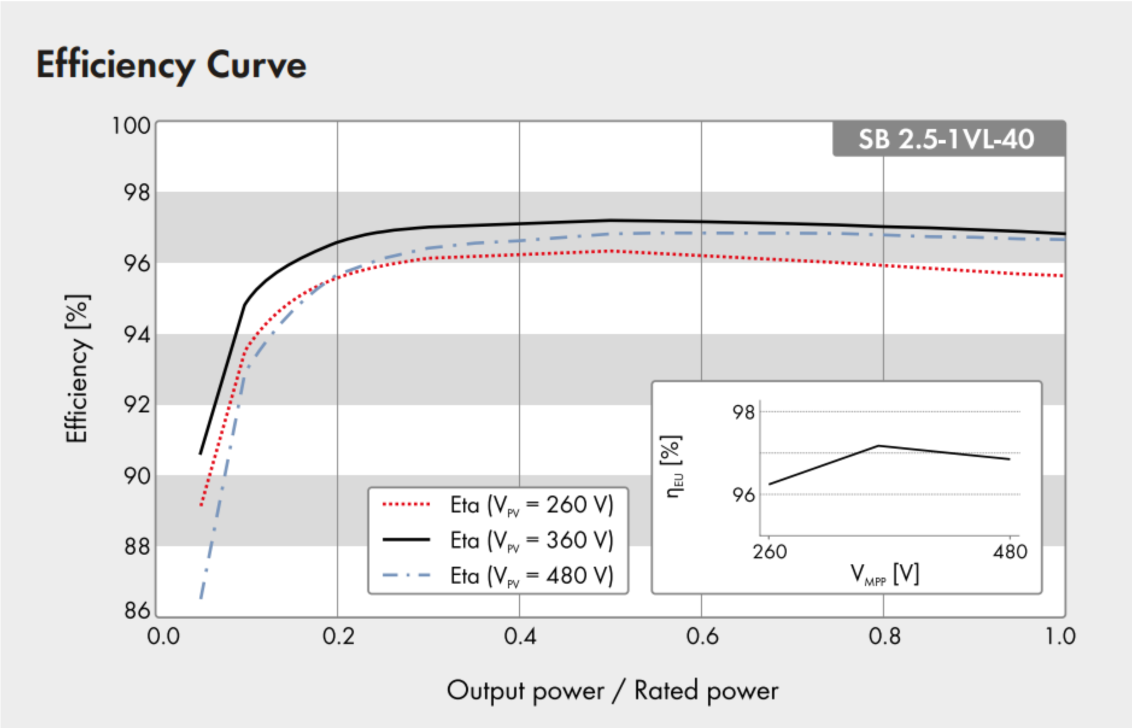


Figure 15 | Efficiency curve of Sunny Boy 2.5-1 VL-40 inverter. Source: SMA

EURO EFFICIENCY

In order to carry out more accurate PV system yield calculation and allow comparison of different inverters based on their efficiency, the European standard of efficiency measurement was introduced. It is obtained as a weighted average of inverter efficiencies at different power load based on their frequency in the Central European climate. The Euro efficiency takes into account six different efficiencies at different power output and is calculated according to formula 4.9. [15] It takes into account that most power in Central European climate is generated at the 50% power range of PV generator power rating and is assumed for 48% of the operating time over the year.

$$\eta_{Euro} = 0{,}03 \cdot \eta_{5\%} + 0{,}06 \cdot \eta_{10\%} + 0{,}13 \cdot \eta_{20\%} + 0{,}1 \cdot \eta_{30\%} + 0{,}48 \cdot \eta_{50\%} + 0{,}2 \cdot \eta_{100\%} \quad [\%] \quad (3.15)$$

where $\eta_{x\%}$ inverter efficiency at x% of power range

However, the Euro efficiency is usually calculated only at nominal voltage of the inverter, while the actual voltage vary during the operation. Hence, for the calculation purposes the Euro efficiency should be lowered accordingly.

3.4 LOAD MANAGER

The load manager provides the ability to use the generated power more efficiently. It is set by the user to switch on and off specific loads to use the surplus generated power. The controlled devices are usually heating devices which can be operated independently without strict requirements to their time of operation. These might represent water boiler or house heating. Other appliances, such as washing machine and dish washer might be also controlled but these require to be set according to the behavior of the residents.

3.5 BATTERIES

Batteries are not a necessary component of grid-tied PV systems. However, due to the fact that solar irradiance is usually high during hours when consumption is low, they provide higher utilization of energy produced by the PV generator. Primarily the energy consumption should be optimized as much as possible for when the solar irradiance and therefore produced solar power is high. However, this optimization can in some cases dramatically decrease comfort of the residents.

Batteries are constructed by connecting cells in series and parallel. In the battery cells, electrical energy is converted into chemical while the battery is being charged, the opposite process takes place during discharging. The batteries are rated according to the power and energy capacity. Other important specifications are:

- charge-discharge efficiency,
- life span - stated in number of cycles,
- depth of discharge - specifies the extent to which the battery is able to be discharged,
- self-discharge – how much of the energy is lost by the time the battery is not being used,
- energy density,
- operating temperature. [19]

To compare different types and technologies of batteries the various specifications need to be taken into account. The battery comparison is done according to the price of an energy unit accumulated and used according to the following formula.

$$\text{Price per kWh} = \frac{Price}{C \cdot \mathrm{V} \cdot SL(DOD) \cdot \frac{\mathrm{DOD}}{100} \cdot \eta_{C/D}} \quad [\mathrm{CZK}] \quad (3.16)$$

where C battery capacity in Ah

V battery nominal voltage

DOD depth of discharge in percent

SL(DOD) service life in cycles at DOD

$\eta_{C/D}$ charge-discharge efficiency

3.5.1 BATTERY TYPES

Not all battery types are suitable for usage in PV systems and as described in Chapter 1.2.3, some of the nickel-cadmium (Ni-Cd) and lead-acid batteries do not comply with the Czech subsidy program *Nová zelená úsporám*. In this chapter only the types which do comply with the subsidy program are described.

The main important parameters regarding batteries are their capacity, service life and depth of discharge (DOD). The capacity of battery is a measure of electrical energy storage potential. It can be measured in amp-hours (Ah) or wat-hours (Wh). The amp-hours represent the amount of current in amperes which is the battery able to provide over one hour. The watt-hours are obtained by multiplying the battery capacity in amp-hours with its average voltage. [20] The service life of battery is specified in a number of charge-discharge cycles before the capacity drops to 80%. [21] The depth of discharge represents the amount of used energy compared to the amount of energy available at full charge. [20] The battery service life is dependent on the battery depth of discharge during its lifespan. The manufacturers therefore usually provide the service life as a function of depth of discharge.

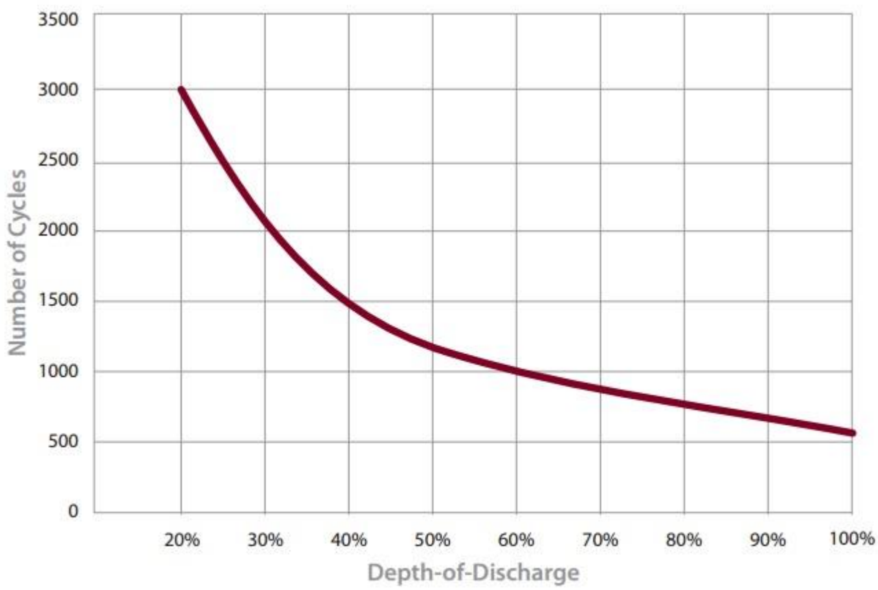


Figure 16 | Service life of lead-acid battery as a function of depth of discharge. Source: Trojan T-105 battery data sheet

LEAD-ACID BATTERIES

There are several types of lead-acid batteries. Shallow cycle batteries also called "start-up" batteries, such as automotive batteries, are not suitable for PV systems. These batteries are cheap but are designed to provide high amount of current for short period of time (e.g. when starting a car) and to be maintained mostly at full charge.

The PV systems require batteries that are able to provide small to moderate amount of current over long periods of time. These batteries are referred to as deep cycle batteries. There are several types of deep cycle lead-acid batteries – wet-cell (flooded), AGM (absorbed glass mat) and gel, depending on their electrolyte form. The wet-cell type requires maintenance in form of refilling the electrolyte with distilled water. The other differences of AGM/gel to flooded type are approximately double investment costs, shorter life cycle, slower self-discharge rate, higher efficiency in charging and discharging. [22]

Compared to lithium-ion batteries, the lead-acid batteries are less expensive but provide shorter service life and smaller depth of discharge. They are usually suitable for smaller PV installations.

Lithium-Ion Batteries

Lithium-ion batteries are very lightweight and energy and power dense. On the other hand, the manufacturing complexity cause the batteries to be expensive to produce, the other major drawback is capacity loss with deep discharging and high charge levels. Depending on the material used for anode, cathode and electrolyte, the parameters of lithium-ion batteries can change dramatically.

Advantages of lithium-ion batteries:

- no memory effect,
- high open circuit voltage,
- low self-discharge rates (5-10% per month).

Disadvantages of lithium-ion batteries:

- costs,
- capacity loss with high temperatures and high charge levels,
- capacity loss with deep discharges,
- cell capacity diminishes due to charging deposits resulting in lowering battery ability to deliver current. [12]

3.6 Charge Controller

The charge controller provides fundamental tasks for achieving optimized operation of batteries. High-quality charge controllers can make significant difference in extending the service life of the batteries. The tasks which the charge controller carries out are following:

- providing optimum charge to the batteries,
- over-discharge protection,
- overcharge protection,
- preventing unwanted discharging,
- information about battery state of charge. [15]

Many inverters with DC output for battery charging also include the charge controller.

3.7 Cables and connection systems

This chapter covers the connection of individual PV system components into a safe working installation. A distinction must be made between:

- module/string or inter-array cables – connection of PV modules and strings together and to the PV combiner box (if required),
- DC main cable – connection between the PV combiner box and the inverter,
- AC main cable – connection of the inverter to the house power grid.

3.7.1 *Module/String Cables*

The module cables are generally used outdoors (on the roof) and therefore need to be able to withstand the climate conditions including resistance to UV rays, weather and high range of temperatures. Roof tile manufacturers have measured temperatures on the roofs reaching up to 70°C. In order to avoid faults to the ground and short-circuits, the positive and the negative pole should be connected with separate cables. There are special *solar cables* being made for outdoor PV installations. [15]

Module cable requirements		
1	mechanical resistance	compression, tension, bending, shear loads
2	weather resistance	UV, ozone, heat, cold, water
3	earth fault-proof installation short-circuit proof installation	individual cable with double insulation

Table 12 | Module cable requirements. Source: Planning & Installing Photovoltaic Systems

Special attention should be given to connecting string cables. Poor contacts can lead to an increased fire risk. To simplify the installation most of the manufacturers are nowadays offering touch-proof plug connectors. These connectors have different positive and negative plug to eliminate the risk of incorrect interconnection of cables and their locking mechanism ensures a proper connection and prevents from accidental disconnection. Plug connectors have a transfer resistance of less than 5 milliohms. [13] [15]

Figure 17 | Plug connectors used for connecting PV modules. Source: Multi-Contact AG

3.7.2 PV COMBINER BOX

The PV combiner box, also called array junction box, is used to connect the parallel strings. Even if the PV array consist of a single string, the junction box might be used to interconnect individual cables from the modules to DC main cable which is then connected to the inverter. The combiner box houses string over-current protection, such as fuses or circuit breakers.

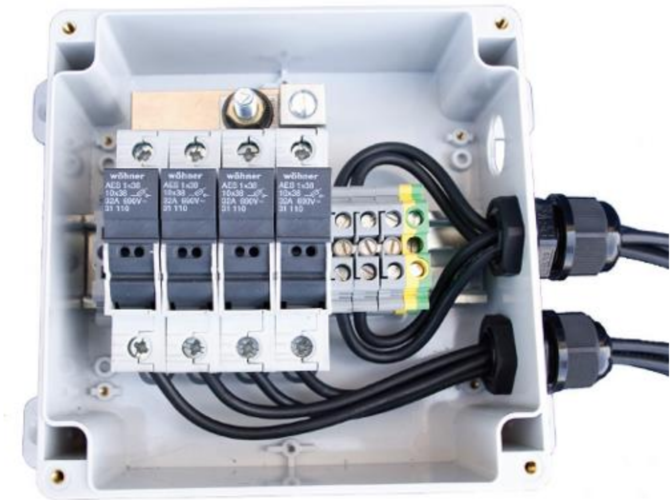


Figure 18 | PC combiner box with 15A fuses. Source: SolarBOS

3.7.3 DC MAIN CABLE

If the junction box is located outside, the same requirements as for module cables need to be followed. However, for cost reasons a PVC-sheathed cable of type NYY or NYM laid in protective pipe might be used. For junction boxes placed indoors no extra protection is needed. To ensure short-circuit and earth fault proof laying, individual single-wire sheathed cables for positive and negative connection are recommended. If multi-wire cables are used the yellow/green ground wire must not carry any voltage. The cable cross sectional area, typically 2,5 mm^2, 4 mm^2 and 6 mm^2, should be selected according to the PV array output voltage and output current and minimize voltage drop. [15]

3.7.4 AC MAIN CABLE

The AC connection cable connects the AC output of the inverter to the low-voltage house power grid via the protection equipment. Usually cable of type NYY, NYM or NYCWY is used. For a single-phase inverter, the connection is made using three-pole cable. In case of a three-phase inverter, five-pole cable is employed. [15]

3.8 SYSTEM PROTECTION

The design of the system protection is important for safe and reliable operation. This chapter covers various overcurrent protection, grounding, bonding, surge suppression and disconnector location.

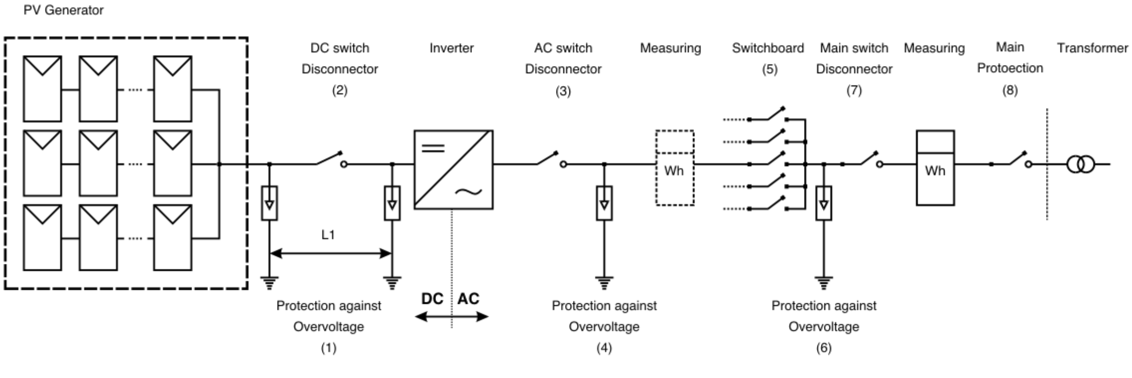


Figure 19 | Diagram of grid-connected PV system. Source: OEZ

3.8.1 PV ARRAY REVERSE CURRENT AND OVER-CURRENT PROTECTION

Either DC fuses or DC circuit breakers are used as over-current protection of the PV array. Usually referred to as string (miniature) fuses and string (miniature) circuit breakers these components protect string cables from overloading. If the string protection devices are not used the string cables must be dimensioned to handle the maximum short-circuit current of the PV generator less the string current. The string fuses or string circuit breakers should be located in the combiner box.

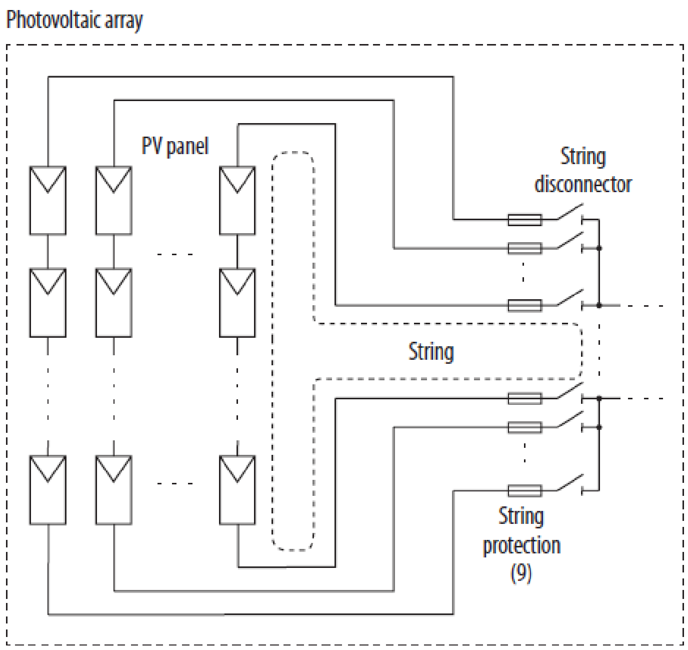


Figure 20 | PV array reverse current and over-current protection. Source: OEZ

3.8.2 *LIGHTNING AND SURGE PROTECTION*

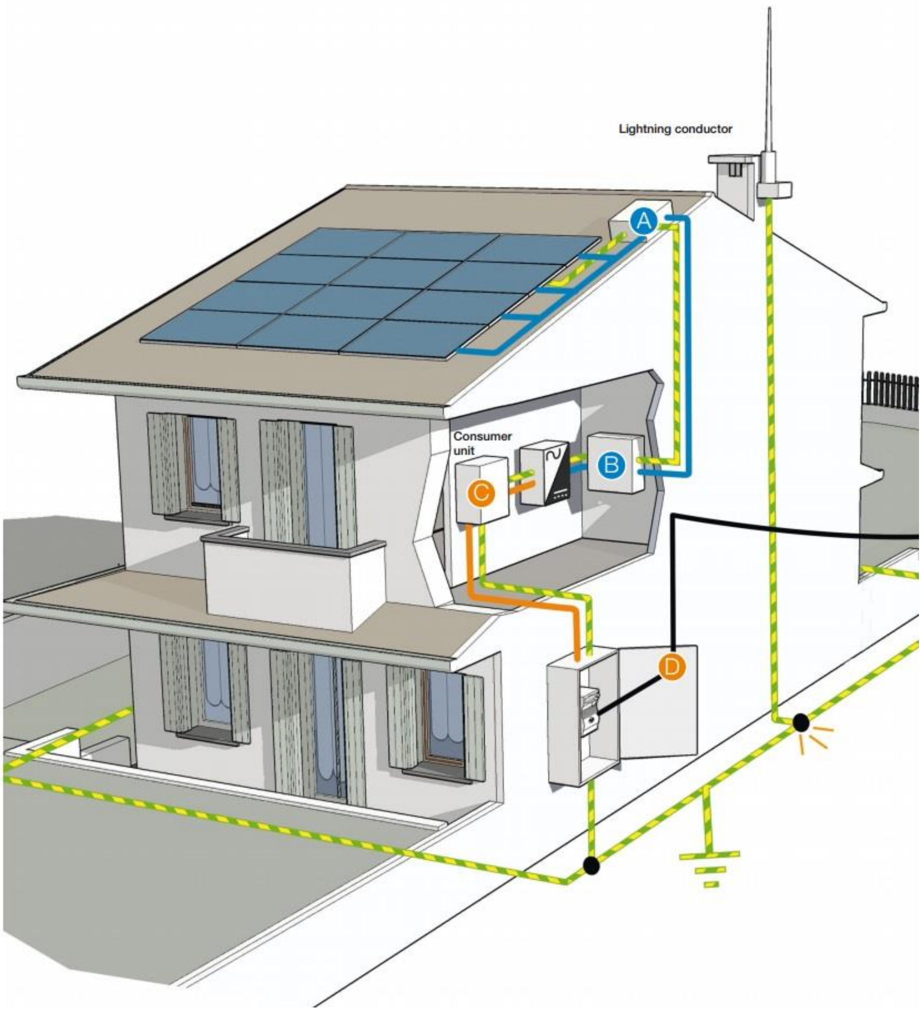


Figure 21 | Lightning and surge protection devices location. Source: ABB

DC SIDE PROTECTION

In general, there are either houses with lightning protection or without. If the lightning protection isn’t required, no risk is expected for the PV system either. In this case, for the DC side only surge protection of type 2 is required.

When installed on buildings with lightning rod, the photovoltaic system, according to standards in the Czech Republic, should not impair lightning and surge protection of the building. If the PV modules are placed in the zone of protection of the air terminals (strike termination devices) and are outside the arcing distance (usually between 0,5 and 1 meter) at the same time, the protection requirements are the same as in the previous case.

If the two requirements aren't fulfilled, the lightning current might be diverted into the building. Therefore, a conductive connection of the lightning rod and frame of the PV panels is required. Additionally, the lightning and surge protection type 1 has to be installed.

If the distance between the PV generator and the inverter is less than 10 meters, only one surge/lightning protection device is required. IN case the distance is larger, both the PV generator and the inverter DC input has to be protected. [23]

AC Side Protection

The AC side requires the surge arrester to be installed to protect the PV system from surge coming from the distribution grid. If the distance between inverter and the switchboard is less than 5 meters, only the switchboard protection is required.

3.8.3 Disconnectors

In case of faults it must be possible to isolate equipment from PV generator and power grid. Therefore, a disconnector (switch/isolator) is installed on the DC and AC side of the inverter as shown in Figure 19. The disconnectors must have load switching capability. The DC main switch has to be rated for the maximum open-circuit voltage (at -10°C) and short-circuit current of the PV generator. It has to be placed in an accessible place, e.g. in combiner box or directly before the inverter.

4. Planning and Sizing the PV System

For the specific object in this thesis the most suitable PV system is a grid-tied single-phase system with central inverter. Therefore, only planning of this system will be described in this chapter.

4.1 System sizing

Before choosing system components system size should be roughly estimated according to the power demand and user requirements. With grid tied systems, due to the low electricity purchase prices of the distributors, the surplus energy cannot be effectively utilized without its accumulation either in form of heat in hot water storage tanks or in form of chemical energy in batteries. Therefore, the system size should be chosen so the system electricity production corresponds to the summer consumption. In this case the surplus energy should be minimized because, generally, the winter consumption is higher due to the fact that more power is used for lighting, the residents are generally present for longer periods and electricity might be used for heating as well. Concurrently, the PV system energy production is significantly lower due to the lower incident solar irradiance.

4.2 Component placement

Before selecting the individual components, the planning of their placement should be performed. There are several requirements which have to be considered:

- easy access to the components which might require maintenance (inverter, combiner box, etc.),
- the shortest possible distance between components to reduce cable losses,
- indoor/outdoor placement with respect to the extra costs of equipment protection measures against environmental factors and weather.

4.2.1 PV Array Location

The energy produced by the PV system is highly dependent on the orientation of the PV modules. The dependence of the incident irradiance on the PV module inclination and azimuth is shown in the Figure 22. The usual placement in the residential application is the roof of the building. After deciding about the placement of the PV array, appropriate mounting system should be selected. If the roof doesn't have required inclination, the mounting system might be designed to provide the necessary adjustment.

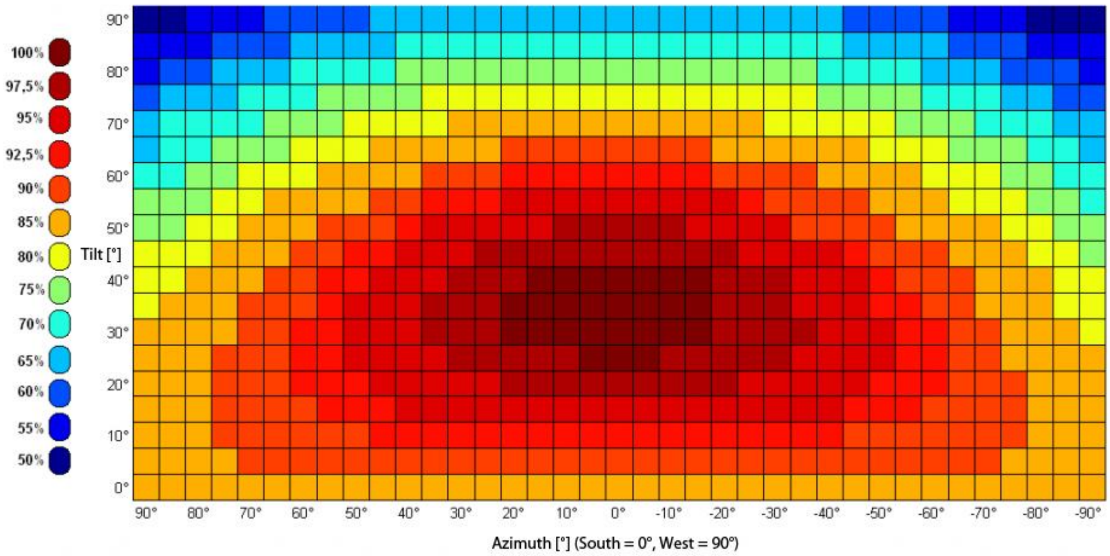


Figure 22 | Amount of incident irradiance dependent on the inclination and azimuth of the PV panel in Czech Republic

4.2.2 INVERTER LOCATION

When deciding about inverter location, several aspects need to be taken into account:

- Inverters are sensitive to temperature. Due to this fact, they shouldn't not be located in direct sunlight. Keeping the inverter operating out of extreme temperatures increases its performance and lifetime.
- The inverter produces heat. Therefore it should be located in place with passive ventilation. Placement in air-conditioned room requires additional energy to remove the produced heat. This reduces the overall effectiveness of the PV system.
- Inverters require maintenance. For this reason, they should be placed in a location with easy access.
- The location should be decided according to the distance of DC and AC connection. The DC input of the inverter is connected to the PV array, the AC output is connected to the main switchboard. To reduce the cable losses, the distances should be reduced to minimum.

4.3 Component Selection and Specifications Matching

A PV system can easily last 20 years with moderate levels of maintenance. [12] However, with selecting high-quality components, quality design and installation and proper maintenance, the chances for exceeding this lifetime are significantly higher. The inverters are a weak point of the system. But unless there is a defect in the design, installation or product, the right inverter will last 15 to 20 years. [12] The inverters usually come with 5 to 10 year warranty, however, many of manufacturers offer warranty extension up to 20 years. The PV panels are usually the most expensive part of the system but based on their design and with quality installation, they can easily last up to 40 years. [12]

The proper maintenance of the PV system and data evaluation will allow the defective panels and other components to be replaced under warranty period. That will allow to get the highest possible lifetime of individual system components.

4.3.1 Module Selection

The main parameters which need to be borne in mind when choosing PV module are its efficiency, temperature coefficient, price per Wp, degradation parameters and warranty. It is also advisable to choose trustful manufacturer which produces high quality reliable products and offers high standard of customer service.

4.3.2 Inverter Selection and Sizing

Firstly the invertor type needs to be selected according to the placement of the inverter. Many manufacturers offer residential inverters designed for outdoor use. As a rule, inverters designed for outdoor operation might be installed either outdoors or indoors, whereas indoor inverters might be installed indoors only.

Inverter power rating

In general, the inverter maximum input power should be selected to match the maximum power output of the PV array. Selecting inverter with significantly higher power input, known as inverter over-sizing, reduces the inverter operating efficiency and therefore, the overall power output. To achieve the highest possible inverter efficiency the power output of the PV array and rated power input of the inverter should be as close as possible. Sometimes designers install PV arrays with higher rated power than is the maximum input power of the inverter because of the unavoidable power losses due to temperature, non-ideal module orientation, cable losses, etc. [13] This allows cheaper inverter to be installed, known as inverter under-sizing. In past it was common to under-size inverter based on the values of hourly irradiance data, indicating only small amount of irradiance levels above 850W/m^2. New methods of gathering data on a minute or even second basis indicate that significant amount of irradiance might be available at the higher levels compared to the levels of 15-minute or hourly based data. [15]

4.3.3 MATCHING VOLTAGE SPECIFICATIONS

There are two voltage specifications which need to be met. Firstly, the maximum voltage of the PV array shouldn't exceed the maximum system voltage stated in the PV module data sheet. Secondly, the PV array voltage should match the inverter operating voltage range. The maximum input voltage of the inverter should not be exceeded, as higher values might damage the inverter electronics. On the other hand, exceeding the minimum input voltage of the inverter, known as the turn-off voltage, causes the invertor to shut down, which decreases the efficiency of the PV system.

The inverter operating voltage range isn't necessarily the same as its MPP tracker voltage range, in fact, in most cases the MPPT voltage range is smaller. It is desirable for the overall system efficiency to match the MPPT voltage range, otherwise the inverter wouldn't be able to work in the maximum power point of the PV array and the whole PV system would underperform.

NUMBER OF MODULES IN A STRING

As stated in Chapter 3.2.3, the PV array voltage is determined by the number of modules connected in the string. The inverter voltage range limits the number of modules which might be connected in a string. As mentioned in Chapter 3.2.2, the PV module voltage is highly dependent on cell temperature. Therefore, the minimum and maximum amount of modules in a string must be determined according to the site specific temperature conditions.

The highest module voltage which might occur is the open circuit voltage at minimum cell temperature. As long as the module might not have been heated up, the lowest cell temperature should be equal to the lowest ambient temperature for the installation site. The maximum number of modules in a string is then determined according to the Formula 4.1. This figure should be rounded down to a nearest whole number.

$$N_{max} = \frac{V_{max,inv}}{V_{OC}(T_{min})} \qquad [-] \qquad (4.1)$$

where N_{max} is the maximum number of modules in a string

$V_{max,inv}$ maximum input voltage of the inverter

$V_{OC}(T_{min})$ open circuit voltage of PV module at minimum temperature

The lowest module voltage is the maximum power point voltage at the highest possible ambient temperature. The cell temperature, however, might be higher due to the module being heated up during its operation according to the Formula 3.7. The maximum number of modules in a string is then determined according to the Formula 4.2. The MPP voltage is calculated analogically to the open-circuit voltage calculation presented in Formula 3.11. This figure should be rounded up to the nearest whole number.

$$N_{min} = \frac{V_{min,inv}}{V_{MPP}(T_{cell,max})} \qquad [-] \qquad (4.2)$$

where N_{min} is the minimum number of modules in a string

$V_{min,inv}$ minimum input voltage of the inverter

$V_{MPP}(T_{cell,max})$ maximum power point voltage of PV module at maximum cell operating temperature

VOLTAGE OPTIMIZATION

When optimizing the PV array output voltage, it should be borne in mind that it affects the inverter efficiency, as was mentioned in Chapter 3.3.3. By closely matching the PV array voltage to the inverter voltage the yield can be increased by several percent. [15]

4.3.4 MATCHING CURRENT SPECIFICATIONS

The inverter maximum input DC current shouldn't be exceeded. The inverter manufacturers generally specify the maximum DC input current and the maximum DC input current per string. As stated in the Chapter 3.2.3, the maximum string current is the short circuit current of a single module and the PV array maximum output current is the sum of maximum string currents. The output current of a PV module doesn't vary as dramatically as the output voltage. However, it does increase slightly with increasing temperature. Because of small significance of this increase, designers often do not account for it when sizing the PV array, unless the value of the array output current is very close to the input current value of the inverter. [15]

4.3.5 CABLE SELECTION

When selecting the cables, three essential criteria should be considered:

- cable voltage rating,
- cable current carrying capacity,
- minimizing cable losses.

The cable voltage rating should never exceed the PV system voltage. The same applies to the current carrying capacity. As mentioned in chapter 3.7, in case no string circuit breakers or fuses are implemented, the cables has to be dimensioned to handle the maximum short-circuit current of the PV generator less the string current. The cable cross section area should be calculated to comply with the national standards for allowed voltage drop. Various connecting and protective components should be added to calculate the total voltage drop and set the cross section area accordingly. According to the Czech standard ČSN 33 2130 the allowed total voltage drop is below 2%.

4.4 SYSTEM POWER CALCULATION

In order to design and evaluate the PV system, on one hand simple computational tool for the system power generation is needed, on the other hand this tool should be sufficiently reliable and take specifics of the installation into account. The complex simulation models aren't often used in practice and their usage for conventional systems doesn't even make sense.

For the purposes of the photovoltaic systems annual electricity production, in the Czech Republic a standard EN 15316-4-6 was set. This method uses the peak PV generator power without taking the actual operational conditions for particular PV modules and other system components into account.

In this work more accurate methods are presented. These methods allow to take into account the effect of irradiance and temperature on the efficiency of the specific PV modules as well as the losses of the system. The irradiance and temperature data for 15-minute intervals for average day in each month were obtained.

4.4.1 Yield Calculation

The electricity generated by the PV system depends on actual solar irradiation on tilted PV modules, temperature, as well as parameters of the used equipment and losses of the whole PV system. The calculation of the generated electricity is performed using 3 methods and compared afterwards with the PVGIS online calculator.

Model 1

The first method calculates the power generation according to the energy balance using the PV module efficiency dependent on temperature and irradiance.

$$\mathrm{E} = \mathrm{A} \cdot \mathrm{G} \cdot \eta(G, T) \cdot \mathrm{PR} \cdot \tau \qquad [\mathrm{kWh}] \quad (4.3)$$

where E produced energy

A PV array surface area

η(G,T) PV panel efficiency dependent on irradiance and temperature,

G irradiation on tilted panels

PR performance ratio – coefficient for losses

τ time period in hours

The irradiation value G is the irradiance on tilted array surface with respect to its inclination and azimuth. The panel efficiency includes its dependency on irradiation calculated according to Formula 3.2, and the temperature dependency calculated according to Formula 3.3. The performance ratio calculation is presented in the next chapter.

Model 2

The method 2 uses the temperature and irradiation dependency of the PV generator I-V curve presented in Chapter 3.2.2. The power output is calculated according to the module fill factor, short-circuit current as a function of irradiance and open-circuit voltage as a function of temperature. The model is neglecting the minor current change with changing temperature and voltage change with changing irradiance.

$$E = FF \cdot I_{SC}(G) \cdot V_{OC}(T_{cell}) \cdot PR \cdot \tau \qquad \text{[kWh]} \qquad (4.4)$$

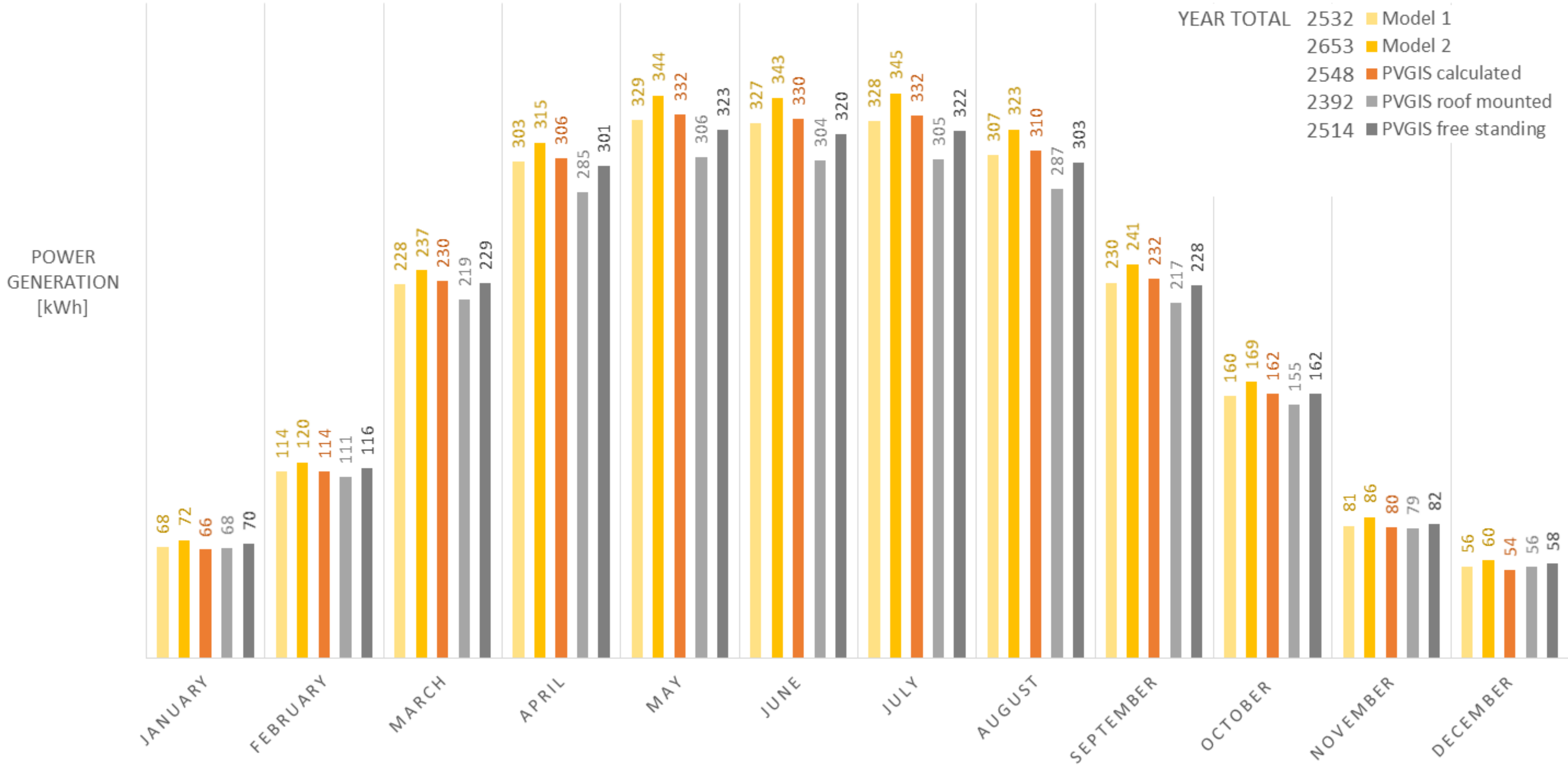
PVGIS method

The PVGIS method is an alternation to the Method 1. The main difference is the calculation of the module efficiency as a function of irradiance and time and different method of cell temperature calculation, mentioned in Chapter 3.2.2,

$$E = A \cdot G \cdot \eta_{PVGIS}(G, T) \cdot PR \cdot \tau \qquad \text{[kWh]} \qquad (4.5)$$

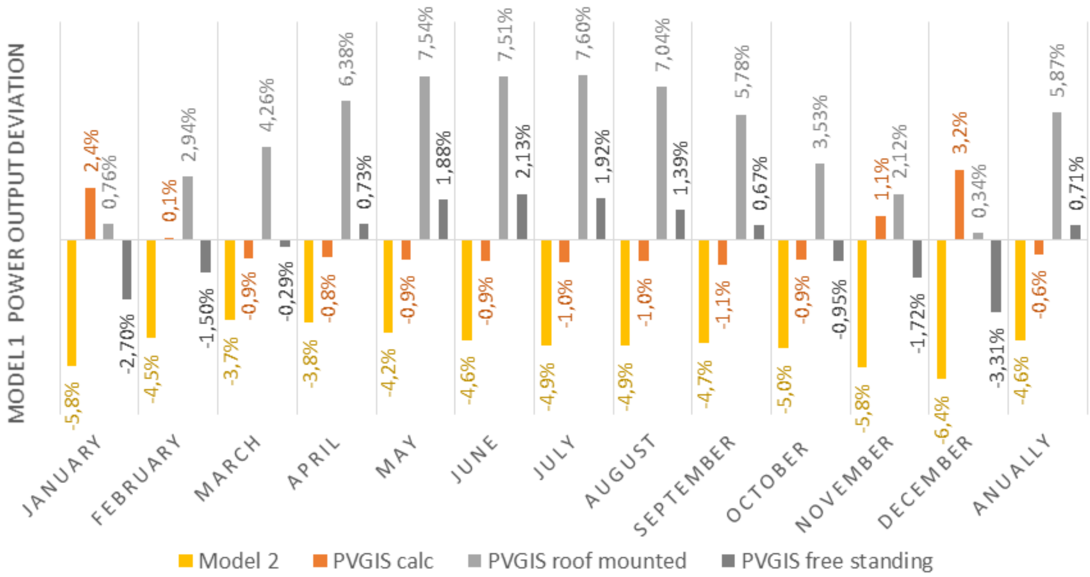
Methods comparison

The power output of the PV system was calculated in 15-minute intervals for average day of each month. The comparison of the results for 2,5 kWp system with PR = 0,847 with AmeriSolar 250W AS-6P30 poly-crystalline silicon panels is presented in Graph 18. Values calculated using PVGIS online calculator for free standing and building integrated PV generator were added to the comparison, the performance ratio was selected the same as for the models. The only difference is different temperature input values and module specifications in PVGIS online calculator which represent an average polycrystalline module.



Graph 18 | Comparison of PV system power generation according to the calculation method used

From the Graph 18 it can be seen that the outputs vary. The deviation between the Method 1 and 2 is about 4-7% between individual months and 4,8% annually. The deviations of both Model 1 and Model 2 are presented in Graph 19 and Graph 20.



Graph 19 | Model 1 power output deviation compared to the other models

Graph 20 | Model 2 power output deviation compared to the other models

Although the PVGIS calculated values are calculated using the temperature coefficient for building integrated PV generator the power generation values are significantly higher than the values calculated in the PVGIS software online both for building integrated and free standing systems. This indicates differences in input data. The difference might come from temperature data or the six coefficients affecting the power output temperature and irradiance dependency.

The PVGIS temperature calculations for building integrated PV generators give slightly higher temperature values than the calculation using INOCT. This is understandable because the method using INOCT takes into account creating gap between the panels and the roof itself. This ensures better ventilation and therefore reduces the cell operating temperature.

4.4.2 System losses

The performance ratio (PR) indicates the system’s actual output value compared to an ideal system operating without losses. It is calculated according to the Formula 4.6.

$$PR = \eta_{Euro} \cdot (1 - k_{Zt}) \cdot (1 - k_{ZDC}) \cdot (1 - k_{ZAC}) \cdot (1 - k_{Zs}) \cdot (1 - k_{Zd}) \qquad [\%] \qquad (4.6)$$

where

η_{Euro}	inverter Euro efficiency
k_{ZDC}	DC losses – incl. cables, fuses, circuit breakers and other DC components
k_{ZAC}	AC losses
k_{Zs}	losses due to shading
k_{Zd}	losses due to dust and snow…
k_{Zar}	losses due to angular reflectance effects

Temperature Losses

As mentioned in the Chapter 3.2.2, the operation temperature of the PV module has large effect on its power output. High operating temperatures lead to power losses. Therefore, to obtain characteristics of temperature losses during the day, the daily temperature profiles for average day of each of 12 months are estimated according to the Chapter 2.1.2. The losses are implemented into the module efficiency and are calculated in 15-minute intervals during average day for each month, according to the nominal operating cell temperature obtained from the Formula 3.7.

DC and AC Components Losses

DC and AC power losses are calculated as a voltage drop in percent of cables in DC and AC section and other components, such as surge and over-voltage protection, disconnectors etc.

The cable voltage drop increases with increasing cable length, increasing current and decreasing cable cross sectional area. Therefore, the PV system components location should be chosen to minimize the cables length, thus reducing the power losses. The voltage drop of the cable might be calculated according to the Formula 4.7 from Czech standard ČSN 33 2130. However in this work, Formula 4.10 is used.

$$\Delta V = \frac{b \cdot L \cdot P}{g \cdot S \cdot V_s} \qquad [V] \qquad (4.7)$$

where	b	cable length factor, b=2 for single phase wiring, b=1 for three-phase wiring
	L	simple length of the cable
	P	transmitted power
	g	cable conductance
	S	cable cross sectional area
	V_s	phase voltage

$$\Delta V = b\left(\rho \cdot \frac{L}{S} \cdot \cos\varphi + \lambda \cdot L \cdot \sin\varphi\right) \cdot I \qquad [V] \qquad (4.8)$$

where	b	cable length factor, b=2 for single phase wiring, b=1 for three-phase wiring
	ρ	resistivity of the conductor material (if not specified, 0.023 for copper and 0.037 for aluminum (at ambient temperature = 25°C) [$\Omega \cdot mm^2/m$]
	L	simple length of the cable
	S	cable cross sectional area
	cos φ	power factor, cos φ=1 for DC circuit or resistive load (sin φ=0)
	λ	reactance per length unit
	I	transmitted current

Voltage drop as a percentage is then calculated according to the Formula 4.9.

$$\Delta V(\%) = \frac{\Delta V}{V} \cdot 100 \qquad [\%] \qquad (4.9)$$

where V phase voltage

The losses of other components need to be acquired from the component data sheets.

LOSSES DUE TO SHADING

Shading resulting from the location involves shading produced by the PV generator surroundings and the building itself. Trees, neighboring buildings and horizon obstacles can all lead to reducing the amount of incident irradiance. In order to determine the losses caused by shading, shading analysis should be performed. During the analysis, the shadow outline of the surroundings is recorded and its effect on power losses is estimated.

LOSSES DUE TO DUST AND SNOW

Losses caused by dust, bird droppings, leaves, air pollution, and other types of soiling has strong and long lasting impact. The effect is decreased with sufficient inclination due to self-cleaning effect caused by running rainwater. An inclination of 12^0 is usually sufficient for panels to self-clean. [15] The losses due to soiling of PV array in a normal location and with sufficient inclination can be assumed as 2-5%. [24]

Snow on a PV array usually melts faster than surrounding snow, so, generally, shading occurs only during short time period, again this effect is reduced by sufficient inclination of the panels. [15]

LOSSES DUE TO ANGULAR REFLECTANCE EFFECTS

Losses due to angular reflectance effects represent reflection losses due to the light incidence angle not being perpendicular relative to the module plane. PVGIS software allows to estimate this kind of losses depending on the inclination and azimuth of the modules.

LOSSES DUE TO MODULE DEGRADATION

The losses due to module degradation don't immediately effect the PV system performance but play non-neglectable role in a long term system evaluation. The rate of degradation is according to the study [25] in average between 0,6-0,7% a year. To maintain the conservative approach, the values 0,7% is used in this work when not stated otherwise in the module data sheet.

4.4.3 BATTERY PERFORMANCE

When calculating the power which can be saved to batteries and used afterwards, the efficiency of battery charge-discharge cycle has to be used. This value varies for different types of batteries and if not stated in the data sheet, the average value for specific type is considered. Moreover, the inverter causes another losses due to power conversion, these are usually stated in the inverter data sheet (usually as 'DC to AC efficiency').

The battery capacity degradation is calculated from the stated battery service life according to its usage in the considered PV system. Firstly, the annual amount of battery cycles is calculated according to the Formula 4.10. The period until the battery degrades to 80% of its initial capacity for the specific installation is then calculated according to the Formula 4.11. Finally, the annual battery degradation coefficient is calculated according to the Formula 4.13 which is a modification of the Formula 4.12.

$$E_{T_{SL}} = C \cdot V \cdot DOD \cdot SL(DOD) \quad [kWh] \quad (4.10)$$

where
$E_{T_{SL}}$ total energy charged and discharge over servicelife of the battery
C battery capacity in Ah
V battery voltage
DOD depth of discharge
SL(DOD) battery service life in cycles at DOD

$$T_{80\%} = \frac{E_{T_{SL}}}{E_a} \quad [years] \quad (4.11)$$

where
$T_{80\%}$ period in years until the battery degrades to 80% of its initial capacity for the specific installation
E_a battery annual energy charged and discharge for the specific installation

$$1(1 - d_{aB})^{T_{80\%}} = 0{,}8 \quad [-] \quad (4.12)$$

where d_{aB} *the annual battery degradation*

$$d_{aB} = 1 - \frac{2^{\frac{2}{T_{80\%}}}}{\sqrt[T_{80\%}]{5}} \quad [\%] \quad (4.13)$$

4.5 Consumption Optimization

To use most of the generated energy even during the working days when the residents aren't present and the consumption is low while the incident irradiance is at its peak, consumption optimization is performed. In order to not affect the resident's comfort, only the house heating and water heating is optimized. This will ensure that at the days of sufficient sunshine during the heating season, the house will be heated to optimal temperature by the time the residents are back from work. This optimization will not only mean the electricity costs savings, but also reduce the energy consumption as the house won't be heated up suddenly in a short period of time. Apart from the house heating which is needed only in part of the year, the water heating is needed throughout the whole year. Its optimization is more crucial, as the PV system produce higher amount of surplus energy during summer compared to the winter. The power consumption used for the water heating is presented in Chapter 2.5.

Currently the A/C conditioning which will be used for the house heating is only used occasionally. Most of the heating is provided by the wood stove. This provides a room for optimization and costs savings. Not only is the heat production using the air conditioning with heat pump more efficient but it can effectively use the surplus energy produced by the PV system. In order to estimate the maximum possible power consumption of the air conditioning units to provide the same amount of heat which is currently produced by burning the firewood, the data presented in Chapter 2.6 are used. The power consumption of the air conditioning units is calculated according to the Formula 4.14, using the SCOP coefficient characteristics presented in Chapter 2.4. The output of the calculation is presented in Table 13. It is assumed that each of the two outdoor air conditioning units will contribute with the same amount of heat produced. Therefore, an average value of SCOP for both units is used. This actually means that half of the heat is produced by the unit located in living room and the other half by the units in kitchen and bedroom. From the monthly total power consumption the average day consumption is calculated. This energy is then added to the consumption at the times of surplus power generation of the PV system.

$$P_{AC,input} = \frac{Q_{wood,ef}}{SCOP(T_{AVG})} \quad [kWh] \quad (4.14)$$

where $P_{AC,input}$ power input of the air conditioning units

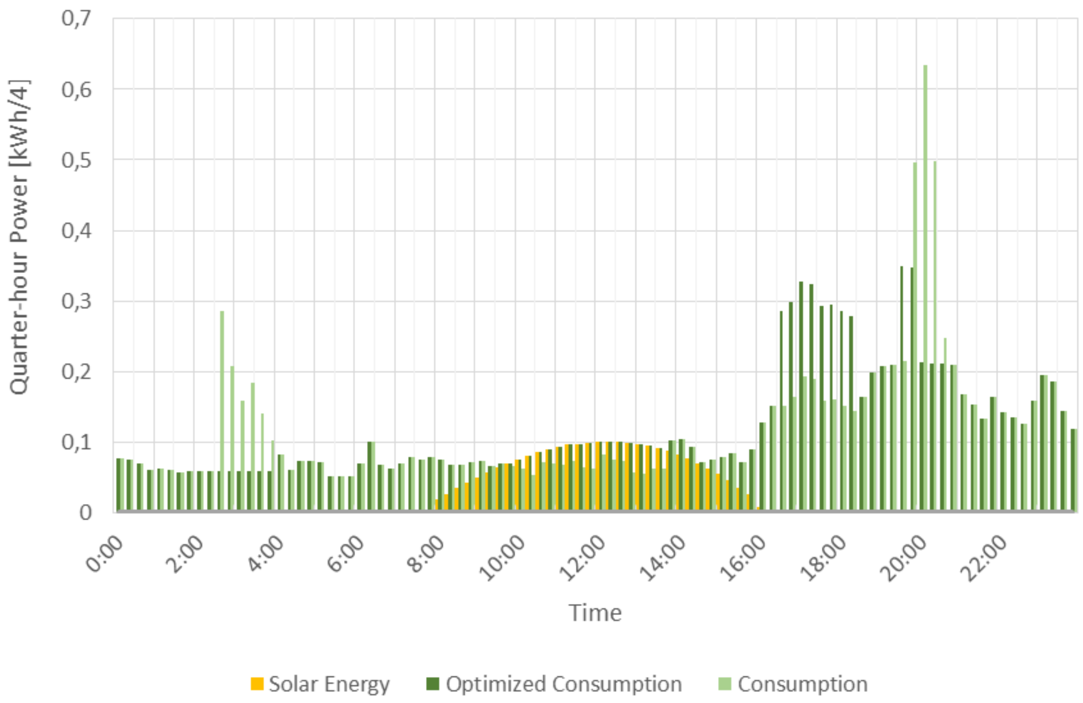
$Q_{wood, ef}$ heat produced by the firewood which is effectively used for heating the house

$SCOP(T_{AVG})$ Seasonal Coefficient of Performance of the A/C units at average outdoor temperature

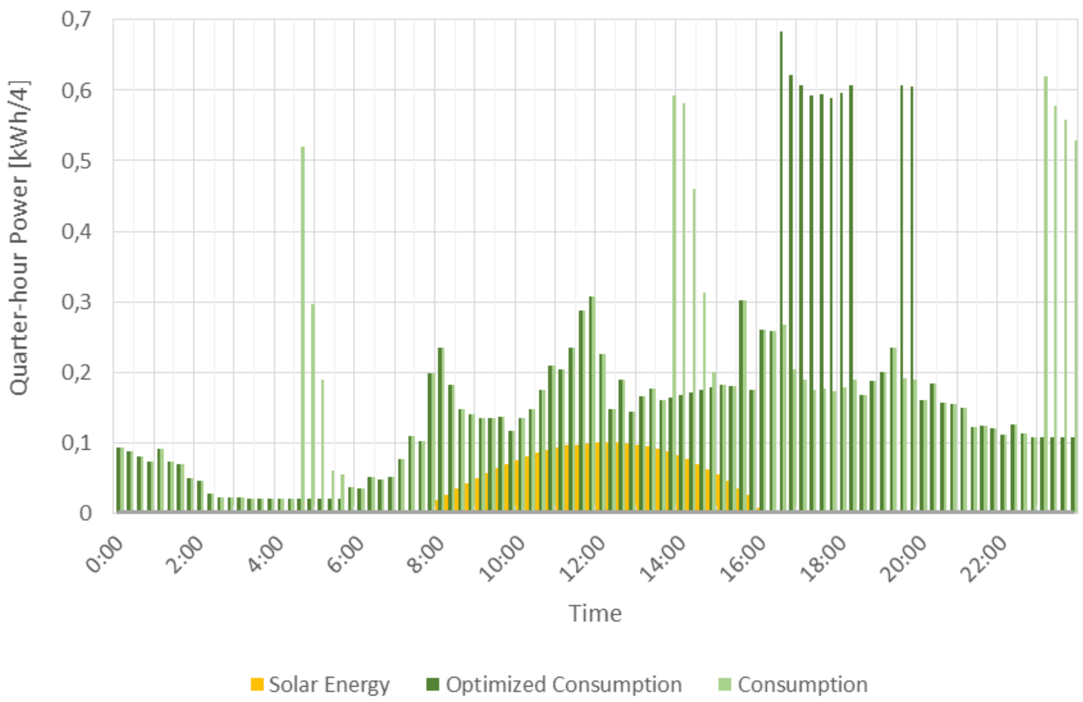
Month	Average Temp [°C]	Heat from wood [kWh]	SCOP	Power Cons. of A/C [kWh]	Daily Cons. of A/C [kWh]
January	-0,5	1526,6	3,85	396,5	12,79
February	0,4	1322,2	4	330,5	11,80
March	4	1161,6	4,85	239,5	7,73
April	9,5	823,5	5,7	144,5	4,82
May	13,5	157,3	5,9	26,7	0,86
June	16,5				
July	19				
August	19				
September	14,5	59,2	5,95	9,9	0,33
October	10,5	820,7	5,75	142,7	4,60
November	5	1135,8	5,05	224,9	7,50
December	1	1406,7	4,2	334,9	10,80
Year avg/total	**9,37**	**8413,6**		**1850,2**	

Table 13 | Monthly and daily A/C unit power consumption for house heating

With change of the times of the water boiler operation and with substitution of the wood stove heating with the air conditioning unit, the power consumption is optimized. This means raising the power consumption by switching on the water boiler or the air conditioning unit at the time of surplus power generation of the PV system. There are several components on the market which are able to switch on the desired appliances. For example the *SMA Home Manager* which uses radio controlled sockets or *WATTrouter M SSR* manufactured by Czech company Solar Controls. The improvement in consuming the PV system generated power is presented in Graph 21 and Graph 23. The values are presented for average working and weekend day in January and June in 15-minute intervals.



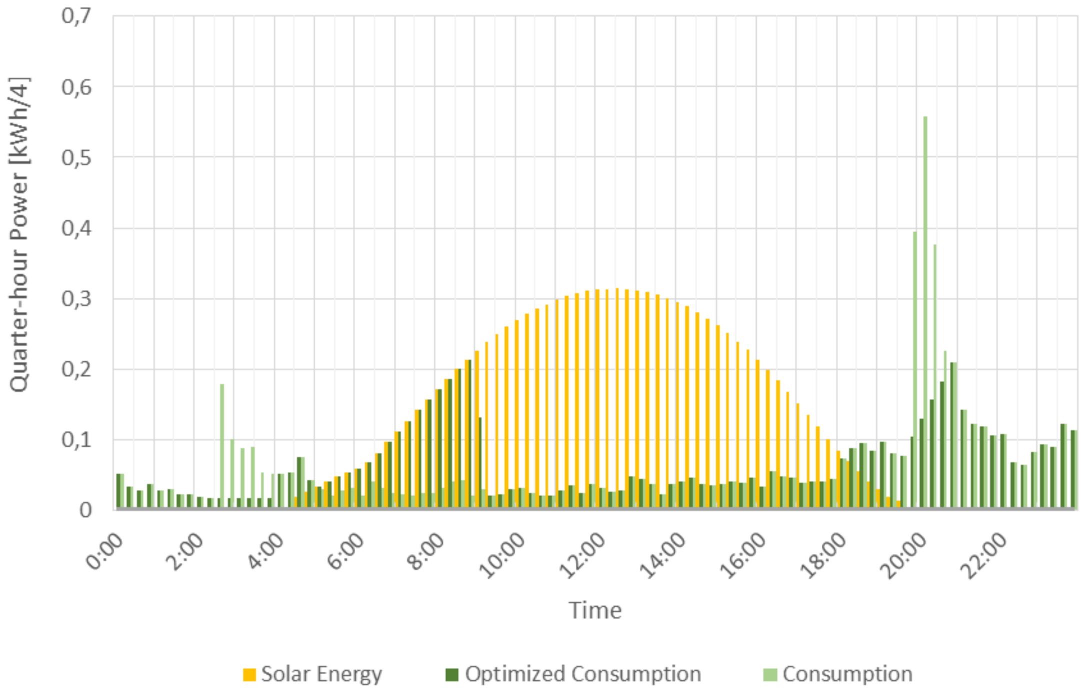
Graph 21 | January average working day power consumption and PV system generation



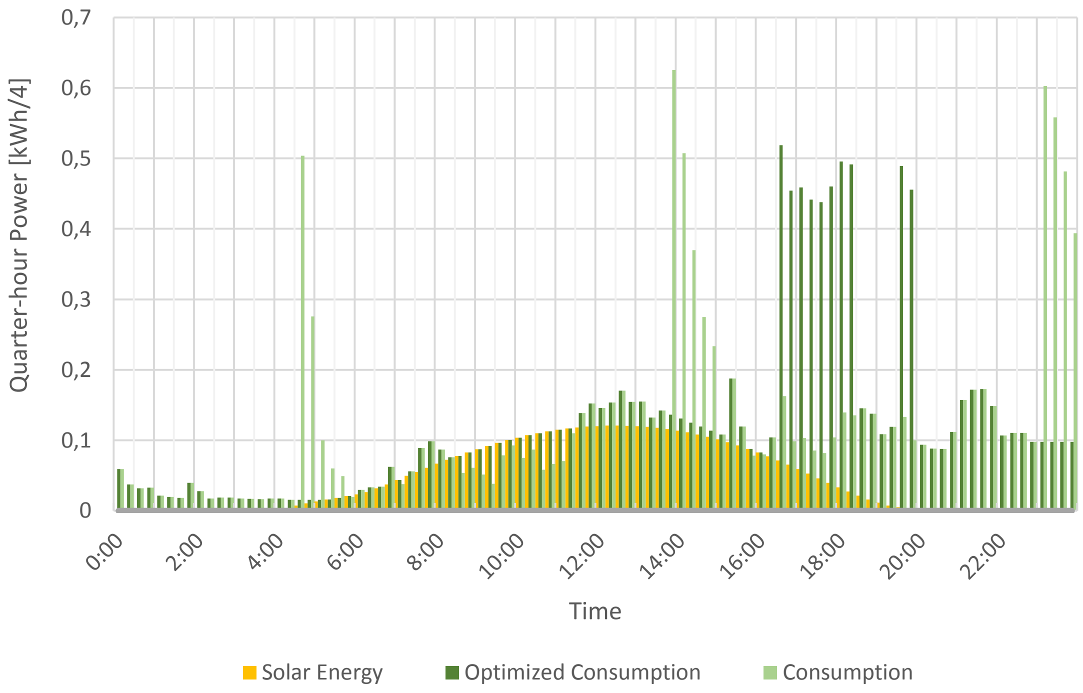
Graph 22 | January average weekend day power consumption and PV system generation

In January the improvement isn't any significant and on average day the water heating needs to be performed in the evening. The time of is here set to 16 o'clock to ensure that by the evening enough of hot water is produced. During the high tariff in period from

18:30 to 20:00 the boiler is set to turn off and continue in operation afterwards until the daily average of consumed power for water heating is met.



Graph 23 | June average working day power consumption and PV system generation



Graph 24 | June average weekend day power consumption and PV system generation

In order for the consumption optimization to work in this way, the water boiler needs to be disconnected from the HDO system, this requires the change of electricity tariff.

5. Design of PV system

In this chapter the design of specific PV system variants is presented. It includes choosing appropriate components of the system as well as their parameters according to the power consumption of the house and economical aspects. Furthermore, the system safety and protection equipment is designed in this chapter.

5.1 Considered Variants

There are 3 main variants of considered PV systems:

1. PV system with accumulation of surplus energy into hot water and house heating/cooling.
2. PV system with accumulation of surplus energy into hot water, house heating/cooling and batteries.
3. PV system for direct water heating.

All the system variants are designed to comply with the subsidy program, therefore, the aim is to fulfill all necessary requirements to obtain the financial subsidy.

5.2 PV System with Heat Accumulation

The first variant is the PV system with usage of surplus energy for water and house heating. In order to redistribute the surplus energy the system needs to be equipped with a load managing device which is able to switch on specific devices such as boiler and air-conditioning. In this variant electricity accumulation devices aren't used. Therefore, the surplus energy which is not used for house and water heating is fed into the distribution grid.

5.2.1 *Sizing the system*

In order to comply with the subsidy program requirements, at least 70% of the produced power has to be consumed in the place of production. The annual power consumption of the considered house is around 3,5MWh. After the comparison of the consumption to the energy generation, 2,5kWp system was chosen as the default one.

5.2.2 System Components

PV Modules

No difference in PV module choice has to be made among the three system variants. The considered PV module types are presented in Table 14. The Canadian Solar module is the most expensive one due to the fact that all the others were discounted. The Benq module was, for example, originally 6 049 CZK including VAT, discounted by 19,8% to 4 815 CZK, 4 890 CZK including the recycling fee of 39 CZK.

Parameter	Unit	AmeriSolar 250W AS-6P30	CANADIAN SOLAR CS6P-P 260	OMSUN FCP 250W	AUO BenQ PM060P00
Technology		pc-Si	pc-Si	pc-Si	pc-Si
Efficiency [%]		15,37	15,65	15,2	16,1
Nominal power	Wp	250	260	250	260
Warranty	years	12	12	12	10
Price incl. VAT	CZK	4749	5636	4310	4890
Price incl. VAT	CZK/Wp	19,0	21,7	17,2	18,8
length	m	1,64	1,665	1,64	1,639
width	m	0,992	0,999	0,991	0,983
V_{oc}	V	38	37,92	38,41	37,7
I_{sc}	A	8,75	8,67	8,51	8,83
V_{mp}	V	30,3	31,25	31,36	31,2
I_{mp}	A	8,26	8,33	7,98	8,34
Temp coef. P_{max}	%/K	-0,43	-0,43	-0,475	-0,39
Temp coef. V_{oc}	%/K	-0,33	-0,33	-0,338	-0,3
NOCT	°C	45	44,8	45	46
Max ser. fuse	A	15	15	10	15
Max sys. voltage	V (DC)	1000	1000	1000	1000

Table 14 | Considered PV module types

As the default module for the system, the *AUO BenQ Green triplex PM060P00* is chosen. The reason is the price per Wp, which is the second lowest after the *OMSUN OMP 250W* module. The BenQ module has, however, much better temperatures coefficients and, therefore, better performance at higher temperatures. The comparison of systems with each module is provided in economic evaluation in the following chapters.

INVERTER

Figure 23 | SMA Sunny Boy 2,5 and GoodWe GW2500-NS inverters. Source SMA

As an inverter, the *SMA Sunny Boy 2,5* and *GoodWe GW2500-NS* are chosen as the best options. The specifications of both inverters are presented in Table 15. Both inverters offer all necessary features, such as MPP tracker, system data monitoring with possibility to send the data to computer or even to a smartphone or tablet. Other benefit is the ability to place the inverters outdoors. One of the important aspects is the possibility to extend the warranty up to 20 years. Other considered alternative inverter was for example *Fronius Galvo 2.5*. Although it has similar specifics as the mentioned inverters, with price of 27 900CZK and warranty extension to 20 years priced at 19 440CZK it is significantly more expensive.

Technical Data	SMA Sunny Boy 2,5	GoodWe GW 2500-NS	
Max DC power	2,65	2,7	kW
Rated input voltage	360	-	V
Max input voltage	600	500	V
Min/initial input voltage	50/80	80	V
MPPT voltage range	260-500	80-450	V
Max input current	10	18	A
Number of strings	1	1/2	
Nominal AC output	2,5	2,5	kW
Max AC output	2,5	2,5	VA
Nominal AC voltage range	180-280	180-270	V
Max output current	11	12,5	A
EU efficiency	96,7%	97,0%	
Price incl. VAT	21 366	16 323	CZK
Warranty	5	5	years
- extension to 20 years	17 280	15 498	CZK
Number of phases	1	1	

Table 15 | Variant 1 inverter specifications

Specifications Matching

Firstly, the voltage specifications of the inverter need to be matched with the PV generator. This process was described in Chapter 4.3.3. Ideally, the voltage of the PV generator should be within the range of the MPP tracker so the highest possible performance is achieved. The temperature extremes in the Czech Republic might be up to 45°C in summer and -15°C in winter. The corresponding minimum and maximum voltage is presented in Table 16.

Module Operating Voltage		
T_{min}	-15	°C
$T_{cell,min}$	-15	°C
Maximum voltage (V_{oc} at T_{min})	43,0	V
T_{max}	45	°C
T_{cell} at T_{max}	80	°C
Minimum voltage (V_{mp} at $T_{cell,max}$)	26,1	V

Table 16 | PV module operating voltage

Based on the PV module operating voltage range, the minimum and maximum number of modules in a string is calculated. Firstly, matching PV modules with the *SMA Sunny Boy* inverter is presented. To match the MPPT voltage range of 260-500V, only 10-11 modules are allowed to be installed in a string. Due to the fact that this inverter allows only 1 string to be connected, it is concurrently the only possible configuration of the PV array.

With 10 modules in a string, each with nominal power of 260Wp, the total power output of the generator is 2,6kWp. With 11 PV modules, the nominal power output of the PV generator is 2,86kWp which exceeds the maximum DC input of the inverter (2,65kW). However, as long as this output is only achievable at low temperatures and high irradiance, to reach it, the irradiance on tilted surface and the ambient temperature would have to reach values specified in Table 17. Although this situation might happen, with the specified irradiance, the ambient temperature would in most cases be higher than the specified values. Considering the situation might occur, it would mean no danger for the system. The inverter would simply limit the input power and the surplus power wouldn't be used. This phenomenon is called inverter 'clipping'.

Power [kW]	Irradiance on tilted s. [W/m²]	Ambient temperature [°C]	
		Model 1	Model 2
2,65	900	-25,48	-26,79
	1000	-2,37	3,17
	1100	15,82	26,87

Table 17 | Temperature and irradiance levels to achieve specified power

The *GoodWe GW2500-NS* inverter offers wider MPPT voltage range. Therefore, from 4 up to 10 modules might be connected in a string. In order to comply with the requirement of the 70% consumption of the produced energy, the variant with 10 modules and 2,6kWp nominal power is chosen for both inverter variants.

LOAD CONTROL

Figure 24 | SMA Sunny Home Manager. Source: SMA

The load manager device is necessary for using the surplus energy for house and water heating. Therefore, it allows to increase self-consumption. *The SMA Sunny Home Manager* represents one of the more sophisticated load managers. It monitors the PV system by communicating with the SMA or other inverter and reading connected energy meters. Through the radio-controlled sockets it is then able to control the loads. The device is receiving location-based weather forecast via the Internet and based on the information it creates the PV system yield forecast. It also logs data on PV generator, grid feed-in and purchased electricity. It is than able to create a load profile of the household individually for each day of the week.

Figure 25 | WATrouter M SSR. Source: Solar controls

The *WATTrouter Eco* or *M SSR* is a simpler devices. It doesn’t offer the weather forecast or ability to create load profiles. It consists of measuring module and a regulator which uses connected relays to fluently regulate connected devices. The M

SSR model has the ability to control the devices via Wi-Fi connected devices, such as computers or smartphones.

Cables and Connecting Systems

As stated in previous chapters, the cables and connections should be chosen to minimize losses. Decision whether higher investment costs are worth minimizing losses should be always part of the economical evaluation of the project.

The best location for the inverter is in the basement room right next to the main switchboard. This position allows the wiring from the PV generator located on the roof to be less than 10 meters. The interconnection of the PV modules is done with the cables and connectors included, each module comes with 1 meter long cable with the YS-254/255 connector with a transfer resistance of less than 5 milliohms. Selected cables and calculated voltage drop are presented in Table 18. The voltage drop of plug connectors for interconnecting the PV modules is presented in Table 19. The AC connection is less than 1 meter long. Therefore, the AC cable losses and price are neglected.

DC Cables			
I	PV generator I_{mp} at STC	8,34	A
V	PV generator V_{mp} at STC	312	V
Modules interconnection			
S	Cross sectional area	4	mm^2
L1	Cable length modules connection	10	m
b	cable length factor	1	-
R/km	Resistivity	5,09	Ω/km
ΔV	**Volt drop over cables**	**0,42**	**V**
ΔV(%)	**Voltage drop**	**0,14%**	
PV generator to inverter connection			

	Cable Type	NYY-O 1x4	
	Price	21,33	Kč/m
S	Cross sectional area	4	mm^2
L2	PV array to inverter	8	m
b	cable length factor	2	-
R/km	Resistivity	4,61	Ω/km
ΔV	**Volt drop over cables**	**0,62**	**V**
ΔV(%)	**Voltage drop**	**0,20%**	

Table 18 | DC cable types and voltage drop

Plug connectors			

	Type	YS-254/255	
R	Resistance	5	mΩ
ΔV	Voltage drop	0,0417	V per plug connector
N	Number of connectors	22	
ΔV	**Connectors voltage drop**	**0,9174**	
ΔV(%)	**Voltage drop**	**0,29%**	

Table 19 | PV array plug connectors voltage drop.

Protective Devices

Due to the fact that the house isn't in the risk of being struck by the lightning because of the presence of tall trees on the North of the house, it isn't equipped with a lightning protection system. Therefore, according to the facts mentioned in Chapter 3.8.2, on the

DC side protection type II is required. Because of the cable length between the PV generator and DC side of the inverter is shorter than 10 meters, only one protective device is required. With respect to the highest system DC voltage of 422V which was calculated in previous chapter, the surge protection device CITEL DS50PVS-500 is chosen. It allows maximum operating voltage of 530V. Therefore, it will protect the inverter from its maximum voltage of 600V of being exceeded.

Figure 26 | Surge protective device CITEL DS50PVS-500. Source: CITEL

Modules Mounting

The mounting of the PV modules to the roof needs a special construction which is designed for the specific roof surface. After contacting the company Silektro which is offering VarioSole roof construction, a price of 1 050CZK without VAT for construction for 1 PV module was obtained. The construction maintains a gap between the roof and the PV modules which helps the air to flow under the modules and thus reduces their operating temperature.

5.3 PV System with Electricity Accumulation

The system with electricity accumulation requires, apart from batteries itself, more sophisticated inverter which is able to charge the batteries through its DC output. There are basically two options of connecting the batteries to the system. The first one is to obtain the inverter with integrated battery charger. The second option is to use standard on-grid inverter with battery controller as a separate component. After analyzing the component prices, the first option seems as a cheaper variant.

INVERTER

Most of the inverters with the ability to charge batteries are designed for the off-grid operation and come in a three-phase version which is significantly more expensive than a single-phase version. According to the local power distributor only PV systems with power exceeding 4,6kWp are required to be three-phased. With power of less than 4,6kWp, single-phase connection is possible and in most cases it is more economical as well.

The most suitable inverter is *Growatt 3000HY*. In Table 20 its specifications are shown in comparison with the best alternative, *GoodWe GW3648-ES* inverter.

Type		GoodWe GW3648-ES	Growatt 3000HY
Max DC power	kW	4,2	4,5
Max input voltage	V	580	500
Min input voltage	V	150	116
MPPT voltage range	V	125-550	250-450
Max input current	A	11	18
Number of strings		2	1
Nominal AC output	kW	3,6	3
Max AC output	kVA	3,6	3
Max output current	A	16	13
EU efficiency		97,0%	95,0%
DC to AC efficiency		95,0%	93,0%
Price incl. VAT	CZK	68 759	44 050
Warranty	years	5	5
- extension to 20 years	CZK	81 837	?
Number of phases		1	1
Battery output power	W	4,8	4,5
Battery voltage	V	48	48
DC Disconnector		yes	yes

Table 20 | Variant 2 inverter specifications

BATTERIES

As mentioned in Chapter 1.2.3, the minimum battery capacity is set by the subsidy program requirements to 1,75kWh per kilowatt-peak of the PV generator in case of lead-based and traction acid batteries and to 1,25kWh/kWp in case of using modern technology batteries with high amount of deep discharge cycles such as lithium-ion and LiFePO4. The considered battery types are presented in Table 21. Due to the fact that both inverter mentioned in previous chapter has 48V battery connection, the amount of battery units has to be selected with respect to that. The same principle as mentioned for PV modules in Chapter 3.2.3 applies for connecting individual batteries to form battery packs. The amount of batteries needed in series connection is 48 divided by the unit voltage. To add extra capacity, at least the whole number multiple of the calculated amount of batteries has to be added in the parallel connection.

Batteries		Trojan	Trojan	Hoppecke solar.bloc	LFP100AH	LFP200AH	BMZ	BMZ ESS 3.0
Technology		lead-acid flooded	lead-acid flooded	lead-acid AGM	LiFePO4	LiFePO4	Li-Ion	Li-Ion
Unit voltage	V	12	8	12	3	3	24	48
Unit capacity	Ah	85	170	90	40	200	108	121,5
Total unit capacity	Wh	1020	1360	1080	120	640	2797,2	6743,25
DoD		50%	50%	63%	80%	80%	90%	80%
Cycles at DoD		1 200	1 200	2 000	5 000	5 000	4 000	5 000
Price incl. VAT	Kč	5 782	5 911	7 237	1 730	8 652	48 850	112 750
Price per capacity	Kč/kWh	5 669	4 346	6 701	13 516	13 516	17 464	16 720
Price/kWh over life-time	Kč/kWh	10,62	8,14	5,48	3,56	3,56	3,56	5,00
Warranty	years	2	2	2	2	2	5	7
Required maintenance		yes	yes	no	no	no	no	no
Cycle efficiency		89%	89%	97%	95%	95%	97%	97%

Table 21 | Considered battery types

5.4 PV System for direct water heating

The main advantage of the PV system variant for direct water heating are the savings in investment costs due to DC power supply for water heating. Therefore, the inverter which is a big part of the initial investment cost isn't necessary. However, according to the requirements in subsidy program, technology for efficient optimization, such as MPP tracker, is required. Furthermore, because of the current boiler being able to be powered only with AC power, boiler with both DC and AC input have to be obtained.

5.4.1 Sizing the System

From the estimation in Chapter 2.5, the approximate power consumption for water heating in an average year is around 850kWh. However, the amount is not evenly distributed over days of the week. Much higher demand is observed during weekends.

In total, consumption for water heating during the weekends accounts for 441kWh, whereas during the working days for 407kWh. After considering these facts, the best utilization has the PV system with nominal power of 1kWp. It ensures that nearly 95% of the generated power is used for water heating during the weekends. A system with higher installed power would produce surplus energy which cannot be used. Therefore, the PV generator would have to be switched off even during the weekends. On the other hand, systems with smaller installed power aren't able to provide enough energy to cover the needs during the weekend days.

5.4.2 *COMPONENTS*

The default PV modules are the same as in the previous two variants. However, this isn't the best solution due to the nominal power of the modules. More economical in this variant is to choose panels with nominal power of 255Wp or less. The selection of PV modules is discussed in economical evaluation further in this work.

DC/DC CONVERTER WITH MPP TRACKER

To use as much power as the PV modules can produce and to comply with the subsidy program requirements, the MPP tracker needs to be installed. There aren't many of converters which fulfill all specifications needed. Most of them is designed for battery charging. The possible DC/DC converters with MPPT are presented in Table 22.

Type		LXDC Power Box 1-2kW	Marko DC/DC converter
Max DC power	kW	2	2,5
Rated input voltage	V	85-350	180-270
Max input voltage	V	350	400
Min input voltage	V	85	24
MPPT voltage range	V	85-350	220-360
Max input current	A	10	
Max AC output	kVA	2	2,6
Nominal AC voltage range	V	-	150-300
Max output current	A	10	
EU efficiency		98,5%	96,0%
Price incl. VAT	CZK	8490	8490
Warranty	years	2	?
- extension to 20 years	CZK	-	-

Table 22 | DC/DC converters with MPP tracker

The biggest concern with these products is the warranty. Whereas the *LXDC Power Box* has a warranty of 2 years, the warranty of the Marko isn't specified. Information about warranty extension wasn't possible to obtain from the manufacturers. The *LXDX Power Box* is better option in nearly all of the parameters. It offers wider MPPT voltage range, higher efficiency and at least some information about the warranty. The LXDC Power Box data sheet is annexed in Appendix 6.

Specifications matching

The minimum number of PV modules which might be connected to the convertor in one string is calculated the same way as in the previous variants. The MPPT voltage range of 85-350V provides possibility of connecting 4-8 PV modules in a string, regardless the choice of the modules presented in Table 14.

If the current exceeds the 6A limit the MPP tracker is turned off and the PV modules are directly powering the heating element of the boiler.

Water Boiler

When choosing water boiler with the ability to be powered both with DC power from the PV generator and AC power from the grid in case there is not enough sunshine, there aren't many possibilities on the Czech market. Basically the only type of the boiler which is possible to be obtained is made by the Czech manufacturer DZ Dražice.

The boilers are available with water accumulation volume of 95-195 liters and are equipped with universal heating element which is able to connect PV generator with output power of 1,1,5 or 2kW. However, these boilers are relatively expensive, the price range is from 16100CZK to 18600CZK depending on the tank volume. [26] Due to the relatively small difference in price between the 95 liter and 155 liter boiler, the later one is chosen.

Protective devices

The surge protection device is the same as in the previous variants but due to the fact that the DC/DC converter isn't equipped with the DC disconnector, the 2 pole OEZ OPVA10 disconnector is installed between the PV generator and the converter. The disconnector datasheet is annexed in Appendix 8.

6. Economic Evaluation

The economic model evaluates the total production of solar energy by the PV system over certain time period (e.g. 20 years) and calculates the energy savings according to the amount of consumed energy produced by PV system. The surplus energy might be sold to the power distributor according to the tariffs. Knowing the investment and operation costs of the PV system along with the costs saved by producing the electricity from the PV system, the economic evaluation is performed.

6.1 Methods Used

6.1.1 Net Present Value (NPV)

Net Present Value is the sum of capital expenditures and income from the investment which are recalculated by discounting to their present value (the time when the investment is made).

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1-r)^t} = \sum_{t=0}^{T} DCF_t$$

$$NPV = CF_0 + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_T}{(1+r)^T} \qquad \text{[CZK]} \quad (6.1)$$

where	CF	cash flow
	DCF	discounted cash flow
	T	investment lifetime
	t	year
	r	discount rate

NPV represents the amount of money the investor will obtain on top of the invested amount. The investment is profitable in case that NPV ≥ 0. In case the value is lower, the investment project won't reach the required revenue.

The basic prerequisite of this method is the estimation of future cash flows which is not always easy and accurate. Another difficulty is to set correctly the discount rate. The discount rate represents the required revenue and should reflect the inflation and the investment risk. The investment risk should take into account the uncertainty of future revenue, it is clear that the higher the risk of the investment, the higher the required revenue. [27] [28]

6.1.2 Internal Rate of Return (IRR)

The Internal Rate of Return indicates the relative profitability of the investment in percentage over its lifetime. Therefore, it is actually the discount rate at which the NPV=0.

$$\sum_{t=0}^{T} \frac{CF_t}{(1-IRR)^t} = 0 \qquad [\%] \qquad (6.2)$$

When determining the investment profitability by using the IRR indicator, it is necessary to take into account the required discount rate (required revenue) since this method does not consider it. To consider the investment profitable, the value of IRR should be greater than the required discount rate. [27] [28]

6.2 Input Data

The accuracy of the economic evaluation using the mentioned methods depends on the accuracy of the input data and its correct forecast during the lifetime of the investment.

6.2.1 Power Generation and Consumption

As mentioned in previous chapters the PV system power generation is apart from set conditions, such as location, mounting position and components used, dependent on solar irradiance and ambient temperature. The correct evaluation of the electricity cost savings depends on the correct estimation of how much generated power can be consumed. Due to the fact that the irradiance and temperature, as well as power consumption are significantly changing on the hourly, daily and monthly basis, for the most accurate results, these data should be obtained with the small enough time step.

In this work irradiance and power consumption data in 15-minute intervals for average day in each month were obtained. The in-depth consumption analysis is presented in Chapter 2.3, the irradiance data are presented in Chapter 2.1.1. In order to maintain the conservative approach, the Method 1 is used to determine the system power output, due to the fact that the output power values were lower compared to the Method 2.

As the temperature input data, the maximum and minimum temperature values for average day in each month were used to model the 15-minute daily profile. The data and the modelling process are presented in Chapter 2.1.2. Taking into account all these input data, fairly accurate model of power generation is created.

6.2.2 *Electricity prices*

The electricity prices are obtained from the distributor price list for the particular product used. The price of electricity in Czech Republic consist of variable price which is dependent on the amount of consumed electricity and fixed monthly price which depends on the maximum power input according to the nominal value of the main circuit breaker. Due to the fact that the model calculates savings compared to the initial state, only the components of the price which are saved thanks to the lowered consumption are required for the calculation. The variable electricity price components which are saved in case of consuming power generated by the PV system are listed in Table 23 along with the price paid by distribution network operator for electricity exported. As can be seen the price paid for the exported electricity is relatively low and therefore it is advisable to consume as much produced energy as possible.

Variable electricity prices		
Product	D 45d Přímotop 3x25 A (eTarif)	
electricity - high tariff	1,75	CZK/kWh
electricity - low tariff	1,53	CZK/kWh
network service fee - high tariff	0,313	CZK/kWh
network service fee - low tariff	0,0738	CZK/kWh
RES, system services, market operator fee	0,727	CZK/kWh
Exported electricity	0,500	CZK/kWh

Table 23 | Electricity price variable components

The forecast of the future electricity prices for households is not easy to determine. The Czech Republic is now in a state of uncertainties connected with future change of electricity payments structure. The national Energy regulatory institute (ERÚ) came with new structure which should have come into force from 2017. Due to the concerns about the significant increase of electricity payments for certain groups of customers along with reduced motivation for power consumption reductions, the proposed structure was scraped and it will be redone. This makes the future situation highly uncertain.

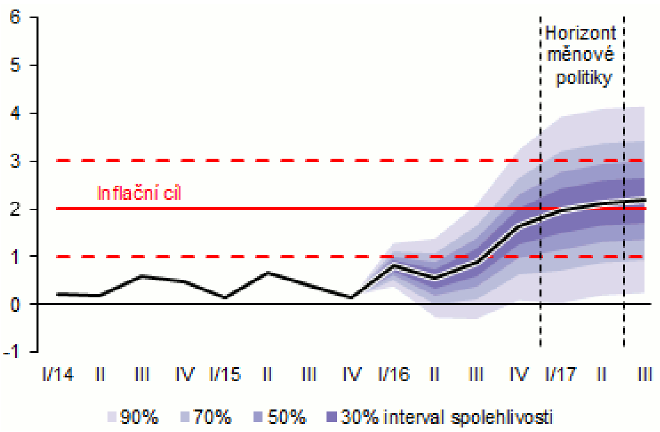
As a result, the future prices of electricity, distribution and service fees are set according to their trend in previous years. The price of the electricity itself is decreasing because of the higher rate of renewable energy sources (RES) in power generation which are payed through off-market subsidies. As a result, the subsidy payments are increasing adequately. The decentralized use of RES also means higher demands on distribution networks and therefore it's reflected in increase of network service fees. The over-estimation of the future increase of the mentioned values would however raise the profitability of the investment. Therefore, to maintain the conservative approach the individual variables are set according to the following table.

Annual change of electricity bill components	
Price of electricity	**-0,30%**
Network service fee	**0,30%**
RES, system services, market operator fee	**0,40%**
Exported electricity	**0,00%**

Table 24 | Electricity bill components annual increase (+) and decrease (-)

6.2.3 INFLATION

The inflation in the economic model affects prices of insurance and material and component costs. Current inflation in Czech Republic is around 0,5%, the average annual inflation in 2015 was 0,3%. [29] Due to the fact that long term target of the Czech national bank is 2% the inflation for the 20 year period of the investment evaluation, the inflation was set to 2%. [29]



Graph 25 | Inflation target of the Czech National Bank. Source Czech National Bank

6.2.4 Discount Rate

The discount rate of individuals who don't invest their funds is set according to their opportunity of valorizing their money. The residents of the specified house are having their money on current account with interest rate of 1,3%. Taking into account the risk of uncertain future electricity prices the discount rate of the investment into the PV system is set to 2%.

6.2.5 Additional Investment and Operational Costs

The additional investment costs are the costs of installation, project plan and shipping cost of the equipment. After a consultation with RWE senior specialist for innovations, the installation costs were set as 13% from the initial investment costs for the PV system itself and the shipping and project cost as 4 000CZK for the system for water heating, 7 000CZK for the system without batteries and 10 000CZK for the PV system with batteries.

The operational costs include insurance of 0,1% of the PV system costs and a yearly sum of 0,5% of total investment.

6.3 Evaluation of The System Variants

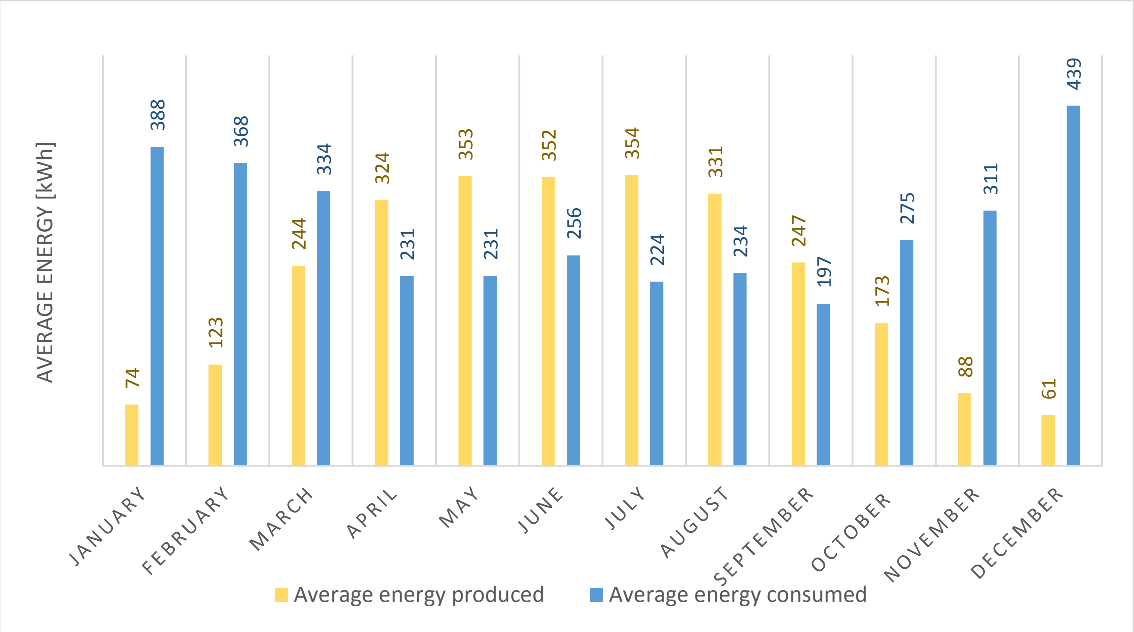
The three main variants represent three different investment opportunities each with different initial investment. The Variant 3 (system for direct water heating) represents the variant with the lowest initial investment and the Variant 2 (system with battery accumulation) the highest initial investment.

6.3.1 Variant 1

The main variant, the system with using the surplus energy for water and house heating, represents the middle variant in terms of initial investment costs. As mentioned before, the profitability of the investment depends on the rate of the produced energy which is effectively consumed. Another important factor is to fulfill the criteria for obtaining the investment subsidy via the subsidy program. This variant is designed to comply with the C.4 subcategory of the subsidy program.

Generated Energy Consumption

In the Graph 26 the average energy production of the PV system with nominal power of 2,5kWp is presented in comparison to the electricity consumption. It can be clearly seen that in winter months when the consumption is high the system produces the least energy. The opposite situation occurs during the summer months with the generation exceeding the consumption. The PV system produces on average around 2596kWh of energy annually and the average annual consumption is around 3645kWh.

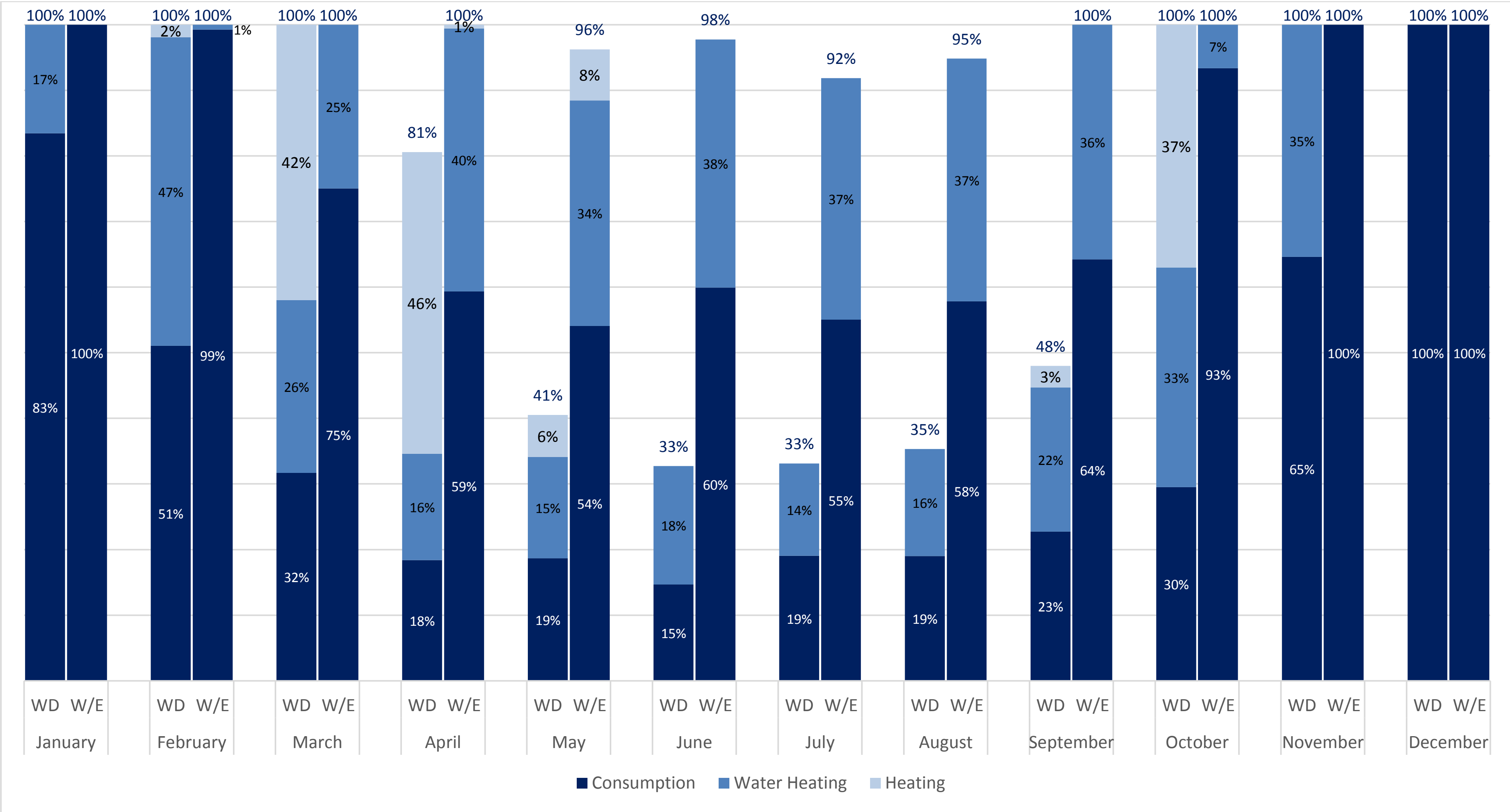


Graph 26 | Energy generation vs consumption for 2,5kWp system

The Graph 27 represents the amount of generated energy consumption divided into working and weekend days for each month. It can be seen that the consumption optimization significantly helps to increase the ratio of consumed energy. In fact the total directly consumed energy nearly doubled from 990kWh before optimization to 1831kWh after introducing the consumption optimization. Relatively to the total consumption, before optimization was 27% directly consumed and 50% after it. The power generation and consumption analysis of this variant is being presented in Table 25.

	All days			Working days			Weekends			
	Total	HT	LT	Total	HT	LT	Total	HT	LT	
Power generation	**2569,0**	492,0	2077,0	**1835,0**	397,7	1437,3	**734,0**	94,2	639,7	kWh
-directly consumed	**71%**	76%	70%	**60%**	70%	57%	**98%**	100%	97%	
Power consumption	**3644,7**	423,3	3221,4	**2191,4**	267,9	1923,5	**1453,3**	155,4	1297,9	kWh
- for water heating	**828,0**	**0,0**	**828,0**	**457,7**	0,0	457,7	**370,4**	0,0	370,4	
Cons. covered by PV system	**987,0**	160,7	826,3	**494,2**	98,6	395,5	**492,8**	62,0	430,7	kWh
-ratio of cons. covered	**27%**	38%	26%	**23%**	37%	21%	**34%**	40%	33%	
Optimized cons. covered	**1818,7**	372,8	1445,9	**1102,7**	278,5	824,2	**716,0**	94,2	621,7	kWh
-ratio of cons. covered	**50%**	88%	45%	**50%**	104%	43%	**49%**	61%	48%	
Import from dist. network	**2101,9**	247,4	1854,5	**1324,9**	169,2	1155,6	**777,0**	78,2	698,8	kWh
Import/Consumption	**58%**	58%	58%	**60%**	63%	60%	**53%**	**50%**	**54%**	
Export to dist. network	**750,3**			**732,3**			**18,0**			kWh
Export/Produced power	**29%**			**40%**			**2%**			

Table 25 | Variant 1 generation and consumption analysis



Graph 27 | Amount of PV produced energy consumption for 2,5kWp system (WD- working day, W/E – weekend day)

INVESTMENT COSTS

The total investment cost of the PV system including the installation, project plan and shipping costs is presented for two different types of modules and inverter in the following table. In this case, the choice of the modules and inverter can save up to 12% of the initial investment costs with the nominal PV generator power being just 4% lower. Due to the fact that the inverter is with its complex electronics the most vulnerable part of the PV system from the perspective of malfunction, both variants include the inverter warranty extension to 20 years to prevent any additional costs which would be needed for inverter repair and maintenance.

	Variant A (2,5kWp)		Variant B (2,6kWp)	
Item	Type	Price (CZK)	Type	Price (CZK)
PV modules	OMSUN FCP 250W (10×)	43 100	AUO BenQ PM060P00 (10×)	48 900
Inverter	GoodWe GW2500-NS	16 323	SMA Sunny Boy 2,5	21 366
Inverter warranty extension		15 498		17 280
Power manager	WATTrouter M SSR	9 090	WATTrouter M SSR	9 090
Cable, protective devices		2 581		2 581
Roof mounting construction		12 705		12 705
PV system		**99 297**		**111 292**
Project plan + shipping		7 000		7 000
Installation		12 909		14 550
Total investment		**119 206**		**133 472**
Subsidy		**55 000**		**55 000**

Table 26 | PV system investment costs

EVALUATION

In the Table 27 it can be seen that even the cheaper system doesn't offer required profitability. With the discount being set to 2%, the NPV value is -2 087CZK and the IRR 1,65%. Although the Variant B doesn't meet the subsidy program requirement of the ratio of consumed energy, the economic indicators were calculated with the financial subsidy. The reason for this step is the ability to raise the consumption during the summer using the air-conditioning to cool the house. While the cooling of the house was performed in the previous years, after consultation with the residents, it was confirmed that the cooling wasn't always done to the most suitable extent. Although the increase of cooling would raise the comfort of living for the house residents, it isn't included in electricity cost savings.

			Variant A	Variant B
Connection to distribution grid			yes	yes
Installed nominal power	kWp		2,5	2,6
Investment costs	CZK		119 206	133 472
Subsidy	CZK		55 000	55 000
NPV	CZK		-2 087	-17 025
IRR			1,65%	-0,49%
Subsidy program		**min**		
Requirements			met	not met
MPPT		yes	yes	yes
Module efficiency		15%	15,20%	16,10%
Var. 2,3				
Produced energy consumed	kWh	1 700	1 831	1 854
Rate of energy consumed		70%	70,6%	68,8%

Table 27 | PV system economic evaluation

6.3.2 VARIANT 2

The Variant 2 which is designed to comply with the C.5 subcategory of the subsidy program contains PV system which accumulates the surplus energy to batteries for later use. This allows for higher amount of produced energy to be used.

INVESTMENT COSTS

The costs of the additional equipment compared to the first variant is around 45 000 - 80 000CZK higher, depending on the battery technology. These costs are without the inverter warranty extension (the manufacturer didn't provide any specification about price of the warranty extension) and it is assumed that the batteries will be present in the system for its whole lifetime without their exchange. The degradation of batteries is calculated according to Chapter 4.4.3. Whereas the LiFePO4 batteries will easily last the 20 years expected lifetime of the system, reaching around 86,5% of their rated capacity after the 20 years. The lead-acid batteries would degrade to 80% of its capacity in the specified installation on an average in 9 years.

Item	Variant A (2,5kWp) Type	Price (CZK)	Variant B (2,6kWp) Type	Price (CZK)
PV modules	OMSUN FCP 250W (10×)	43 100	OMSUN FCP 250W (10×)	43 100
Inverter	Growatt 3000HY	44 050	Growatt 3000HY	44 050
Inverter warranty extension		0		0
Power manager	WATTrouter M SSR	9 090	WATTrouter M SSR	9 090
Batteries	Trojan lead-acid (5,04kWh)	23 644	LFP040AH LiFePO4 (4,10kWh)	55 360
Cable, protective devices		2 581		2 581
Roof mounting construction		12 705		12 705
PV system		**135 170**		**166 256**
Project plan + shipping		10 000		10 000
Installation		17 572		21 695
Total investment		**162 742**		**198 581**
Subsidy		**70 000**		**70 000**

Table 28 | PV system with batteries investment costs

EVALUATION

As can be seen from the values presented in the following table, the variant of the system with batteries isn't profitable even without the costs for inverter warranty extension with both the NPV and IRR values being significantly negative.

			Variant A	Variant B
Connection to distribution grid			yes	yes
Installed nominal power	kWp		2,5	2,5
Investment costs	CZK		162 742	198 581
Subsidy	CZK		70 000	70 000
NPV	CZK		-21 842	-67 519
IRR			-0,73%	-4,88%
Subsidy program		**min**		
Requirements			met	met
MPPT		yes	yes	yes
Module efficiency		15%	15,20%	15,20%
Produced energy consumed	kWh	1 700	1 806	1 806
Rate of energy consumed		70%	82,2%	84,4%
Minimum battery capacity	kWh		4,38	3,125
Battery capacity	kWh		5,04	4,096

Table 29 | PV system with batteries economic evaluation

6.3.3 VARIANT 3

The Variant 3 is a PV system with direct water heating designed according to the subsidy program subcategory C.3. The benefit of this variant are the costs savings due to the fact, that the water boiler is powered by the DC power. Therefore, no inverter is needed. However, the special boiler with DC and AC input is needed. Due to the fact that the sum of the costs for the boiler and the MPP tracker exceed the price of most inverters, this variant loses its benefits.

INVESTMENT COSTS

Item	Type	Price (CZK)
PV modules	OMSUN FCP 250W (4×)	17 240
MPP tracker	LXDC Power Box 1-2kW	8 490
Cable, protective devices		2 306
Roof mounting construction		5 082
PV system		**33 118**
Water boiler (DC+AC)		17 000
Project plan + shipping		4 000
Installation		4 305
Total investment		**58 424**
Subsidy		**29 212**

Table 30 | PV system for direct water heating investment costs

EVALUATION

Due to the fact that the investment cost of the water boiler is nearly 30% of the total cost of the entire system including installation, project plan and shipping, the evaluation was also carried out for the case the boiler wouldn't be needed. The NPV for the variant which takes into account investing into the water boiler is -10 493CZK, with the IRR being -2,34%. Without necessity of the investment into the water boiler, the variant would nearly reach the required profitability.

			with water boiler	w/o water boiler
Connection to distribution grid			no	no
Installed nominal power	kWp		1	1
Investment costs	CZK		58 424	41 424
Subsidy	CZK		29 719	21 219
NPV	CZK		-10 493	-503
IRR			-2,34%	1,74%
Subsidy program		**min**		
Requirements			met	met
MPPT		yes	yes	yes
Module efficiency		15%	15,20%	15,20%
Var. 1,2				
Hot water cons. coverage		50%	79%	79%
Minimum tank capacity	l		45	45
Tank capacity	l		160	125

Table 31 | The PV system for diret water heating evaluation

Conclusion

In this work three main variants of photovoltaic system for family house were designed. The main variant is the 2,5kWp system with usage of the surplus energy for water heating and house heating/cooling. The second variant uses accumulation into the batteries on top and the third variant is intended for direct DC power water heating in order to save costs with buying the invertor.

For each system all the needed components were picked from many options according to their price and specifications. It is necessary to pay attention to component specifics while putting them together. Especially the operating range of the invertor needs to be matched with the PV generator operating voltage according to the specific temperature conditions.

With a respect to the component specifications, the power generation for each system was calculated in 15-minute intervals for average day in each month. As input data for the calculation the irradiance values for the same time intervals were obtained from the PVGIS online database. The local temperature for the corresponding time periods was estimated from daily minimum and maximum average temperature over past 30 years. The power produced by the PV system was compared to the 15-minute power consumption again for average day in each month. The power consumption data were collected for the year 2014 and 2015.

This allows to perform a fairly accurate estimation of how much produced power is in the 96 intervals during average day in each month consumed and which part of this energy needs to be fed into the distribution network. This estimation is crucial for the final economic evaluation of the system variants because the price paid for the electricity exported to the grid is too low for the export to be profitable. Due to the fact that the highest amount of produced power needs to be directly consumed in order to achieve the highest possible profitability of the system, the consumption optimization was introduced. It uses the present water boiler and air-conditioning unit equipped with heat pump to turn on while the PV system is generating surplus power and therefore accumulate the energy into the hot water and into the heating/cooling of the house. For the 2,5kWp system, which after accounting the losses produces around 2 570kWh of energy, the consumption optimization almost doubles the directly used energy from 987kWh to 1 820kWh, which is from 27% of total power consumption to 50%.

The costs of each system were reduced to their minimum by careful search for the cheapest yet reliable products. The total cost of the system might be reduced with this measure by tens of thousands of Czech Korunas. Apart from this none of the system variants is profitable under the stated conditions. The variant with accumulation of the energy into hot water and house heating/cooling achieved according to its NPV and IRR the best result. It's NPV reached with the discount rate being set to 2% -2 087CZK with the IRR being 1,65%. Even though, the financial subsidy of 55 000CZK is almost half of the needed investment costs of approximately 120 000CZK. This indicates that under current electricity prices the PV system still isn't profitable for this particular house even with the subsidy program. Considering the uncertain situation about electricity prices in the future, installing a PV system on this particular house isn't recommended. Those changes might make the system even more unprofitable. The best solution is to wait for the upcoming changes and carry out the evaluation while taking the knowledge about the changes into account. Moreover, the investment costs of the PV technology and batteries are continuously decreasing. Therefore, the investment might become profitable in near future.

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APPENDIX

Appendix 1 | Solar irradiation data

Time	Irradiance W/m²											
	January	February	March	April	May	June	July	August	September	October	November	December
4:00 - 4:15												
4:15 - 4:30						34						
4:30 - 4:45						48	38					
4:45 - 5:00					41	62	52					
5:00 - 5:15					54	75	65	24				
5:15 - 5:30					68	88	78	38				
5:30 - 5:45				39	80	100	90	51				
5:45 - 6:00				53	93	112	102	63				
6:00 - 6:15				67	104	115	113	75	31			
6:15 - 6:30				80	116	140	128	80	45			
6:30 - 6:45			43	95	143	166	154	106	59			
6:45 - 7:00			60	124	171	194	182	134	79			
7:00 - 7:15			83	155	200	222	211	165	104	37		
7:15 - 7:30		34	109	187	230	250	240	196	130	58		
7:30 - 7:45		51	136	220	260	278	269	228	158	80		
7:45 - 8:00		72	165	253	289	307	298	260	186	103	34	
8:00 - 8:15	34	92	193	286	319	335	327	293	215	127	49	
8:15 - 8:30	47	112	222	319	348	362	355	325	243	151	67	36
8:30 - 8:45	63	131	250	351	376	388	382	356	272	175	83	49
8:45 - 9:00	76	150	277	383	403	414	408	387	299	198	98	63
9:00 - 9:15	90	169	304	413	428	438	433	416	326	220	113	74
9:15 - 9:30	102	186	329	441	453	461	457	444	351	242	128	86
9:30 - 9:45	114	202	352	468	476	483	480	471	375	262	141	96
9:45 - 10:00	125	217	375	493	497	503	501	496	397	281	153	106
10:00 - 10:15	135	231	395	517	517	522	520	519	418	299	165	115
10:15 - 10:30	145	244	414	538	536	540	538	540	437	315	175	123
10:30 - 10:45	153	256	431	558	552	555	554	559	454	330	185	130
10:45 - 11:00	160	266	446	575	567	569	568	577	469	342	193	136
11:00 - 11:15	166	274	459	590	580	581	581	591	482	353	200	141
11:15 - 11:30	171	281	469	603	590	591	591	604	493	362	205	145
11:30 - 11:45	174	287	478	613	599	600	600	614	502	370	210	149
11:45 - 12:00	177	291	485	621	606	606	607	622	509	375	213	151
12:00 - 12:15	179	293	489	626	611	611	611	628	513	378	215	152
12:15 - 12:30	179	294	491	629	614	613	614	631	515	380	215	153
12:30 - 12:45	178	294	490	630	614	614	615	631	515	379	214	152
12:45 - 13:00	176	291	488	627	613	612	613	629	512	376	212	150
13:00 - 13:15	172	287	483	623	609	609	610	624	507	371	209	147
13:15 - 13:30	168	282	475	615	603	603	604	617	500	364	204	143
13:30 - 13:45	162	274	465	605	595	596	596	607	490	355	197	138
13:45 - 14:00	155	265	453	593	585	586	587	595	478	344	190	132
14:00 - 14:15	146	255	438	578	573	575	575	580	464	331	180	124
14:15 - 14:30	136	242	421	560	558	561	561	563	447	316	170	116
14:30 - 14:45	125	228	402	540	542	545	544	543	428	298	158	106
14:45 - 15:00	113	212	381	517	523	528	526	521	406	279	144	95
15:00 - 15:15	99	195	357	493	502	508	506	496	383	258	129	83
15:15 - 15:30	84	176	331	465	480	487	484	470	357	234	112	66
15:30 - 15:45	65	155	303	436	455	463	460	442	330	210	94	51
15:45 - 16:00	47	133	274	405	429	439	435	411	301	183	72	17
16:00 - 16:15	16	109	243	372	401	412	408	379	270	155	51	
16:15 - 16:30		81	210	337	372	385	379	346	239	126	17	
16:30 - 16:45		55	176	301	341	356	350	311	206	96		
16:45 - 17:00		32	142	264	309	326	319	276	172	63		
17:00 - 17:15			108	227	277	295	288	241	139	36		
17:15 - 17:30			71	190	244	264	256	205	106			
17:30 - 17:45			42	153	212	233	224	170	72			
17:45 - 18:00				117	179	202	192	136	44			
18:00 - 18:15				84	148	172	161	104	21			
18:15 - 18:30				52	118	143	132	74				
18:30 - 18:45				28	90	116	104	46				
18:45 - 19:00					64	90	78	27				
19:00 - 19:15					41	67	56	11				
19:15 - 19:30					27	48	38					
19:30 - 19:45						34	25					
19:45 - 20:00						21						
20:00 - 20:15												
Avg. Day Total [Wh]	1033	1924,75	3552	5027,25	5356,25	5563,25	5468,25	5137	3862,25	2553	1298,75	856,25
Days in month	31	28	31	30	31	30	31	31	30	31	30	31
Monthly Total [Wh]	32023	53893	110112	150818	166044	166898	169516	159247	115868	79143	38963	26544
Year Total [kWh]	**1269,066**											

GreenTriplex PM060P00 (250 ~ 265 Wp)

Electrical Data

Typ. Nominal Power P_N	250 W	255 W	260 W	265 W
Typ. Module Efficiency	15.5%	15.8%	16.1%	16.4%
Typ. Nominal Voltage V_{mp} (V)	30.6	30.8	31.2	31.6
Typ. Nominal Current I_{mp} (A)	8.17	8.28	8.34	8.36
Typ. Open Circuit Voltage V_{OC} (V)	37.4	37.6	37.7	37.9
Typ. Short Circuit Current I_{SC} (A)	8.69	8.76	8.83	8.89
Maximum Tolerance of P_N	0 / +3%			

- Above data are the effective measurement at Standard Test Conditions (STC)
- STC: irradiance 1000 W/m², spectral distribution AM 1.5, temperature 25 ± 2 °C, in accordance with EN 60904-3
- The given electrical data are nominal values which account for basic measurements and manufacturing tolerances of ± 10%, with the exception of P_N. The classifications is performed according to P_N
- Black back sheet is utilized for 250-260W; white back sheet is for 250-265W

Temperature Coefficient

NOCT	46 ± 2 °C
Typ. Temperature Coefficient of P_N	-0.39 % / K
Typ. Temperature Coefficient of V_{OC}	-0.30 % / K
Temperature Coefficient of I_{SC}	0.07 % / K

- NOCT: Normal Operation Cell Temperature, measuring conditions: irradiance 800 W/m², AM 1.5, air temperature 20 °C, wind speed 1 m/s

Mechanical Characteristics

Dimensions (L x W x H)	1639 x 983 x 40 mm (64.53 x 38.70 x 1.57 in)
Weight	18.5 kg (40.79 lbs)
Front Glass	High transparent solar glass (tempered), 3.2 mm (0.13 in)
Cell	60 multicrystalline solar cells
Back Sheet	Composite film
Frame	Anodized aluminum frame
Junction Box	IP-67 rated with 3 bypass diodes
Connector Type & Cables	TE Connectivity PV4: 1 x 4 mm² (0.04 x 0.16 in²), Length: each 1.0 m (39.37 in) YUKITA YS-254/ YS-255: 1 x 4 mm² (0.04 x 0.16 in²), Length: each 1.065 m (41.93 in) MC KST4/KBT4: 1 x 4 mm² (0.04 x 0.16 in²), Length: each 1.0 m (39.37 in)

Operating Conditions

Operating Temperature	-40 ~ +85 °C
Ambient Temperature Range	-40 ~ +45 °C
Max. System Voltage IEC/UL	1000 V / 1000 V
Serial Fuse Rating	15 A
Maximum Surface Load Capacity	Tested up to 5400 Pa according to IEC 61215 (advanced test)

Warranties and Certifications

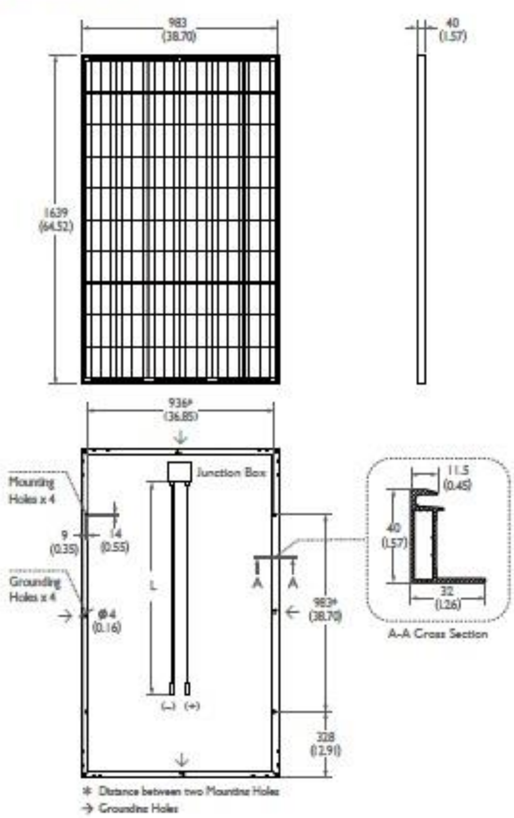
Product Warranty	Maximum 10 years for material and workmanship
Performance Guarantee	Guaranteed linear degradation to 80% for 25 years *1
Certifications	According to IEC/EN 61215, IEC/EN 61730 and UL 1703 guidelines *2

*1: Please refer to warranty letter for detail
*2: Please confirm other certifications with official dealers

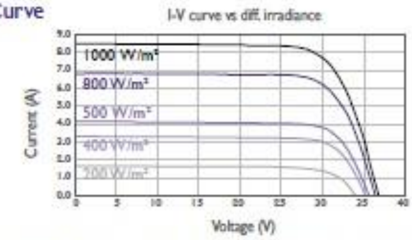
Packing Configuration

Container	20' GP	40' GP	40' HQ
Pieces per Pallet	26	26	26
Pallets per Container	6	14	28
Pieces per Container	156	364	728

Dimensions mm (inch)



I-V Curve



Current/voltage characteristics with dependence on irradiance and module temperature.

Dealer Stamp

AU Optronics Corporation
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Tel: +886-3-500-8899 www.BenQSolar.com

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Appendix 3 | PV module data sheet - OMSUN FCP 250W

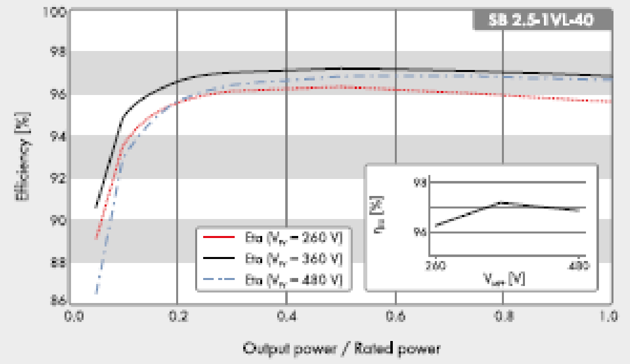
ELECTRICAL CHARACTERISTICS				
FCP265-245W POLY 60 CELLS				
Model	FCP265	FCP260	FCP250	FCP245
Peak Power Pmpp	265W	260W	250W	245W
Voltage at Vmpp	32.84V	32.35V	31.36V	30.86V
Current at Impp	8.07A	8.04A	7.98A	7.94A
Open Circuit Voltage Voc	38.56V	38.49V	38.41V	38.32V
Short Circuit Current Isc	8.60A	8.56A	8.51A	8.47A
Module Efficiency	16.01%	15.80%	15.20%	14.90%
Wattage Tolerance	4.99W	4.99W	4.99W	4.99W
FCP240-225W POLY 60 CELLS				
Model	FCP240	FCP235	FCP230	FCP225
Peak Power Pmpp	240W	235W	230W	225W
Voltage at Vmpp	30.38V	29.90V	29.37V	28.85V
Current at Impp	7.90A	7.86A	7.83A	7.80A
Open Circuit Voltage Voc	38.22V	38.11V	37.99V	37.86V
Short Circuit Current Isc	8.43A	8.39A	8.34A	8.31A
Module Efficiency	14.71%	14.41%	14.10%	13.80%
Wattage Tolerance	4.99W	4.99W	4.99W	4.99W
FCP220-190W POLY 60 CELLS				
Model	FCP220	FCP210	FCP200	FCP190
Peak Power Pmpp	220W	210W	200W	190W
Voltage at Vmpp	28.34V	27.32V	26.30V	25.28V
Current at Impp	7.77A	7.71A	7.65A	7.59A
Open Circuit Voltage Voc	38.01V	38.15V	37.31V	37.48V
Short Circuit Current Isc	8.27A	8.22A	8.18A	8.14A
Module Efficiency	13.40%	12.80%	12.20%	11.60%
Wattage Tolerance	4.99W	4.99W	4.99W	4.99W
FCP180-100W POLY 60 CELLS				
Model	FCP180	FCP150	FCP130	FCP100
Peak Power Pmpp	180W	150W	130W	100W
Voltage at Vmpp	22.84V	18.35V	18.00V	17.79V
Current at Impp	8.07A	7.92A	7.27A	5.63A
Open Circuit Voltage Voc	25.56V	22.49V	21.41V	21.20V
Short Circuit Current Isc	8.60A	8.56A	7.80A	6.09A
Module Efficiency	14.70%	13.52%	12.40%	12.22%
Wattage Tolerance	4.99W	4.99W	4.99W	4.99W

TEMPERATURE COEFFICIENT	
Temp. Coefficient at Isc	0.072 (%/k)
Temp. Coefficient at Voc	-0.338 (%/k)
Temp. Coefficient at Pmpp	-0.475 (%/k)
Normal Operating Cell Temperature (NOTC)	45±2°C
Degradation (% per year)	0.60%
Measured Power Tolerance	±3%
Maximum System Voltage	1000V
Operating Module Temperature	-40 to +85°C
Standard Testing Conditions (STC)	Irradiance 1000w/m²/Module temp 25°C/Air Mass 1.5

MECHANICAL CHARACTERISTICS	
Dimensions	1640mm x 991mm x 40mm
Weight	20.5kg
No. of Cells	60 cells (156mm x 156mm)
Glass	3.2mm low tempered iron glass
Frame	Extra strong anodized aluminium frame
By-Pass Diodes	3, 6
Junction Box	MC4 compatible
Cables	1000mm x 4mm²

Appendix 4 | Inverter data sheet – Sunny Boy 2,5

Efficiency Curve



● Standard features ○ Optional – Not available

Data at nominal conditions

Last revision: March 2015

Technical Data	Sunny Boy 1.5	Sunny Boy 2.5
Input (DC)		
Max. DC power (@cos φ = 1)	1,600 W	2,650 W
Max. input voltage	600 V	600 V
MPP voltage range	160 V to 500 V	260 V to 500 V
Rated input voltage	360 V	360 V
Min. input voltage / initial input voltage	50 V / 80 V	50 V / 80 V
Max. input current	10 A	10 A
Max. input current per string	10 A	10 A
Number of independent MPP inputs / strings per MPP input	1 / 1	1 / 1
Output (AC)		
Rated power (at 230 V, 50 Hz)	1,500 W	2,500 W
Max. apparent AC power	1,500 VA	2,500 VA
Nominal AC voltage	220 V / 230 V / 240 V	220 V / 230 V / 240 V
Nominal AC voltage range	180 V to 280 V	180 V to 280 V
AC power frequency/range	50 Hz, 60 Hz / -5 Hz to +5 Hz	50 Hz, 60 Hz / -5 Hz to +5 Hz
Rated power frequency/rated grid voltage	50 Hz / 230 V	50 Hz / 230 V
Max. output current	7 A	11 A
Power factor at rated power	1	1
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited	
Feed-in phases/connection phases	1 / 1	1 / 1
Efficiency		
Max. efficiency / European weighted efficiency	97.2 % / 96.1 %	97.2 % / 96.7 %
Protective Devices		
DC-side disconnection point	●	●
Ground fault monitoring / grid monitoring	● / ●	● / ●
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / –	● / ● / –
All-pole sensitive residual-current monitoring unit	●	●
Protection class (according to IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III	I / III
Reverse current protection	Not required	Not required
General Data		
Dimensions (W / H / D)	460 / 357 / 122 mm (18.1 / 14.1 / 4.8 inches)	
Weight	9.2 kg (20.3 lbs)	
Operating temperature range	-40 °C to +60 °C (-40 °F to +140 °F)	
Noise emission, typical	<25 dB	<25 dB
Self-consumption (at night)	2.0 W	2.0 W
Topology	Transformerless	Transformerless
Cooling method	Convection	Convection
Degree of protection (according to IEC 60529)	IP65	IP65
Climatic category (according to IEC 60721-3-4)	4K4H	4K4H
Maximum permissible value for relative humidity (non-condensing)	100 %	100 %
Features		
DC connection / AC connection	SUNCLIX / connector	SUNCLIX / connector
Display	–	–
Interfaces: RS485, Bluetooth®, Speedwire / Webconnect, WLAN	– / – / ● / ●	– / – / ● / ●
Integrated web server	●	●
Warranty: 5 / 10 / 15 / 20 / 25 years	● / ○ / ○ / ○ / ○	● / ○ / ○ / ○ / ○
Certificates and approvals (others available upon request)	AS4777.3, C10/11/2012, VDE-AR-N4105, CEI0-21Int, NEN-EN50438, G83/2, EN50438, VFR2014	
Type designation	SB 1.5-1VL-40	SB 2.5-1VL-40

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Appendix 5 | Inverter data sheet - GoodWe GW2500-NS

Technical Data	GW1000-NS	GW1500-NS	GW2000-NS	GW2500-NS	GW3000-NS
DC Input Data					
Max. DC power [W]	1200	1800	2300	2700	3200
Max. DC voltage [V]	450	450	450	500	500
MPPT voltage range [V]	80~400	80~400	80~400	80~450	80~450
Starting voltage [V]	80	80	80	80	80
Max. DC current [A]	10	10	10	18	18
No. of DC connectors	1	1	1	1/2 (optional)	1/2 (optional)
No. of MPPTs	1	1	1	1	1
DC connector	AMPHENOL/ MC4/ SUNCLIX			AMPHENOL/ MC4/ SUNCLIX	
AC Output Data					
Norminal AC power [W]	1000	1500	2000	2500	3000
Max. AC power [W]	1000	1500	2000	2500	3000
Max. AC current [A]	5	7. 5	10	12. 5	13. 5
Norminal AC output	50/60Hz; 230Vac			50/60Hz; 230Vac	
AC output range	45~55Hz/55~65Hz; 180~270Vac			45~55Hz/55~65Hz; 180~270Vac	
THDi	<3%			<3%	
Power factor	0.9 leading~0.9 lagging			0.9 leading~0.9 lagging	
Grid connection	Single phase	Single phase	Single phase	Single phase	Single phase
Efficiency					
Max. efficiency	96.5%	97.0%	97.0%	97.5%	97.5%
Euro efficiency	>96.0%	>96.0%	>96.0%	>97.0%	>97.0%
MPPT adaptation efficiency	99.9%	99.9%	99.9%	99.9%	99.9%
Protection					
Residual current monitoring unit	Integrated			Integrated	
Anti-islanding protection	Integrated			Integrated	
DC switch	Integrated (optional)			Integrated (optional)	
AC over current protection	Integrated			Integrated	
Insulation monitoring	Integrated			Integrated	
Certifications & Standards					
Grid regulation	G83/2, VDE0126-1-1, AS4777.2&.3, EN50438, ERDF-NOI-RES_13E;			G83/2, VDE0126-1-1, AS4777.2&.3, EN50438, ERDF-NOI-RES_13E;	
Safety	According to IEC62109-1&-2, AS3100			According to IEC62109-1&-2, AS3100	
EMC	EN 61000-6-1, EN 61000-6-2, EN 61000-6-3, EN 61000-6-4, EN 61000-3-2, EN 61000-3-3			EN 61000-6-1, EN 61000-6-2, EN 61000-6-3, EN 61000-6-4, EN 61000-3-2, EN 61000-3-3	
General Data					
Dimensions (WxHxD)	344*274.5*128mm			344*274.5*128mm	
Weight [kg]	7.5			8.5	
Mounting	Wall bracket			Wall bracket	
Ambient temperature range	-25~60°C (> 45°C derating)			-25~60°C (> 45°C derating)	
Relative humidity	0~95%			0~95%	
Max. operating altitude	3000			3000	
Protection degree	IP65			IP65	
Topology	Transformerless			Transformerless	
Night power consumption [W]	<1			<1	
Cooling	Nature convection			Nature convection	
Noise emision [dB]	<25			<25	
Display	LCD			LCD	
Communication	USB2.0; WiFi or RS485			USB2.0; WiFi or RS485	
Standard warranty [years]	5/10/15/20/25 (optional)			5/10/15/20/25 (optional)	

2 TECHNICKÉ PARAMETRY

Technické parametry zařízení LXDC POWER BOX 1-2, 1-4 a 1-6 kW DC

Provozní režimy:

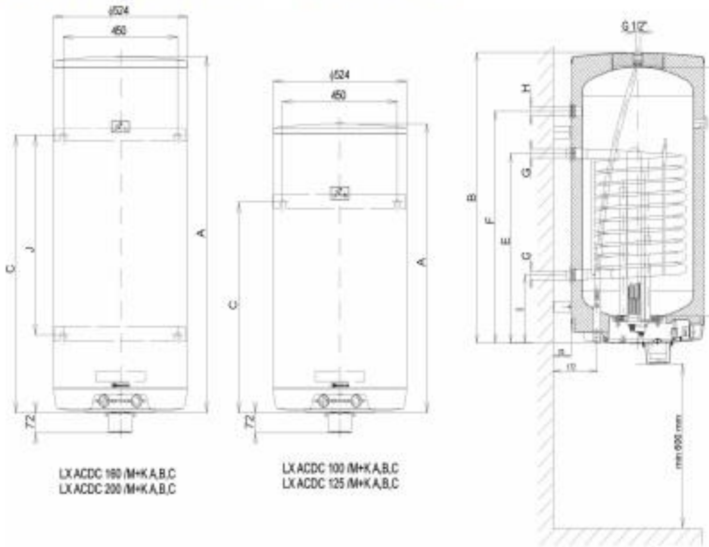
- ON MPP – řízené napájení DC topného tělesa s využitím DC/DC převodníku s funkcí MPP
- OFF MPP – neřízené – přímé napájení DC topného tělesa z FVP

Vstupný proud pro změnu režimů:	≤6,0A/5,8A (režim ON MPP); ≥6,0A/5,8A (režim OFF MPP)
Maximální vstupní napětí:	350 VDC, 2 x 350 VDC a 3 x 350 VDC
Maximální vstupní proud:	10A, 2 x 10A a 3 x 10A
Výstupná zátěž:	volitelný výkon: 1kW, 1,5kW, 2kW, 3kW, 4kW, 5kW, 6kW
Charakter výstupného napětí a proudu:	stejnosměrné napětí a proud
Provozní PWM frekvence:	16kHz +/-0,5kHz
Minimální startovací vstupní napětí:	85 VDC
Minimální vstupní proud pro stálý provoz PWM:	100mA
Pracovní rozsah MPPT:	85 až 350 VDC
Maximální výstupní napětí pro jednotlivé typy:	350 VDC, 2 x 350 VDC a 3 x 350 VDC
Maximální výstupní proud pro jednotlivé typy:	10A, 2 x 10A a 3 x 10A
Průměrná účinnost (výkon 2 kW):	98,5%
Vlastní spotřeba:	2 W - přes den při provozu 0 W - mimo provoz
Rozměry (š x v x h):	255 x 270 x 95 mm, 500 x 420 x 95 mm a 500 x 420 x 95 mm
Hmotnost:	2,4 kg, 3,9kg a 4,9kg
Stupeň krytí:	IP 45
Pracovní okolní teplota:	0 až 35 °C
Skladovací teplota:	-25 až +60 °C

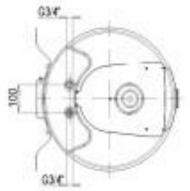
Solární ohřívače TV pro připojení k fotovoltaickým panelům LX ACDC/M+K ABC 100 – 200 litrů

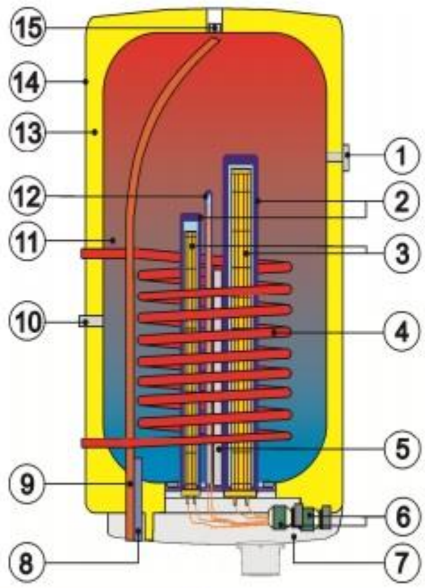
Popis označení
LX ACDC/M+K ABC 200
LX ACDC/M+KW ABC 200

LX.......... typové označení
ACDC .... topná jednotka na střídavý i stejnosměrný proud
M.......... označení pro ohřívač se stykačem který umožňuje přepnout po ohřátí zásobníku na měnič (do sítě)
K............ zásobník s teplovodním výměníkem
W.......... zásobník s teplovodním výměníkem v horní části zásobníku
A,B,C..... výkonová řada topné patrony na fotovoltaiku
A........... 1kW
B........... 1,5kW
C........... 2 kW
200........ objem zásobníku



	LX ACDC 100/M+K A,B,C	LX ACDC 125/M+K A,B,C	LX ACDC 160/M+K A,B,C	LX ACDC 200/M+K A,B,C
A	881	1046	1235	1287
B	876	1041	1230	1282
C	636	801	1005	793
D	524	524	524	584
E	701	701	701	685
F	551	551	831	895
G	G1"	G1"	G1"	G1"
H	G3/4"	G3/4"	G3/4"	G3/4"
I	261	261	261	245
J	-	-	815	600



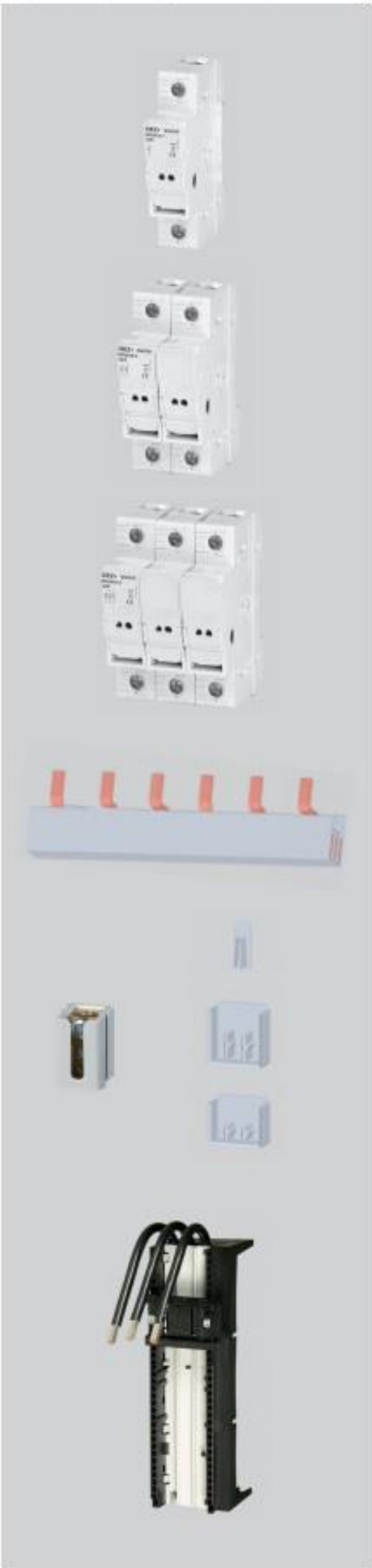


1 - Indikátor teploty
2 - Jímky topných těles
3 - Keramická topná tělesa
4 - Trubkový výměník
5 - Hořčíková anoda
6 - Provozní termostaty s vnějším ovládáním a bezpečnostní termostaty
7 - Kryt elektroinstalace
8 - Napouštěcí trubka studené vody
9 - Vypouštěcí trubka teplé vody
10 - Cirkulace
11 - Ocelová smaltovaná nádoba
12 - Jímka pro snímače termostatů
13 - Polyuretanová bezfreonová izolace
14 - Plášť ohřívače
15 - Další výstup teplé vody

DRAŽICE
ČLEN SKUPINY NIBE

Družstevní závody Dražice – strojírna s.r.o.
Dražice 69
294 71 Benátky nad Jizerou
Tel.: 721 238 889
E-mail: jaroslav.oliva@dzd.cz
www.dzd.cz

POJISTKOVÉ ODPÍNAČE OPVA10 DO 32 A



Pojistkové odpínače OPVA10 jsou určeny pro válcové pojistkové vložky PVA10, PV10 velikosti 10x38. Umožňují bezpečně odpínat jmenovité proudy a nadproudy. Přístroje splňují podmínky pro bezpečné odpojení. Opačné připojení je přípustné a nemá vliv na technické parametry ani na bezpečnost obsluhy.

- Pojistkové odpínače OPVA10 lze v uzavřeném stavu zaplombovat.
- Přístroje jsou řešeny jako modulární a pro výřez v rozváděči 45 mm.
- Montáž na „U" lištu typu TH35 dle ČSN EN 60715 nebo na desku (doporučena ocelová lišta).
- OPVA10...S-signalizace stavu pojistkové vložky.
- Stav pojistkových vložek lze signalizovat pomocí elektronické signalizace viz str. D17.

Pojistkové odpínače

Typ	Kód výrobku	I_e [A]	Počet pólů	Hmotnost [kg]	Balení [ks]
OPVA10-1	41005		1	0,063	12
OPVA10-1-S	41006		1	0,068	12
OPVA10-1N	41007		1+N	0,133	6
OPVA10-2	41008	32	2	0,128	6
OPVA10-2-S	41009		2	0,137	6
OPVA10-3	41010		3	0,193	4
OPVA10-3-S	41011		3	0,193	4
OPVA10-3N	41012		3+N	0,271	3

Příslušenství

Popis	Typ	Kód výrobku	Hmotnost [kg]	Balení [ks]
Jednopólová propojovací lišta, průřez 10 mm², max. proud 63 A jmenovité pracovní napětí 690 V a.c./1000 V d.c., délka 210 mm	**S1L-210-10**	38475	0,047	50
Jednopólová propojovací lišta, průřez 16 mm², max. proud 80 A jmenovité pracovní napětí 690 V a.c./1000 V d.c., délka 1 m	**S1L-1000-16**	37375	0,302	50
Dvoupólová propojovací lišta, průřez 10 mm², max. proud 63 A jmenovité pracovní napětí 415 V a.c., délka 210 mm	**S2L-210-10**	38476	0,110	20
Dvoupólová propojovací lišta, průřez 16 mm², max. proud 80 A jmenovité pracovní napětí 415 V a.c., délka 1 m	**S2L-1000-16**	37378	0,447	20
Třípólová propojovací lišta, průřez 10 mm², max. proud 63A jmenovité pracovní napětí 415 V a.c., délka 210 mm	**S3L-210-10**	38482	0,110	25
Třípólová propojovací lišta, průřez 16 mm², max. proud 80 A jmenovité pracovní napětí 415 V a.c., délka 1 m	**S3L-1000-16**	37379	0,737	20
Koncová krytka, pro jednopólové lišty o průřezu 10, 16 mm²	**EKC-1**	37383	0,0005	10
Koncová krytka, pro dvou a třípólové lišty o průřezu 16 mm²	**EKC-2+3**	37384	0,001	10
Koncová krytka, pro třípólové lišty o průřezu 10 mm²	**EKC-3**	37385	0,001	10
Připojovací blok, umožňuje napájení propojovacích lišt vodiči o průřezu až 35 mm², použití bloku rozšiřuje montážní šířku o další N - póly	**ES-35-GS**	00175	0,03	10
Adaptér na přípojnice s roztečí 60 mm, tloušťka přípojnic 5 nebo 10 mm, šířka přípojnic 12 ÷ 30 mm, kabelový vývod dole, max. proud 63 A	**GA-60/63/54-1x7,5**	11883	0,56	1

Parametry

Jmenovitý pracovní proud	I_e		32 A
Jmenovité pracovní napětí	U_e		690 V a.c./440 V d.c.
Rozsah napětí LED signalizace			110 ÷ 690 V a.c./d.c.
Kategorie užití		400 V a.c. 690 V a.c.	AC-22B AC-20B
Smluvený tepelný proud s pojistkovou vložkou	I_{th}		32 A
Jmenovitý kmitočet	f_n		50 ÷ 60 Hz
Jmenovité izolační napětí	U_i		800 V a.c.
Jmenovitý podmíněný zkratový proud s pojistkovými vložkami PV (efektivní hodnota)	I_c	400 V a.c. 690 V a.c.	100 kA 50 kA
Jmenovité impulzní výdržné napětí	U_{imp}		6 kV
Velikost pojistkové vložky	průměr x délka		10x38
Max. ztráty pojistkové vložky	P_v		3 W
Jmenovitý krátkodobý výdržný proud	I_{cw} 1 s		1,6 kA
Jmenovitá zkratová zapínací schopnost při 440 V d.c.	I_{cm}		3,5 kA