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Федеральное государственное автономное образовательное учреждение
высшего образования
**«НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ»
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МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ / MASTER'S THESIS

Тема работы / Theme

«Технико-экономическое обоснование вариантов построения фотоэлектрических станций для объектов малоэтажного строительства»
«Economical and Technical Aspects of Solar Panels Installation on a Single-family House»

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Томск / Tomsk – 2016

Министерство образования и науки Российской Федерации
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Институт **Энергетический (ЭНИН)**
Направление подготовки **13.04.02 – Электроэнергетика и электротехника**
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ЗАДАНИЕ
на выполнение выпускной квалификационной работы

В форме:

магистерской диссертации

Студенту:

Группа	**ФИО**
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Тема работы:

«Технико-экономическое обоснование вариантов построения фотоэлектрических станций для объектов малоэтажного строительства» «Economical and Technical Aspects of Solar Panels Installation on a Single-family House»	
Утверждена приказом директора (дата, номер)	

Срок сдачи студентом выполненной работы:	

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 функционирования (эксплуатации) объекта или изделия в плане безопасности эксплуатации, влияния на окружающую среду, энергозатратам; экономический анализ и т. д.).*	Объект исследования: Системы электроснабжения на основе солнечных фотоэлектрических установок. Цель работы: сравнительный анализ применения установок малой солнечной фотоэнергетики в России и в Чешской республике.

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 применения возобновляемых энергоисточников, включая энергию Солнца. - Определение нагрузок объекта электроснабжения. - Оценка солнечного потенциала рассматриваемых территорий. Технико-экономическое обоснование принимаемых решений.
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Работа выполняется на английском языке

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Table of Contents

1 Introduction

Renewable resources are a frequently discussed topic lately. This year's heat waves in India or Iran, droughts in California and other places do not allow humankind to ignore the climate change anymore. This thesis focuses on specific part of lowering the carbon footprint – decentralized photovoltaic electricity production. The major problem with low-CO_2 technologies in this field were costs. However, in places with higher electricity prices and abundant sunshine solar panels started to be a cost-effective solution in the past years.

I decided to explore solar panels as a key renewable power source for a couple of reasons. Firstly, it is scalable. The lowest limit is tens of watts, the highest is restricted only by the size of a roof. Secondly, it does not have any moving parts. Compared to many other renewable technologies, photovoltaic system lacks any moving components, thus the maintenance is easier. Thirdly, it openly shows the owner's attitude about sustainable energy sources. In addition, electricity bill is a significant portion of monthly expenses for a family and it would be reasonable to reduce it.

This thesis' goal is to explore two potential places for utilization of photovoltaic technology. One is a city of Dobrichovice in the Czech Republic and the other is Kolpashevo in the Russian Federation. There are two views explained in this thesis, technical point of view and economic analysis.

Technical variables include insolation, solar electricity production, house power needs or ratio of utilized electricity. Economic breakdown comprises of figures like net present value, internal rate of return or payback period.

In chapter 3, basic renewables potential is discussed, both from global and local perspective. In addition, fundamental solar technologies are described

Chapter 4 explains the utilized methodology of technical calculations and economic algorithms.

Chapter 5 debates the results and provides comparison of the situation in Dobrichovice and Kolpashevo. This part answers the essential question, whether or not it is economically reasonable to invest in roof solar panels. When not, which circumstances need to change in order for the project to be viable.

It is possible, that the purchase of photovoltaic system would be profitable under current conditions. Perhaps, a government involvement would be necessary. Alternatively, some market trends or figures would need to change.

2 Problem Definition

Cost of electricity from renewable resources (especially wind and solar) have been going down lately. [1] The primary goal of this thesis is to evaluate whether it is economically viable to replace part or all electricity consumption of an ordinary household by renewables, particularly by photovoltaic panels.

As a base for comparison would be used a model of a non-existing house. This virtual residential unit is located in two places, one is a city of Dobrichovice in the Czech Republic and the other is a city of Kolpashevo in the Russian Federation.

First, let me describe the global perspective.

3 Theoretical Framework

3.1 Renewable Energy Sources

Since ancient times electricity was generated from non-renewable sources. In the beginning coal and wood was used, later oil, natural gas and uranium. Those resources will not last forever. That is why it is reasonable to find other possibilities.

There is a large group of practically infinite sources. We call them renewable energy sources. It could be the Sun, which transfers light to the Earth the whole day. Rivers, flowing down to the seas and oceans. The wind. The Moon. Geothermal power. And the others. Many choices. But only one problem. To produce electricity so the process would be economically effective.

3.1.1 The Sun

The Sun radiates from its surface 70 to 80 thousand kW/m^2. The Earth receives only a fraction of the total power. At the sea level on a sunny day, 0.855 to 1 kW/m^2 reaches surface. [2] Of course, this number varies based on location and time. Calculations regarding this topic will be mentioned later.

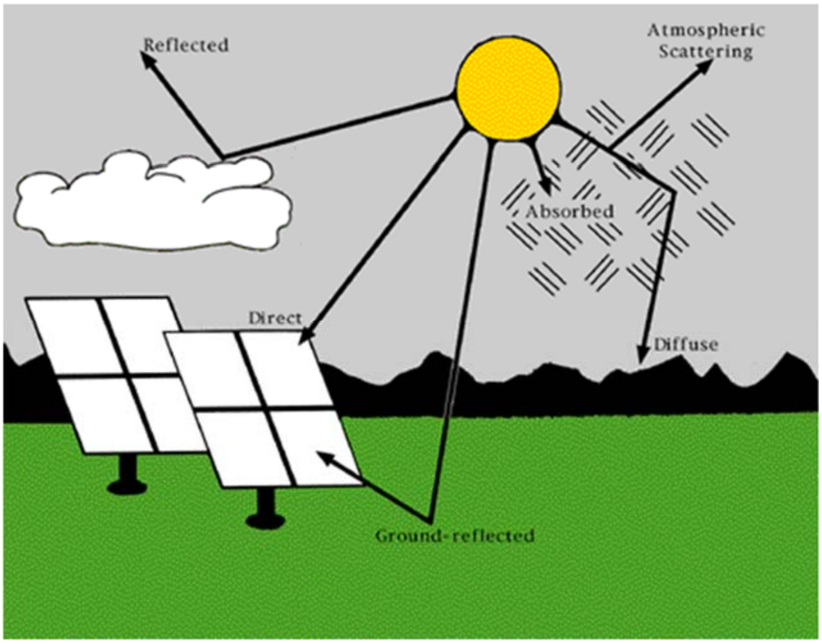

Figure 1 Direct, diffuse and ground-reflected irradiances [3]

Figure 1 explains terms connected to sun irradiance [2]:

- Direct irradiance (the light going directly from the Sun to the surface of Earth).
- Diffuse irradiance (the result of sunlight passing through the atmosphere and being diffused).
- Ground-reflected radiation (what is reflected from Earth's surface)
- Global irradiance (sum of direct, diffuse irradiance and sometimes ground-reflected radiance, based on significance).
- Sunshine duration (how many hours the Sun shines).

The most important is how much energy the Sun delivers each day, month, year. When we calculate global irradiance and sunshine duration, we receive the following table:

Latitude → Month ↓	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
January	5,8	4,8	3,7	2,5	1,3	0,5	0	-	-	-
February	6,1	5,3	4,3	3,2	2	1	0,2	0	-	-
March	6,4	6	5,3	4,4	3,4	2,2	1,1	0,3	0	-
April	6,3	6,3	6,1	5,6	4,9	3,9	2,8	1,7	0,6	0,1
May	5,9	6,3	6,5	6,4	6,1	5,5	4,6	3,6	2,9	2,3
June	5,5	6,2	6,6	6,8	6,7	6,4	5,9	5,2	4,7	4,7
July	5,4	6,1	6,6	6,8	6,8	6,3	6	5,3	5	4,9
August	5,7	6,2	6,3	6,5	6,2	5,7	5	4	3,2	3
September	6,1	6,3	6,2	5,8	5,1	4,3	3,2	2,1	1	0,4
October	6,3	6	5,5	4,7	3,7	2,6	1,5	0,5	0	-
November	6,1	5,4	4,5	3,5	2,3	1,2	0,4	0	-	-
December	5,8	4,9	3,8	2,6	1,5	0,5	0	-	-	-
Average	5,95	5,82	5,45	4,90	4,17	3,34	2,56	2,27	2,18	2,57

Table 1 Average solar radiation, kWh/m² [2]

As we can see, the amount of average solar radiation reduces significantly with latitude. At the equator, insolation averages at 5.95 kWh/m² and closer to poles it goes down to 2.18 kWh/m² and this number is achieved only during summer months.

The two locations that are going to be examined in this diploma thesis are Dobrichovice in the Czech Republic and Kolpashevo in the Russian Federation. Dobrichovice has a latitude of 49.9° N [4] and Kolpashevo has a latitude of 58.3° N [5]. Thus, the average solar radiation would be approximately 3.34 kWh/m² and 2.56 kWh/m², respectively.

3.1.2 The Wind

The potential of harnessing the power of the wind varies greatly from place to place. It depends on the movements of air mass as a result of seasonal and/or weather changes. Let us take a closer look at this illustration.

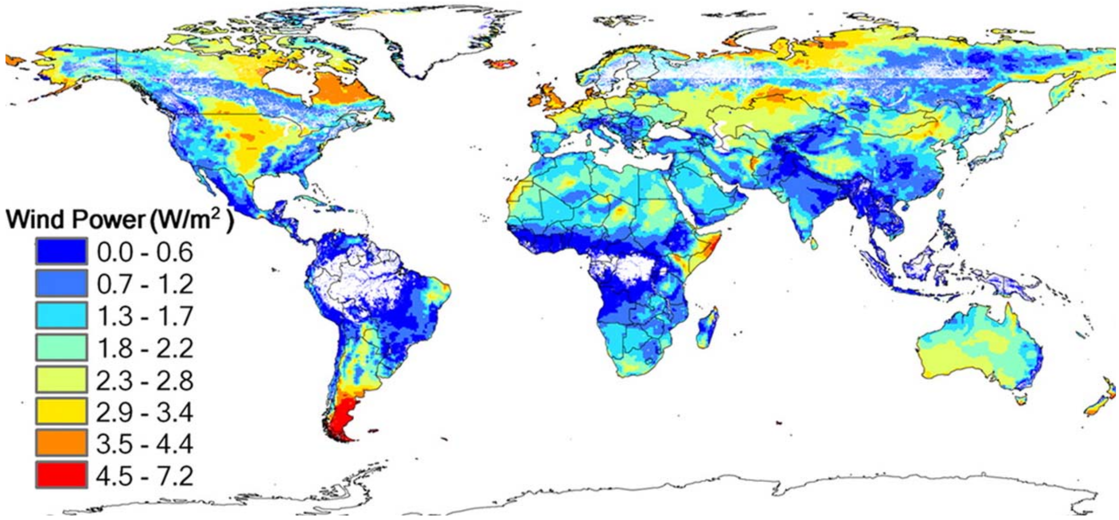

Figure 2 Global potential for wind-generated electricity [6]

As we can see in Figure 2, some regions are more suitable for the exploitation of wind power. That is why there are many wind turbines being built or already standing in places like northern Germany or Denmark.

"The potential of wind power as a global source of electricity is assessed by using winds derived through assimilation of data from a variety of meteorological sources. The analysis indicates that a network of land-based 2.5-megawatt (MW) turbines restricted to nonforested, ice-free, nonurban areas operating at as little as 20% of their rated capacity could supply >40 times current worldwide consumption of electricity, >5 times total global use of energy in all forms." [6]

Moreover, the price of electricity produced from the wind turbines is expected to drop significantly in the following decades, mostly due to economies of scale and manufacturing improvements. [7]

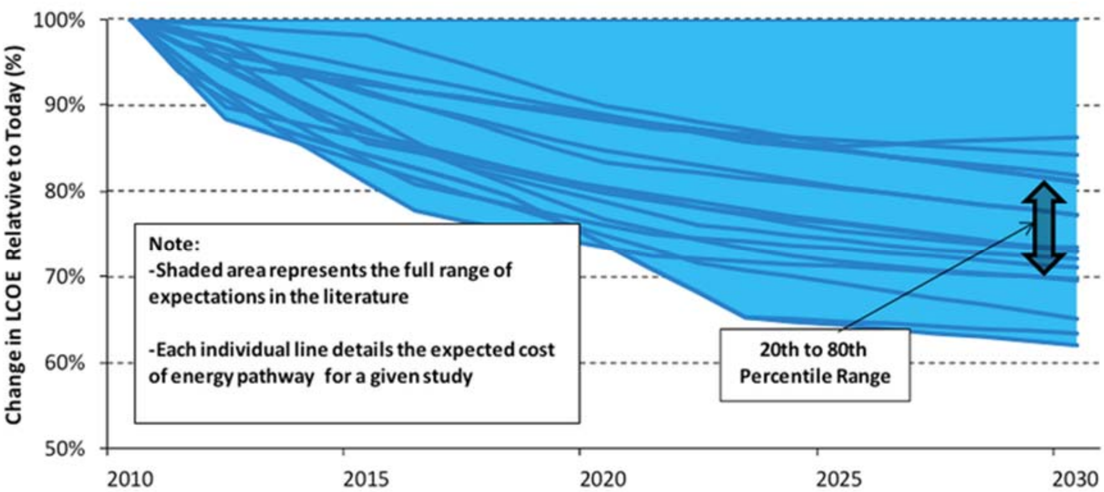

Figure 3 Estimated range of future wind levelized cost of electricity across 18 scenarios [7]

"The data presented in Figure 3 suggest an approximate 0%–40% reduction in LCOE through 2030. By focusing on the results that fall between the 20th and 80th percentiles of scenarios, however, the range is narrowed to roughly a 20%–30% reduction in LCOE. Initial cost reductions range from 1%–6% per year. By 2030, all but one scenario envisions cost reductions falling below 1% per year." [7]

3.1.3 Hydropower

Hydropower is the most flexible and consistent of the renewable energy resources, capable of meeting base load electricity requirements as well as meeting peak and unexpected demand due to shortages or the use of intermittent power sources. [8]

There are three types of hydropower stations: 'run of river', where the electricity is generated through the flow of a river; 'reservoir', where power is generated through the release of stored water; and 'pumped storage', where stored water is recycled by pumping it back up to a higher reservoir in order to be released again. [8] Pumped storage is very important in the context of other renewables, because it is one of the few economically viable options of electricity storage.

According to all the above information, hydropower seems like an ideal solution of all our electricity needs. Its development is limited in two factors though. The first is the limited potential for new hydropower installations, especially in most developed economies of Europe and Northern America. Other limiting factors are investment capacity and the social and environmental impacts of large dams. [9]

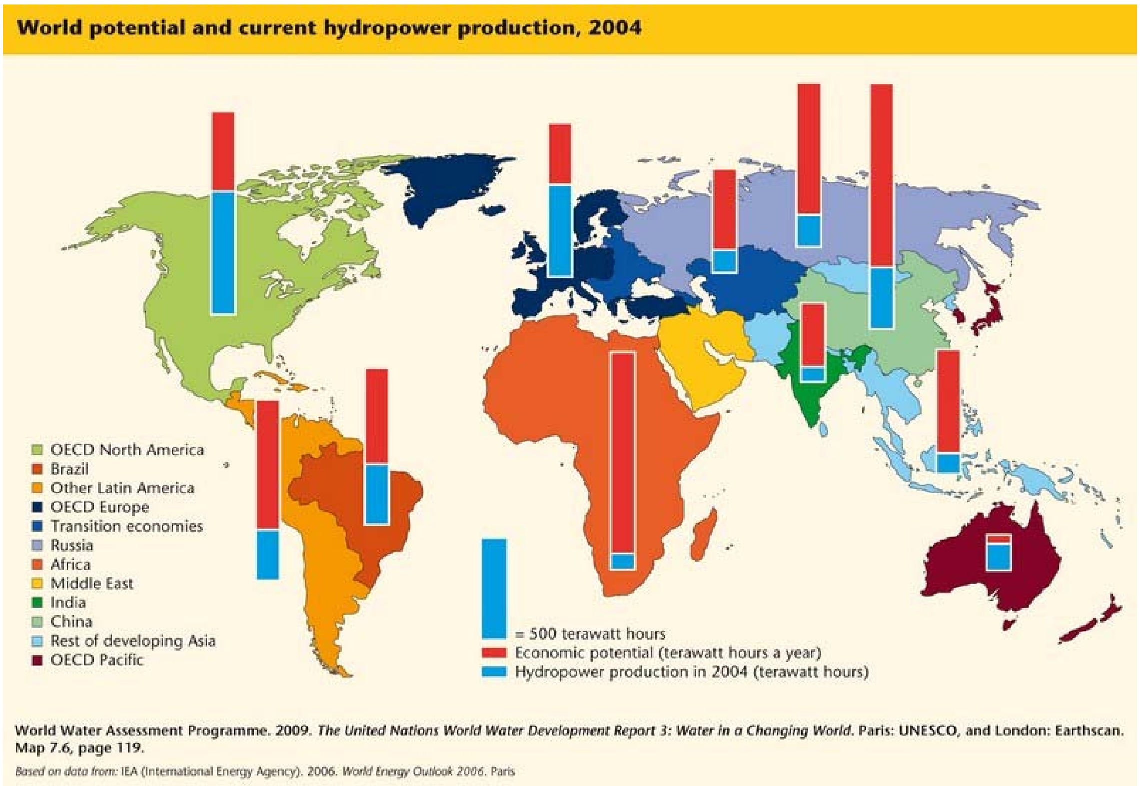

Figure 4 World potential and current hydropower production [9]

3.2 Local Potential of Renewables

The scope changes from a global point of view to a local one, specifically the two cities mentioned earlier – Dobrichovice and Kolpashevo.

3.2.1 Renewables Potential, Dobrichovice

The city of Dobrichovice is located in Central Bohemian Region, about 25 kilometers south-west of Prague, Czech Republic. It has a population of about 3000 and several hundred temporary inhabitants (mainly from Prague). Its latitude is approximately 50°N. [10]

Figure 5 Location of Dobrichovice in the Czech Republic [11]

This city was selected because this region is a common destination for families leaving Prague as a result of deurbanization. It is easy to imagine a model two-story house as used in this thesis to be situated in a city like Dobrichovice.

A household uses energy for three main purposes – heating, hot-water supply and for lighting and running home appliances. A majority of homes in Czech Republic use sources like natural gas or coal for heating and providing hot water. [12] Electricity is thus utilized only as a source of lighting and running other machines – washing machines, fans, TVs.

3.2.1.1 Ecology

Conventional electricity production is burdened by tremendous environmental impact because majority of world power is obtained from fossil fuels. The most alarming is the worldwide production of CO_2, one of the key global warming factors. As can be seen in Figure 6, the most environmentally damaging is coal, with CO_2 production ranging from 750 to 1231 g per kWh generated. Following coal is electricity produced from oil with 550 – 946 g/kWh and natural gas sending into atmosphere 399 to 644 g of CO_2 per kWh. What may be surprising is the difference between “greenness” of photovoltaics compared to other environmentally friendly sources like wind or hydropower. The reason is high energy requirements when manufacturing and decommissioning solar panels and relatively low real output during their lifetime. [13]

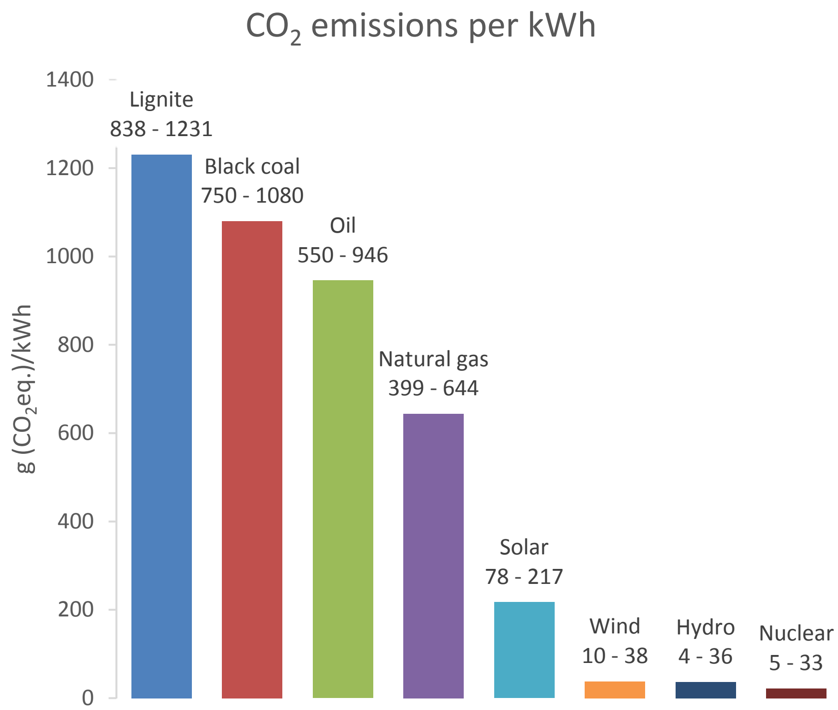

Figure 6 CO2 emissions per kWh [14]

According to Figure 7, almost half of electricity in the Czech Republic is generated in thermal power plants burning brown or black coal. As I have mentioned earlier, those sources produce high amounts of CO_2 and are with natural gas the least environmentally friendly. Other significant portion of electricity is generated in nuclear power plants. Atomic energy has low CO_2 footprint, but the problem lies in the social and economic spheres. Nuclear waste is radioactive for many years and nobody wants to have it in his/her backyard. Czech law regulations define that 1.17 kg of CO_2 is produced per every kWh generated. [15]

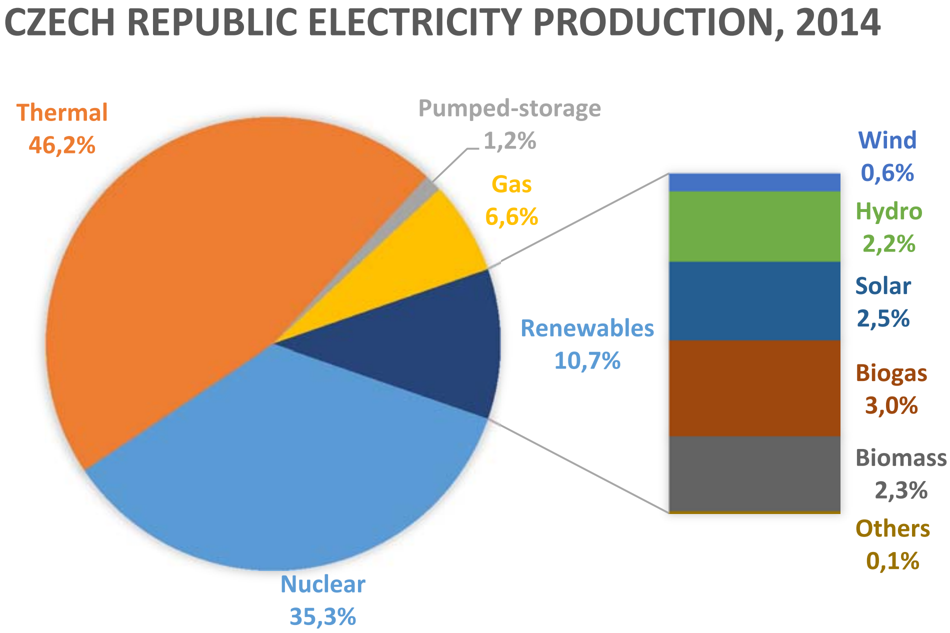

Figure 7 Czech Republic gross electricity generation, 2014 [16]

According to the previous numbers, every kWh produced in a decentralized manner by renewables should lower the carbon footprint by about 1 kg.

3.2.1.2 Economy

Europe's household electricity prices are in general the highest in the world. [17] Effective usage of alternative and new emerging sources are therefore more likely to be economically achievable.

In Central Bohemian Region, the average price of electricity for a residential customer was 0.157 EUR/kWh. [18] The price comprises of three main groups. The first one is an actual price of electricity bought on the market plus trader's margin. It is not regulated and forms about 45% of total household electricity expense before tax. The second part is regulated; consumer mostly pays for the transportation and distribution of energy and subsidizing of renewables. This part accounts for about 55% of price before taxes. The third group consists of taxes; the biggest is VAT that adds an additional 21% to the total electricity bill. [19]

Detailed price breakdown can be observed in Figure 8.

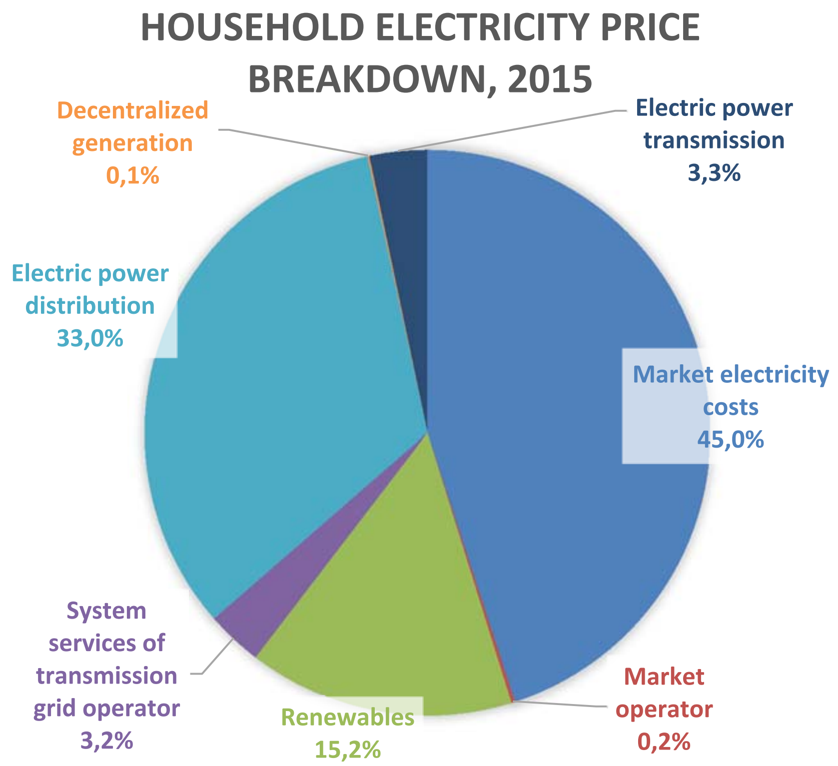

Figure 8 Household electricity price breakdown in 2015 – without taxes [19]

Czech governments no longer offers direct subsidies for new photovoltaic electricity sources. However, it provides some aids for other renewables. [20]

3.2.1.3 Suitability of Various Renewable Sources

Many renewable energy sources are straight on an unrealizable option.

Hydropower needs a suitable water source. In this thesis, I assume the building plot is an ordinary place on the outskirts of a city without any nearby river or creek.

Biomass is suitable especially for heating purposes. However, in this model all the heat generation for managing the house temperature or warming the household water is supplied by natural gas.

To produce electric power from the wind the most important factor is the wind speed. In this region, the average wind speed is 3 m/s [21] with seasonal averages ranging from 2 to 4 m/s [22]. The speed is unsuitable for efficient electricity production. [23] Additionally, wind turbines have distinct visual characteristics. Not everybody would like to have a tall pole in his or her garden or on the roof.

Utilization of solar power is much more suitable compared to other renewables. The city of Dobrichovice lies in region of average annual insulation of about 1057 to 1084 kWh/m2, as stated in Figure 9. In addition, the model house has unused roof area which can be utilized for the installation of photovoltaic panels.

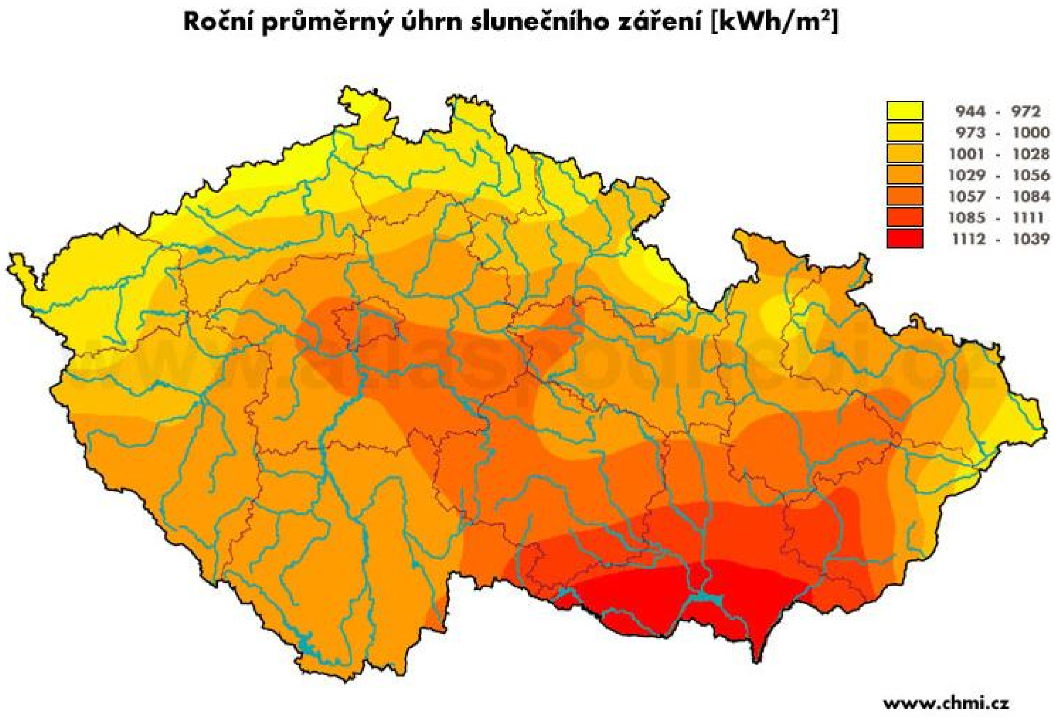

Figure 9 Average annual insolation (kWh/m2) [24]

3.2.2 Renewables Potential, Kolpashevo

The city of Kolpashevo is located in the middle of Tomsk Oblast, about 237 km from Tomsk, Russian Federation. It has about 24 000 inhabitants. Its latitude is 58°N, which puts Kolpashevo 8 more degrees to the north compared to Dobrichovice. [25]

Figure 10 Location of Tomsk Oblast in Russia [25]

Figure 11 Location of Kolpashevo in Tomsk Oblast [25]

This city was selected because it is a good representation of the climate of Tomsk Oblast and a local administrative center. It is easy to imagine a model two-story house as used in this thesis to be situated in a city like Kolpashevo.

Majority of households in Tomsk Oblast use either natural gas or central heating system for both hot water supply and heating. [26] Electricity is thus utilized only as a source of lighting and running other equipment – washing machines, fans, TVs.

3.2.2.1 Ecology

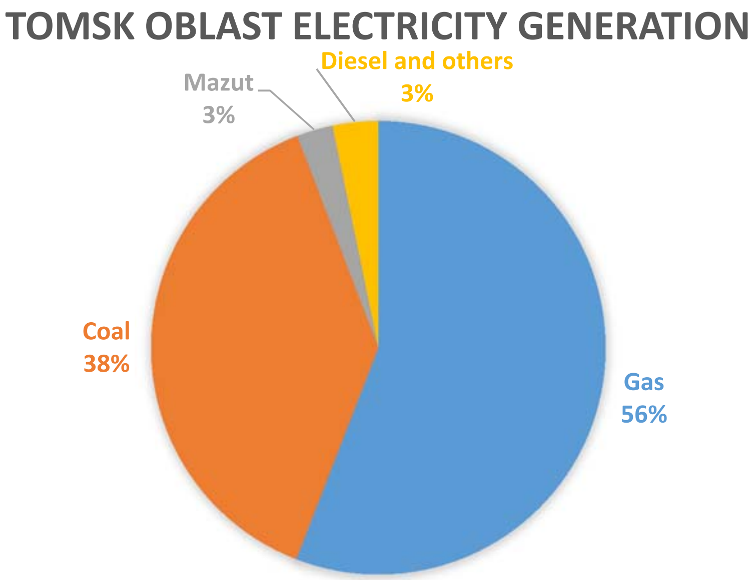

Figure 12 Tomsk Oblast electricity generation [27]

Electricity in Tomsk Oblast is generated mostly from natural gas. Its share accounted for about 56% in 2010. The second most common source is coal with 38%. It is important to note that about half of the necessary electric power was imported from neighboring regions. [28] [27]

As seen in figure Figure 12, coal, oil and natural gas are the most non-environmentally friendly of sources in terms of produced CO_2 per kWh. Every bit of electricity produced by renewables is therefore helping to protect both local and global climate.

3.2.2.2 Economy

Electricity household costs vary in many areas. There are different tariffs ranging from cheap village or town ones to more expensive prices for city dwellers. There is also a variation for peak and night hours and others. Residential house in Kolpashevo would most likely be charged 0.033 EUR/kWh. [29]

There is no possibility for a non-company to sell any electricity to the electric network as opposed to laws and regulations of the Czech Republic. [26]

Regional or state government offers no subsidies or financing plans for photovoltaic sources. [26]

Many inhabited areas in northern and northeastern part of Tomsk Oblast are not connected to the central electricity grid. The distances are too vast for the connection to be economically cost-effective. Because of that, those villages and individual houses use diesel generators to produce electrical energy. It is not hard to imagine how expensive it is to transport the fuel and to maintain the engines. [30] The actual electricity price produced in this way can be approximately from 0.238 to 0.476 EUR/kWh. Those costs are however not covered by the households but are added to the electricity bill of other customers. [26] Nevertheless, this is not the case with my model house in Kolpashevo, which is connected to the regular electricity network.

3.2.2.3 Suitability of Various Renewable Sources

In terms of wind energy, average wind speed varies throughout the year from 2.1 m/s to 4.2 m/s at the height of 10 m. It is a similar situation as in Dobrichovice; those speeds are unsuitable for most of the wind turbines. At 50 m above ground the wind speeds are faster along the river Ob (passes through Kolpashevo), but such a tall tower in the vicinity of a house would be disturbing. [30]

Hydropower bears the similar problems as in Dobrichovice. It requires very specific conditions, which are not present.

Biomass is suitable especially for heating purposes. However, in this model all the heat generation for managing the house temperature or warming the household water is supplied by natural gas.

Tomsk Oblast has tremendous potential in terms of geothermal energy. At the technologically approachable depth of 1 – 4 km there are colossal supplies of safe, cheap and green energy. Still, those resources are not developed yet, they are in research and development phase. [30]

As seen in Figure 13, the central part of Tomsk Oblast (where Kolpashevo is situated) receives average annual insolation of about 1000 – 1100 kWh/m^2 which is comparable to the data in Dobrichovice. At the latitude of 58°N, solar panels can be effectively used approximately from March until August. During the other months, the panels' electricity generation falls 4 to 5 times compared to the summer months. [30]

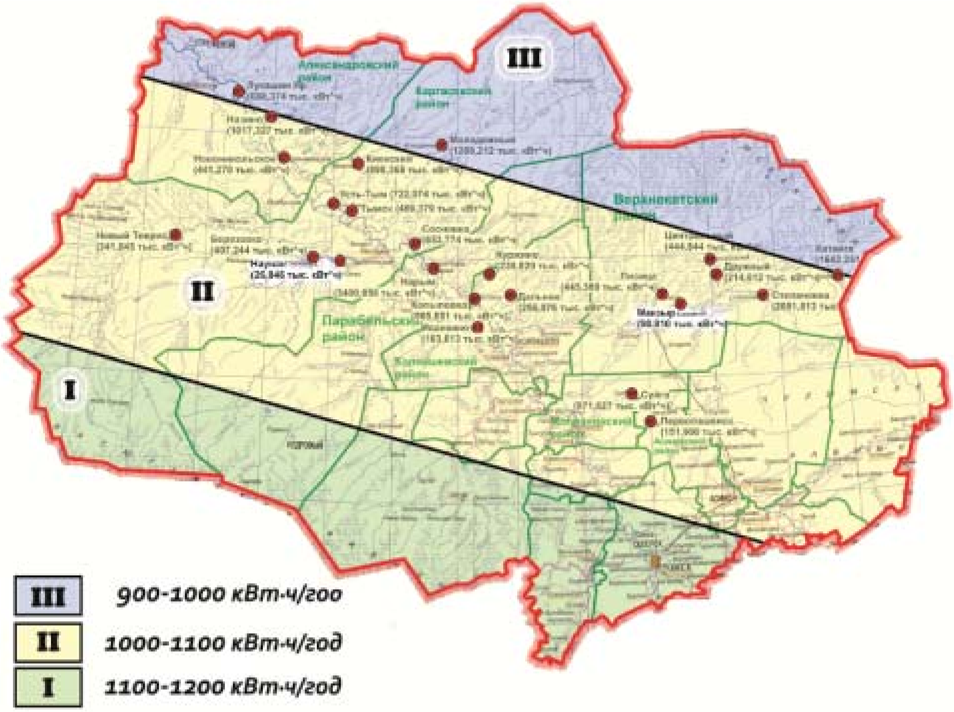

Figure 13 Solar potential in Tomsk Oblast, kWh/m2/year, Kolpashevo lies in the middle II part [31]

3.3 Solar Panel Technologies

Most of the solar panels produced today are based on silicon semiconductor material. However, there are many other materials in the development and some of them are economically competitive with existing silicon ones. [32]

There are three common types:

- Monocrystalline modules.
- Polycrystalline modules.
- Thin-film modules.

Differences lay in form of material used, efficiency of energy conversion, engineering processes and manufacture costs. [32]

Silicon solar cells typically produce about 0.5 V. [32] That is why a number of cells are connected in series to form a solar module. A panel consists of several modules grouped together physically and electrically. A collection of panels is called an array. (see Figure 14)

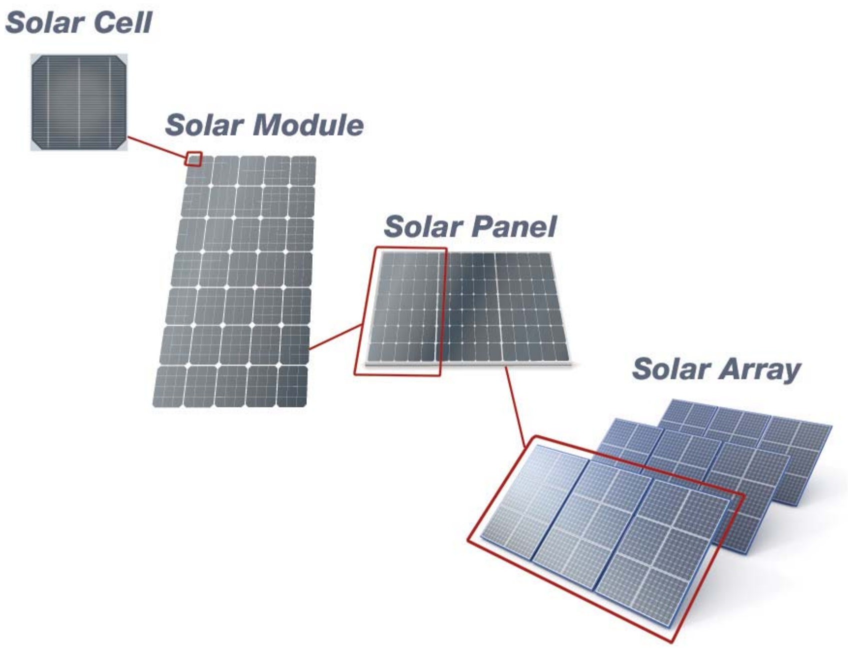

Figure 14 Terminology regarding solar panels [33]

Voltage and current characteristics vary at different insolation levels. From Figure 15, it can be seen that current is proportional to the insolation. The lower the insolation, the lower maximum current is achievable. In short-circuit scenarios the current is limited. [32]

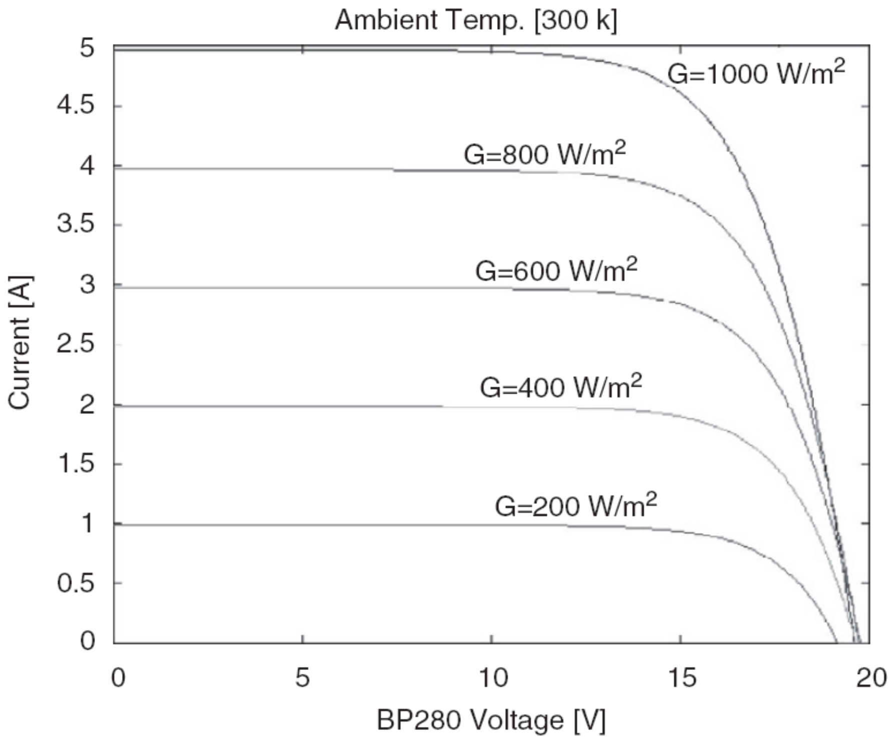

Figure 15 Typical current-voltage (I-V) characteristic curves for different insolation

3.3.1 Monocrystalline Modules

Monocrystalline silicon is a material widely used for decades in electronics and solar cells. Most monocrystals are grown using Czochralski process, where ingots up to 2 meters in length are grown from a seed crystal.

Monocrystalline solar panels can be easily distinguished from other technologies by octagonal shape of individual cells. The reason lies in the technology processes. Each solar cell is produced by slicing the monocrystalline ingot that is originally of circular cross-section.

Figure 16 Monocrystalline silicon solar cells [34]

Monocrystalline panels have the highest efficiency of mass produced panels. The efficiency is usually from 15% to 20%. [35]

This technology is ideal both for roofs situated to the south (± 5 – 10°) and for 2-axis trackers. Actual power of a single panel is in the range of 170 – 290 W. Manufacturers generally rate the lifespan to 30 years with guaranteed 90% initial efficiency after 10 years of usage and 80% of initial efficiency after 25 years. [36]

3.3.2 Polycrystalline Modules

Polycrystalline silicon is made using a simpler method than the Czochralski process used to form monocrystalline ingots. Molten silicon is simply poured into a cast and carefully cooled with a seed crystal. This casting method forces the crystal surrounding the seed to form many, smaller crystals. [37]

The efficiency of polycrystalline modules is slightly lower, than their monocrystalline counterparts are. The efficiency of polycrystalline-based solar panels is typically 13 - 16%. [35]

Figure 17 Poly-Si array [38]

It is also important to address aesthetics. While mono-Si solar panels form classic 'white square' at the corners of individual cells, poly-Si modules have more uniform look. Therefore, it may be easier for customers to accept this technology.

3.3.3 Thin-film Modules

This technology comprises of absorbing layer deposited on substrate or superstrate. [39]

There are three most commonly used materials for the absorbing layer:

- Cadmium telluride (CdTe)
- Amorphous or microcrystalline silicon
- Cu(InGa)Se_2.

Thin-film panels are usually made in different manner than crystalline silicon solar cells. Large glass plates form superstrates for thin-film absorber deposition. Those absorbers are then separated into individual cells, looking like the traditional crystalline silicon panels. [39]

Significant advantage of thin-film technology is the possibility to deposit absorber on variety of materials, ranging from metal foils to plastics. Those substrates can be flexible, opening the doors to incorporation of solar panels on the modern buildings. [39]

Figure 18 Thin-film solar array [40]

I would like to talk about the looks in the case of thin-film solar panels. Most often, thin-film panels have uniform, dark-blue or black finish. This is important, because some more design-conscious investors may choose this technology. It is easier to incorporate them into the overall architectural idea of a building.

4 Methodology

In this part, various methods and calculations would be defined that were used in my research. At the beginning, we will look at the incident sun power and its energy potential. Then, house power needs would be determined. At the end, the focus of this chapter will turn to economic factors of solar panels installation.

4.1 Calculation of Insolation

In order to accurately calculate the share of electricity used by the model house, it is necessary to identify the hour-per-hour electricity production of a photovoltaic array.

My algorithm may be a little confusing, so I will present it in a diagram:

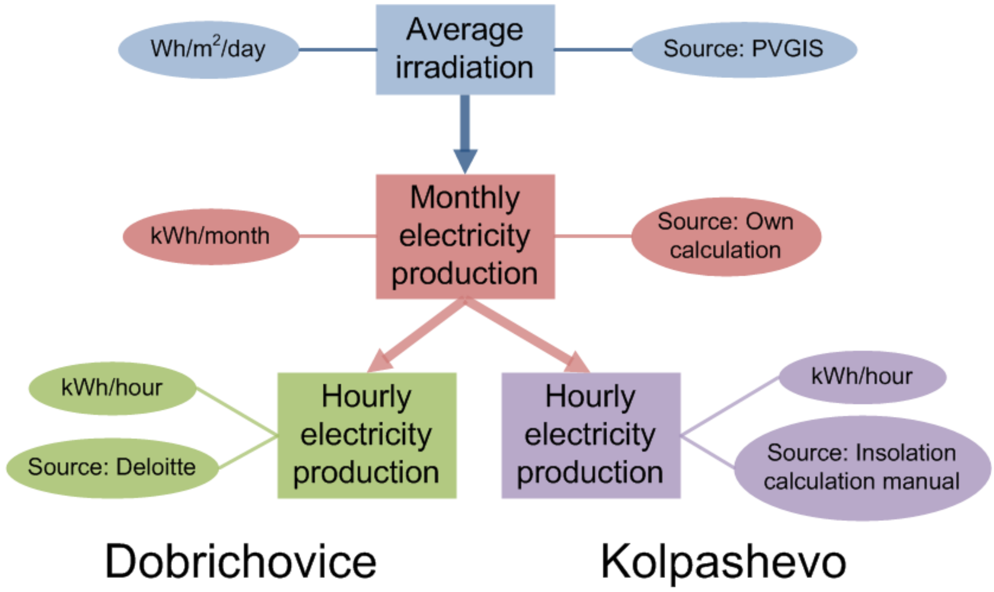

Figure 19 Diagram of hourly electricity production calculation

Firstly, I will use data from PVGIS to determine how much sunlight on average reaches the surface in Dobrichovice and Kolpashevo. The figures represent mean energy that falls on a square meter every day. The data is averaged monthly.

Secondly, incident energy will be used to calculate energy produced by the panels every month. Those numbers will represent panels' monthly electricity generation.

In case of Dobrichovice, I will use the information I obtained from Deloitte representing percentage productions every hour of every day.

Regarding Kolpashevo, the formation of hourly data will come from a Russian insolation calculation manual.

I am aware, that the calculations are not transparent. I wanted projects in both cities to be comparable. That is the reason I used single data source. Then, I utilized the data for Czech Republic and my previous calculations for Tomsk Oblast to put the single information basis into distinct, but analogous, hourly representations.

4.1.1 PVGIS

PVGIS software is a European initiative to offer complex solar calculations to general public.

"The model algorithm estimates beam, diffuse and reflected components of the clear-sky and real-sky global irradiance/irradiation on horizontal or inclined surfaces. The total daily irradiation (Wh.m^{-2}) is computed by the integration of the irradiance values (W.m^{-2}) calculated at regular time intervals over the day. For each time step during the day the computation accounts for sky obstruction (shadowing) by local terrain features (hills or mountains), calculated from the digital elevation model." [41]

PVGIS is indeed a powerful tool. In my diploma thesis, I only used a fraction of it due to synchronization of both my researches in the Czech Republic and Russian Federation.

4.1.1.1 Average Monthly Irradiation

PVGIS software is straightforward; it is only necessary to type in the location, system peak power, slope and azimuth. Locations are given; I mentioned them earlier in the thesis. In order for the model to be scalable, I would not use PVGIS's calculated electricity production, only more general irradiation per square meter. Consequently, peak power setting is insignificant. As for slope and azimuth, in order to maximize the economic output of the model, the system is set to optimal values. Azimuth is 0° for both cities and panels' slope is set to 34° for Dobrichovice (according to PVGIS data) and 45° (according to the calculations that will be mentioned later).

	Average irradiation	
	Dobrichovice	**Kolpashevo**
Jan	1 040	941
Feb	1 930	2 550
Mar	3 500	4 190
Apr	4 870	3 890
May	5 070	5 360
Jun	5 310	5 590
Jul	5 200	5 560
Aug	4 860	4 690
Sep	3 810	3 180
Oct	2 570	1 830
Nov	1 310	897
Dec	913	673
Year	**3 370**	**3 280**

Wh/m²/day

Table 2 Average irradiation

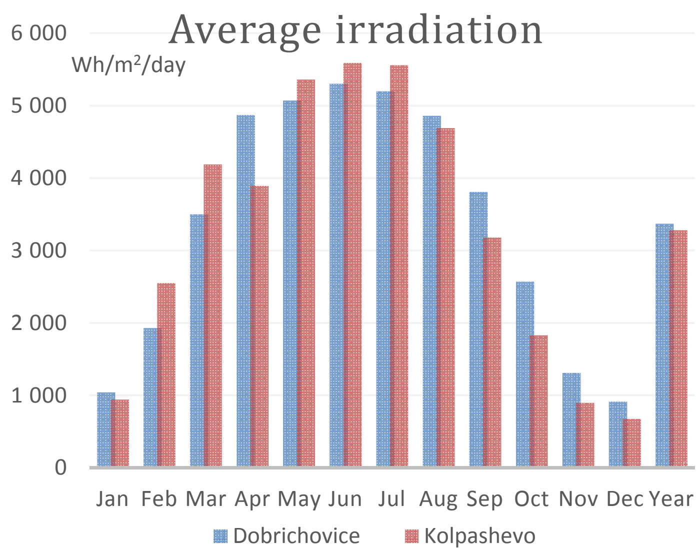

Figure 20 Average irradiation

As can be seen in Table 2 and Figure 20, in both of the areas, the average annual irradiation is around 3300 Wh/m^2/day. However, in comparison, Dobrichovice receive about 3% more average energy when the panels have their respective optimal inclination.

It is also worth to note other differences. Kolpashevo has more significant differences between summer and winter. In the winter period, irradiation can go as low as 673 Wh/m^2/day and in the summer 5590 Wh/m^2/day. This situation is not favorable for the economy of the project, as the highest electricity consumption would be in the winter and the lowest in the summer. Subsequently, more electrical energy would be sent to the electrical network which is not paid well (in the case of the Czech Republic) or not at all (in the case of the Russian Federation).

The last subject to mention is a steep drop in the irradiation in Kolpashevo in April. I assume the reason may be the loss of snow that reflects the incoming light in the winter months. On the other hand, it may be also some kind of inaccuracy in the program, because at the average April temperature of -0.4 °C, the snow would still be present.

4.1.1.2 Losses

There are also three vital coefficients used in the PVGIS model. Estimated losses due to temperature and low irradiance, estimated losses due to angular reflectance effects and other losses. Those losses are 12.7%, 3.1% and 8% for Dobrichovice and 10.3%, 2.9% and 8% for Kolpashevo.

4.1.2 Dobrichovice Hourly Irradiation

To put the monthly data into a more precise manner, it is necessary to come up with an hourly representation. I obtained aggregate data of selected photovoltaic power plans in the Czech Republic and their hourly electricity production. Those records come from my friend from Deloitte and he asked me not to disclose the origin. The statistics are based on monthly electricity production, so it is necessary to calculate monthly figures first.

Monthly electricity production of a PV system is calculated as:

$$E_m = H_d \times d \times P_p \times \eta_i \times (1 - L_t - L_{ar} - L_c)$$

Equation 1 Monthly electricity production of a PV system (kWh)

H_d – Average daily insolation; d – Days in a month; P_p – System peak power; η_i – Efficiency of an inverter (95%); L_t - Losses due to temperature and low irradiance; L_{ar} - Losses due to angular reflectance effects; L_c – Losses in cables etc.

The system electricity generation is as follows:

	Dobrichovice el. generation		
	1 kWp	5 kWp	10 kWp
Jan	23	117	235
Feb	39	197	393
Mar	79	395	790
Apr	106	532	1 063
May	114	572	1 144
Jun	116	580	1 159
Jul	117	587	1 173
Aug	110	548	1 096
Sep	83	416	832
Oct	58	290	580
Nov	29	143	286
Dec	21	103	206
Year	**896**	**4 478**	**8 957**

kWh

Table 3 Dobrichovice solar system electricity generation

Model is possibly scalable to even greater peak powers, but it is unreasonable, mostly in connection with the house power needs and Czech legislation. Any photovoltaic producer above 10 kWp needs to be officially registered which leads to other administrative costs and complications.

The hourly data I mentioned earlier are a percentage of monthly electricity production. There are 8760 individual figures, so instead of putting them here I will only present them in Figure 21.

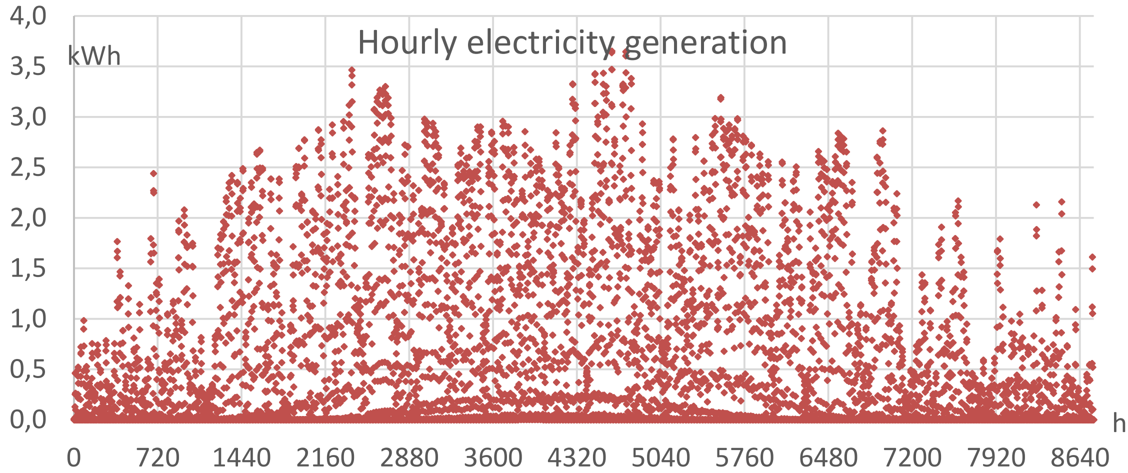

Figure 21 Annual hourly electricity generation in Dobrichovice

This distribution has higher variability than the irradiation that came from PVGIS model. It more closely represents how a real PV system would behave. I would like to note that the first peak is in the spring period, approximately in the month of April where the temperatures are cool enough to ensure the panels work at high efficiency and at the same time, the sun shines at almost 5 kWh/m^2/day.

4.1.3 Kolpashevo Hourly Irradiation

Sadly, I did not have similar real data in the case of a Russian city of Kolpashevo. It was necessary to come up with results comparable to those for Dobrichovice. In the following chapters, I will explain the approach to calculating the hourly data.

4.1.3.1 Core Understandings and Variables

Based on the methodology of [42], the distance between the Sun and the Earth is on average 150 million km. Because of Earth's movement around sun inclined on an elliptical orbit, solar irradiation changes over the course of year.

Out of the Earth's atmosphere (higher than 150 km above the surface) incident sunlight has power of 1395 W/m^2. This value is called solar constant S_0. The real irradiation that reaches surface depends on day of the year, latitude, hour of the day and weather conditions.

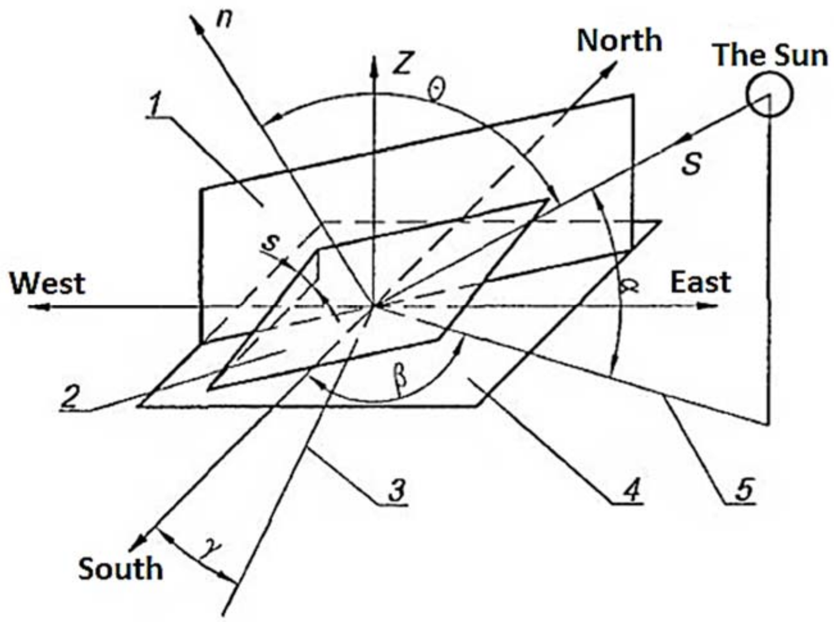

Figure 22 Diagram for calculation of incident sunlight on Earth's surface

1	Vertical plane
2	Inclined plane
3	Horizontal projection of a normal to an inclined plane
4	Horizontal plane
5	Horizontal projection of sunlight
Z	Normal to a horizontal plane
n	Normal to an inclined plane
S	Direct sunlight to Earth's surface
α	Solar altitude
β	Solar azimuth angle
γ	Plane azimuth angle
θ	Angle between the direct sunlight and the inclined plane
s	Plane inclination angle

Table 4 Explanation of a Figure 22

The model based on the variables defined above is capable of computing the power of the incident sunlight based on the latitude, time, day of year, southwards orientation of a plane, incline of a plane and accounts for weather conditions.

4.1.3.2 Solar Radiation Calculation

To easier understand the computations, based on the methodology of [42], let me give you an example. The necessary initial data are as follows:

S_0 = 1395 W/m^2 (solar constant)

N = 121 (order of the day in a year)

c = 0.43 (degree of transparency of the atmosphere)

φ = 58.3° (latitude)

γ = 0° (surface southwards orientation)

a = 0.383 (coefficient dependent on the environment, land/sea)

b = 0.38 (coefficient, empirically obtained)

n = 0.7 (cloudiness)

First, the angle of the sun δ is found as:

$$\delta = 0.41 \sin\left(360 \frac{284 + N}{365}\right) = 0.26\, rad$$

Equation 2 Angle of the sun δ (rad)

Then, I can calculate the sine of the solar altitude α:

$$\sin\alpha = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega$$

Equation 3 Sine of the solar altitude α (rad)

Where ω is the hour angle:

$$\omega = \frac{12 - hour}{12\pi}$$

Equation 4 Hour angle ω (rad)

Hour angle is a conversion from traditional 24-hour system and expresses it in angle, ranging from 3.14 rad at 0:00 to 0 rad at 12 o'clock, and to -3.14 rad at the following midnight.

Solar altitude α simulates the Sun's movement on the sky, more precisely the angle between the sunlight and horizontal plane. It is dependent on latitude, day of the year and local time.

Nevertheless, the solar panel will not have a horizontal orientation. To account for its inclination and azimuth, there is the angle θ:

$$\theta = \sin\delta \sin\varphi \cos s - \sin\delta \cos\varphi \sin s \cos\gamma + \cos\delta \cos\varphi \cos s \cos\omega \\ + \cos\delta \sin\varphi \sin s \cos\gamma \cos\omega + \cos\delta \sin s \sin\gamma \sin\omega$$

Equation 5 Angle ϑ (rad)

Angle θ represents the angle of incidence of direct solar radiation on the inclined surface.

As a next step, it is necessary to determine the direct solar radiation incident on orthogonal surface S_{ort}:

$$S_{ort} = \frac{S_0 \sin \alpha}{\sin \alpha + c}$$

Equation 6 Direct solar radiation incident on orthogonal surface S_{ort} (W/m^2)

The solar panel is not oriented orthogonally to the incident sunlight. Most of the time, the light rays fall in different angles. This is what S_{incl} compensates for:

$$S_{incl} = S_{ort} \cos \theta$$

Equation 7 Direct solar radiation incident on inclined surface S_{incl} (W/m^2)

As was mentioned earlier, the usable part of Sun's energy does not consist only of direct rays, but also of diffused solar energy. Diffused solar radiation incident on horizontal surface D_{hor} is determined as:

$$D_{hor} = \frac{1}{3}(S_0 - S_{ort}) \sin \alpha$$

Equation 8 Diffused solar radiation incident on horizontal surface D_{hor} (W/m^2)

Diffused solar radiation incident on inclined surface D_{incl} is then:

$$D_{incl} = D_{hor}(0.55 + 0.434 \cos \theta + 0.313(\cos \theta)^2)$$

Equation 9 Diffused solar radiation incident on inclined surface D_{incl} (W/m^2)

Ground-reflected solar radiation does not have significant effect on the total incident energy and would not be calculated. [42]

The total incident solar power Q_{incl} is then:

$$Q_{incl} = S_{incl} + D_{incl}$$

Equation 10 Total solar radiation incident on inclined surface Q_{incl} (W/m^2)

When accounting for clouds:

$$Q_{cld} = Q_{incl}(1 - (a + bn)n)$$

Equation 11 Total irradiance including cloudiness Q_{cld} (W/m^2)

Cloudiness data found on [43].

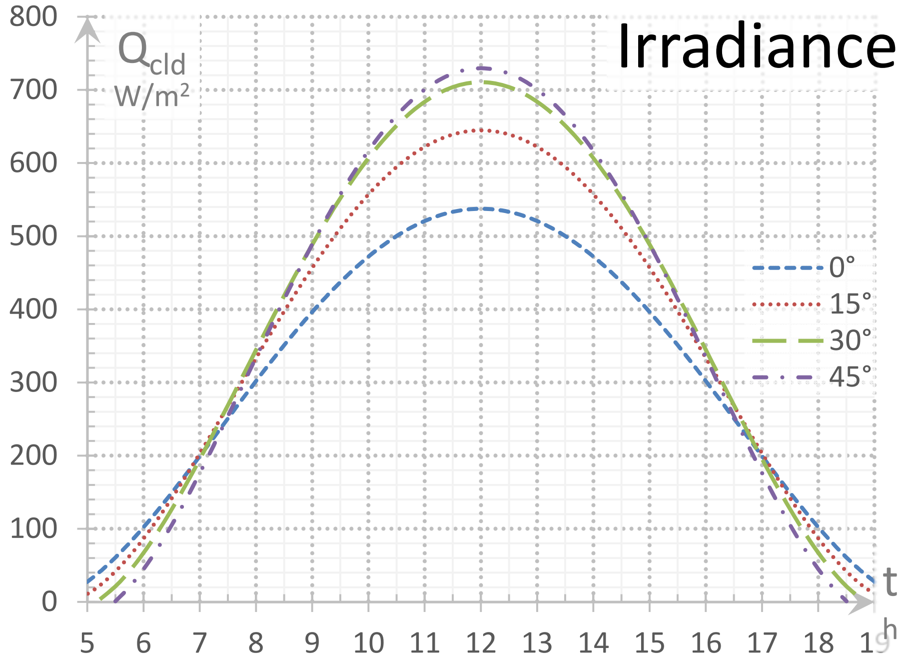

Figure 23 Example of hourly irradiance

Figure 23 demonstrates the outcomes of the model based on different inclination of photovoltaic panels at the day number 121 (beginning of May). It is able to calculate incident energy for any inclination and southward orientation of a plane. I would not disclose other functions, because it is not necessary for this particular comparison. The model does not account for temporary reductions in incident energy such as shades cast by trees, clouds or other surrounding obstacles. According to the amount of received annual energy, the optimal inclination for Kolpashevo is approximately 45° degrees and southward orientation of 0°. It is not economically viable to change inclination during the year or install a 2-axis tracker.

Using this methodology, I was able to emulate hourly data for the entire year. It is important to note, that the figures that came up from this model are used only to give a form to the number I obtained from PVGIS.

4.1.3.3 Intersection of Both Methodologies

PVGIS data explained in the chapter 4.1.1.1 form a basis. They determine the amplitude in order for the diagrams of Dobrichovice and Kolpashevo to be comparable. Insolation calculations described in 4.1.3 are multiplied by monthly figures. The monthly electricity production comes from the same formula (Equation 1) as in the case of Dobrichovice calculations. This leads to following table:

	Kolpashevo el. generation		
	1 kWp	**5 kWp**	**10 kWp**
Jan	22	109	218
Feb	53	267	535
Mar	97	486	972
Apr	87	437	874
May	124	622	1 244
Jun	126	628	1 255
Jul	129	645	1 290
Aug	109	544	1 088
Sep	71	357	714
Oct	42	212	425
Nov	20	101	201
Dec	16	78	156
Year	**897**	**4 487**	**8 973**

kWh

Table 5 Kolpashevo solar system electricity generation

When we compare both monthly tables (Table 3 and Table 5), it is worth to point out that the projected annual electricity production is virtually the same. There are slight differences in the individual months as was discussed earlier, but the overall output differs in the manner of a few percent.

Putting together the monthly PVGIS data and the previously described calculations of hourly irradiation, we obtain:

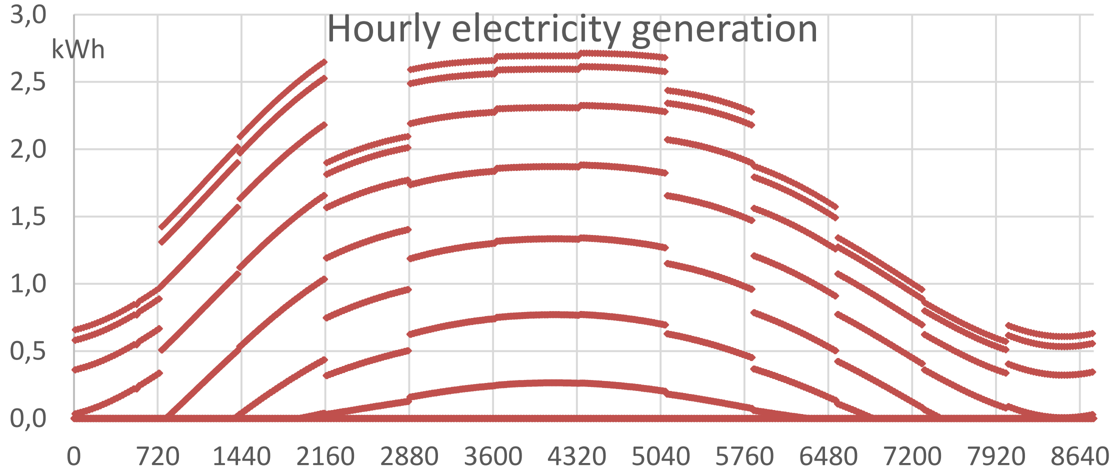

Figure 24 Annual hourly electricity generation in Kolpashevo

Figure 24 comprises of 8760 data points, as well as its counterpart for Dobrichovice. This picture seems much less refined. It is because there are no real hourly data as a basis. In addition, the cloudiness and various shades during the day are averaged, so there are no significant differences between the data from one day to the other. However, the biggest difference is still pronounced. The electricity production from photovoltaic panels in Kolpashevo has more notable difference between summer and winter compared to Dobrichovice.

4.2 Daily Load Diagrams

For further economic calculations, it is necessary to have a generation-consumption balance diagram. Every household has its individual daily load diagram based on appliances and other electric equipment present. It is logical to expect higher energy consumption in the morning and late evening and lower energy consumption during the work time and at night. This contrasts with electricity generation from photovoltaic panels that would be greater during the day, peak around noon and be zero at night. This causes imbalance between consumption and generation. When produced electricity is abundant, it needs to be sold back to the electrical network or accumulated. Nevertheless, accumulation is out of scope of this paper. When there is a shortage of power, it needs to be supplied from the network. Those situations are very different from the economical point of view. This chapter will cover the technical issues connected with the load diagrams representing the consumption side.

Similarly, to the computations regarding panels' hourly electricity production, I will explain the algorithm of obtaining the daily load diagrams.

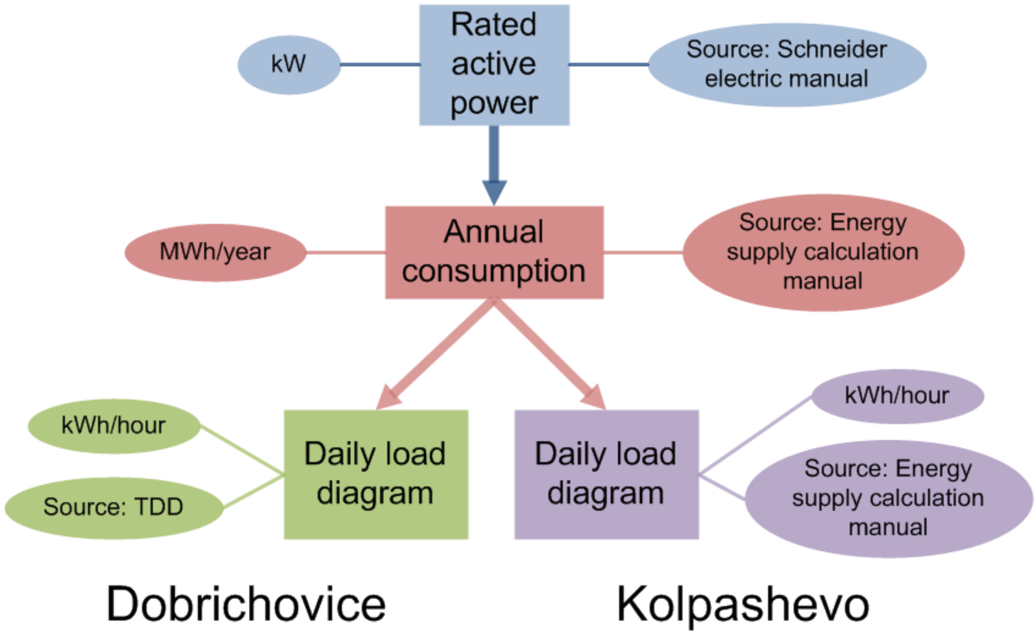

Figure 25 Diagram of daily load diagram calculation

First, house appliances are defined and then then their rated active power is calculated. The result is a single number representing households' power needs. As a source of those estimates, a manual from Schneider Electric is used.

Secondly, another manual for calculation of energy supply is utilized to obtain annual consumption of the houses. This is also a single number representing how many MWhs a home would need in a year.

Finally, different methodologies are applied to form a load diagram for each hour of a year. In case of Dobrichovice, TDD diagram data serves as a basis and when calculating Kolpashevo, one Russian manual is used.

This algorithm ensures the final data are both comparable and distinct for each location.

4.2.1 House Blueprint

As a model for this thesis, I chose an average two-story house with a combined floor area of 128.9 m^2. As was stated earlier, both the heating and warming of the household water is done by natural gas and will not be considered in the comparison of electricity consumption. According to the general data, I suspect that installing photovoltaic panels may not be economically viable at this moment (in the case of Kolpashevo) and at the edge of having a positive NPV (in the case of Dobrichovice). Having this in mind, I decided to calculate with more ideal conditions – the roof is heading to the south (southward orientation = 0°) and it has the ideal angle, 34° in the case of Czech household and 45° in the case of Russian one. As a rational owner would do, the house is connected to the cheapest supplier of electric power in the region.

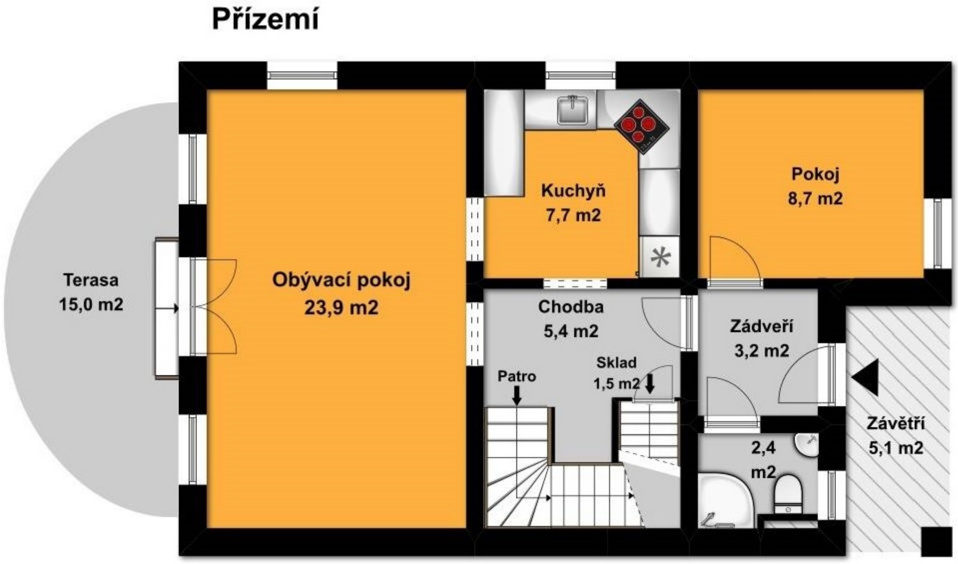

Figure 26 House blueprint, 1st floor [44]
Translation: Přízemí – 1st floor, Terasa – Terrace, Obývací pokoj – Living room, Kuchyň – Kitchen, Pokoj – Guest bedroom, Chodba – Corridor, Sklad – Storage room, Zádveří – Hall, Závětří – Terrace, Patro – 2nd floor

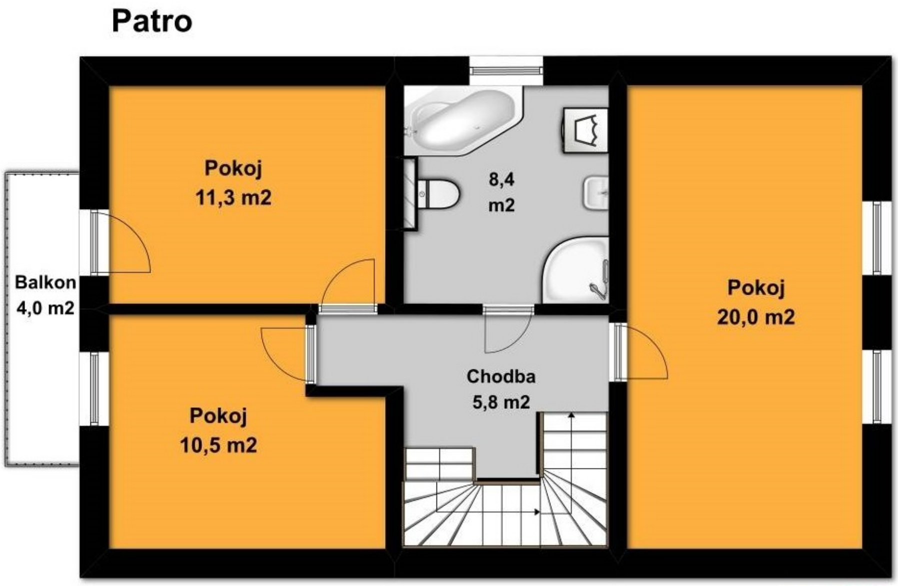

Figure 27 House blueprint, 2nd floor [44]
Translation: Balkon - Balcony, Pokoj – Room, Chodba – Corridor

As can be seen in Figure 26 and Figure 27, house has rather conventional layout with a living room, a kitchen and a guest bedroom on the first floor and three rooms and a bathroom on the second floor. In the kitchen, there are most of the appliances with high electricity consumption, namely a stove, a fridge and a dishwasher. Living room is meant to be used frequently; a family of four occupies this building.

4.2.2 Home Appliances and Other Equipment

The calculations in the chapter 4.2.2 (and some following chapters) are based on a document from Schneider Electric [45]. However, the original purpose of the manual was to determine the nominal power of a circuit breaker. During my consultations with associate professor Plotnikov we made many corrections so the model's outputs would provide more real figures. The original results provided an annual consumption of 73 MWh, which is not in line with the common technical sense.

	Room	Area, m²	Appliance	P_n, W		Room	Area, m²	Appliance	P_n, W
1st floor	**Living room**	23,9	Air cond.	1 500	**2nd floor**	**Master bedroom**	20	Lighting	20
			Home th.	800				Sockets	100
			Lighting	24		**Office**	11,3	Lighting	11
			Sockets	133				Sockets	67
	Kitchen	7,7	Stove	7 500		**Kids bedroom**	10,5	Lighting	11
			Dishwash.	2 200				Sockets	67
			Fridge	600		**Corridor**	5,8	Lighting	6
			Lighting	8				Sockets	33
			Sockets	67		**Bathroom**	8,4	Washing m.	2 200
	Guest bedroom	8,7	Lighting	9				Fan	500
			Sockets	67				Lighting	8
	Hall	3,2	Lighting	3				Sockets	67
			Sockets	33		**TOTAL**	**128,9**		**16 762**
	Bathroom	2,4	Fan	500					
			Lighting	2					
			Sockets	33					
	Corridor	5,4	Lighting	5					
			Sockets	33					
	Storage room	1,5	Lighting	2					
			Sockets	33					
	Terrace 1	5,1	Lighting	5					
			Sockets	33					
	Terrace 2	15	Lighting	15					
			Sockets	67					

Table 6 Home appliances and other equipment

As can be seen in Table 6, in installed nominal power the most notable appliances are a stove, a dishwasher, a washing machine and an air conditioner. Others include lighting and sockets.

All the lighting in the house is built on LED technology. One square meter then needs about 1 W of nominal power to assure sufficient light conditions. [26]

The approach of Schneider Electric is to assume 100 W per one socket and one socket per every 6 m² of floor area. In my case, this number was divided by 3 to better account for the fact, that I am not trying to find the power of circuit breaker but home's daily and annual load. [26]

4.2.3 Rated Active Power

I will apply now two coefficients to better approximate the actual power needs using the same manual from Schneider Electric [45].

Demand factor K_d:

$$K_d = \frac{P_r}{P_n}$$

Equation 12 Demand factor K_d (-)

Where P_r represents rated power and P_n nominal power.

Utilization factor K_u:

$$K_u = \frac{P}{P_n}$$

Equation 13 Utilization factor K_u (-)

Where P is the actual needed energy of an appliance or equipment.

Both demand factor and utilization factor are based on the empirical experience.

	P_n, W	K_d	K_u	cosφ	P_r, W	Q_r, VA	S_r, VA	I_r, A
Lighting	129	0,6	0,6	1	46	0	46	
Sockets	833	1	0,8	0,9	667	323	741	
Stove	7 500	0,5	0,4	1	1 500	0	1 500	
Dishwasher	2 200	0,6	0,6	0,8	792	594	990	
Fridge	600	1	0,5	0,95	300	99	316	
Air conditioning	1 500	0,7	0,6	0,8	630	473	788	
Washing machine	2 200	0,8	0,6	0,8	1 056	792	1 320	
Fan	1 000	0,6	0,6	0,8	360	270	450	
Home theater	800	0,8	0,6	0,8	384	288	480	
TOTAL	**16 762**			**0,86**	**5 735**	**2 838**	**6 630**	**10,1**

Table 7 Rated active power and other data

Demand factor, utilization factor and cosφ come from the Schneider handbook. Some of the numbers have been adjusted to better reflect the reality.

Rated active power P_r:

$$P_r = P_n K_d K_u$$

Equation 14 Rated active power P_r (W)

Rated reactive power Q_r:

$$Q_r = P_r \tan\varphi$$

Equation 15 Rated reactive power Q_r (VAr)

Rated apparent power S_r:

$$S_r = \frac{P_r}{\cos\varphi}$$

Equation 16 Rated apparent power S_r (VA)

According to the data above, the household should have a peak output of 5.7 kW under normal circumstances. For customers at the 0.4 kV voltage level the reactive power is not paid for.

4.2.4 Seasonal Differences

According to [46], household electricity consumption follows inverse annual pattern than photovoltaic panels' production. It is usually higher during winter and lower in the summer.

Percentage of rated active power																									
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	#
Win	25	25	25	25	25	35	50	60	40	30	30	35	40	30	30	30	40	70	100	95	70	50	35	30	
Spr	25	25	25	25	25	35	45	50	40	30	30	35	40	30	30	30	30	40	50	70	100	20	50	30	
Sum	20	20	20	20	25	30	40	45	40	30	30	30	35	30	30	30	30	30	35	40	70	100	60	25	
Fall	25	25	25	25	25	35	45	55	40	30	30	35	40	30	30	30	30	40	70	100	85	60	40	30	

Table 8 Percentage of rated active power in various seasons

In the Table 8, we can observe two distinct peaks. The first maximum occurs in the morning at about 7 and can reach up to 60% of rated power. The second peak takes place when people return from their jobs at about 18 and the power needs can be up to 100% of P_r.

When Table 8 is multiplied with the peak rated active power, the following is obtained:

Daily load profiles, kW																									
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	#
Win	1,4	1,4	1,4	1,4	1,4	2,0	2,9	3,4	2,3	1,7	1,7	2,0	2,3	1,7	1,7	1,7	2,3	4,0	5,7	5,4	4,0	2,9	2,0	1,7	
Spr	1,4	1,4	1,4	1,4	1,4	2,0	2,6	2,9	2,3	1,7	1,7	2,0	2,3	1,7	1,7	1,7	1,7	2,3	2,9	4,0	5,7	1,1	2,9	1,7	
Sum	1,1	1,1	1,1	1,1	1,4	1,7	2,3	2,6	2,3	1,7	1,7	1,7	2,0	1,7	1,7	1,7	1,7	1,7	2,0	2,3	4,0	5,7	3,4	1,4	
Fall	1,4	1,4	1,4	1,4	1,4	2,0	2,6	3,2	2,3	1,7	1,7	2,0	2,3	1,7	1,7	1,7	1,7	2,3	4,0	5,7	4,9	3,4	2,3	1,7	

Table 9 Daily load profiles

The annual electricity consumption E_y is computed as:

$$E_y = E_{win} + E_{spr} + E_{sum} + E_{fall}$$

Equation 17 Annual electricity consumption E_y (kWh)

Where E_{win}, E_{spr}, E_{sum}, and E_{fall} represent the total electricity needs for every season. For example, E_{win} is determined as:

$$E_{win} = (31 + 31 + 28) \sum_{h=1}^{24} P_r$$

Equation 18 Winter electricity consumption E_{win} (kWh)

Where the numbers 31, 31 and 28 are the number of days in December, January and February and P_r is the rated power from Table 9.

According to Equation 17, the annual electricity consumption of such a household is 19.8 MWh. I decided the differences between Dobrichovice and Kolpashevo are not fundamental in terms of electricity consumption, so the base number is the same for both locations. What will differ though is how the diagrams would look like in hourly representation.

4.2.5 Dobrichovice Daily Load Diagram

There is a great tool called Typical Diagram of Supply or TDD in Czech. It comes up from aggregate data of many households and is thus a perfect source for this thesis. TDD supplies hourly percentage of maximum of annual maximum power. To maintain comparability with Kolpashevo data I decided to form the diagram using this formula:

$$P_h = \frac{TDD_h}{\sum_{h=1}^{8760} TDD_h} E_y$$

Equation 19 Hourly power needs P_h (Wh), Dobrichovice

Where TDD_h is Typical Diagram of Supply's percentage rating at the given hour and E_y represents annual household electricity needs.

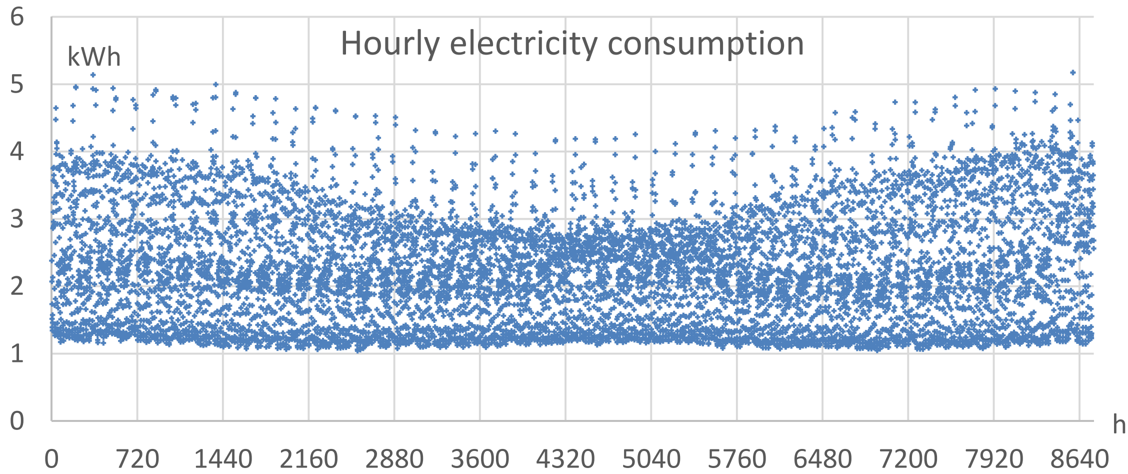

Figure 28 Daily load diagram, Dobrichovice

Figure 28 pictures the annual hourly consumption of a model house. As can be seen, minimal power is a little more than 1 kW and maximal reaches 5 kW in the peaks of the winter period.

4.2.6 Kolpashevo Daily Load Diagram

I was not so lucky to have so precise hourly data in case of Kolpashevo. I used an algorithm described in [46] to receive appropriate numbers with seasonal changes.

	k_P
Jan	1
Feb	1
Mar	0,8
Apr	0,8
May	0,8
Jun	0,7
Jul	0,7
Aug	0,7
Sep	0,9
Oct	0,9
Nov	0,9
Dec	1

Table 10 Coefficient of seasonality k_p

Combining the data in Table 9 and Table 10, we obtain the annual hourly electricity consumption of a house in Kolpashevo.

$$P_h = \frac{N_h}{\sum_{h=1}^{8760} N_h} E_y$$

Equation 20 Hourly power needs P_h (Wh), Kolpashevo

Where N_h is normalized diagram's percentage rating at the given hour and E_y represents annual household electricity needs. Normalized diagram's percentage rating N_h is calculated as multiplying the appropriate value from table Table 9 and Table 10.

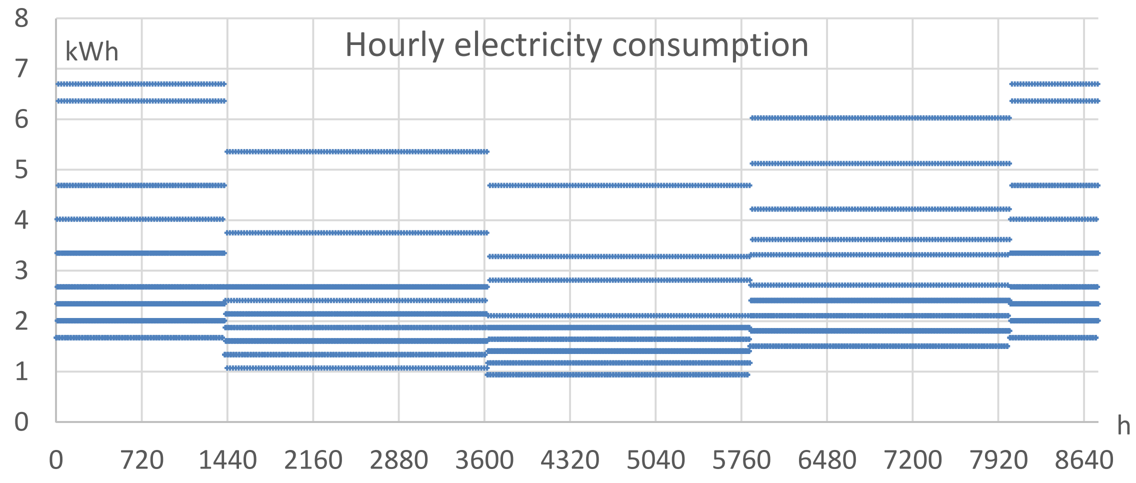

Figure 29 Daily load diagram, Kolpashevo

Similarly to the situation with the insolation chart, Kolpashevo graph seems less refined, less real. The overall trends are the same, however. Minimal power consumption varies between a little bellow 1 kW in the summer and about 1.5 kW in the winter. Maximal power needs are in winter, approximately 6.7 kW.

Figure 28 and Figure 29 are different. One of the notable discrepancies is the maximum power. In Dobrichovice, it is slightly above 5 kW, where in Kolpashevo the maximum lies at about 6.7 kW. This is not to indicate dissimilarity between the two models but it mostly stems from the assumption that the annual power needs are the same and then applying distinct methodologies for each city.

Maximum power needs during an hour do not need to necessarily match with the actual peak power demand. Those figures serve as an hourly average. Peak power is only limited by the main circuit breaker.

4.3 Generation-Consumption Balance

The logical next step is to put the chart of electricity production and consumption together. There are two situations that can occur:

- Production surplus. The installed photovoltaic system produces more power that the house can use at that given hour. This is an undesirable situation, because when the excess energy is sold to the electrical network, I usually receive little to no monetary compensation.
- Production deficit. Home consumes more power than the solar panels can supply. This is an undesirable situation as well, because the necessary kWhs need to be bought from the electric network.

Having those two situations in mind, it is logical to assume, that the optimal circumstance is when the production and consumption is 'just right', when the photovoltaic electricity squeezes out as many network energy as possible, but at the same time does not have a significant surplus.

To discover this ratio of purposely-used electricity, it is necessary to calculate the balance between generation and consumption at every given hour.

Generation surplus G_s is calculated as:

$$G_s = G_h - P_h$$

Equation 21 Generation surplus G_s (Wh)

Where G_h stands for electricity generation at a given hour and P_h is actual house power needs. Surplus only takes place when $G_h > P_h$.

The annual sum of surpluses G_{as} would be:

$$G_{as} = \sum_{h=1}^{8760} G_s$$

Equation 22 Annual generation surplus G_{as} (Wh)

In a similar fashion, generation deficit can be found as:

$$G_d = P_h - G_h$$

Equation 23 Generation deficit G_d (Wh)

Deficit only occurs when $P_h > G_h$.

The annual sum of deficits G_{ad} is thus:

$$G_{ad} = \sum_{h=1}^{8760} G_d$$

Equation 24 Annual generation deficit G_{ad} (Wh)

When the generation and consumption are equal, there is neither deficit nor surplus. However, this situation does not happen often as data show.

The conclusions lead to a crucial figure utilized electricity ratio u:

$$u = \frac{G_a - G_{as}}{G_a}$$

Equation 25 Utilized electricity ratio u (-)

G_a stands for annual panels' electricity generation and G_{as} for annual generation surplus.

As was discussed earlier, this ratio is crucial for the system to be cost-effective. The panels, invertor and other components are a rather big investment for an ordinary household. Assume the utilized electricity ratio is low. Then much of the generated power is sent to the network and, basically, lost without much or any financial benefit for the family. Those assumptions are valid until the surplus electricity is not highly honored by the distribution network or by local government in the form of subsidies. However, it is highly unlikely, because the surplus occurs at the time when the kWhs are not needed by the rest of the network.

4.3.1 Generation-consumption Balance in Dobrichovice

Let us take a look at one particular example of such a balance in Dobrichovice, as represented in Figure 30.

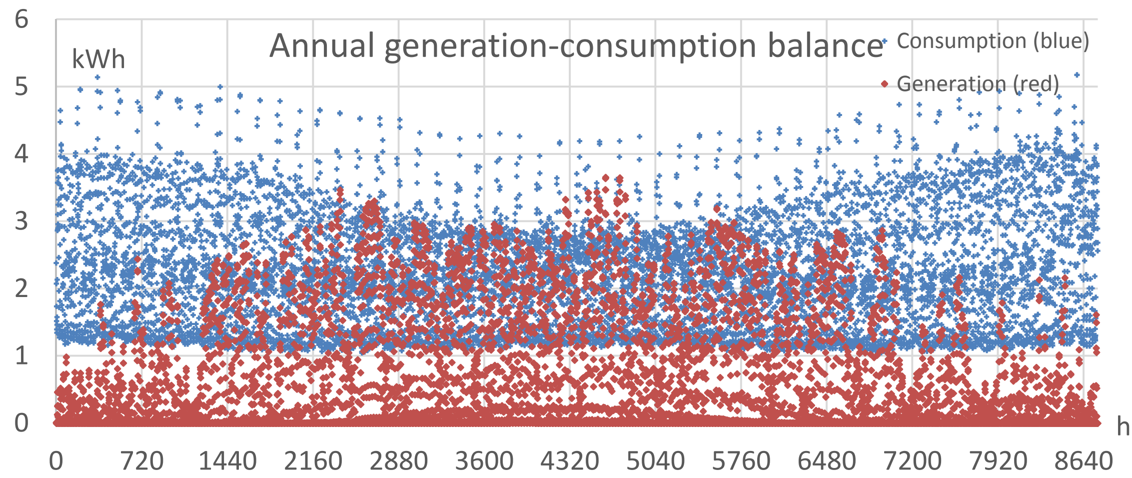

Figure 30 Annual generation-consumption balance, Dobrichovice

In this illustration, a 5 kWp system is installed. Its electricity generation is represented by the red dots and house's power needs are represented by the blue dots. Even though the panels have their peak production in the summer, most of the red part of the chart is 'covered' under the blue consumption one. This means we could expect high utilized electricity ratio. In this circumstance, solar system makes 4478 kWh of electrical energy with only 183 kWh surplus energy sold to the distribution network for a small fee. The utilized electricity ratio u would be 95.9%.

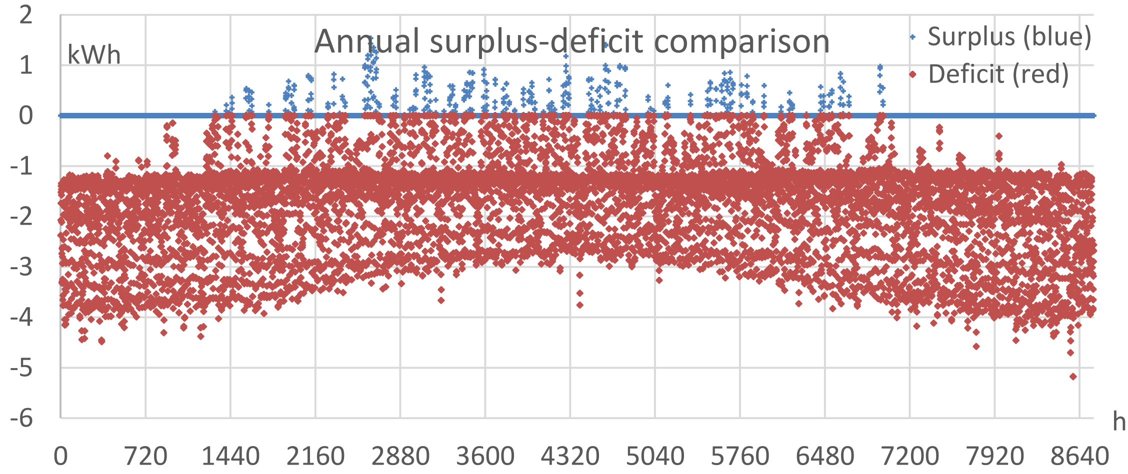

Figure 31 Annual surplus-deficit comparison, Dobrichovice

As can be seen in Figure 31, the period of generation surpluses takes place from spring until fall as expected. It is also worth noting that by installing a 5 kWp photovoltaic system, out of 19.8 MWh of house's power needs, only 4.3 MWh are fulfilled using solar electricity. Both Figure 30 and Figure 31 are just examples of how the model works with specific numbers.

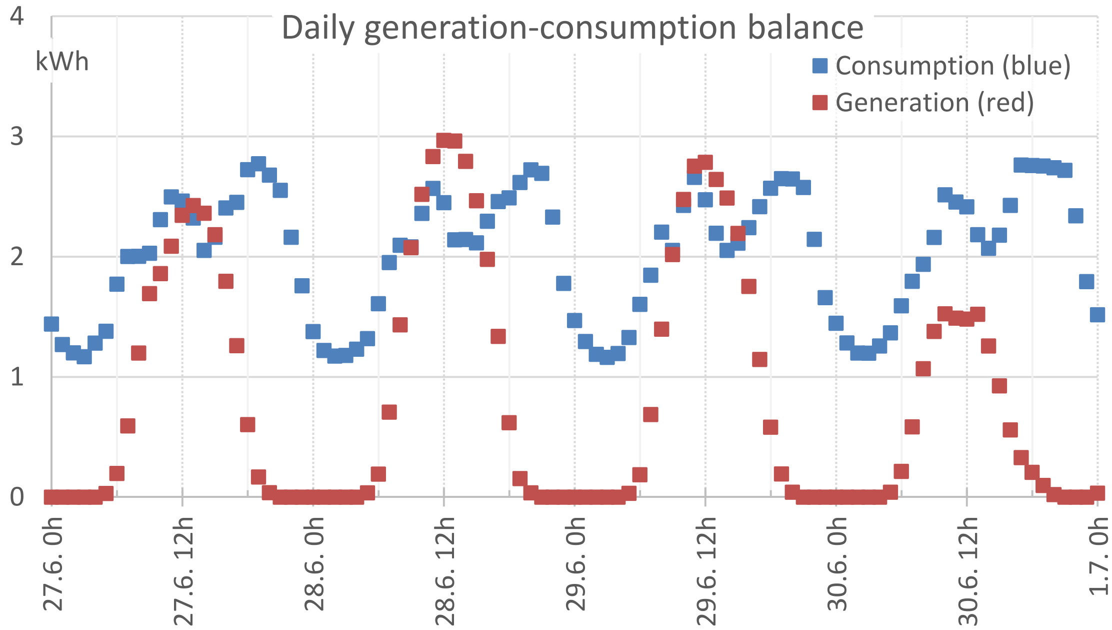

Figure 32 Generation-consumption balance, June 27th - 30th, Dobrichovice

According to the Figure 32, even in summer days the household consumes most of the panels' production. It is mostly due to the high minimal loads during the work time and during the night. This form of a diagram may be questionable, but it stems from the TDD diagrams, which I consider to be a trustable source.

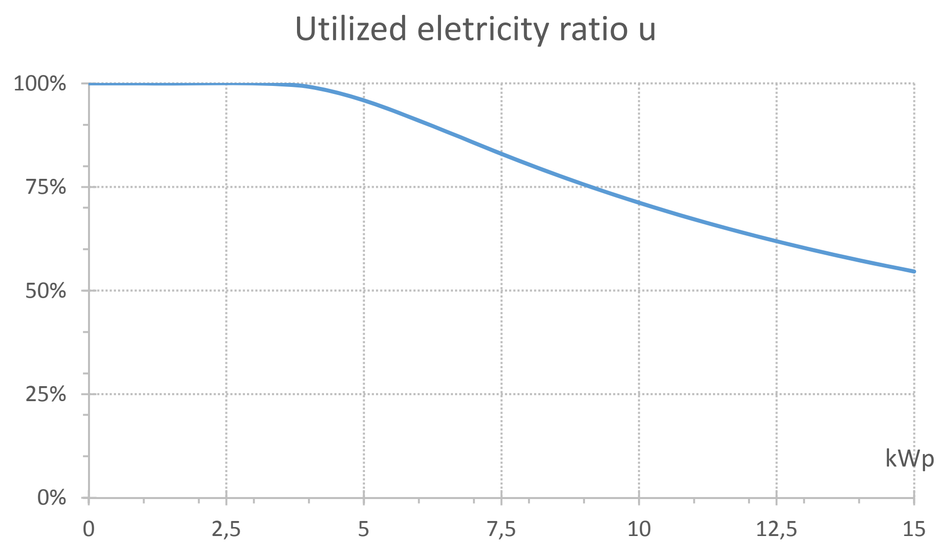

Figure 33 Utilized electricity ratio u – installed power comparison, Dobrichovice

Figure 33 illustrates, how much of the panels' production is utilized based on the installed capacity of the solar system. When the percentage is 100%, we may assume that we are not fully utilizing the potential of the household's electricity consumption. With the u bellow, say, 80% it is possible that the benefits from having higher energy output would be lower than the additional costs connected with the purchase and installation of the system. The optimal peak power may be somewhere between 4 kWp and 7.5 kWp.

4.3.2 Generation-consumption Balance in Kolpashevo

For comparison, I will use the same rated peak power of solar system – 5 kWp.

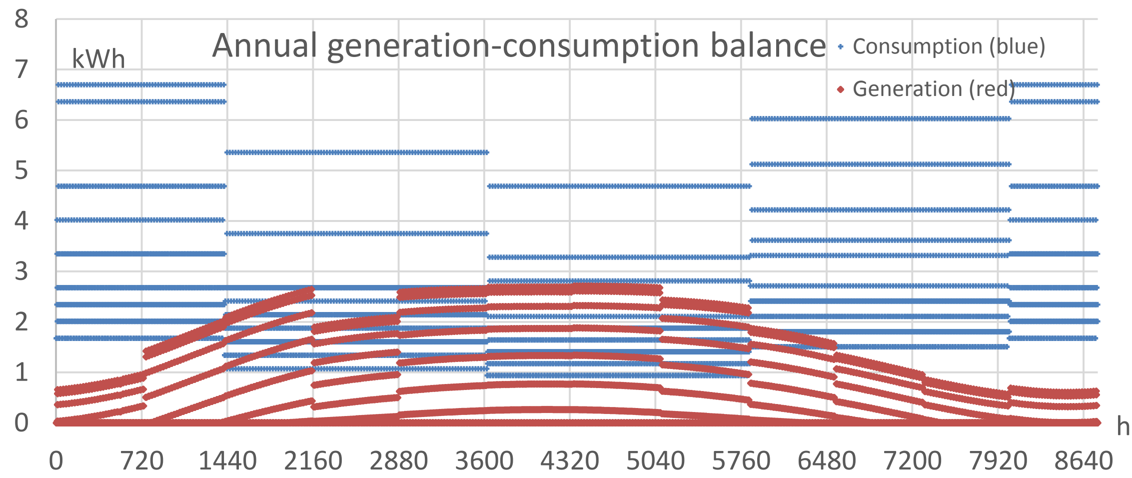

Figure 34 Annual generation-consumption balance, Kolpashevo

At the first glance, it may look that all of the produced energy is consumed by the house, but it is not the case. If we zoom on a particular days, we can take for example June 27th - 30th, the situation would be clearer.

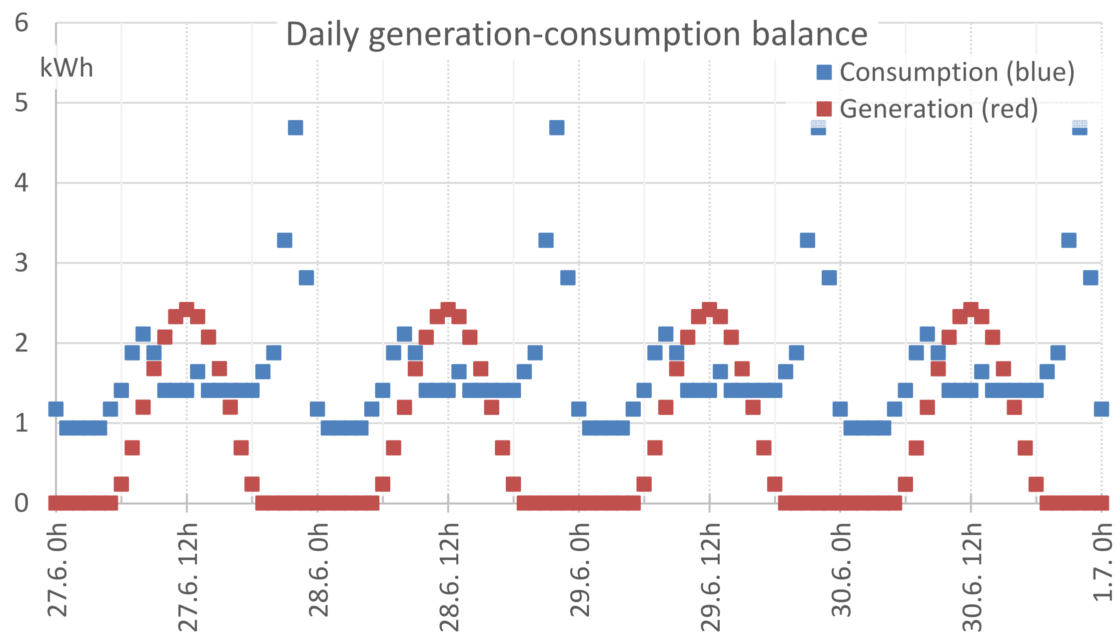

Figure 35 Generation-consumption balance, June 27th - 30th, Kolpashevo

Figure 35 depicts summer days, June 27th to June 30th. xEspecially during the summer months, the generation does not match the consumption. This leads to overproduction of electricity in the middle of the day.

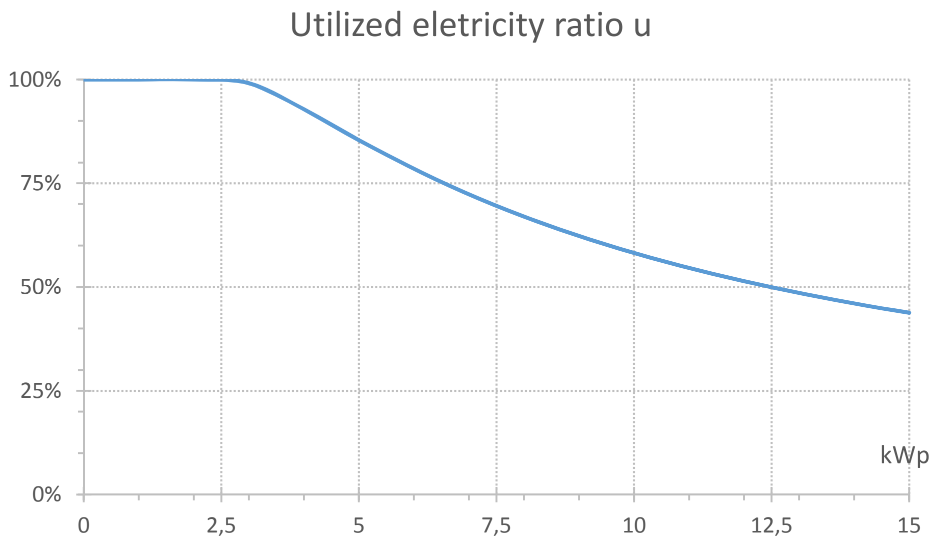

Figure 36 Utilized electricity ratio u – installed power comparison, Kolpashevo

The utilized electricity ratio chart for Kolpashevo looks a little bit different from the one for Dobrichovice. Its slope is steeper, for example at 5 kWp u for Dobrichovice would be 95.9%, where in the case of Kolpashevo the number is 85.4%. It is hard to account those differences to any single factor, because both methodologies of forming the algorithms are vastly different.

In addition, answering the question where would lie the optimal peak power is impossible, because current economic and legislative environment in Tomsk Oblast does not allow this project to be cost-effective. The question is more ‘What needs to change?’ than ‘Is it economically achievable?’.

4.3.3 Degradation Rate

Solar panels do not produce the same amount of electricity forever. As every other technology, they are prone to some kind of degradation. The issue with photovoltaic panels is that the manufacturing processes change rapidly, new companies emerge and vanish and nobody is sure, how long current panels will last. Usually, manufacturers provide some kind of warranty. Most often, they declare the panels will keep 90% of their output after 10 years and 80% when 25 years pass. The question is: ‘Would those firms be around in 10, 15, 20 years?’. Moreover, if they would still be in business, how hard would it be to get some compensation? Those questions are hard to answer and add some more risk to the overall project.

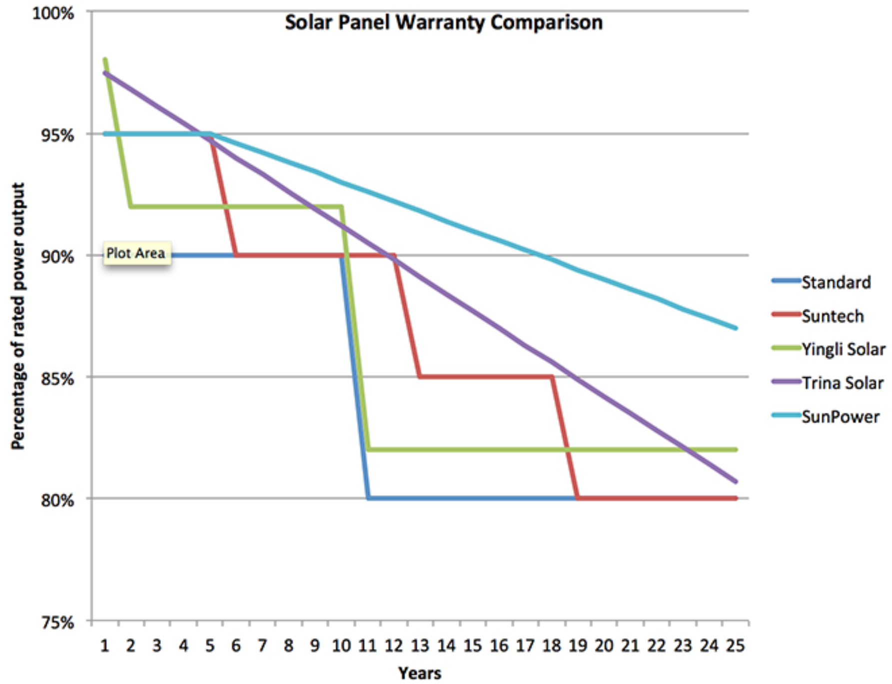

Figure 37 Solar panel warranty comparison [47]

As can be observed in Figure 37, manufacturers vary in their warranties. In most of the offers I managed to find, the panels used polycrystalline technology. I will use a base degradation of 0.7 percentage points a year. This leads to an output of 93.7% after 10 years and an output of 83.2% after 25 years, which is in line what most companies offer.

The aging of the panels bring two results to the model. The photovoltaic system produces 0.7 p.p. less energy every passing year. That has definitely a negative impact on the cash flow of the project. However, at the same time this phenomenon increases the utilization factor u. With each passing year, the chart of electricity generation is more and more ‘covered’ by the dots representing electricity consumption. According to my calculations, this leads to an increase of the utilized electricity ratio u by about 0.25 percentage point a year. This goes against the degradation, because more energy can be utilized by the household itself.

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6 Table of Figures

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9 Abbreviations

EUR – EMU Euro
RUB – Russian Ruble
CZK – Czech Crown
kW - Kilowatt
kWp – Kilowatt peak
kWh – Kilowatt hour
MWh – Megawatt hour
TDD – Typický diagram dodávky (Typical Diagram of Supply)
DIY – Do it yourself
CR – Czech Republic
RF – Russian Federation
GDP – Gross Domestic Product
PPP – Purchasing-power parity
PRC – People’s Republic of China
ERU – Energetický regulační úřad (Office for Regulations in Power Engineering)
OTE – Operátor trhu s elektřinou (Electricity Market Operator)

Table of Contents

10 Economic

After explaining the core technical algorithms, I would like to complete the methodology explanation with an economical model. Installation of solar panels may make environmental sense straight on, because the power needed to produce panel is 'repaid' by the panel's generation in the matter of years. For this technology to make economic sense, it is a more complex issue. In recent history, photovoltaic technology was not cost-effective without any support from the government. As we can see from the events in the Czech Republic that took place mostly in the years 2009 and 2010, it is not easy to subsidize photovoltaic electricity production. The technology, manufacturing and economics change rapidly and legislative branch of the government is sometimes too slow to react and too vulnerable to lobbying and other practices at the intersection of business and politics.

You do not need to be an expert on economics of power engineering to come up with an easy rule of a thumb to determine whether photovoltaic system would be a good investment or not. There are three main factors influencing the economics of such a system:

- Investment costs of panels and other necessary peripherals
- Amount of sunlight
- Electricity price

Price of panels has been falling significantly in the last years, but the same cannot be said for other necessary equipment like inverters, cables and supplementary services. As I would describe later in my thesis, both panels and inverters are a bit more expensive in Russian Federation than in the Czech Republic. The most reasonable explanation is bigger supply and demand in Europe because of more widespread scheme of subsidizations. Investment costs are noteworthy aspect of this model, so in this case Dobrichovice are favored.

As we discussed in previous chapters, the amount of sunlight is more or less the same in Kolpashevo and Dobrichovice. The only variance is in slightly more difference between summer and winter insolation in case of Tomsk Oblast. Obviously, the more sunlight, the better.

In this case, the electricity price makes the most significant difference. Where in the central part of the Czech Republic, the cost of electricity could be around 0.155 EUR/kWh, Tomsk Oblast utility charges only 0.033 EUR/kWh. This is a tremendous dissimilarity favoring Dobrichovice.

10.1.1 Investment

This subchapter explains the fundamental part of a photovoltaic system economic model – the initial investment. It is not the only moment when it is necessary to put in some of your own money. There is also a need to replace an inverter approximately every 10 years and maintenance costs here and there can account for about 1% of the initial investment every year.

The whole time we are talking about photovoltaic panels, but they are just a part of the whole solar system:

- Photovoltaic panels
- Inverter
- Racking
- Cables and other material
- Transportation and labor costs
- Paperwork and blueprints
- Sales tax

Each of those costs is different in the two countries so I would describe them separately.

10.1.1.1 Investment Costs, Czech Republic

Czech solar energy market is developed. The reason is a solar boom in 2009, 2010 and 2011, where the subsidies were remarkably generous and helped the installation of many photovoltaic systems. Sadly, most of them were not roof-mounted, but stand-alone units, usually occupying farmers' fields. After the initial boom some of the companies survived the shift and they now offer a wide variety of services from measurements to installation of a complete system.

To make the assumptions as precise as possible I asked about 25 leading suppliers of photovoltaic systems in the Czech Republic. Out of those, eight companies provided the necessary data. This led me to 14 offers in total, ranging from 2 kWp to 10 kWp. Vast majority of the panels were polycrystalline. Most of the invoices I received were from the years 2014 and 2015. In general, the deals were similar, but some differences can be found.

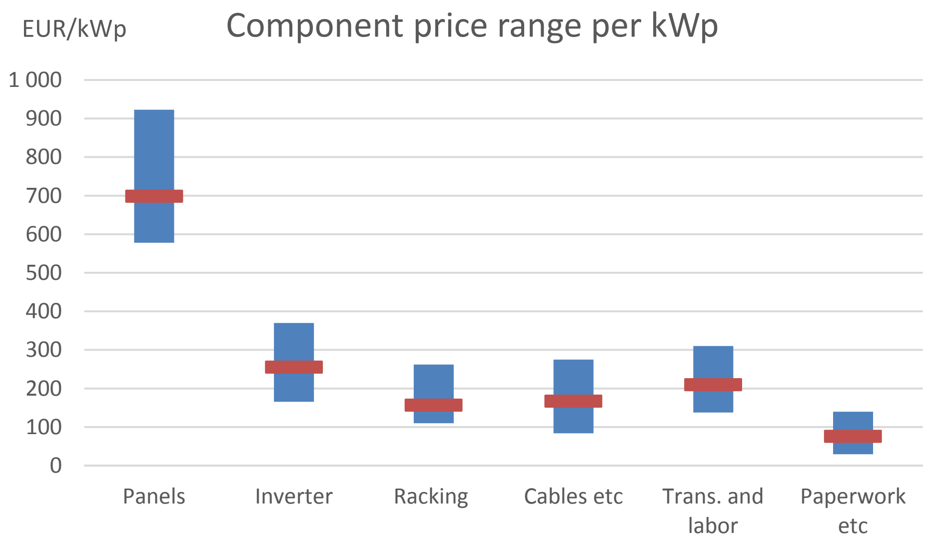

Figure 38 Component price range per kWp, Dobrichovice

	MIN	AVG	MAX	% of total
Panels	578	698	923	44,7%
Inverter	166	255	370	16,3%
Racking	110	157	262	10,0%
Cables etc	84	167	275	10,7%
Trans. and labor	138	209	310	13,4%
Paperwork etc	30	75	140	4,8%
Total before VAT	1 215	1 562	1 875	100,0%
Total after VAT	1 397	1 796	2 156	115,0%

EUR per kWp

Table 11 Component price range per kWp, Dobrichovice

As can be observed in Figure 38, the most expensive part are, without any doubt, the panels themselves. Their price can vary depending on the supplier from 578 EUR/kWp to 923 EUR/kWp; the mean is 698 EUR/kWp. Other cost intensive component is the inverter. Its average price is 255 EUR/kWp. The issue with inverter is it needs to be replaced approximately every 10 years. It influences the cash flow big time. Other arrangements like racking system for fastening the panel, cables or transportation and labor average between 150 and 200 EUR/kWp. The total average costs of photovoltaic systems are 1796 EUR/kWp.

When a certified company installs the system in bulk, it is eligible for discounted sales tax of 15%. However, the individual purchases afterwards (like invertor) are burdened by a VAT of 21%.

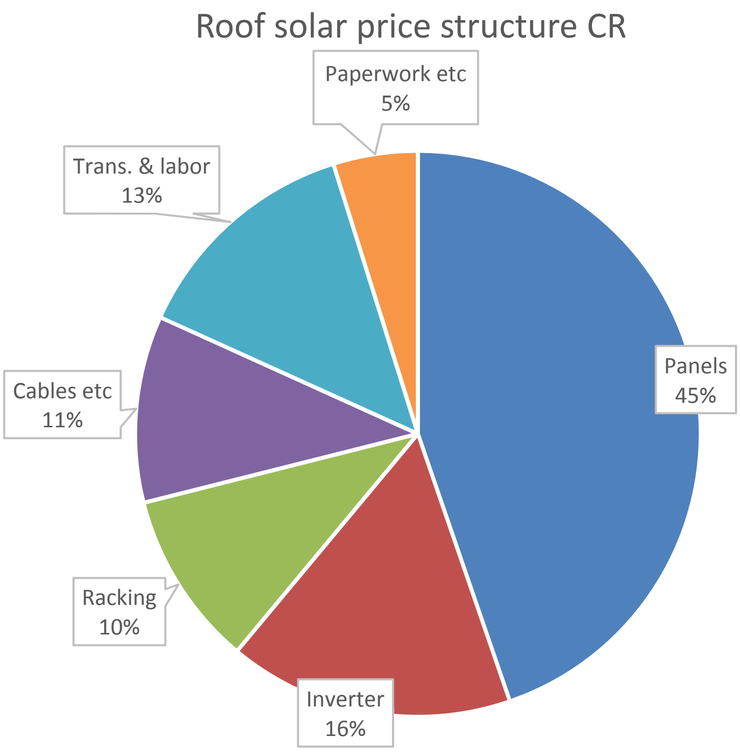

Figure 39 Roof solar system price structure per kWp, Dobrichovice

On average, panels are less than half of the price of a complete system before sales tax. All of the other components take substantial portions as well. Inverter accounts for 16%, racking for 10%, cables and other electrical equipment takes 11%, transportation and labor form together 13% and paperwork, blueprints and other services are 5% of the total costs.

Both the technical and economic calculations are based on the installed power of the photovoltaic system. I believe that all the parameters are behaving in a linear manner, the more kWp, the more energy produced and the higher the investment costs would be, proportionally. Between the powers of 1 to 10 kWp, this assumption should be correct.

10.1.1.2 Investment Costs, Russian Federation

Compared to the Czech Republic, market for solar systems and its components is not fully developed in RF. The majority of offers from Russian companies are DIY kits, mostly for hobbyists or for people not connected to the distribution network. An average kit usually contains solar panels, inverter, batteries and charge controller. All of the other components are missing, customer are supposed to buy all the other necessary equipment and install the system themselves. Facing this situation, I decided to combine the data from Czech and Russian markets. The idea behind my algorithm is to search for deals on Russian internet for the individual components and then try to approximate the costs of other parts and services.

I found 21 different offers for panels, either single, or included in sets. Vast majority of the panels were polycrystalline. Their price range from 849 EUR/kWp for the cheapest to 1548 EUR/kWp for the most expensive. The average lies at 998 EUR/kWp. That is about 30% more expensive than the prices in the Czech Republic. I think the maturity of the solar market is to blame. It is also possible, that there would be some discounts for orders of 10, 20 or more panels.

I also compared 24 different inverters. Costs vary from 114 EUR/kW to 468 EUR/kW. Average is 258 EUR/kW. I found a slight relationship between the price per kW and the nominal power of the inverters, but to much a greater extent differences between individual sellers are present. Price of inverters in RF is similar to the purchase costs you may expect in CR.

Price of racking was chosen to be the same as in the Czech Republic that means 157 EUR/kWp. There is no reason to assume the costs would be heavily different.

The same is true for the price of cables and other materials. It stands at 167 EUR/kWp.

I decided to adjust the transportation and labor costs a little. Russia has cheaper petrol and workforce, so the transportation and labor cost are lowered using a difference in GDP (PPP) between CR a RF. The same has been done to the costs connected with the paperwork, blueprints and other services.

Average per kWp		
Panels	998	55,0%
Inverter	258	14,2%
Racking	157	8,6%
Cables stc	167	9,2%
Tran. & labor	174	9,6%
Paperwork etc	63	3,4%
Total before VAT	1 815	100,0%
Total after VAT	2 142	118,0%

EUR/kWp

Table 12 Average price of components per kWp, Kolpashevo

Overall, the price of a full photovoltaic system would be approximately 2142 EUR/kWp. The installment costs would be about 19% more expensive than in the Czech Republic. The main reason is the price of the panels themselves. In addition, Russian sales tax is 18%, 3 percentage points higher than Czech VAT.

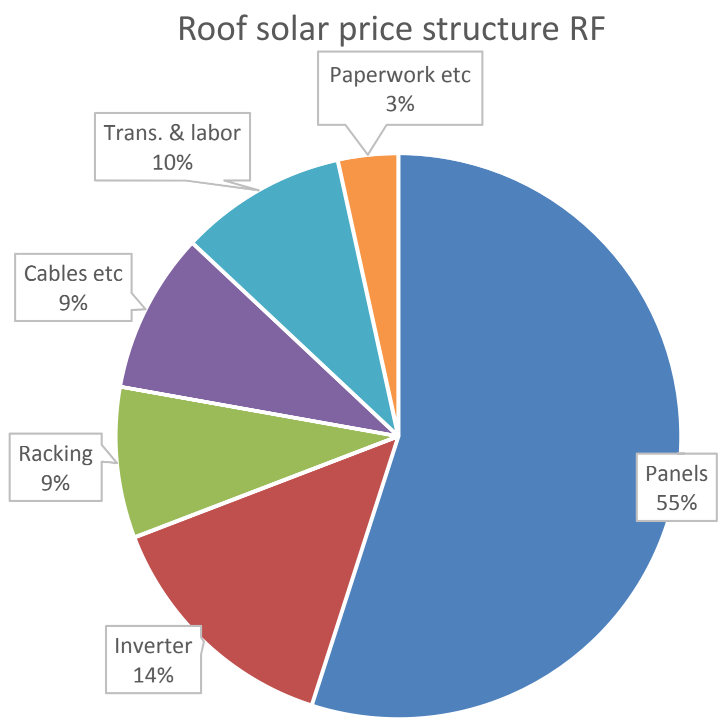

Figure 40 Roof solar system price structure per kWp, Kolpashevo

The biggest difference in price structure is a bit larger share of panels, which account for 55% of the total costs. Inverter has 14%, racking 9% and cables 9%. Transportation & labor, and paperwork & blueprints account for smaller portion (10% and 3%, respectively) because of lower Russian GDP compared to CR.

Russian Federation can benefit from its newly formed economic and political ties with Mainland China. PRC is world’s biggest producer of photovoltaic panels. When green energy starts to be more willingly supported by the Russian government, import of this technology may considerably decrease prices.

10.1.1.3 Investment Costs

Initial investment I is calculated as a multiplication of the average investment costs per kWp.

$$I = I_{kWp}P_{peak}$$

Equation 26 Initial investment I (EUR)

Where I_{kWp} denotes average investment costs per kWp and P_{peak} is peak installed power of a photovoltaic system. Average investment costs are 1796 EUR/kWp in Dobrichovice model and 2142 EUR/kWp in Kolpashevo. P_{peak} will be between 1 and 10 kWp.

10.1.1.4 Financing Options

It is possible to offset the initial investment payment by incorporating borrowed capital. Introducing a financing plan brings benefits in terms of lower initial investment, thus making the project possible for a wider audience. The problem is that not using your own capital hurts the NPV. Assuming, of course, that interest rate is greater than discount rate. Nevertheless, for ordinary households it is unlikely to receive interest rate lower than the discount rate. The reason is the interest rate needs to bear a risk of customer not being able to pay. As I stated before, photovoltaic technology is on the verge of being cost-effective, so I would not use any other financing than homeowner's own capital.

10.1.2 Repeating Costs

Solar systems tend to be easy to maintain. They do not have any moving parts unlike wind turbines or diesel generators. However, there are two main sources of additional repeating costs:

- Repurchase of inverter
- Maintenance costs

Inverters are expected to last no more than 15 years. More likely, their lifespan would be around 10 years. In my model, inverters are replaced every ten years. Inverters are 16% of investment costs in case of Dobrichovice and 14% in case of Kolpashevo. Those additional investments into renewal are also influenced by inflation. In addition, the inverters are a source of risk. What if the machine would not last 10 years, but only seven? This risk needs to be included in the discount rate.

Inverter renewal IR_i:

$$IR_i = IP_{kWp}(1 + infl)^i$$

Equation 27 Inverter renewal IR_i (EUR)

Where i is current year, IP_{kWp} is the inverter price per kWp and infl stands for inflation. Average inverter price is 255 EUR/kWp in the Czech Republic and 258 EUR/kWp in Russian Federation.

Maintenance costs include additional expenses connected with ordinary operation of the system. Sometimes parts needs to be replaced. In addition, the panels need to be cleaned of leaves or snow. There are some administrative burdens connected with the ownership of photovoltaic panels on the roof. Those issues are covered in the maintenance costs. Maintenance cost are expected to be around 1% of the investment cost every year plus inflation.

Maintenance costs MC_i:

$$MC_i = 1\% \times I(1 + infl)^i$$

Equation 28 Maintenance costs MC_i (EUR)

Where i is current year, I is the initial investment costs and infl is inflation.

There is one expense not included in the model. It is the cost of insurance. I decided not to incorporate it into the algorithm for a reason. The general insurance of a building quite commonly includes a coverage of peripherals, like solar panels. I suppose that an owner of a house would have this insurance regardless of having photovoltaic panels or not. Especially, when an insurance is required by a bank when you have a mortgage. When this insurance is not present, the owner probably has higher tolerance to risk and thus does not need any coverage.

10.1.3 Inflation

Inflation means year-on-year change in consumer prices. In my model, some of the formulas include inflation. It is the case with inverter renewals and maintenance costs. I suspect those expenses to increase over time on a same rate as a basket of consumer goods used in inflation calculations.

Even though the base currency of the Czech Republic is Czech Crown and in Russia, it is Russian Ruble, this thesis uses EUR as a medium of comparison.

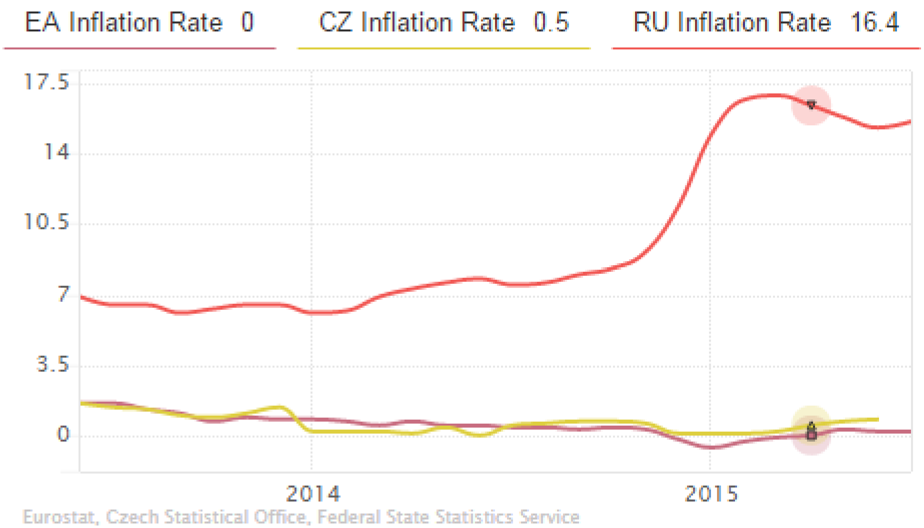

Figure 41 Euro area, CR and RF inflation rates [1]

As is depicted in Figure 41, inflation rates in Euro area, CR and RF are vastly different. At the beginning of 2015, inflation in EA and CR was close to 0%, but in Russia it was more than 16%. In my opinion, both inverter and maintenance price in the future will be more likely linked to stable Euro, than any of the local currencies. In lieu with this logic, I will use an inflation of 2% for model in Czech Republic and Russia. [2]

10.1.4 Saves on Electricity Bill

The main source of positive cash flow are the savings a household makes on its utility bill for electricity. Every kWh 'squeezed out' by the solar panels does not need to be purchased from the distribution company. Alternatively, it is necessary to purchase only part of it. That is why the utilized electricity ratio is so important. It directly influences the positive side of cash flow of the project.

10.1.4.1 Saves on Electricity Bill, Dobrichovice

In the Czech Republic, the legislature is changing rapidly in this field. Not many years ago, there were some subsidies on electricity produced from photovoltaic panels. Nowadays those subventions were cancelled. Additionally, confusions arisen as to whether it is necessary to pay for the services of distribution network when you are generating some of your own kWh by a solar system. To estimate the savings as close as possible I used following formula:

$$S_i = UE_i(NEP - RS)(1 + CNEP)^i$$

Equation 29 Savings on electricity bill S_i (EUR), Dobrichovice

Where i is an appropriate year, S_i indicates savings on electricity bill, UE_i is utilized solar electricity, NEP represents network electricity price, RS are the costs of regulated services and CNEP is a change in network electricity price.

Utilized solar electricity stands for the amount of electricity that was produced by the photovoltaic panels and purposely used by the house's appliances and other equipment.

$$UE_i = EP_i \times u_i$$

Equation 30 Utilized solar electricity UE_i (Wh), Dobrichovice

Where i is current year, EP_i is panels' annual electricity production and u_i is utilized electricity ratio. Both of those numbers change in time. Panels' produce less and less energy as they age. As a result, the amount of utilized energy gets bigger, because the chart of energy production is more and more 'hidden' bellow the consumption. This phenomenon was closely described in previous chapters.

$$EP_i = G_y(1 - i \times DR)$$

Equation 31 Panels' annual electricity production EP_i (Wh), Dobrichovice

Where i is current year, G_y is what the panels produce in the first year and DR is the degradation rate.

$$u_i = u + i \times CU$$

Equation 32 Utilized electricity ratio u_i (-), Dobrichovice

Where i is current year, u represents the initial utilized electricity ratio and CU stands for the annual change in utilized electricity ratio. u_i cannot be greater than 100%.

Going back to Equation 29, there are still some variables that are not properly explained. For example, the network electricity price NEP. This number is based on the cheapest possible supplier of electricity in the region. According to Energostat, the most favorable prices are offered by the company Europe Easy Energy. [3] Data from this company put a price tag of 0.155 EUR/kWh for this household.

As for regulated services RS, I exchanged some emails with ERU (Czech office responsible for regulations in the field of power engineering) and from their answers there are two important messages. The algorithm of calculating the subsidies for renewables will change from 2016, but the actual numbers will be known in November

2015, after my thesis is finished. The second essential message is how it is in 2015. For every kWh your photovoltaic panels produce, you need to pay for:

- System services 3.9 EUR/MWh
- Support of renewables 18.3 EUR/MWh
- Compensation for OTE 0.257 EUR/MWh
- Sales tax of 21%

When put together, costs of regulated services a roof photovoltaic system operator needs to pay are 0.0272 EUR/kWh.

The last unexplained variable from Equation 29 is the change in network electricity price CNEP. It is next to impossible to predict electricity prices in the future. There are many regulatory measures in place in both the European Union and in the Czech Republic. Those rules can significantly change from one year to the other. In addition, the fuel prices can rapidly adjust their price according to economic, political and technological environment. Because of those reasons, I am accepting an annual change in electricity price for an ordinary customer to increase by the same rate as inflation. Czech central bank and European central bank put their inflation goals on 2% year-on-year.

10.1.4.2 Saves on Electricity Bill, Kolpashevo

In my model, I use the exact same equations for Kolpashevo as I used in chapter 10.1.4.1 for Dobrichovice. I will only talk about the different input numbers that enter those calculations.

There are no possible renewables subventions in place in Russian Federation. They are planned, but have not been incorporated yet.

The electricity market in Tomsk Oblast is vertically integrated. That means, than all means of transportation, distribution and electricity supply are owned by a single company. This situation does not give consumer any possibility to change their energy supplier in comparison with the situation in the Czech Republic.

According to Department of tariffs regulations of Tomsk Oblast, the price for 1 kWh is 0.033 EUR. [4] This is almost 5 times cheaper than the electricity in the Czech Republic.

There are no needs to pay for regulated services when you have your own photovoltaic power plant, but do not expect to receive anything when you send surplus energy back to the network.

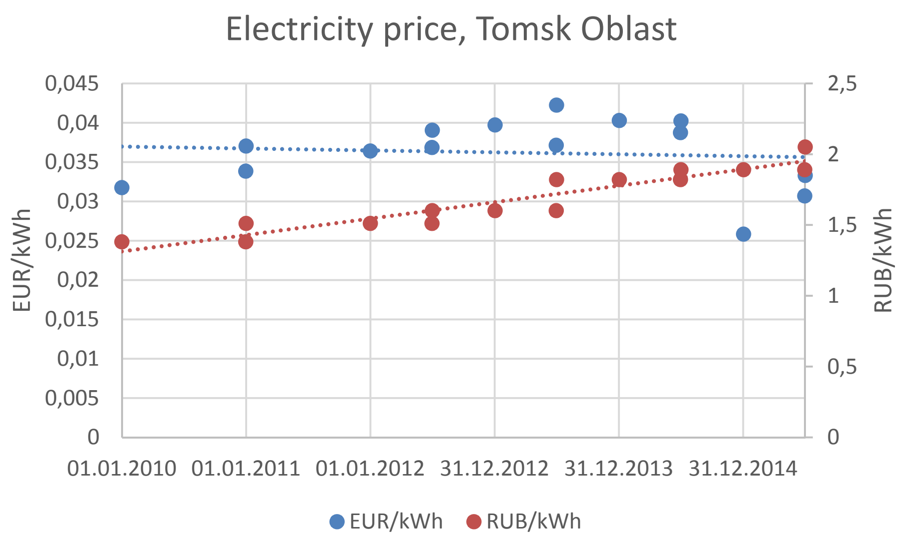

Figure 42 Electricity price, Tomsk Oblast [5]

As pictured in Figure 42, the price is regulated and during the past 5 years rose on average by 8.8% annually when denominated in Russian ruble. The problem is, that in 2014 Russian Federation got involved in the Ukrainian conflict. As a result, western countries put sanctions against RF in place. That, connected with lower oil prices, caused turmoil in exchange rates and EUR/RUB rate fluctuated heavily. The trend between 2010 and 1.7.2014 was a rise of about 6% every year in price of electricity when counted in EUR. Assuming the Russian economy will stabilize in the near future, but its inflation would still remain above the inflation of EMU, I put the future change in network electricity price to 4%. Nevertheless, predicting the behavior of both Russian energy companies and EUR/RUB exchange rate seems next to impossible and may be a source of great inaccuracy.

10.1.5 Feed-in Tariffs

Feed-in tariffs represent the money the owner of a roof solar receives when he/she sells the surplus electric power to the distribution network. They can be entirely based on market forces or there could be some government-guaranteed prices in place.

In the Czech Republic, no guaranteed feed-in prices are offered for new installations. When the electric energy is sold directly to the distribution network, the amount received can be between 0.011 and 0.022 EUR/kWh. [6] In my model, I use 0.0185 EUR/kWh. This amount is taxed by an income tax of 15%.

In the case of Tomsk Oblast, there is no possibility of any feed-it tariffs.

Feed-it tariff revenue FI_i:

$$FI_i = GS_i \times FIT(1 + CFIT)^i - IT$$

Equation 33 Feed-in tariff FI_i (EUR)

Where i is current year, GS_i is generation surplus, FIT is the selling price of surplus energy, CFIT stands for change in feed-in tariff and IT is income tax.

10.1.6 Cash Flow

Cash flow represents the amount of money you receive (or lose) every given period of time when a project is running. In the case of this thesis, the main negative factors influencing cash flow are the initial investment, repurchases of inverter and maintenance costs. The positive factors include expenses saved by incorporating photovoltaic panels and revenues from feed-in tariffs.

Cash flow is calculated as:

$$CF_i = -I - IR_i - MC_i + S_i + FI_i$$

Equation 34 Cash flow CF_i (EUR)

Where i is current year, I symbolizes the initial investment, IR_i is inverter renewal, MC_i are maintenance costs, S_i represents money saved using solar panels and FI_i stands for feed-in tariffs revenue.

Cumulative cash flow is a sum of capital flow from a project:

$$CCF_i = \sum_{y=0}^{i} CF_i$$

Equation 35 Cumulative cash flow CCF_i (EUR)

Where i is current year. CCF_i is used in some further economic indicators like PP (Payback Period).

10.1.7 Discount Rate

It is more valuable to receive 1000 EUR today than next year. The reason is you can use the money to bring you a benefit, most often an interest. Discount rate addresses this issue of differences in value of money in time.

As a basic benchmark of a discount rate, I used 10-year bonds of EMU economies. The interest rates are not the same throughout those countries. For example, Slovakia yields interest rate of 0.5% and Greece has 11.43%. Most of the other states, however, have their rates between 1% and 3%. [7] Therefore, I will take 2% as a basis.

Now the question is: 'Would you rather invest your money into European bonds or a roof photovoltaic power plant? Are the risks the same?'. I would argue that they are not. Sure, countries can go bankrupt. We had this a couple of times in past decades. Argentina, Iceland, Russia, Zimbabwe and others. Nevertheless, most of the time, government bonds are recognized as a safe investment. On the other hand, there are many risks connected with a photovoltaic system. The panels may degrade faster, than stated by the manufacturer. Inverters may not last as long as expected. The costs of electricity may not rise as we would like. Weather may be unfavorable for several years. Do not take me wrong, solar panels are a rather safe investment. However, not as safe as government bonds.

Because of the reasons stated above, my model uses a discount rate of 3%. I cannot see vital differences between RF and CR when regarding investment into euro bonds or risks connected with the ownership of photovoltaic panels. I used the same discount rate in both countries. The nature of obtaining this figure implies that it is necessary to perform a sensitivity analysis, which I will do in one of the following chapters.

10.1.8 Discounted Cash Flow

Discounted cash flow incorporates the concept of discount rate into the idea of annual cash flows. With each passing year, the value of a constant flow of monetary instruments contributes to the present value by lower and lower extent. When expressed in a formula:

$$DCF_i = \frac{CF_i}{(1+r)^i}$$

Equation 36 Discounted cash flow DCF_i (EUR)

Where CF_i means cashflow in year i and r represents discount rate.

Discounted cashflow in year i would be always smaller than non-discounted cashflow, as long as the discount rate is greater than 0%.

Cumulative discounted cashflow $CDCF_i$:

$$CDCF_i = \sum_{y=0}^{i} DCF_i$$

Equation 37 Cumulative discounted cash flow $CDCF_i$ (EUR)

Cumulative discounted cash flow is used in further economic indicators like NPV (Net Present Value).

10.1.9 Payback Period

Payback period represent how many years it takes for a project to pay its initial investment costs. In other words, when the cumulative cash flow (CCF_i) becomes positive. It is arguably the most understandable indicator of economic properties of an investment.

$$PP = number\ of\ years\ until \sum_{y=0}^{i} CF_i\ becomes\ positive$$

Equation 38 Payback period PP (years)

A purchase of a photovoltaic system is most often an act of an ordinary citizen who does not have any education in neither engineering nor economics. Payback period is easy to handle, straightforward single number that anybody can understand. I argue it is the most important economic figure regarding this type of investment for an uneducated individual. However, it does not account for two important factors. The first is the value of money in time, which PP does not reflect. The second issue is payback period does not take into account what happens after the initial investment is paid off. The figure is thus used as a reference, what an everyday customer may think about this project.

I assume for the project to be interesting for a consumer, the payback period must be shorter than 15 years. At PP of 15 years, it means your investment brings you an interest of 6.7% every year with very low risks. The deal gets even better at PP of 10 years, which leads to a 10% return every year. In this circumstance, many homeowners may choose to install a solar system, driving down the prices even further, inducing a positive feedback loop.

10.1.10 Net Present Value (NPV)

Net present value indicates, what is the net benefit when carrying on with the project at current terms. In comparison to payback period, NPV includes the value of money in time.

$$NPV_i = \sum_{y=0}^{i} DCF_i = CDCF_i$$

Equation 39 Net present value NPV_i (EUR)

Where i is current year, DCF_i represents discounted cash flow and $CDCF_i$ stands for cumulative discounted cashflow.

NPV is easy to grasp. When it is below zero, the investment is not worthy of realizing, because it will not bring any value in terms of present. When NPV is positive, the project is cost-effective based on the standing figures.

I used NPV in two distinct variants. NPV_{25} assumes the panels only last 25 years, as guaranteed by the manufacturers. NPV_{40} accepts the lifecycle to be 40 years. This is a hard assumption to asses, because the current technology has not been around for many years. There are some examples from the history of photovoltaic panels:

- Britain's first solar panel still works after 60 years. [8]
- A module outperforms its factory specs after 30 years. [9]
- Kyocera has reported several solar power installations that continue to operate reliably and generate electricity even though they are nearly 30 years old. [10]

All of those are just examples, not scientific proofs. Nevertheless, it is reasonable to assume the panels would still be working after 40 years. The other issue is that when you are for example 30 years old and you decide to purchase the photovoltaic system, after 40 years, you would be probably retired. Thus, a lifespan of 40 years is an upper limit for any economic considerations.

10.1.11 Internal Rate of Return (IRR)

The internal rate of return asks a question: 'What is the discount rate for this project to have NPV = 0?'. As the name suggests, IRR calculates a rate of return an investment has.

$$\sum_{y=0}^{i} \frac{CF_i}{(1 + IRR)^i} = 0$$

Equation 40 Internal rate of return IRR (%)

In a similar manner as with NPV, I will discuss IRR at two different situations. When the life cycle of a panel is supposed to be 25 years and when it is 40 years.

11 Results

The outcome is not surprising. As was expected, economic, politic and climate environment in the Czech Republic allow this project to be somehow cost-effective. In the case of Kolpashevo, great changes would need to be made leading the investment to be a rational, viable option.

11.1 Discussing Default Variant

In this part, I would like to sum up the default figures used throughout the calculations and to look at the results and outcomes of the investment into the roof photovoltaic system.

11.1.1 Default Variant, Dobrichovice

First, let me summarize the default setting of variables.

Technical

- Household
  - Annual house power needs = 19 771 kWh
  - Utilized electricity ratio – calculated by the model
  - Change in utilized electricity ratio = 0.25%
- Solar panels
  - System peak power – main optimization variable
  - Degradation rate = 0.7%
- Inverter
  - Inverter efficiency = 95%
- Miscellaneous
  - Losses due to temperature and low irradiance = 12.7%
  - Loss due to angular reflectance effects = 3.1%
  - Loss in cables etc. = 8%

Economic

- General
  - Inflation = 2%
  - Discount rate = 3%
  - CZK/EUR exchange rate = 27 CZK/EUR [11]
  - Income tax = 15%
  - Network electricity price = 0.155 EUR/kWh
  - Costs of regulated services = 0.0272 EUR/kWh
  - Change in network electricity price = 2%
  - Feed-in tariff = 0.0185 EUR/kWh
  - Change in feed-in tariff = 2%
- Investment
  - Investment VAT rate = 15%
  - Individual components VAT rate = 21%
  - Price of panels = 698 EUR/kWp

- Price of inverter = 255 EUR/kWp
- Price of racking system = 157 EUR/kWp
- Price of cables and other material = 167 EUR/kWp
- Price of transportation and labor = 209 EUR/kWp
- Price of paperwork and blueprints = 75 EUR/kWp
- Investment costs before VAT = 1562 EUR/kWp
- Investment costs after VAT = 1796 EUR/kWp
- Maintenance costs = 1% of investment

The most important step is to determine optimal system peak power. Excel provides a solver tool that puts this number to approximately 4.5 kWp. As a basis for optimization, I used a maximization of NPV after 40 years. The other bases were not reasonable, because payback period does not put difference between powers from 1 to 5 kWp and NPV after 25 years is negative. At this peak power, the utilized electricity ratio is 98%. Not unforeseeably, the model puts the optimal solution to be close to 100% utilization.

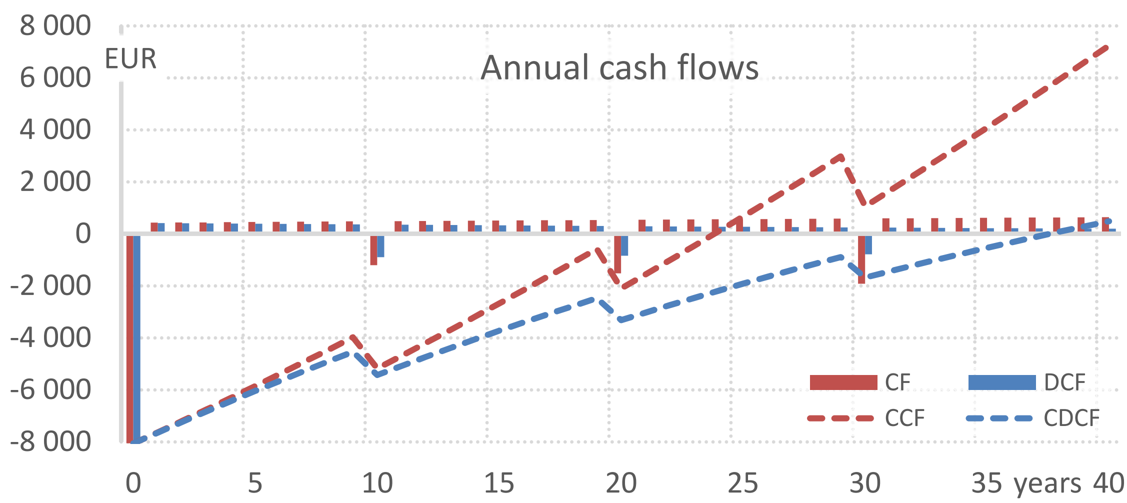

Figure 43 Annual cash flows, default variant, Dobrichovice

Figure 43 visualizes two major economic variables. Cashflow and discounted cashflow. At the point, where cumulative cashflow (CCF) crosses zero lies the payback period. In this case, it is 24 years. That is far away from stated goals of 10 or 15 years. Cumulative discounted cashflows represent NPV at any given time. As can be seen, when assuming the lifespan of the project is 40 years, NPV is positive and equal to 498 EUR. This means investment brings an increase in terms of today's value of money. This is barely a great result considering the initial investment is more than 8000 EUR. IRR_{25} (life cycle of 25 years) is 0.64% and IRR_{40} is 3.36%.

According to those figures, the investment is possible, especially if a customer would be a solar enthusiast, but it is on the very edge. However, the results are exceptionally sensitive and only slight changes in some of the variables can lead to vastly different outcomes.

11.1.2 Default Variant, Kolpashevo

In a same way as in Dobrichovice, let us look at the default parameters.

Technical

- Household
  - Annual house power needs = 19 771 kWh
  - Utilized electricity ratio – calculated by the model
  - Change in utilized electricity ratio = 0.25%
- Solar panels
  - System peak power – main optimization variable
  - Degradation rate = 0.7%
- Inverter
  - Inverter efficiency = 95%
- Miscellaneous
  - Losses due to temperature and low irradiance = 10.3%
  - Loss due to angular reflectance effects = 2.9%
  - Loss in cables etc. = 8%

Economic

- General
  - Inflation = 2%
  - Discount rate = 3%
  - GDP (PPP) per capita RF = 24 805 USD [12]
  - GDP (PPP) per capita CR = 29 925 USD [12]
  - RUB/EUR exchange rate = 63 RUB/EUR [11]
  - Income tax = 13%
  - Network electricity price = 0.033 EUR/kWh
  - Change in network electricity price = 4%
- Investment
  - VAT rate = 18%
  - Price of panels = 998 EUR/kWp
  - Price of inverter = 258 EUR/kWp
  - Price of racking system = 157 EUR/kWp
  - Price of cables and other material = 167 EUR/kWp
  - Price of transportation and labor = 174 EUR/kWp
  - Price of paperwork and blueprints = 63 EUR/kWp
  - Investment costs before VAT = 1815 EUR/kWp
  - Investment costs after VAT = 2142 EUR/kWp
  - Maintenance costs = 1% of investment

Parameters differ mostly in the economic terms. Because of unfavorable figures, it is impossible to calculate the optimal peak power. Payback period would always be infinity, NPV are negative and IRR is either incalculable or negative. I decided to put in the same installed power as in the case of Dobrichovice, 4.5 kWp. Utilized electricity ratio at this level is 89.2%. It is lower than in CR, the main reason is different algorithm.

However, it makes sense even from the logical point of view. Climate conditions in RF tend to be more extreme than in the middle of Europe.

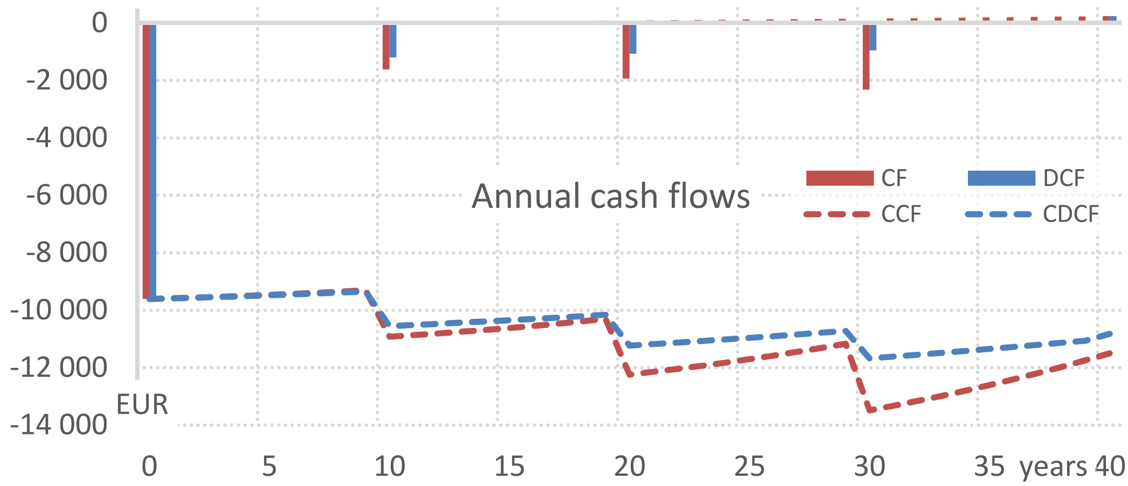

Figure 44 Annual cash flows, default variant, Kolpashevo

Figure 44 depicts how hostile economic environment is for investments like this in Russia. This type of project requires high costs of electricity, incredibly low investment expenses or government involvement. All of those factors are unsatisfied in Tomsk Oblast. The problem is projected maintenance costs take almost all the benefits away. In addition, a repurchase of an inverter every 10 years considerably drains the cash flow. NPV_{25} is - 10 960 EUR, NPV_{40} - 10 821 EUR. IRR is negative or impossible to compute. PP is infinity (or much longer, than 40 years at the very least).

However, this investment is definitely not recommended at this moment, it would be interesting to observe, what needs to change for this venture to be cost-effective.

11.1.3 Comparison of Default Variants

The technical results look very similar:

Technical results			
	Dobrichovice	**Kolpashevo**	
Annual house power needs	19 771	19 771	*kWh*
Panels' electricity production	3 996	4 026	*kWh*
Electricity surplus	80	436	*kWh*
Electricity deficit	15 854	16 181	*kWh*
Utilized solar electricity	3 916	3 590	*kWh*
Utilized electricity ratio	98,0%	89,2%	

Table 13 Technical results comparison, default variant

Both roof solar systems produce similar amounts of electricity every year, even the utilized amount of energy does not crucially differ. The economic results are vast, however.

Economic results			
	Dobrichovice	**Kolpashevo**	
Payback period	24	---	*years*
NPV after 25 years	-1 914	-10 960	*EUR*
NPV after 40 years	489	-10 821	*EUR*
IRR after 25 years	0,6%	---	
IRR after 40 years	3,4%	---	

Table 14 Economic results comparison, default variant

Economic results are almost incomparable. While most other parameters are similar, the major divergence is in the price of electricity. Even after accounting for regulated services, costs per kWh are 4 times larger in the Czech Republic than in Tomsk Oblast. This is the key factor leading to such a diverse outcomes.

11.2 Sensitivity Analysis

All of the default numbers were chosen with consideration to all of the circumstances. However, nobody can precisely predict the future. Even a mammoth Czech energy company, CEZ, made a huge mistake in foreseeing the future. Back in 2011, it started construction of a brand new gas power plant with nominal power of 880 MW. The investment costs were about 740 million EUR. Expectations were that the prices of emission allowances and fuel costs would make this plant profitable. Even though the power station was ready to be fully operational after just 2 years after the beginning of the construction, it was never put into full-scale action. The economic circumstances changed so unfavorably, that the plant now stands idle. Moreover, it may be like this for years to come. [13]

I presented the story mostly for the purpose to realize, that markets may change in very short periods of time. What was cost-effective today may not be profitable tomorrow. And the other way around. It is important to observe how the results shift when we let some of the parameters change.

11.2.1 Sensitivity Analysis, Dobrichovice

The Czech model is extraordinarily sensitive in many ways. Some of the important figures rely solely on the investor (system peak power), others are mostly in the hands of the market (electricity price, inflation), while particular parameters are only dependent on legislature (regulated services, investment incentives).

11.2.1.1 System Peak Power

In chapter 11.1.1 I used Excel's solver function to come up with the optimal peak power of the solar system with regards to the NPV. However, the situation might be more complicated from other points of view.

System peak power, kWh					
Peak P, kWh	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
1,0	24	-418	118	0,68%	3,38%
2,0	24	-836	235	0,68%	3,38%
3,0	24	-1 255	353	0,68%	3,38%
3,5	24	-1 464	411	0,68%	3,38%
4,0	24	-1 679	465	0,67%	3,38%
4,5	24	-1 922	489	0,63%	3,35%
5,0	25	-2 243	436	0,52%	3,28%
5,5	25	-2 688	259	0,28%	3,15%
6,0	26	-3 240	-76	-0,04%	2,96%
7,0	29	-4 530	-1 144	-0,74%	2,46%
8,0	31	-6 029	-2 514	-1,49%	1,94%

Table 15 System peak power sensitivity analysis, default variant, Dobrichovice[1]

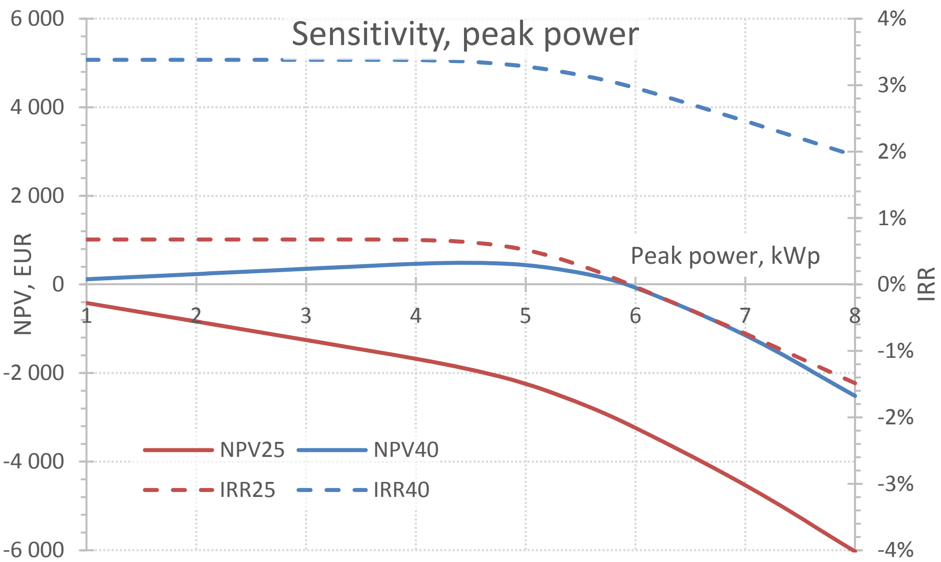

Figure 45 System peak power sensitivity analysis, default variant, Dobrichovice

The payback period cannot be lower than 24 years, and this would probably not convince anybody to put panels on their roof. When taken 25-year scope, both NPV and IRR lead us not to carry on with the project at all. NPV_{25} and IRR_{25} are having their maximum values the lower the system peak power gets. At the life expectancy of 40 years, things get a little bit brighter. NPV_{40} has its maximum at the previously stated 4.5 kWh and IRR_{40} reaches 3.38% from 1 to 4 kWp.

When taken the 40 years' operating lifespan, investment is the most cost-effective roughly between 4 and 5 kWp. Nevertheless, as I stated earlier, this assumption of long project life is very questionable.

[1] The values in the first column do not use the same step of 1 kWp. Around the 4.5 kWp, a step of 0.5 kWp was used for better precision.

11.2.1.2 Discount Rate

Discount rate is a parameter that requires some degree of guessing, the necessity for a sensitivity analysis is undebatable.

Discout rate		
DR	**NPV_{25}**	**NPV_{40}**
0%	668	7 243
0,5%	136	5 678
1,0%	-349	4 327
1,5%	-793	3 158
2,0%	-1 199	2 144
2,5%	-1 572	1 261
3,0%	-1 914	489
3,5%	-2 229	-187
4,0%	-2 519	-782
4,5%	-2 786	-1 307
5,0%	-3 033	-1 772

Table 16 Discount rate sensitivity analysis, default variant, Dobrichovice

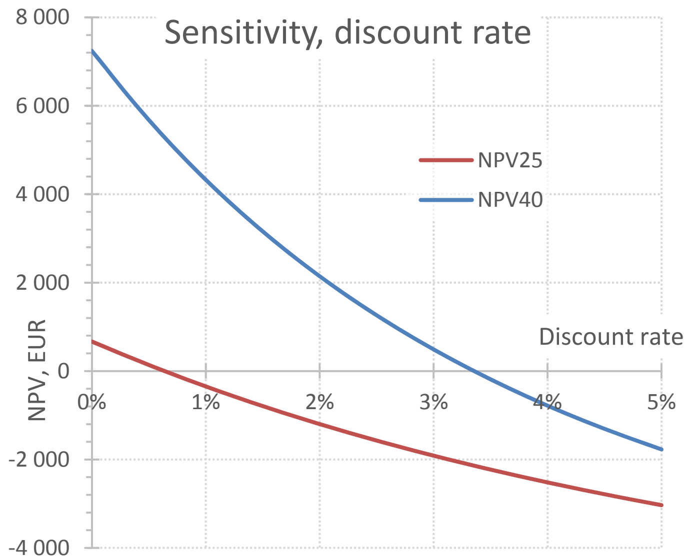

Figure 46 Discount rate sensitivity analysis, default variant, Dobrichovice

The default discount rate is 3%. NPV_{25} starts to be positive at a discount of 0.5%. This rate could possibly be acceptable when the economy would be in deflation and the project would be risk-free. Although there were signs that some European economies might have short-term deflation tendencies, I would argue at this moment this situation is unlikely. In addition, photovoltaic panel investment is not riskless, as we discussed earlier. However, it is possible to accept the possible discount rate to be between 2% and 3%. This would put NPV_{40} to up to 2144 EUR, which presents this venture in more favorable light. Setting the discount rate at 4% or 5% would be a mistake, because some Czech stocks can offer annual dividends with this rate and risk connected with owning shares is definitely higher, than risk of having a photovoltaic system on the roof.

11.2.1.3 Inflation

Inflation seemingly does not influence much in my model – only repeating costs like inverter renewal and maintenance costs. Its impacts may be more substantial, however.

Inflation					
Inflation	**PP**	**NPV_{25}**	**NPV_{40}**	**IRR_{25}**	**IRR_{40}**
-1,0%	20	-553	3 006	2,40%	4,89%
-0,5%	20	-740	2 692	2,18%	4,72%
0%	21	-941	2 343	1,94%	4,52%
0,5%	22	-1 157	1 953	1,67%	4,29%
1,0%	23	-1 391	1 519	1,37%	4,03%
1,5%	24	-1 642	1 033	1,03%	3,72%
2,0%	24	-1 914	489	0,64%	3,36%
2,5%	25	-2 207	-120	0,18%	2,91%
3,0%	28	-2 524	-803	-0,35%	2,35%
3,5%	32	-2 865	-1 571	-0,99%	1,62%
4,0%	37	-3 234	-2 434	-1,78%	0,61%

Table 17 Inflation sensitivity analysis, default variant, Dobrichovice

Looking at Table 17, one may notice inflation has some effect on economic characteristics. Especially when assuming the life cycle of a project to be 40 years, NPV_{40} can change from positive to negative in a matter of few percentage points' difference in annual price increase. The issue is even central banks have limited ways to control and predict inflation. For example, the estimates of Czech national bank is the inflation would be somewhere between 1% and 3% at the beginning of 2017. [14] That is a sizable span considering the guess is just 18 months ahead and this organization is the one with all the information.

Yes, inflation has moderate impact on the cost-effectiveness of this investment. However, in my opinion, it is likely, that in the near future, we will not see any major slumps or hiccups and the inflation will stay close to but below 2%.

11.2.1.4 Network Electricity Price

At this point, the results start to be more interesting, because the price of electricity the house obtains from the distribution network is a major source of revenue for this investment.

Network electricity price, EUR/kWh						
CZK/ kWh	EUR/ kWh	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
3,51	**0,13**	36	-3 919	-2 354	-2,49%	1,10%
3,78	**0,14**	31	-3 111	-1 208	-1,12%	2,07%
4,05	**0,15**	25	-2 303	-62	0,10%	2,95%
4,19	**0,155**	24	-1 899	511	0,66%	3,37%
4,32	**0,16**	23	-1 495	1 083	1,19%	3,77%
4,59	**0,17**	20	-687	2 229	2,20%	4,54%
4,86	**0,18**	17	120	3 375	3,14%	5,27%
5,13	**0,19**	16	928	4 521	4,02%	5,97%
5,40	**0,20**	15	1 736	5 667	4,85%	6,64%
5,67	**0,21**	14	2 544	6 812	5,65%	7,29%

Table 18 Network electricity price sensitivity analysis, default variant, Dobrichovice

Change in network electricity price					
Change	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
-1,0%	41	-4 883	-5 152	-7,26%	-8,28%
-0,5%	41	-4 475	-4 455	-5,31%	-3,68%
0%	41	-4 035	-3 677	-3,77%	-1,46%
0,5%	40	-3 562	-2 807	-2,48%	0,09%
1,0%	33	-3 053	-1 833	-1,34%	1,33%
1,5%	27	-2 505	-740	-0,31%	2,40%
2,0%	24	-1 914	489	0,64%	3,36%
2,5%	22	-1 277	1 874	1,52%	4,23%
3,0%	21	-590	3 436	2,36%	5,04%
3,5%	19	152	5 203	3,16%	5,81%
4,0%	17	953	7 202	3,92%	6,55%

Table 19 Change in network electricity price sensitivity analysis, default variant, Dobrichovice

The first table corresponds with a change that can happen right now of in the foreseeable future. A government can alter some regulated prices. Or the industry Europe-wide will require more electricity thus pushing the costs up. Alternatively, European Union may use measures to shift the price in a specific way. Events like that are certainly not unimaginable. In case of drastic changes, when each kWh would cost 0.2 EUR, payback period drops to 15 years, making this investment interesting for many more people. On the other hand, even a slight drop to 0.15 EUR/kWh can make the project not cost-effective, because even NPV_{40} would be negative.

The other table represents a long-term trend. It asks a question: 'How would the price of electricity change in 10, 20 or 40 years?'. Future trends may address the same issues as current trends. We have seen electricity prices stagnating or slightly dropping in the Czech Republic due to widespread use of renewables throughout the Europe. This state is favorable to the consumer. On the other hand, traditional energy sources are not receiving new investments. That may lead to complications. The problem is, how long can European energy sector hang on before the prices would be forced to rise? Those are hard questions. Similarly to the results in Table 18, the more expensive the electrical power is, the more profitable it is to have photovoltaic panels on your roof. I suggest that in the years to come the electricity prices would either rise at the level of inflation or even faster.

11.2.1.5 Costs of Regulated Services

The regulated services you need to pay for when you have solar power plant installed have been put into place not so long ago. They have been introduced by a government agency, involving a couple of papers and signatures. In the same way, those regulations can be easily changed or lifted.

Costs of regulated services, EUR/kWh						
CZK/ kWh	EUR/ kWh	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
0,00	**0,00**	17	284	3 607	3,32%	5,41%
0,27	**0,01**	19	-524	2 461	2,39%	4,69%
0,54	**0,02**	22	-1 331	1 316	1,40%	3,93%
0,73	**0,027**	24	-1 913	491	0,64%	3,36%
0,81	**0,03**	25	-2 139	170	0,33%	3,12%
1,08	**0,04**	29	-2 947	-976	-0,86%	2,26%
1,35	**0,05**	35	-3 755	-2 122	-2,19%	1,30%

Table 20 Costs of regulated services sensitivity analysis, default variant, Dobrichovice

When those regulated services costs are reduced to zero, the project gets cost-effective straight on, even when talking about NPV_{25}. It is still a few years short of the other goal, PP of 15 years. From the other perspective, payments for those services can be raised. Even a raise to 0.04 EUR/kWh would make NPV_{40} negative.

Czech government is in a complicated situation. It would like to support photovoltaics. But the public is afraid of similar subsidy fiasco that already happened. Therefore, it is politically problematical to address this issue. In my opinion, the measures of putting those additional costs on photovoltaics owners were a way to compensate for the mistakes of the past. It is debatable how it will change with planned adjustment of payments for renewables.

11.2.1.6 Maintenance Costs

Maintenance costs are one of the expenses, which you may underestimate when considering an investment to a photovoltaic power plant. But how big impact do they have?

Maintenance costs, % of investment					
Maint.	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
0,00%	18	-136	3 144	2,85%	5,09%
0,25%	19	-580	2 480	2,33%	4,68%
0,50%	21	-1 025	1 817	1,79%	4,26%
0,75%	23	-1 469	1 153	1,23%	3,82%
1,00%	24	-1 914	489	0,64%	3,36%
1,25%	25	-2 359	-174	0,01%	2,87%
1,50%	29	-2 803	-838	-0,66%	2,36%
1,75%	31	-3 248	-1 502	-1,37%	1,81%
2,00%	36	-3 692	-2 166	-2,14%	1,22%

Table 21 Maintenance costs sensitivity analysis, default variant, Dobrichovice

Looking at Table 21, maintenance expenses have a surprisingly high impact on the overall profitability. Estimating upkeep costs to be below the base 1% line may significantly improve the cost-effectiveness. On the other hand, maintenance costs of 2% deem the project not economically viable.

The number 1% is an educated guess. However, observing its impact on the result, it might need a further research from an actual project to determine it more specifically.

11.2.2 Sensitivity Analysis, Kolpashevo

From the point of view of sensitivity, Kolpashevo model is significantly different from its Dobrichovice counterpart. In this case, markets will not influence one of the vital components – electricity price. In addition, the project is not cost-effective from any point of view at this moment.

11.2.2.1 Sensitivity Analyses That Do Not Have Serious Impact

As I stated before, the solar panel investment in Kolpashevo is not economically interesting in current market situation. There are many parameters that influenced the results of the Czech model, but have no impact whatsoever on RF model.

System Peak Power

In default variant we took the 4.5 kW for granted. However, the sensitivity analysis leads us to the conclusion, that the project is not cost-effective at any given installed peak power. NPVs are lower and lower with reducing the power capacity of a solar system. At 1 kWp, NPV_{25} is - 2384 EUR and NPV_{40} is very similar. Payback period is more than 40 years and IRR is either negative or incalculable.

Changing system peak power will never make the project profitable without a modification of other parameters.

Discount Rate

When the discount rate is set to 0%, both NPV_{25} and NPV_{40} are negative, around - 11 500 EUR. Setting discount rate at 10% leads to NPVs of approximately - 10 000 EUR. The reason is the cash flow from savings of electric power is insignificant compared to the investment itself. Discount rate has almost no impact on the cost-effectiveness of the venture in the tested range of 0% to 10%.

Inflation

Best scenario is there would be deflation of Russian prices compared to EUR. In this circumstance, at inflation of -1%, NPV_{40} drops from its base value of - 10 821 EUR to - 8014 EUR, which is still not a desirable value. At inflation of 9%, NPVs drop to - 18 563 EUR (NPV_{25}) and - 35 389 EUR (NPV_{40}). Payback period will still be more than 40 years and IRR is either negative or incalculable.

Reasonable variations in inflation will never make the project profitable.

Maintenance Costs

Even when maintenance cost are set to 0%, the cash flow would never be high enough to offset the investment and inverter renewal costs. NPV_{40} is - 7508 EUR when the maintenance expenses are zero.

11.2.2.2 Network Electricity Price

Network electricity price, EUR/kWh						
RUB/ kWh	EUR/ kWh	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
1,89	**0,03**	> 40	-11 204	-11 249	xxx	< 0%
2,08	**0,033**	> 40	-10 915	-10 743	xxx	< 0%
2,52	**0,04**	> 40	-10 242	-9 564	< 0%	< 0%
3,15	**0,05**	> 40	-9 279	-7 879	< 0%	< 0%
3,78	**0,06**	> 40	-8 317	-6 195	< 0%	< 0%
4,41	**0,07**	40	-7 354	-4 510	< 0%	0,09%
5,04	**0,08**	37	-6 392	-2 825	< 0%	1,14%
5,67	**0,09**	34	-5 430	-1 141	< 0%	2,05%
6,30	**0,10**	29	-4 467	544	< 0%	2,87%
6,93	**0,11**	26	-3 505	2 229	< 0%	3,61%

Table 22 Network electricity price sensitivity analysis, default variant, Kolpashevo

Change in network electricity price					
Change	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
0,0%	> 40	-12 153	-13 734	xxx	xxx
1,0%	> 40	-11 918	-13 253	xxx	xxx
2,0%	> 40	-11 646	-12 638	xxx	xxx
3,0%	> 40	-11 329	-11 847	xxx	xxx
4,0%	> 40	-10 960	-10 821	xxx	< 0%
5,0%	> 40	-10 528	-9 483	xxx	< 0%
6,0%	> 40	-10 023	-7 727	< 0%	< 0%
7,0%	> 40	-9 431	-5 410	< 0%	< 0%
8,0%	37	-8 737	-2 342	< 0%	1,55%
9,0%	33	-7 921	1 737	< 0%	2,94%
10,0%	30	-6 961	7 178	< 0%	4,23%

Table 23 Change in network electricity price sensitivity analysis, default variant, Kolpashevo

It is important to note that the price of electricity in Tomsk Oblast is entirely regulated. That leads to a conclusion that any change can happen anytime. The only limit is a willingness of customers to pay. However, there would need to be really drastic changes for the investment to be cost-effective. When taken a lifespan of 40 years, the current price per kWh would need to increase three fold. Alternatively, electricity costs would need to rise at a rate of 9% annually. Both of those scenarios are possible, but highly unlikely.

11.3 Possible Alternatives

In this chapter, I would like to pinpoint other alternatives that may make the investment a reasonable choice. Scenarios will include government involvement in form of incentives and subsidies or possibilities of change in market conditions.

11.3.1 Dobrichovice

Situation in Dobrichovice is not far from having some realistic potential. Still, the stated goal of 15 or 10-year payback period has not been achieved. I will not write about any subsidies in form of payment for kWh produced from photovoltaic panels. This approach has been in place earlier in the Czech Republic and most likely will not be repeated.

11.3.1.1 Investment Incentives

This is an idea that may have strong influence on the feasibility of the investment and at the same time, it is very real. It speaks about an institution or fund (in this case probably Czech or European government) to pay for part of the investment. The idea is that renewable energy sources should be supported for the reduction of greenhouse gasses.

Investment incentives, % of investment					
Incent.	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
0%	24	-1 914	489	0,64%	3,36%
10%	22	-1 109	1 295	1,51%	4,02%
20%	19	-303	2 100	2,56%	4,82%
30%	16	503	2 906	3,82%	5,81%
40%	14	1 308	3 712	5,41%	7,08%
50%	12	2 114	4 517	7,51%	8,82%
60%	9	2 919	5 323	10,51%	11,40%
70%	6	3 725	6 128	15,31%	15,76%
80%	4	4 530	6 934	24,78%	24,88%
90%	2	5 336	7 739	53,07%	53,07%

Table 24 Investment incentives, possible alternatives, Dobrichovice

A highly debated solution to the problem. Government may provide part of the necessary capital needed for investment. We have seen this in many other circumstances through the program Zelena usporam. However, even in the new program there are no incentives for new roof solar power plants. [15] I think it is highly possible some incentives may be available in the near future.

Incentives of more than 30% of the investment would be needed to achieve payback periods of 15 years and lower. This amount of subsidy is imaginable.

This example can also be interpreted as a decline in price of a whole system, as is suggested in [16].

11.3.1.2 Decrease in Panel Costs

In essence, it is similar to investment incentives. Decrease in panel costs will lead to lower initial expenses. Nevertheless, this change is not led by the government, but by the photovoltaics market itself.

Panels price decline, % of panel costs					
Decline	PP	NPV_{25}	NPV_{40}	IRR_{25}	IRR_{40}
0%	24	-1 914	489	0,64%	3,36%
10%	23	-1 474	968	1,12%	3,73%
20%	22	-1 034	1 447	1,64%	4,12%
30%	20	-595	1 926	2,19%	4,55%
40%	18	-155	2 405	2,78%	5,01%
50%	17	285	2 884	3,42%	5,51%
60%	16	725	3 364	4,11%	6,06%
70%	15	1 165	3 843	4,87%	6,66%
80%	14	1 605	4 322	5,70%	7,34%
90%	13	2 044	4 801	6,64%	8,11%

Table 25 Decrease in Panel Costs, possible alternatives, Dobrichovice

For the investment to have a positive NPV_{25} the price of panels needs to halve. To achieve a payback period of 15 years, a 70% price reduction in panels' costs is necessary. How long will it take? There is a rule called Swanson's law stating that the cost of the photovoltaic cells needed to generate solar power falls by 20% with each doubling of global manufacturing capacity. [17] At present rates, costs halve approximately every 10 years. [18] Swanson's law definitely has its limits. The current limits lie in the costs of silicon. However, as with the Moore's law for transistors, technology may still find its way.

In conclusion, panels' costs are slowly declining, making the investment more cost-efficient.

11.3.2 Kolpashevo

Situation in Kolpashevo does not allow for many possibilities to improve the economic feasibility of a roof solar power plant. There is one involving a government intervention and other with multiple parameters shifted in an appropriate direction.

11.3.2.1 Subsidies of Renewables

Idea involves Tomsk Oblast subsidizing every kWh produced utilizing photovoltaic panels by a fixed sum. Additionally, the subvention is expected to rise at a rate of 4% every year, the same way electricity price is inflating.

Renewables subsidy, EUR/kWh						
RUB/ kWh	**EUR/ kWh**	**PP**	**NPV_{25}**	**NPV_{40}**	**IRR_{25}**	**IRR_{40}**
0,00	**0,00**	> 40	-10 960	-10 821	xxx	< 0%
1,26	**0,02**	> 40	-8 872	-7 250	< 0%	< 0%
2,52	**0,04**	38	-6 784	-3 679	< 0%	0,60%
3,78	**0,06**	31	-4 696	-108	< 0%	2,57%
5,04	**0,08**	24	-2 608	3 463	0,61%	4,16%
6,30	**0,10**	20	-520	7 034	2,56%	5,54%
7,56	**0,12**	17	1 568	10 606	4,25%	6,79%
8,82	**0,14**	15	3 655	14 177	5,76%	7,94%
10,08	**0,16**	14	5 743	17 748	7,15%	9,03%
11,34	**0,18**	12	7 831	21 319	8,44%	10,08%

Table 26 Renewables subsidy, possible alternatives, Kolpashevo

In order to make the NPV of this project profitable from the scope of 40 years, Tomsk Oblast (or Russian government) would need to subsidize by approximately 0.07 EUR per kWh. That means paying twice the current grid electricity price as a support for renewables. Such a generous subvention does not seem likely, but it is a possibility. To make the photovoltaic roof panels more widespread, the government would need to pay at least 0.14 EUR/kWh. This is still for an ideal house, with roof in appropriate angle and oriented to the south.

It would need significant commitment from Tomsk Oblast administration to make this investment cost-effective.

11.3.2.2 Combination of Multiple Factors

It is more like a what-if scenario. I came up with several parameters that would need to adjust:

- Price of panels would decline 30%.
- Government would offer to pay for 30% of an investment.
- Grid price would rise to 0.048 EUR/kWh.
- Local administration would propose a subsidy of 0.048 EUR/kWh.

The scenario may be unlikely. It involves both market and regulatory services to make changes in favor of the investment. Panels' price is a little bit higher in RF compared to CR, one of the factors can be lower trade volumes. Increase in both supply and demand and/or decrease in production costs may lead to lower prices overall. Government and/or local administration may decide to support renewables because of ecologic concerns. When those conditions are met, economic factors look as follows:

- Payback period = 20 years
- NPV_{25} = -196 EUR
- NPV_{40} = 4759 EUR
- IRR_{25} = 2.7%
- IRR_{40} =5.8%

However, fulfilling all of the prerequisites is improbable in the near future, it is not impossible.

11.4 Other Variant for Dobrichovice

In order to make situation in both cities comparable, I made many compromises. One complicated issue, for instance, is whether to incorporate accumulators into the project. It would make sense in Russia, where stand-alone photovoltaic systems are more common. On the other hand, it would increase the investment costs and the project would be insanely expensive in Czech Republic. I decided to focus solely on the solar panels, in order for the investment to have at least some chance to be cost-effective.

Other compromise is the actual electricity consumption of the house. According to Mr. Plotnikov, Associate Professor of Tomsk Polytechnic University, a household in Russia, as presented in this thesis, may need 19 MWh a year. In the Czech Republic, however, this number looks ridiculously overstated. In my experience, home of this size and with those appliances in the Czech Republic can consume 7, maybe 8, but no more than 10 MWh per year. In addition, daily load diagrams seem to have too much power needs during nighttime and when people are working or in school.

According to those observations, I made some additional alterations:

- At nighttime, from 10 pm to 8 am, the house has only 10% of its previous power needs.
- During work time, between 10 am and 5 pm, the household needs 15% of its former active power.
- During the other times, it requires 80%.

This leads to annual consumption of 7.5 MWh, which better suits the perceived situation in Dobrichovice. At this level the electricity price slightly rises, to 0.161 EUR/kWh (compared to 0.155 before). In this situation, the excel optimization sets the optimal peak power at 0.74 kWp, a huge difference from the previous 4.5 kWp.

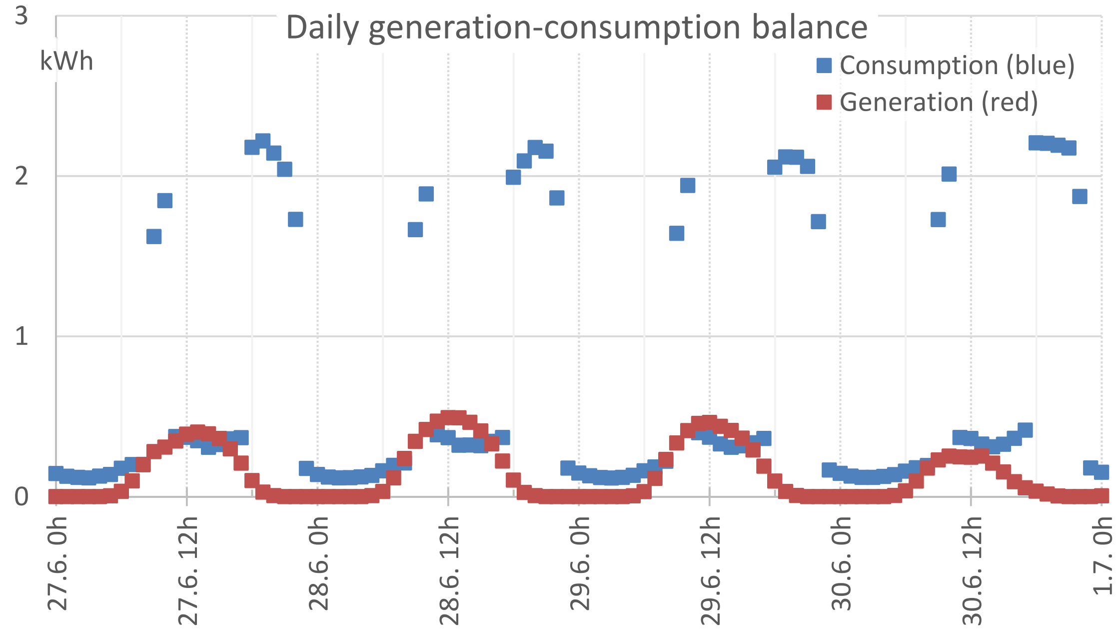

Figure 47 Daily generation-consumption balance, July 27th -30th, alternative variant, Dobrichovice

As can be observed in Figure 47, for the solar system to be economically viable the curve of electricity generation needs to be 'covered' under the line of electricity consumption. It can be argued, that the house power needs during the day are the most important in this type of investment. Utilized electricity ratio is 96.5%, close to 100%, as in previous circumstances.

Economic analysis leads to:

- Payback period = 23 years
- NPV_{25} = -251 EUR
- NPV_{40} = 182 EUR
- IRR_{25} = 1.18%
- IRR_{40} =3.78%

The figures are not significantly different from the default variant. On the other hand, out of 7.5 MWh of annual electricity consumption, only 640 kWh are supplied by the panels. That is more like a hobby project than a major commitment to renewables.

In general, this adjustment only changed the absolute values; the results are principally the same.

12 Conclusions

Situation with an installation of photovoltaic roof system is more complex that it may seem. There are many factors influencing the final result, from technical, to economic, social and environmental. I would like to note that I made many simplifications in order to make both projects comparable. I assumed there would be no difference between the electricity needs of houses in Dobrichovice and Kolpashevo. This is an ambitious statement, but I suppose a logical one. The appliances and other household equipment would be used in a similar manner, because the conditions in CR and Tomsk Oblast do not significantly differ. Except for temperatures. However, natural gas provides both heating and warm water supply and is not therefore included in the model. The other simplification I made regards the orientation of the panels. I presumed that the two houses would face true south and their roofs would have angles 34° and 45°. This is an idealization, nevertheless, not impossible. All of those generalizations were made with a prediction that the investment would not be economically viable and it is thus necessary to present it in optimal conditions.

From the technical point of view, the results are very similar. I added the alternative, more realistic, variant as Dobrichovice 2, for comparison.

Technical results				
	Dobrichovice	**Kolpashevo**	**Dobrich. 2**	
Annual house power needs	19 771	19 771	7 546	*kWh*
Panels' electricity production	3 996	4 026	663	*kWh*
Electricity surplus	80	436	23	*kWh*
Electricity deficit	15 854	16 181	6 906	*kWh*
Utilized solar electricity	3 916	3 590	640	*kWh*
Utilized electricity ratio	98,0%	89,2%	96,5%	

Table 27 Conclusions, technical results comparison

Panels of 4.5 kWp will produce 3996 kWh in Dobrichovice and 4026 kWh in Kolpashevo. I suspect the better results for Kolpashevo stem from more favorable temperatures and snow reflection during winter periods. Utilization, however, is slightly lower in Kolpashevo, 89.2%, whereas in Dobrichovice it reaches 98%. I assume this difference comes firstly from other methodology used in modeling and secondly from bigger disparities between summer and winter in Kolpashevo.

Economic results				
	Dobrichovice	**Kolpashevo**	**Dobrich. 2**	
Payback period	24	---	23	*years*
NPV after 25 years	-1 914	-10 960	-251	*EUR*
NPV after 40 years	489	-10 821	182	*EUR*
IRR after 25 years	0,6%	---	1,2%	
IRR after 40 years	3,4%	---	3,8%	

Table 28 Conclusions, economic results comparison

Economic results pinpoint the dissimilarities. Slightly cheaper investment costs in Dobrichovice (1796 EUR/kWp compared to 2142 EUR/kWh) and 5 times more expensive electric energy (0.155 EUR/kWh compared to 0.033 EUR/kWh) turn this investment to a somehow cost-effective venture. Payback period is 24 years and NPV_{40} stands at 489 EUR. Nevertheless, I would recommend a potential investor to think twice. Even though NPV_{40} is positive and IRR_{40} is greater than the discount rate, profitability is highly dependent on many factors, as was discussed in sensitivity analysis.

On the other hand, the project is not cost-effective in Kolpashevo. Payback period is higher than 40 years (probably infinity), both NPVs are negative and IRRs incalculable. At this moment, putting a photovoltaic panel system on your roof in Kolpashevo is for solar enthusiasts, who would prefer the technology itself and not its economic parameters.

I would also like to identify a couple of opportunities and threats that may influence the investment now or in the near future. Opportunities describe situations when NPV after 25 years is around 0 EUR or positive. Threats on the other hand talk about situations, when the project will be less cost-effective.

Dobrichovice – Opportunities

- Grid electricity price would rise above 0.18 EUR/kWh (≈5 CZK/kWh).
- Grid electricity price would rise by more than 3.5% a year.
- Economy would come to deep deflation.
- Government would cancel the necessity to pay for some regulated services.
- Government would subsidize at least 30% of investment.
- Price of panels would decline by 50% in the near future.

Dobrichovice – Threats

- Grid electricity price would decline.
- Inflation would be more than 4%.
- Government would raise necessary payments for regulated services.
- System or components price would rise.
- Maintenance costs would be more than anticipated 1%.

Kolpashevo – Opportunities

- Government would decide to provide subsidies at least 0.14 EUR/kWh (≈9 RUB/kWh).
- A combination of positive factors would happen:
  - Price of panels would decline 30%.
  - Government would offer to pay 30% of an investment.
  - Grid price would rise to 0.048 EUR/kWh.
  - Local administration would propose a subsidy of 0.048 EUR/kWh.

Kolpashevo – Threats

- The investment is not viable today; many factors can make it even less viable.

The other thing to note is that the comparison is calculated in EUR. Neither Czech Republic nor Russian Federation uses this currency to a greater extent in their economies. I do not feel educated enough in international trade to address all the implications this may create. However, I assume that CZK would be less volatile against EUR, because majority of Czech trade is with countries using this currency or other EU partners. [19] On the other hand, Russia's trade with Euro countries is limited, especially after the events in Ukraine. [20] This difference can be both beneficial and harmful to the cost-effectiveness of the project, depending on particular circumstances.

I am aware that the projected power needs of 19.8 MWh are inconsistent with general knowledge about energy requirements in the Czech Republic. I addressed this issue in the chapter 11.4 with a more realistic 7.5 kWh. Nevertheless, the magnitude of the numbers changed, but the conclusions stayed the same.

It seems like the general tendencies tend to be favorable for photovoltaic energy. Utility prices mostly rose and panels' costs fell in the last few years. In addition, the governments and local municipalities recognize the need to support renewable resources, especially on previously unutilized spaces like roofs. Installing photovoltaic system on your house may be more economically viable in the near future, than it looks today.

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17 Abbreviations

EUR – EMU Euro
RUB – Russian Ruble
CZK – Czech Crown
kW - Kilowatt
kWp – Kilowatt peak
kWh – Kilowatt hour
MWh – Megawatt hour
TDD – Typický diagram dodávky (Typical Diagram of Supply)
DIY – Do it yourself
CR – Czech Republic
RF – Russian Federation
GDP – Gross Domestic Product
PPP – Purchasing-power parity
PRC – People's Republic of China
ERU – Energetický regulační úřad (Office for Regulations in Power Engineering)
OTE – Operátor trhu s elektřinou (Electricity Market Oper

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18 Environmental Impact of Solar Power

[1]

The general opinion spread by media outlets, solar enthusiasts and celebrities pictures solar-based electricity generation as a perfect solution for many of our current environment problems. Reality, as is often the case, is more complicated. While photovoltaic and concentrating solar thermal plants provide clean source of energy, there are many concerns regarding those emerging technologies.

There are several environmental impacts associated with solar power. They include negative aspects:

- Land use,
- Habitat loss,
- Water use,
- Hazardous materials used during manufacturing,
- Disposal and recycling.

And positive aspects:

- Decreased dependency on fossil fuels for electricity generation,
- Decentralization, thus decreased transmission losses.

However, the impacts vary greatly depending on the technology used. Possible technology solutions for solar power production include two broad categories - photovoltaic (PV) solar cells and concentrating solar thermal plants (CSP).

The scale of the system can also affect the environmental impact. Solar system can range from small, distributed rooftop PV arrays to large utility-scale PV and CSP projects

18.1 Land Use and Habitat Lost

Larger-scale solar facilities may raise serious concerns about land degradation and habitat loss. Estimates of total land lost to solar power plants vary. Utility-scale photovoltaic systems may take up from 3.5 to 10 acres per megawatt, while concentrating solar thermal plants can occupy between 4 and 16.5 acres per megawatt of land.

Other renewable energy technology - wind turbine - can share space with agricultural land as seen in many European countries for example, where available real estate is limited. However, impact from utility-scale solar systems can be reduced by placing such facilities at lower-quality locations such as brownfields, abandoned mining land, or near transportation corridors. Smaller-scale residential, commercial or industrial PV systems are often placed on the roof of buildings, thus cutting land impact down to a minimum.

Figure 48 5 MWp Solar Power Plant in Leipziger Land, Germany [2]

18.2 Water Use

With average global temperatures steadily rising, water scarcity becomes a widely discussed topic. In the past couple of years, we hear about droughts of historic proportions. This may lead to social unrests and escalate conflicts around the world, especially in poverty struck regions. This is the reason we should pay increased attention to water usage.

Solar photovoltaic cells do not use any water when generating electricity. Nevertheless, water is used during the manufacturing process. In addition, PV panels need to be regularly cleaned otherwise their output decreases. Thus, some water is used during their maintenance.

Concentrating solar thermal plants (CSP) need to be cooled during their operation as all of the power stations based on converting thermal energy to electricity. Water use is dependent on plant design, location and the technology employed.

CSP plants based on wet-circulating technology with cooling towers require between 2,270 and 2,460 liters of water per 1 mega-watt hour produced. Concentrating solar thermal plants using once-through cooling technology withdraw even more water per hour, but have lower overall consumption, because it is not lost as steam. It is possible to exploit dry-cooling technology that reduces water use by approximately 90 percent. It has its drawbacks though. It increases costs and decreases efficiencies. In addition, at temperatures above 38 degrees Celsius dry-cooling technology is even significantly less effective.

Not coincidentally, many regions in the world that have the highest potential for solar energy are also those with the driest climates, so careful consideration of used technology is essential.

18.3 Hazardous Materials

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