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Estimation of Rooftop Photovoltaic Potential

Master's Thesis

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Katusel asuva päikesepaneeli potentsiaali hindamine

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Author's declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

Nowadays photovoltaics (PV) have a significant importance in contribution to reduce carbon dioxide emissions and are a promising type of a renewable energy sources. Apart of the huge solar PV panel stations the rooftops of buildings in urban areas have a big PV potential and depend on the suitability and geographical location, may produce electricity up to half of national demand or more. However, finding and evaluating of suitable roofs on existing buildings in urban areas for PV remains a topic for further research. In this research different methodologies and approaches to estimate rooftop suitability for PV placement will be explored. Many of the existing tools for analysis of rooftop suitability and solar PV potential are to certain extent complex. The aim of this study is to contribute to the global effort in reducing the carbon dioxide emissions by facilitating the installation of PV panels on the rooftops of buildings by providing a user-friendly web tool for rooftop PV potential analysis.

This thesis is written in English and is 70 pages long, including 6 chapters, 30 figures and 10 tables.

Annotatsioon

Katusel asuva päikesepaneeli potentsiaali hindamine

Tänapäeval päikesepaneelidel on oluline roll süsinikdioksiidi heitkoguste vähendamisel ja see on paljulubav taastuvaenergiaallikate tüüp. Lisaks tohututele päikesepaneelide suurematele jaamadele on linnapiirkondade hoonete katustel piisavalt hea PV potentsiaal, mis sõltub geograafilisest asukohast, vormist, ning lubab toota elektrit kuni poole riigi nõudlusest või isegi rohkem. Siiski jääb PV-le sobivate katuste leidmine ja hindamine linnapiirkondades olevate hoonete jaoks keeruliseks probleemiks. Selles töös uuritakse erinevaid metoodikaid ja lähenemisviise katuse sobivuse hindamiseks päikesepaneelide paigaldamiseks. Paljud olemasolevad katuse sobivuse ja päikeseelektri potentsiaali analüüsimise vahendid on teatud määral keerulised. Selle töö üheks eesmärgiks on välja pakkuda kasutajasõbralikku veebitööriista katuse PV-potentsiaali hindamiseks.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 70 leheküljel, 6 peatükki, 30 joonist, 10 tabelit.

List of abbreviations and terms

API	Application Programming Interface
c-Si	Crystalline Silicon
CIS	Copper, indium, selenide
CSS	Cascading Style Sheets
CSV	Comma-separated values
CdTe	Cadmium Telluride
GIS	Geographical Information System
HTML	HyperText Markup Language
JRC	Joint Research Centre
JSON	JavaScript Object Notation
kWh	Kilowatt hours
LiDAR	Light Detection and Ranging
MWh	Megawatt hours
OSM	OpenStreetMap
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RF	Random Forests
STC	Standard Test Condition
SVM	Support Vector Machine

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1 Introduction

In the world of renewable energy sources, a solar energy is one of the most promising alternatives for replacing the existing fossil-based energy sources. The biggest advantage is that it does not produce a carbon dioxide, what makes it a clean energy source. The most common application of obtained solar energy is a generation of an electricity and heat.

According to [1] the global energy demand in the period between 2002 and 2030 is predicted to grow up to 60%. In the same period, the global share of renewable resources is expected to remain steady which is around 4%. The share for fossil fuels shall grow insignificantly from 80% at the beginning of the period to 82% at the end. For nuclear energy share the trend shall decrease from 7% to 5% at the end of the abovementioned period [2]. In the meantime, considering current market trends BloombergNEF predicts that in 2040 solar has a potential to cover up to 20% of European Union countries electricity demand.

One of the main issues preventing the wide use of solar energy is in high cost of materials that are used to build a solar panel and depend on geographical location the return on investment which can be counted in decades. However, according to [3] between the years of 2010 to 2019 there was the sharp decline in the cost for electricity from solar PVs, the costs reduced for 82%, which gives a promising message for the future of solar applications.

In urban areas there are two popular types of PV systems installation: rooftop and community. Community solar PV system supplies with a power a district or a city. In most cases financial resources to build such system are collected from residents. The benefits of this are that the resident does not need to install anything and the land for PV panels placement can be chosen considering potential environmental limiting factors. The rooftop PV panels allow residents to build their own energy source system. As the costs for solar PV panels have decreased significantly in the past decade and the efficiency has grown, the popularity of rooftop PV systems have an increasing trend.

The cost savings is an important reason for rooftop PV panels installation. In average the tariffs of rooftop solar are 17 to 27% less expensive than other types of energy sources tariffs, such as industrial and commercial. The power gained from rooftop solar panels can cover up to certain extent the electricity demands of the user and reduce his payments for electricity.

Significant benefit of installing rooftop solar panels is the cost savings. Rooftop solar tariffs are 17% and 27% less expensive than manufacturing and commercial solar tariffs, respectively. Rooftop solar panels will also help building owners save money on their utility bills. Rooftop panels provide power to homes, reducing the amount of electricity purchased from the grid and thereby lowering energy prices. It also provides an independence from price fluctuations of electricity obtained from grid. Solar electricity can be calculated for another 10 years. In average solar panels have around 20 years of lifetime and require comparatively less maintenance efforts, which makes it maintenance costs considerably cheaper [4]. Solar panels are flexible in terms of choosing a surface for installation and the buildings roofs are great candidates for this purpose. The mass implementation of rooftop solar PV panels will cover a significant portion of urban electricity demands and will be a reason for reduction of CO_2 emissions.

1.1 Motivation

It is well known that for the rooftop PV panels installation, in order it to be profitable, a complex analysis must be conducted. There are plenty of tools in the market, both free of charge and paid, that can help to calculate energy output of such system and payback period. However, paid solution might not be a case for an average user who wants to assess a capacity of the rooftop of a building of interest and the tools that are available free of charge have different level of complexity.

Most of the existing tools and methodologies for analysis of rooftop PV potential are not user-friendly and require numbers of inputs from the user. For a complete analysis there are numbers of inputs user must provide in order to get reasonably calculated results. For instance, the solar radiation information is necessary and is a key parameter for calculation of energy output. There are different solar radiation databases that can be used

to retrieve radiation data. The user might struggle to find proper values for radiation rates or to choose the correct radiation database.

There are different technologies that are used for solar PV panels manufacturing, each of these technologies has different impact of PV panel's performance. User must consider temperature and the solar irradiance when choosing the PV technology. There are plenty of other parameters that should be considered when calculating the solar PV panel's energy output, these are nominal (peak) power, estimated system loss, mounting position, slope, azimuth etc. Additionally, for payback period estimation user has to know parameters as average electricity price, total installation cost of system, cost of a panel, estimated area for panels installation. For an average person who is interested in placement of the rooftop PV panels system, obtaining all abovementioned parameters can be sophisticated and exhaustive, this can result in an impediment to switch to a green energy source.

The aim of this work is to provide a user-friendly web tool for PV potential estimation by significantly reducing the number of inputs the user must provide, by automating the obtaining of the rest of parameters. This tool will facilitate solar potential analysis for buildings' rooftops in urban area and can be used by policymakers and other users to help in decision making. The problems that have to be resolved:

- Select an open-source map tool, that will provide geographical information system data of an area of interest, which will serve as an initial input.
- Obtain solar radiation information.
- Approximate calculation of the rooftop of interest.
- Definition of optimal values for parameters used to calculate PV energy output.
- Build a calculation methodology to estimate rooftop PV energy output and payback period for such system using data from national electricity provider.
- Build a user-friendly web platform.

The web application is available at address - https://rooftop-pv-calc.netlify.app.

1.2 Literature review

A number of studies have been conducted in this area. For example, work [5] presented classification of the roofs by their useful area suitable for PV installations and potential for obtaining solar energy. To find the optimal location for PVs on existing buildings there is a necessity for an efficient method for evaluation and assessment of suitable rooftops. For classification purposes of roof shapes on their solar PV potential, a novel approach was developed in [5] which is based on kernel-based machine learning technique Support Vector Machine (SVM). It is an efficient machine learning algorithm for classification tasks. Light Detection and Ranging (LiDAR) point data has been used in this work in order to estimate mean value of yearly solar radiation of the rooftops.
In this work authors show that SVM algorithm is a favourable method for classification of roof shapes. Six main roof shape class were presented and ranked based on useful areas for PV installations.

A novel methodology was presented in [6] which combines Geographical Information System (GIS), solar models and machine learning algorithm Random Forests (RF). Methodology contributes for resolving the issue of estimation of rooftop PV potential at the regional scale (200x200 m). The development of an efficient method for locating and evaluating suitable roofs for the optimal PV installation was the main problem authors contributed to. It is noted in the article that a small number of studies were conducted to estimate rooftop solar PV potential at a national and regional scale. A hierarchical approach of several steps was used to estimate rooftop solar PV potential. Authors used a combination of GIS, RF algorithm and physical models to assess physical, geographical and technical potential of PV panels. As a result, authors proposed a methodology for estimation the suitable rooftop area for PV panels installation. Methodology uses roof shape classification and simulation of the PV panels presence. In the article authors stated that the proposed methodology gives a significant improvement for approximating the suitable rooftop area for PV placement and considers the roof geometries.

In study [7] in order to calculate the yearly solar radiation on each square meter of roof area authors used a solar radiation tool combined with digital surface model of the city which was developed using LiDAR data. During the calculation different parameters such as time of year, latitude climatic conditions surface slope and orientation etc. were

considered. The study was conducted in Auckland, New Zealand. Development of an efficient and accurate method for assessment of the solar radiation in the residential sector was the main problem author contributed to and presented the results of LiDAR based assessment of rooftop PV potential and provided an instance of usage of this data for policy insight. The methodology implemented is this study consists of several steps such as LiDAR data processing, solar radiation modelling and verification, aggregation by house and neighbourhood, application for policy insights. To calculate the solar radiation on each square meter of roof area ArcGIS tools was used. For verification purposes authors used an online solar radiation calculator SolarView software. It assesses the solar energy that can be collected by PV panels at a given location, orientation of panel and roof slope using digital terrain model. Authors stated that this study presented the use of a LiDAR data for assessment of rooftop PV potential for an area that is larger compared to area considered in other studies. To provide data for policy insights and municipal planning results were aggregated to a neighbourhood level.

Work [8] presented a methodology for assessment of solar PV potential on several building rooftops. The upward-looking hemispherical viewshed algorithm is the base of the methodology and implemented using area-based modelling approach. The inputs parameters for methodology are effects of shadowing, orientation of the surface, environmental conditions such as atmospheric that may influence solar irradiance on the surface of the earth. The main objective of this study is to develop a methodology using LiDAR data and GIS approach to estimate the daily or monthly solar energy output on each building in a city or region. In order to estimate solar radiation potential authors used an algorithm which is based on GIS upward-looking hemispherical viewshed. The methodology proposed uses ArcGIS tool and consists of five steps such as: selecting of a location of interest, obtaining high resolution LiDAR data, creation of LiDAR-derived data products, creation of radiation map using hemispherical viewshed algorithm, extraction of individual building solar radiation intensity values.

A machine learning technique SVM along with GIS was used in work [9] which was applied in commune levels of urban areas in order to estimate rooftop solar PV potential. The main goals of this study are:

1. Estimation of global horizontal solar radiation on monthly basis and global tilted solar radiation on tilted roofs for Switzerland.

2. Estimation of shadowing effects on the roofs using LiDAR data.
3. Estimation of roof aspects and slopes, suitable rooftop area for PV placement.
4. Estimation of the technical potential of rooftop PV electricity production in Switzerland.

The main motivation for conducting study [9] was a governmental program "Energy Strategy 2050" called to reduce CO2 emissions. In this article authors provided a methodology to turn buildings into much more energy efficient ones. The methodology for estimating rooftop solar PV potential proposed by authors applied a hierarchical structure and consists of three steps, such as estimating a physical potential by assessing the total energy obtained from the sun in urban areas, provide geographic or urban potential, which shows the restrictions on the locations where the solar energy can be captured and used for PV placement, provide technical potential, which shows the transformation of the obtained solar energy into electricity energy considering technical characteristics of the PV technology. To estimate different variables in the hierarchical methodology and to get the overall rooftop solar PV electricity potential a combination of SVM and GIS have been used. Authors state that machine learning algorithm Support Vector regression has not been used to estimate the geographical potential of rooftop solar PV potential.

In order to estimate the solar PV potential for an individual rooftop at hourly temporal resolution, to assess the uncertainties on each step of the potential assessment and combine them to quantify on the final PV potential, work [10] developed a methodology which is a combination of machine learning algorithms, physical models and GIS. The main problem authors tried to solve is that there is no other methodology to estimate solar PV potential at the large scale and high spatio-temporal resolution. To estimate rooftop PV potential authors used big data mining algorithms which required accurate high-resolution environmental and building datasets. In this article authors stated that this study provides an important insight for tackling CO2 policies. The proposed method can be propagated and used for any other region with sufficient accurate data.

The study conducted in [11] proposed a methodology for estimating the rooftop solar PV potential at the urban level. This approach is appliable for different areas of the world and provides accurate PV potential analysis. In order to not to rely on 3D model data the aerial

images were used with image recognition algorithms to get the dimensions of roof areas. This methodology uses publicly available geographical building data. The main goal of this study is to provide a methodology to help the local decision makers by providing and accurate assessment tool for PV potential estimation. The benefits of this methodology are that publicly available data were used and it appliable universally. Approach uses such tools as OpenStreetMap (OSM), aerial images and irradiance and temperature information. The whole approach was carried out with a Java model framework (RE3ASON). The methodology consists of several steps such as using OSM retrieve all the necessary dimensions and location of the buildings, retrieve the aerial image which covers buildings' roof from Bing Maps and clip it to the correct figure, estimation of inclination, roof structure determination, module instalment, simulation of irradiance, electricity output simulation, which depends not only on global solar irradiance, but also of the temperature of the PV panel and its' technical characteristics, assessment of the economical part, detection of the existing PV systems. Authors state that this approach calculates the discrete number of PV panels that are possible for placement, while considering the roofs' shape and the different objects on the roof (chimneys, windows).

A methodology for estimating solar PV potential was proposed in [12]. Methodology based on the estimation of the daily average energy production throughout the year using LiDAR data. The consideration of nonlinear characteristics of various types of PV modules and solar microinverter led to the estimation of produced electrical energy. The efficiency degradation of PV modules considering their age was also considered in the development of the method. The method is to estimate PV potential over LiDAR data and the nonlinear efficiency characteristics of the PV modules and solar inverter are estimated by modelled functions. Authors state that the assessment of the PV modules placement suitability is a big challenge, because many of the existing PV systems assess potential over LiDAR data considering modules' efficiency as a constant, however they are nonlinear. Authors divided the methodology onto several steps such as LiDAR data preparation, estimation of solar irradiance, PV potential estimation and the produced electrical energy, confirmation of the method for horizontal surfaces. In this article authors state that their method is an initial method that considers nonlinear efficiency characteristics of several PV modules and solar inverter.

A study for potential analysis of roof-mounted solar PVs was conducted in Sweden in [13] and introduced a GIS -based complete methodology with energy system modelling procedures. Authors focus on rooftop area approximation, installed capacity potential and electricity production potential at the municipal and national scales. The tested area is a Swedish city of Vasteras. This paper has two goals, first is to estimate exploitation solar energy resources potential of the available area using GIS functions. Second is to elaborate on subsidies and help for projects related to PV systems, which will facilitate the analysis for policymakers and for investors. The proposed approach is based on GIS data along with energy system modelling. These are to simplify the feasibility analysis of geographical and technical potential for rooftop solar PV systems. The methodology consists of three methods. First step is to assess the geographical potential for using solar energy sources on rooftops of different types of buildings such as business, agricultural etc. In order to estimate rooftop solar PV potential authors developed a step-by-step approach, which considers such parameters as geographical data division and classification, approximate area calculation, orientation of the roof and different shadows and obstacles. Second step is to assess the technical potential for PV systems placement. The third step is to transform this methodology to be usable at a national scale, in order to evaluate solar PV potential for the whole country. To authors knowledge, there has not been conducted an accurate and complete assessment for the solar PV potential in this region. Moreover, facilities for the policymakers and investors still needs to be elaborated.

Work [14] conducted a study in Georgetown, Malaysia. Authors present an approach that combines LiDAR and GIS to determine suitable locations for solar PV systems placement. LiDAR data can be a trustable source for height information and reduces the time required for field measurements. The combinative use of LiDAR and GIS can boost the support for green technology applications. The objective of this study is to map suitability area for PV placement using GIS and LiDAR. Authors conducted the research in three major phases:

1. Planning stage. Determination of suitable criteria for PV placement.
2. Acquisition of data provided by LiDAR techniques by carrying out airborne data acquisition.
3. Processing and Analysis. A number of GIS layers were used in order to derive the possible location of PV modules. The generation of suitability map was obtained from ArcGIS software.

1.3 Outline

Current work is structured in the following way. Section 2 describes a theory behind the implementation, it explains importance of solar radiation on solar PV panels, gives an overview of measurement and calculation methods, presents various effects and calculation of PV power output. Section 3 presents overall methodology, describes important parameters, used tools and Application Program Interfaces (APIs), introduces to Photovoltaic Geographical Information System (PVGIS) and calculation of payback period. In Section 4 a realization of a web application is described. Section 5 provides results of calculations and compares them.

2 Theoretical background

There are a number of parameters/factors that affect the output of PV module and result in a decrease of energy production such as shadowing, both temperatures of the air and of the module, reflectance etc. All these factors can impact significantly, however the most important parameter is solar radiation. In this section a theoretical background for PV output calculation and different factors that have an impact to it will be discussed.

2.1 Solar radiation

Solar radiation in basic terms are solar rays descending onto the Earth's surface, in other words it is an electromagnetic radiation. The energy potential of a solar radiation is considered as significant and is used in different applications worldwide, especially it is used to retrieve heat and electricity. It is a vital parameter for solar PV panels, as it is an only energy source for this kind of applications. However, based on the current level of technology it is not possible to convert all received solar radiation into energy, there are a number of factors that prevent solar radiation to be used in full capacity. Moreover, the amount of solar radiation varies based on the geographical conditions, hence the energy that can be received through solar PV panels distinguishes too.

The intensity at which solar radiation is obtained beyond the Earth's atmosphere by a unit surface perpendicular to the solar beam at the Earth's distance from the sun is called – solar constant [15], [16]. The approximate value for solar constant is defined in the range of 1361-1362 W/m^2 [17]. However, the solar radiation measured on the top of the Earth's atmosphere is different from the solar radiation rates on the surface. By the differentiation is meant energy loss, it is determined by different layers of the atmosphere that the sun light has to pass before it actually reaches the surface of the Earth.

There are different factors that result in a differentiation of a spectral distribution of solar radiation such as dispersion, absorption etc, that are caused by ozone and different particles such as water vapor in the atmosphere. The factor that has a highest impact are cloud masses. The solar radiation that passed through the mentioned layers and descends on the Earth's surface is a summation of direct radiation, which is a radiation that is not affected by atmosphere and is available only when the sky is clear, diffuse, which is a

solar radiation that was affected by atmosphere, reflected radiation, solar radiation that was affected by different reflective obstacles. The sum of mentioned parameters is called global radiation, it can be seen that the diffuse is the only part of a global radiation that is always available, because it already considers losses on the atmosphere [17]. In order to estimate the solar radiation rates in normal atmospheric conditions, it is required to know the value for maximum possible radiation data, which can be obtained only in clear ad dry sky conditions [17].

2.2 Overview of measurement and calculation methods of solar radiation

There are two known methods to measure solar radiation: measurement on the ground using specified tools and estimation using satellite data.

To estimate the amount of global radiation tools such as pyrheliometer and pyranometer are used, measurements are conducted at certain locations and then an empirical model is built based on the measurement data obtained to assume the solar radiation available at other locations [18]. However, even if the solar radiation data obtained with measurement tools is more precise the process of the measurement and requirements for the tools are complex. Hence, it is preferred to use data from satellites to estimate solar radiation.

The important advantage of using data from satellites is that it covers a huge area, therefore the solar radiation data can be estimated for the whole area and the accuracy of data is at a satisfactory level which is another positive side. However, the disadvantage of this method is in its calculation complexity, that has to consider such factors as snow or dust that may lead to inaccurate results [17]. In study [17], authors presented a short overview of a method for calculation of solar radiation from satellite data. It was outlined in two steps.

As mentioned above, cloud masses have a reflectivity nature, and the solar radiation intensity is being decreased when it actually reaches the surface of earth. Therefore, the first step is to estimate the impact of clouds on solar radiation using images from satellite. A raw satellite picture that is used for cloud albedo calculation is presented in Figure 2.1
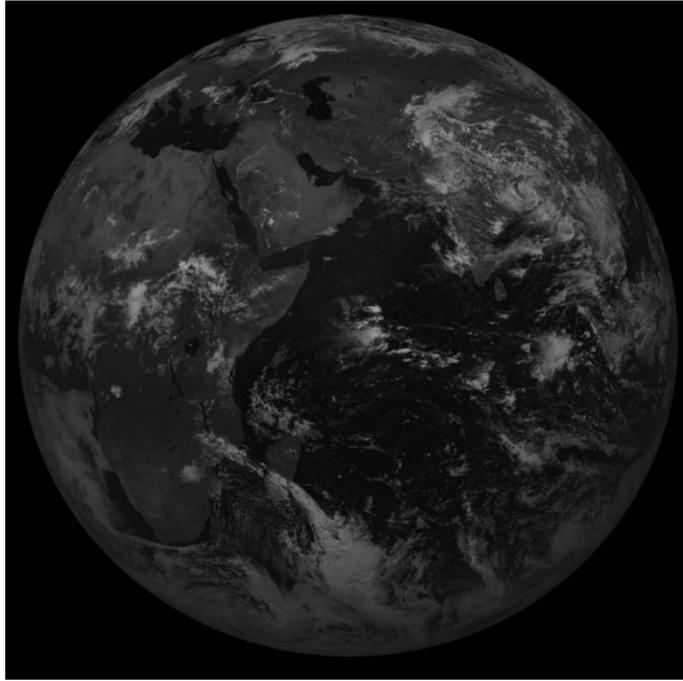
Figure 2.1 Raw satellite image [17].

The method for calculation presented in study [17] assumes that pixel in satellite image is tracked each day for the whole month. Then it is required to determine the clear sky day, which corresponds to the darkest pixel in month. Finally, the reflectivity for all other days in a month are estimated based on the clear sky day and the effective cloud albedo is calculated as in Figure 2.2.
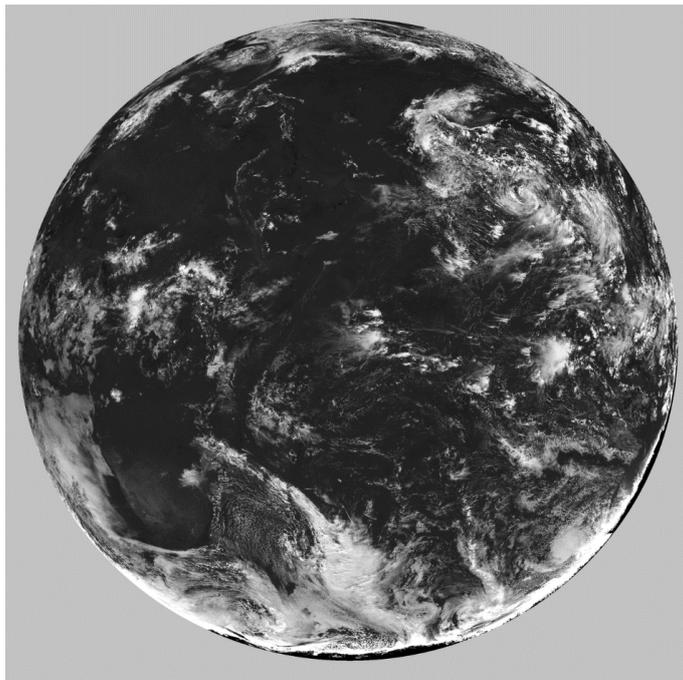
Figure 2.2 Effective cloud albedo calculated from the satellite image [17].

The second step for calculation of solar radiation using satellite image data requires the theory of radiative transfer, which is a branch of atmospheric physics [19] and the consideration of absorbent particles in the atmosphere, which absorbs solar radiation. The calculation is conducted under the condition of the clear sky and using the cloud albedo. A global horizontal irradiance can be seen in Figure 2.3.
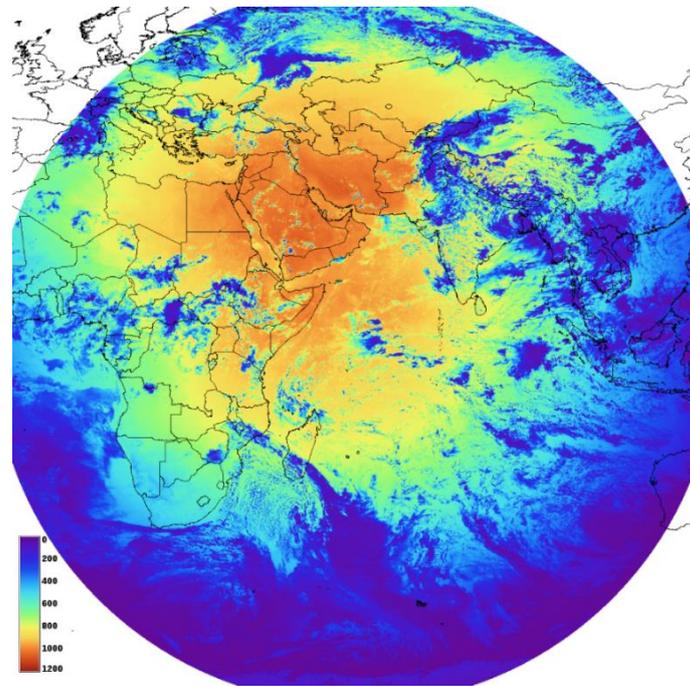
Figure 2.3 Global horizontal irradiance, W/m^2 [17].

Apart of the disadvantages of this method of calculation of global solar radiation which may lead to a failure in a precision of results, the method results at a good level. In calculations of study [17] such factors as inclined planes and shadowing effect are also considered.

The data that was obtained as a result of calculations using satellite images is then usually validated against the solar radiation data that was obtained from the measurement stations on the Earth using abovementioned tools. The solar radiation database that is used in this work was thoroughly calculated and validated in studies such as [17], [20], [21], [22], [23].

2.3 Various effects and calculation of PV power output

PV power output crucially depends on solar radiation falling onto panels surface; however, it is not an only important fact to consider when calculating the actual energy output. These additional factors are shallow-angle reflection, fluctuations in the solar spectrum, irradiance, temperature of air and module, system losses and degradation [17]. The calculation of PV power production under a laboratory conditions is called nominal power or peak power. Most of the PV panels on the market have defined peak powers provided by the manufacturer. The calculation of nominal power is strictly conducted under a Standard Test Condition (STC). According to [24] and [25] the conditions that have to be followed are stated in Table 2.1.

Table 2.1 STC parameters.

Parameters	Standard values
Solar irradiance	1000 W/m^2
Panel temperature	25°
Spectrum of the light	AM 1.5
Wind speed	1 m/sec

It is important to notice, that by panel's temperature is meant the temperature of module itself and not the temperature of the environment and the solar irradiance has to be equally distributed to the whole surface of a PV panel.

As it was mentioned above there are several factors that must be considered when calculating solar radiation production. The shallow-angle reflection causes the reduction of solar radiation descending onto panel's surface, which means that certain amount of sunlight will be reflected before it reaches the module.

In the study conducted by [26] authors presented an analytical model based on theoretical and experimental results and calculated monthly and yearly losses for 10 European locations with different geographical conditions. As an example, the yearly losses respective to locations versus panel's tilt angle presented in Figure 2.4.
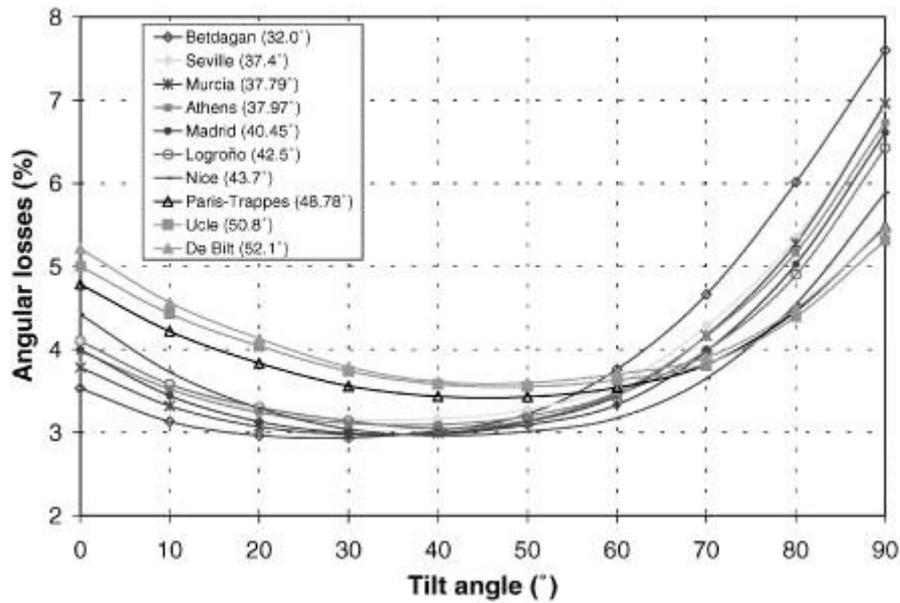
Figure 2.4 Annual angular losses vs. tilt angle [26].

Authors in [26] estimated the annual angular loss at medium altitudes as 3%.

In the study [17] authors approximated the solar radiation loss at 2-4% range and presented a map (Figure 2.5) which reflects the dependence of PV energy output on reflectivity on sharp angles.
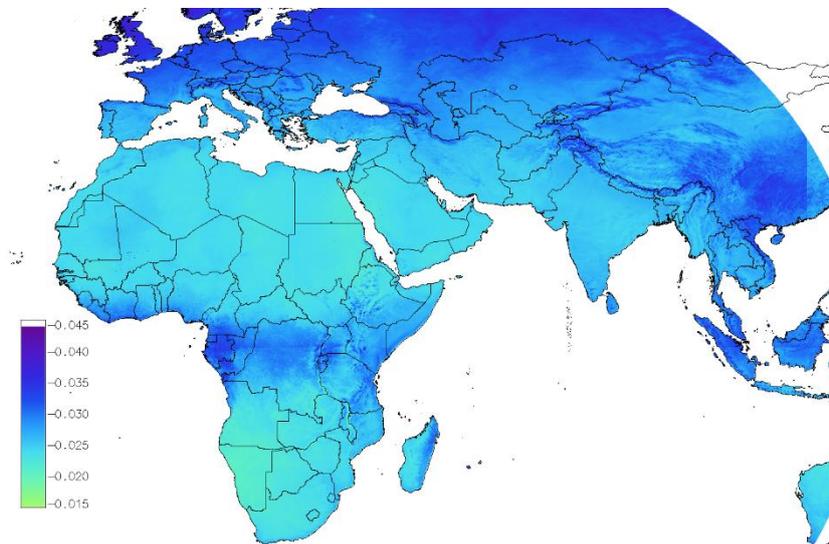
Figure 2.5 Dependence of PV energy production on reflectivity at sharp angles [17].

Another atmospheric parameter that affects solar PV energy production is solar spectrum. The fluctuations in the solar spectrum causes an absorption of solar radiation at a level of different wavelengths [27]. Summarized impact of atmospheric effects on solar radiation is shown in Figure 2.6.
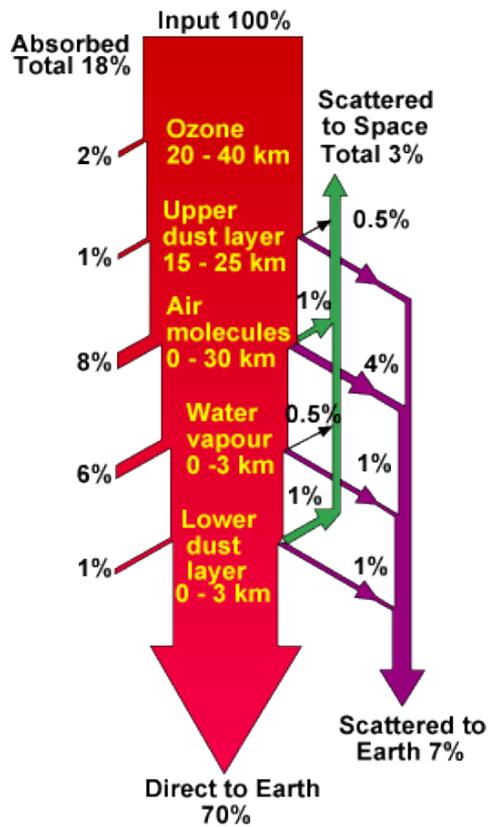
Figure 2.6 Absorption and scattering of incident sunlight in a clear sky conditions [28].

In study [17] authors provided a calculation and showed the dependency of PV power production on the effect of solar spectrum changes, authors considered two types of PV technologies, Crystalline Silicon (c-Si) and Cadmium Telluride (CdTe) and depicted it on maps (Figure 2.7 and Figure 2.8).
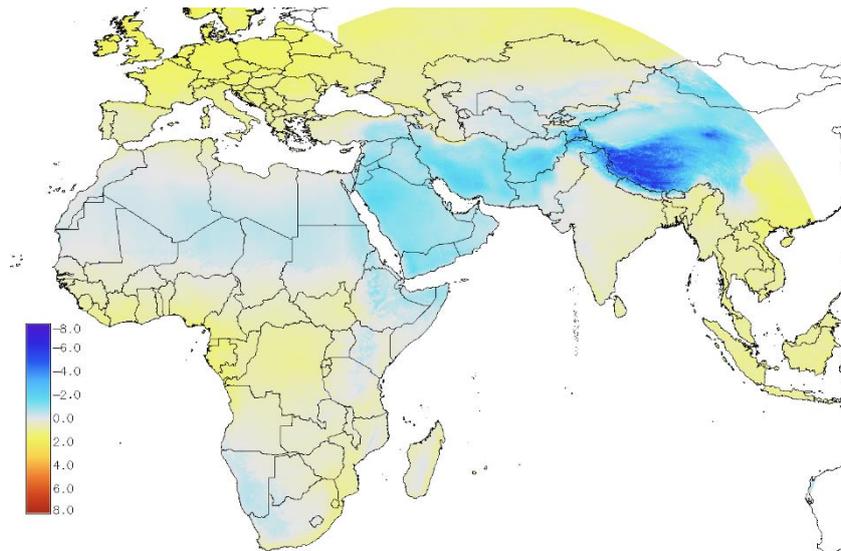
Figure 2.7 Solar spectrum changes impact on PV energy output for c-Si [17].
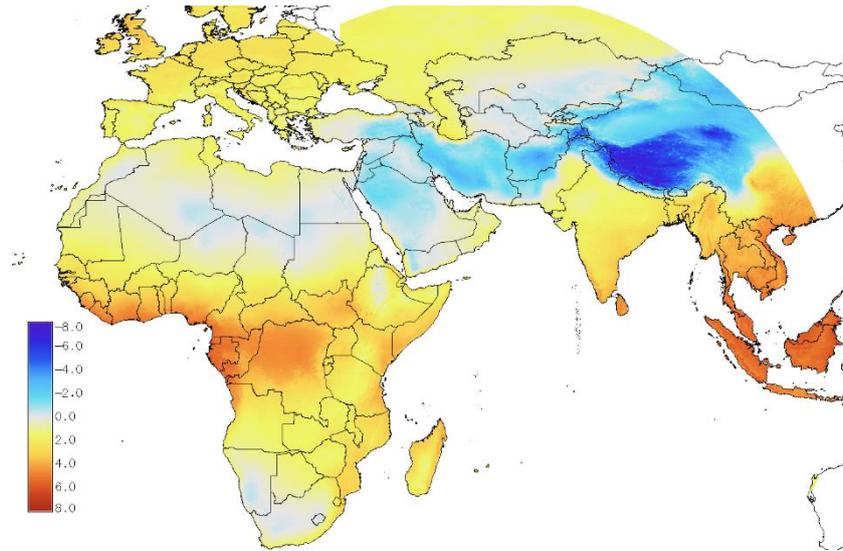
Figure 2.8 Solar spectrum changes impact on PV energy output from CdTe [17].

A huge impact has the module temperature and the solar irradiance on the PV energy production. Depending on the PV technology the output decreases with increasing temperature of the module [17]. In study [29] authors stated that estimation of the dependency between maximum power output and the temperature of the module can give a clear vision of the expected solar PV energy output. Authors presented the following formula to describe this dependency:

$$\Delta\eta_{rel}(G, T) = \frac{P_{max}(G,T)}{P_{max,ref}} \cdot \frac{G_{ref}}{G} - 1, \qquad (2.1)$$

where

$P_{max,ref}$ – maximum power output at the reference condition,

P_{max} – maximum power output,

$\Delta\eta_{rel}$ – dependence,

G – irradiance,

T – temperature.

The measurements conducted at the European Solar Test Installation of the Joint Research Centre (JRC) in study [17] were presented in the form of a graph (Figure 2.9 and Figure 2.10), where relative efficiency dependence on irradiance and temperature for three types of PV technology were compared.
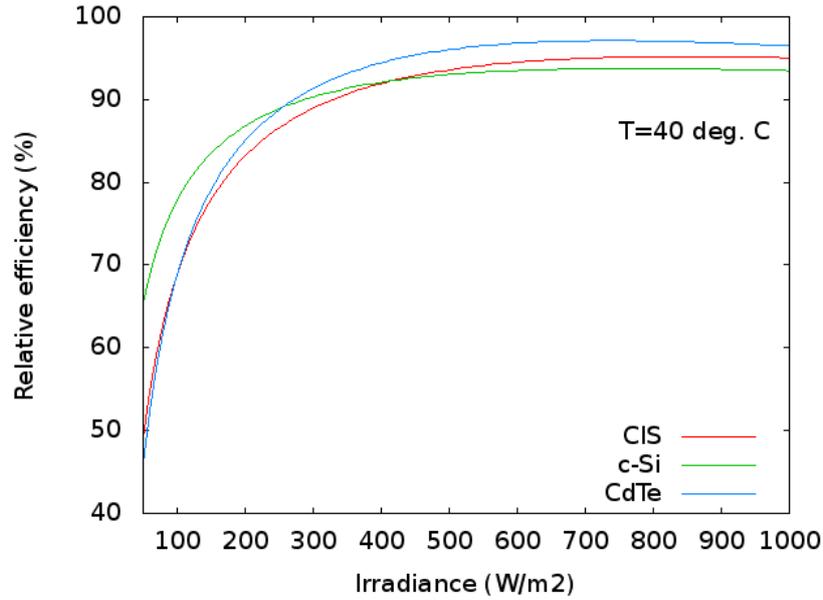
Figure 2.9 Relative efficiency for tree types of PV technology based on irradiance [17].
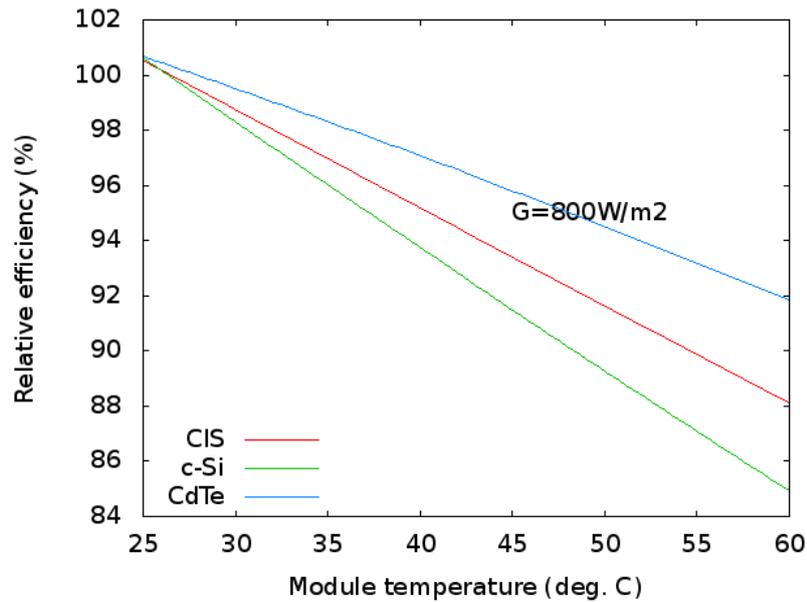
Figure 2.10 Relative efficiency for tree types of PV technology based on temperature [17].

In study [30] authors presented a model for estimating the effect of irradiance and temperature on PV power yield. A sequence of indoor power measurements was conducted to define the empirical coefficients of the model.

The mathematical formulation of this model is as follows:

$$P(G', T') = G'(P_{STC,m} + k_1 \ln(G') + k_2 \ln(G')^2 + k_3 T' + \quad (2.2)$$
$$k_4 T' \ln(G') + k_5 T' \ln(G')^2 + k_6 T'^2),$$

where

$G' \equiv {}^{G}/_{G_{STC}}$ – normalized in-plane irradiance,

$T' \equiv T_{mod} - T_{STC}$ – module temperature,

k – coefficient for relative efficiency.

The irradiance and temperature under STC are as follows:

$G_{STC} = 1000 \ W/m^2$,

$T_{STC} = 25°C$.

The relation between module efficiency under given conditions and efficiency under STC is called relative conversion efficiency [30]. Using abovementioned formula (2.1) relative conversion efficiency can be described as follows:

$$\eta_{rel}(G', T') \equiv {}^{P(G', T')}/_{P_{STC,m}G'}.$$ (2.3)

In addition, authors of [30] presented two graphs (Figure 2.11 and Figure 2.12) that depict dependency of relative efficiency on irradiance and temperature for c-Si module.
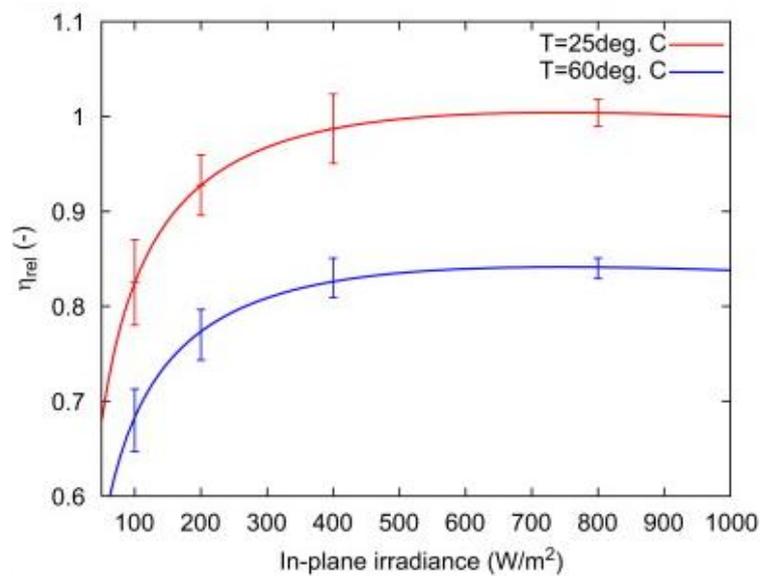
Figure 2.11 Relative efficiency for c-Si module based on irradiance [30].
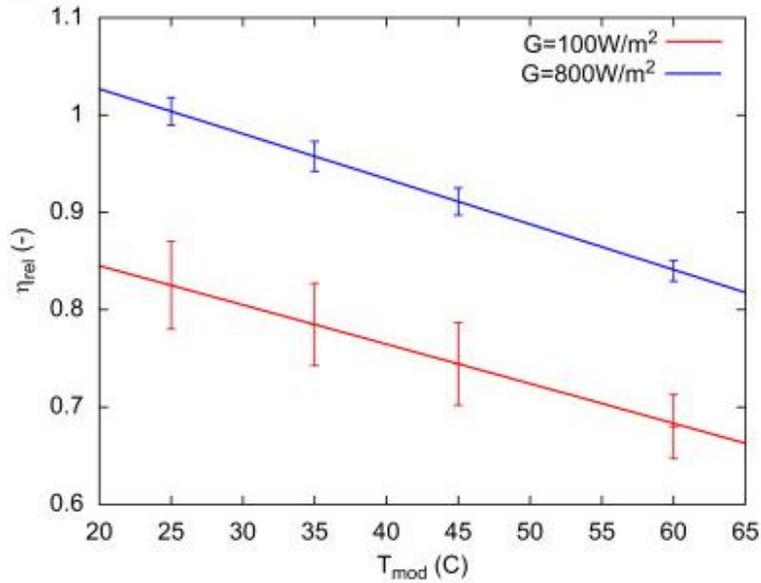
Figure 2.12 Relative efficiency for c-Si module based on temperature [30].

Study [30] considered c-Si type of PV modules, therefore coefficients (Table 2.2) for the relative efficiency were presented only for this type of technology. However, these coefficients for three types such as c-Si, CIS and CdTe were presented in study [17].

Table 2.2 Relative efficiency coefficients.

Coefficient	c-Si	CIS	CdTe
k_1	-0.017237	-0.005554	-0.046689
k_2	-0.040465	-0.038724	-0.072844
k_3	-0.004702	-0.003723	-0.002262
k_4	0.000149	-0.000905	0.000276
k_5	0.000170	-0.001256	0.000159
k_6	0.000005	0.000001	-0.000006

In order to determine module temperature, which depends both on temperature of environment and irradiance, authors in [17] have used the formula for module temperature described in [31]:

$$T_m = T_a + \frac{G}{U_0 + U_1 W}. \tag{2.4}$$

31

As a result, considering all the effects described above authors at study [17] presented a map (Figure 2.13) of relative efficiency for c-Si modules.
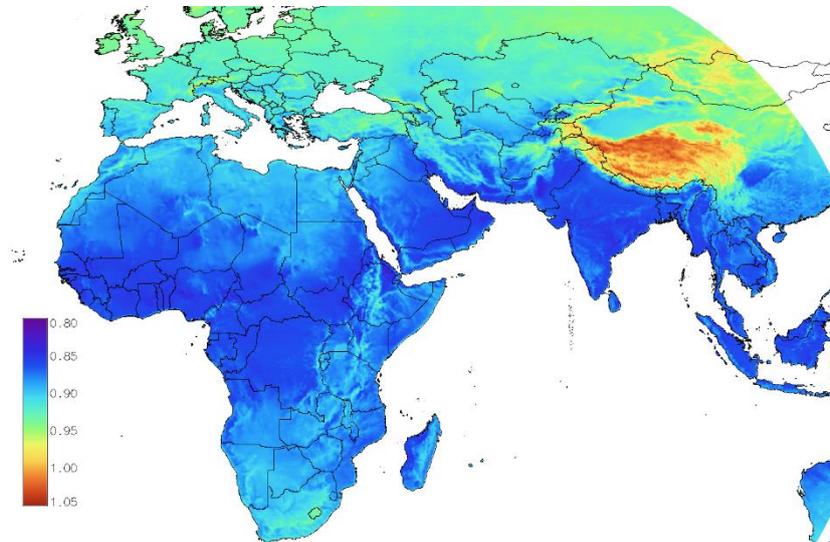
Figure 2.13 Relative efficiency for c-Si modules [17].

As it was mentioned at the beginning of this chapter there are factors as ageing and system loss. Ageing causes a reduction of PV power production due to ageing which means that closer to the end of module's lifetime, energy production will be less than it was at the beginning. Reduction of energy production due to the losses on cables, conversion etc. are related to the system losses. The impact of these effects is important to consider to be able to estimate PV power yield more precisely.

Authors at [32] conducted a thorough research and proposed an average value of 0.5% of power loss due to ageing effects. At last authors at [17] presented an average value of 14% considering both ageing and other system losses.

3 Methodology

In this section a general methodology for solving the stated problem is described. It starts with description of parameters that are important to use in intended web application, enumerates and describes tools and APIs that are exploited and introduces with JRC's web tool for PV Performance analysis.

3.1 Description of parameters

There are certain parameters that the web application uses for calculation and presenting purposes. Each of these parameters are important, because the accuracy of the output data depends on the precision of these parameters.

Table 3.1 Main parameters used in application.

Name of the parameter	Dimension
Address	-
Peak power	kWp
Yearly PV energy production	MWh
Total installation cost	€
Payback period	Years
Cost of a panel	€/m^2
Average electricity price	€/MWh
Estimated area of a rooftop	m^2
Slope angle	Degrees
Azimuth	Degrees
PV technology	-

3.1.1 Address

In the user interface of the application user should be able to enter an address (street and house number) of an interest and integrated online map navigates to that location. These street and house number are passed to OSM API request, which then returns geographical data of that location (i.e., latitude and longitude). Then the obtained geographical

coordinates are consumed by integrated online map to locate the given address on the map.

3.1.2 Peak power

The nominal power of the PV system, which is also known as PV systems' peak power is usually provided by the producer of the PV panel. Peak power represents systems or modules power production at 1000 W/m^2 solar irradiance. If the modules' efficiency is considered to be 100% effective, then to obtain a PV system with 1kW peak power it is necessary to have 1 m^2 of this PV module. Because of the complexity to achieve 100% efficiency of the module, there is a necessity for a larger PV systems area. For instance, if the module has an efficiency of 10% then the required area to get a system with 1kW peak power is 10 m^2 [33].

The efficiency of a solar panel is determined by how much solar energy received by panel can be converted into useful electricity. When the cells of a solar panel interact with sun rays the electrical current is caused. This then transferred into alternating current energy. There are numerous factors that can affect panels' efficiency. One of the main factors is the materials and technology the PV panels were made of such as c-Si, CIS, CdTe etc. The widely used among these is c-Si, which has two major types: monocrystalline and polycrystalline. Polycrystalline panels are considered to be less efficient than monocrystalline because of its' composition, however the same factor guarantees the cheaper price.

Another important factor that affects the solar panels efficiency is reflectance. The higher reflectance of the panel the lesser panels' actual efficiency. This is determined by the number of solar rays reflected when it hits the surface of a solar panel instead of absorption. This can be mitigated by different supplementary materials such as anti-reflective coverings.

Other factors that affect panels efficiency are cloud cover, solar intensity, relative humidity etc. For instance, if the solar panel has an efficiency of 19%, this means that only this percentage out of all sun rays falling onto panels' surface can be converted into electricity. Currently, one of the highest efficiency percentages the solar market can propose is 23%, however the average efficiency range falls into 17-19% [34].

For the purposes of this work, considering external factors, it was decided to assign 17% of average panels' efficiency. The formula for calculation of nominal power (peak power) for PV system can be determined as follows [33]:

$$P_{pk} = A \cdot eff_{nom},$$ (3.1)

where,

P_{pk} – nominal power,

A – area,

eff_{nom} – panels efficiency, in this case 17%.

3.1.3 Yearly PV energy production

The calculated energy production of PV system is requested from non-interactive service of JRC's PVGIS tool. The data represented in monthly and yearly format. The yearly PV energy production describes how much energy can a system with given parameters produce in one year. The data is obtained from API request in kWh, but in this work, data is converted to MWh.

3.1.4 Total installation cost and cost of a panel

The total installation cost parameter determines the possible expenditures for a PV system with given characteristics and used to calculate its' payback period. In this work the additional costs for supplementary tools/instruments and installations cost are not considered. To calculate total installation cost only the area of a PV system and its cost per square meter are taken into account. The price for panel per square meter is determined through the market analysis.

3.1.5 Average electricity price

Another parameter required for payback period calculation is average electricity price. In this work the average yearly electricity price for Estonia was obtained from Nord Pool service.

3.1.6 Payback period

The payback period determines the time in which the possible PV system will cover its' installation cost. In this work the energy consumption of the user is not taken into account,

there are three variables that the payback period depends on, these are: total installation cost, yearly PV energy production and average electricity price. The higher the electricity price the shorter is payback period and the high total installation cost results in longer payback period.

3.1.7 Estimated area of a rooftop

Estimated area of a rooftop is an important parameter and used to calculate the peak power of a PV system, which affects the total energy output of the system and total installation cost. In order to calculate estimated rooftop area, the appropriate coordinates are necessary. In this case these coordinates are geographic and represented in latitudes and longitudes. To calculate area based on these coordinates a side API Turf.js is used. The motivation behind using Turf.js is its ability to take geographical coordinates as an input and return data in square meters. This is determined by the data returned by OSM's Overpass API, which is a GeoJSON data and used as input to get estimated rooftop area. As the output of the Overpass API is related to geographic data, there is a necessity for encoding this to a readable and convenient format, this demand is fulfilled by GeoJSON format. An example of GeoJSON data is presented in Figure 3.1. It supports different geometry types such as [36]:

- Point,
- LineString,
- Polygon,
- MultiPoint,
- MultiLineString,
- MultiPolygon.

```
{
    "type": "Feature",
        "geometry": {
        "type": "Point",
            "coordinates": [125.6, 10.1]
    },
    "properties": {
        "name": "Dinagat Islands"
    }
}
```

Figure 3.1 Example of GeoJSON format data [36].

3.1.8 Slope

As in this work the PV panels are considered as non-tracking (fixed), there is a necessity for a determined slope. Slope is an angle from a horizontal perspective of the PV panels. In cases where the existing rooftop has a different shape rather than flat the slope should be already known. In other cases, PVGIS's non-interactive service can calculate an optimal value for the slope [32], which is appropriate for the purposes of this work because all the roof shapes in the scope of this work are considered as flat. The other roof shapes bring additional complexity for calculations, if the user's interested building's roof has a shape, user can variate slope and azimuth angles to compensate deviations. Figure 3.2 gives a visual description of a slope angle.
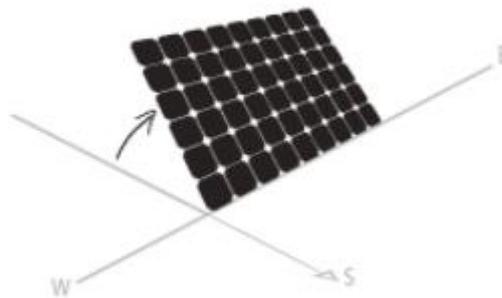
Figure 3.2 Slope of a solar panel [33].

3.1.9 Azimuth

The direction from where the sun rays descend is called azimuth. In northern hemisphere this direction is always due south in southern hemisphere due north. Similar to the slope this parameter can also be optimally calculated by PVGIS's API or user can enter preferred angle in the user interface. Figure 3.3 gives a visual description of the azimuth angles.

Figure 3.3 Azimuth angle of a solar panel [33].

If user decides to use optimal values for the slope and azimuth, PVGIS's non-interactive service will define optimal values in which the highest yearly energy output for the PV system is possible. This also assumes that these angles will be fixed whole year [33].

3.1.10 PV Technology

PV panels' performance and efficiency depend on many factors such as tilt angle, dust, shading, wiring losses etc., however the solar irradiance and temperature have the higher impact among those. The lower temperature and high solar radiation level determine higher performance for the panels [37]. Based on the technology used to produce the PV module this dependency distinguishes [33]. There are three types of PV technologies that are used widely, these are:

- c-Si
- CIS thin film modules
- CdTe thin film modules

c-Si solar panels have longer production time and higher thickness, but this technology is the most researched and this panels have comparatively higher efficiency (15-18%) and the highest power/area ratio.

CIS solar panels are thin (~0.003 mm), have less efficiency (7.5 -9.5%), the supplies of indium are limited.

CdTe usually thicker than CIS panels but thinner than c-Si panels (~0.008 mm), have efficiency in the range of 6 to 9% are made of poisonous materials. For the CdTe and CIS there is a tendency of considerable decrease in production costs [38].

Based on the wide use of these three PV technologies and the capability of PVGIS's non-interactive service to calculate losses with higher precision only for these materials, in this work it was decided to utilize only these three types of PV technologies.

3.2 Tools and APIs

3.2.1 Tools

For realization of an intended solution, a certain number of tools were selected. These are used to build a web platform, which consists of two parts: front end and back end.
A programming language that was selected is JavaScript, because of its flexibility, omni-platform nature, rich library, and comfortable syntax. Moreover, it allows to develop both on client-side and server-side and has different frameworks which facilitates the process. Tools that are used for development:

- Node.js
- React.js
- Postman
- Visual Studio Code
- Google Chrome

JavaScript is more known as a client-side or browser language, however with Node.js it can be used for development on server-side.

Node.js is a back end JavaScript runtime. It is cross-platform, open-source (free to use) and can execute JavaScript in environments apart of web browser. In this work Node.js was used to build the back end of the web application.

The front end of the proposed web application was built with React.js, which is another JavaScript library for building interactive user interfaces. As well as Node.js it is open-source, allows to create reusable components and supported by Facebook.

Working with API is facilitated by using Postman. It is a common API client which facilitates the development, sharing, testing and documentation of APIs for developers. This is accomplished by permitting users to build, secure and read basic and complex HTTP/s requests. The effect is a less boring and productive job [39].

As an environment for writing and editing the code Visual Studio Code was chosen, due to its powerful functionality, but at the same time light weight. It is available for different operating systems and supports multiple programming languages [40]. The main advantage of using this editor is that it provides high convenience and flexibility for developing in JavaScript and its corresponding technologies.

Google Chrome is a modern, fast, powerful browser. It provides developer tools which facilitates development process and is especially good for debugging.

In this work for development purposes several APIs were used. API stands for Application Program Interface; it is a computing interface that specifies how various software or mixed hardware-software intermediaries communicate with one another. It specifies the types of calls or requests that should be made, how they should be made, what data formats should be used, and what conventions should be followed, among other things. It may also have expansion tools, allowing users to expand current features in a variety of ways and to different degrees. To ensure interoperability, an API may be completely customized, unique to a component, or built on an industry standard. APIs support modular programming by hiding details and encouraging users to use the interface regardless of the implementation [41].

3.2.2 APIs

In this work several APIs were used for different purposes, many of them facilitate the process of development by avoiding the creation of already existing functionality. APIs that are used for development:

- OSM
- Leaflet.js
- Turf.js
- Overpass

- Bootstrap
- Chart.js

OSM is a project to create a free global spatial database. Its goal is to compile a database of any geographic feature on the globe. Although it began with street mapping, it has since expanded to include footpaths, houses, rivers, pipelines, woods, beaches, post-boxes, and even individual trees. In addition to physical geography, the project involves administrative borders, land use specifics, bus lines, and other abstract concepts that are not visible in the landscape [42]. OSM provides an open-source and editable map of the world. Most of the contributors for this are volunteers. It is possible to use almost all data and images that are provided by OSM free of charge. Another advantage of using OSM is in its API which is free of charge also, it allows to pull raw geographical data from OSM database.

Another JavaScript library used to work with interactive maps is Leaflet.js. It is the most common free of charge mapping library used among developers. It outstands for its lightness, simplicity, and versatility. In this work this library is used to retrieve online interactive map from OSM.

Turf.js provides advanced geospatial analysis, different spatial calculations, understands and operates with GeoJSON and has various classification and statistics modules [35]. Another advantage of this JavaScript library is that it is open-source and free to use.

Overpass API is a read-only API that allows to get data from OSM database. If a query is sent to this, it returns only the data related to the query, an example of a query is presented in Figure 3.4 and the response for this can be seen in Figure 3.5. The difference between main OSM API and Overpass API is that main API is more focused for editing and Overpass API is consumer oriented, which explains it read-only nature.

```
[out:json];
nwr["addr:street"="Akadeemia tee"]
   ["addr:housenumber"="3"]
   [building](59.3518076,24.55017,59.5915769,24.9262831);
out geom;
```

Figure 3.4 Query example for Overpass API.

```
{
    "version": 0.6,
        "generator": "Overpass API 0.7.56.9 76e5016d",
            "osm3s": {
            "copyright": "The data included in this document is from www.o
penstreetmap.org. The data is made available under ODbL."
    },
    "elements": [
        {
            "type": "way",
            "id": 80539704,
            "bounds": {
                …
            },
            "nodes": [
                …
            ],
            "geometry": [
                …
            ],
            "tags": {
                "addr:city": "Tallinn",
                "addr:country": "EE",
                "addr:housenumber": "3",
                "addr:postcode": "12616",
                "addr:street": "Akadeemia tee",
                "alt_name": "SOC",
                "building": "yes",
                "layer": "1",
                "name": "TTÜ majandus- ja sotsiaalteaduste maja",
                "source": "Maa-amet WMS 2010"
            }
        }
    ]
}
```

Figure 3.5 JSON response for query in Figure 3.4.

To facilitate the building of user interface a front end development framework Bootstrap is used. It provides reusable components for building responsive webpages.

For drawing a graph of monthly energy output of a PV system, another JavaScript library Chart.js is used. It performs data visualization through the following types of charts:

- Line

- Bar

- Radar

- Doughnut and Pie

- Polar area

- Bubble

- Scatter

- Area

- Mixed

3.3 PVGIS

Under a science and knowledge service of European Commission the JRC a web tool for PV performance, solar radiation and typical meteorological year analysis was developed. The tool is named PVGIS.

The usage of this tool is free of charge and it provides access to different analysis tools such as:

- Performance of grid-connected PV

- Performance of tracking PV

- Performance of off-grid PV systems

- Monthly irradiation data

- Average daily irradiance data

- Hourly radiation data

- Typical meteorological year

PVGIS has non-interactive service, which allows to use its functionality through the API. It can be used using different programming languages including Node.js. The non-interactive service accepts input parameters with a certain restrictions and rules and outputs requested data in several formats such as: CSV, JSON, raw CSV (no metadata). An example of minimum usage of PVGIS API, which also shows the minimum required parameters can be seen in Figure 3.6.

```
https://re.jrc.ec.europa.eu/api/PVcalc?lat=45&lon=8&peakpower=1&loss
=14
```

Figure 3.6 Example of minimum usage of the PVGIS API [43].

3.4 Illustration of payback period calculation

In order to calculate payback period in years of proposed PV system the following parameters are necessary: total installation cost of PV system, yearly energy production of the system and average price for electricity.

There are different methods to calculate total installation cost of PV system and for the sake of simplicity and readability in this work the possible expenditures for supplementary materials and installation services are not considered, it is obtained by multiplying the total area of PV panels by its' cost per square meter.

Area of PV panels is obtained by using side API – Turf.js. API returns the approximate area of a rooftop of selected building in square meters based on geographical coordinates. The rooftop is considered as flat, this assumption is made to avoid additional complexity brought by differentiation of rooftop shapes. Another assumption is that the whole output area is considered as a valid area for installing PV panels.

To find out the average price for PV panel per square meter a market analysis has been conducted. In this work three types of PV technologies were considered, these are: c-Si, CIS, CdTe. Based on their characteristics these PV technologies have distinct prices and efficiency. As a main source for price detection a web platform www.enfsolar.com was used. As a result, these conclusions were made:

- c-Si – 41 €/m^2,
- CIS – 176.8 €/m^2,
- CdTe – 82.5 €/m^2.

Further, a calculation formula for total PV system installation is defined as:

$$T = A \cdot r, \tag{3.2}$$

where,

T – total PV system installation cost [€],

A – area of PV panels [m^2],

r – price of a panel per square meter [€/m^2].

Yearly energy production of a PV system is obtained through side API – JRC's non-interactive service. API returns value in kWh, but for calculation purposes it is transferred to MWh.

Average electricity cost was obtained from data provided by NordPool. It is a leading power market in Europe, it delivers power trading across European countries and presents clearing, exchange, arrangement, and corresponding services in intraday and day-ahead markets. This organisation is selected as a Nominated Electricity Market Operator in 15 European countries, such as: Estonia, Latvia, Lithuania, Sweden etc. [44]

Table 3.2 Monthly day-ahead prices for Estonia in different years.

Month/Year	2017	2018	2019	2020
January	33,3	37,1	55,8	30,8
February	35,1	43,4	47,3	28,1
March	30,7	45,3	40,1	24
April	31,2	39,9	42,2	23,7
May	30,7	38,7	42,3	25
June	30,7	47,8	43,5	37,8
July	34,3	54,1	48,9	30,1
August	36,3	55,4	49,1	40,9
September	37,3	50,9	48,8	39,6
October	33,4	46,4	47,7	37,6
November	33,7	52,6	45,7	41
December	32	53,1	39,1	45,5
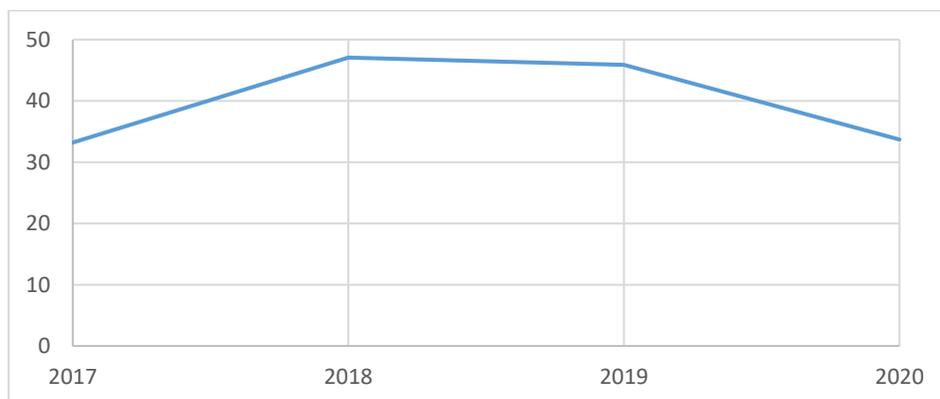
Figure 3.7 Yearly average electricity prices for Estonia.

Market data for Estonia is represented in day-ahead prices hourly, daily, weekly, monthly and yearly. For example, in 2017 average electricity price in Estonia was 33.20 €/MWh, in 2018 it was 47.07 €/MWh, in 2019 it was 45.86 €/MWh and for 2020 it was 33.69 €/MWh. Figure 3.7 shows electricity price trend in different years. In this work, the latest (2020) average yearly electricity price was taken.

Considering all the data mentioned above, the formula for payback period calculation can be determined as follows:

$$P = \frac{T}{PV_{prod/year} \cdot AVG_{el.cost}}, \tag{3.3}$$

where,

P – payback period [years],

$PV_{prod/year}$ – yearly energy production of a PV system [MWh],

$AVG_{el.cost}$ – average price for electricity, in this work the data taken from NordPool is for year 2020, which is 33,69 [€/MWh].

As a test case, a building was selected in Estonian capital Tallinn with address Teaduspargi 8. An approximate area of a rooftop obtained through API request is 3041.88 m^2 and the price for c-Si PV technology is 41 €/m^2. According to formula (1) the total installation cost can be calculated as:

$$T = 3041.88 \text{ m}^2 \cdot 41 \frac{€}{m^2}$$

then,

$$T = 124717.08 €.$$

For the c-Si PV technology the yearly energy output obtained through API request is 463.49 MWh and the average price for electricity is the same as above.

As a result, according to the formula (2) payback period of an installed PV system can be calculated as follows:

$$P = \frac{124717.08 €}{463.49 \text{ MWh} \cdot 33.69 €/\text{MWh}}$$

then,

$$P = 7.98.$$

It can be seen, that in idealistic conditions the recoupment of the solar PV system installed with corresponding characteristics can be expected in 8 years. The main parameters that the payback period depends on are cost of a panel and electricity price. Higher cost of a panel results in a longer payback period and vice versa higher electricity price gives shorter payback period. As there are multiple choices for PV technology and these are distinguished in energy production and cost, correspondingly payback periods for these PV technologies will be different also.

As an example, for the same location the yearly energy output will be:

CIS $PV_{prod/year} = 459.09$ MWh,

CdTe $PV_{prod/year} = 453.73$ MWh.

The total installation cost for CIS technology will be:

$$T_{CIS} = 3041.88 \text{ m}^2 \cdot 176.8 \ \frac{\text{€}}{\text{m}^2}$$

then,

$$T_{CIS} = 537\ 804{,}384 \ \text{€};$$

For CdTe:

$$T_{CdTe} = 3041.88 \text{ m}^2 \cdot 82.5 \ \frac{\text{€}}{\text{m}^2},$$

then,

$$T_{CdTe} = 250\ 955{,}1 \ \text{€}.$$

Using the data calculated above the payback periods for corresponding PV technology is calculated as follows:

$$P_{CIS} = \frac{537\ 804{,}384 \ \text{€}}{459.09 \text{ MWh} \cdot 33.69 \ \text{€/MWh}},$$

$$P_{CIS} = 34.77.$$

$$P_{CdTe} = \frac{250\ 955{,}1 \ \text{€}}{453.73 \text{ MWh} \cdot 33.69 \ \text{€/MWh}},$$

$$P_{CdTe} = 16.4.$$

Due to the lower energy production efficiency and higher costs CIS and CdTe PV panels result in considerably longer payback period compared to c-Si.

4 Realization

In this section a realization of the proposed solution will be described. As the proposed solution is a web application there is a need for building a client-side and server-side services. Client-side service is also named as front end processes user interface operations and serves user's inputs. However, server-side service or back end is for processing required calculations and for making side API requests.

4.1 Back end

Back end is part of a web application that is not interactable, which means a user cannot see it. Operations related to data management and communication become more organized and simplified. The data presented on the webpage can be a result of communication between client-side and server-side services. One of the advantages of implementing the back end is that it adds simplicity for future development and provides organized way for growth.

The main motivation behind server-side service creation is to support front end side with necessary operations. In this work most of the calculations and requests to side APIs are conducted via back end service.

4.1.1 Structure

Back end service perform five basic operations. Based on these operations it can be structured as follows (Figure 4.1):

- Calculation of peak power
- Calculation of PV power output with optimal parameters
- Calculation of PV power output with custom parameters
- Calculation of total installation cost
- Calculation of payback period
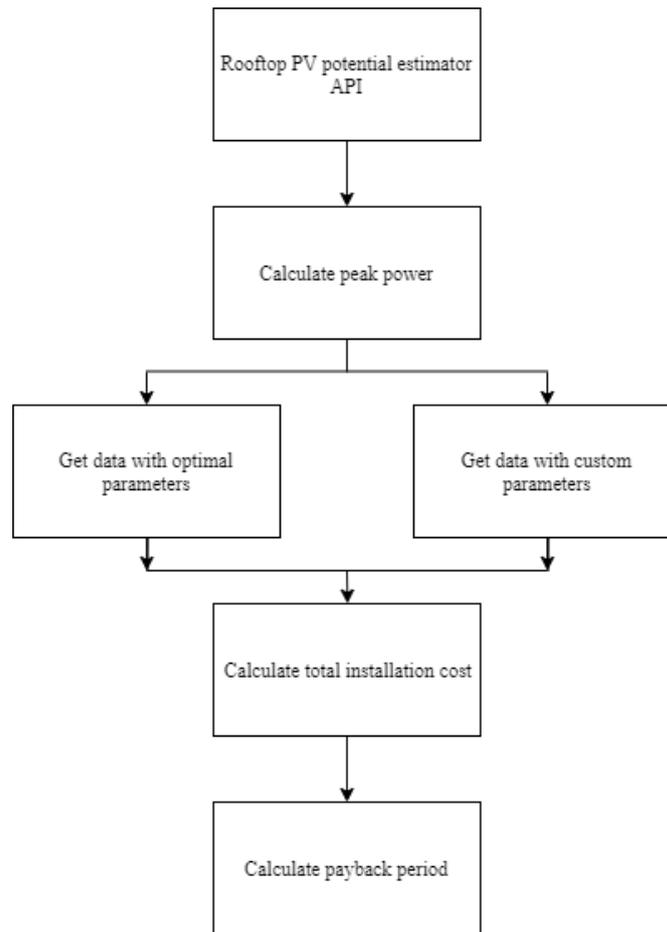
Figure 4.1 Structure of server-side service of web application.

Calculation of peak power, total installation cost and of payback period have been already described in Section 3.4. The output data for calculations with optimal and custom parameters are calculated using the PVGIS API.

4.1.2 Output data for optimal parameters

Non-interactive service of PVGIS tool provides calculation for yearly PV power output and takes as input parameters such as:

- Latitude and longitude
- Radiation database
- Peak power
- PV technology choice
- System loss
- Inclination angle
- Aspect

- etc.

For calculation with optimal parameters there are four parameters that the PVGIS still requires for input, these are: latitude, longitude, peak power, and PV technology of choice. These required parameters are determined in the server-side of the current web application.

Latitude and longitude determine the geographical location of the building and in this work these coordinates determined automatically based on the address provided by user. For peak power PVGIS does not present a default value, it is automatically calculated and passed to the PVGIS API by the server-side of the current web application.

The default PV technology choice is made considering the current market trends, which determines c-Si panels as the most used. For the purposes of this work c-Si technology was selected as an optimal parameter and passed as input to PVGIS API.
There are also parameters that can be defined automatically by PVGIS itself such as: radiation database, system loss, slope and azimuth.

Radiation database provides radiation data that are necessary for PV power yield calculation, there are multiple choices presented by JRC PVGIS such as: PVGIS-SARAH, PVGIS-ERA5, PVGIS-COSMO. For Europe, Africa and Asia the database recommended by JRC is PVGIS-SARAH.

As described in Section 2 the value recommended by JRC for system loss is 14%, in this work it is decided to follow the recommendation and keep this value for both types of calculations.

Inclination angle and aspect also can be calculated by PVGIS, it will set the value in which the maximum PV efficiency can be obtained.

The parameters that the web application requires apart of described above are as follows:
- Cost of a panel per square meter
- Average electricity price
- Estimated rooftop area.

The default values for these parameters are described in Section 3.4.

The estimated rooftop area is calculated using JavaScript library Turf.js, it accepts geographical coordinates of the polygon returned by the Overpass API and returns an estimated area in square meters.

4.1.3 Output data for custom parameters

The proposed web application allows users to customize some of the parameters and achieve more precise results. The Rooftop PV Potential Estimator API takes parameters for customization such as: latitude and longitude, peak power, PV technology, slope and azimuth, cost of a panel per square meter, average electricity price and estimated rooftop area.

Web application offers three types of PV technology to choose from. These are: c-Si, CIS and CdTe.

If there are better options for slope and azimuth, then user can alter default values and insert custom ones. However, the optimal slope value for Estonia is in between 35-40 degrees, at this level it is possible to achieve the maximum power production efficiency [45].

The value for cost of a panel can also be customized, the currency selected matches the currency of Estonia, which is euro. The higher is the cost of a panel then the higher is total installation cost and longer the payback period.

For average electricity price, user must consider the currency defined in the system, which is euro. Otherwise, it can result in improper output data.

Estimated rooftop area can be changed by user to a value of interest. This value is used for peak power calculation, which affects the total yearly PV power yield.

4.2 Front end

Front end web creation, also referred to as client-side development, is the process of creating HTML, CSS, and JavaScript for a website or Web application so that a user can view and communicate with it directly. The difficulty with front end creation is that the methods and strategies used to build the front end of a website change all the time, necessitating the developer's continual awareness of how the area evolves [46].

Moreover, there are numbers of JavaScript libraries and frameworks that facilitate the development process. In this work a JavaScript library React.js was selected as a main library for client-side service creation.

There are three main components in the client-side of current web application, which perform all the necessary interactions with user, takes input and presents output data (Figure 4.2). These components are: Main, Calculations and Map box.
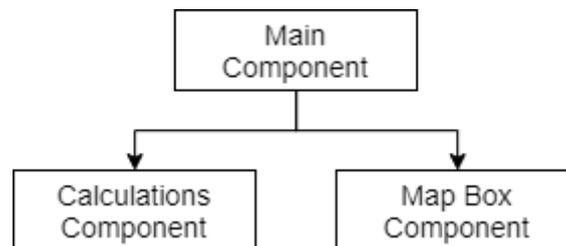
Figure 4.2 General structure of client-side service of web application.

4.2.1 Main component

The Main component is a parent component for the rest all components. All the initial parameters necessary for further steps are defined here.

In order to get an optimized PV energy output and corresponding data, it is required from the user to enter the address of interest through the user interface. There are two parameters necessary for address from user: street and house number. The obtained values of street and house number are then passed to Nominatim API as a search query.

Nominatim is another API for OSM. It is used to find a location based on given name and address worldwide [47]. The search API of Nominatim can locate an object based on the

given textual input. In this work street and house number are used as a textual description for API input. The template for search API is presented in Figure 4.3.

```
https://nominatim.openstreetmap.org/search?<params>
```

Figure 4.3 Nominatim search API format [48].

Above mentioned search API returns a JSON format data with geographic coordinates of the object. The possible fields of a response are:

- Place ID – refers to an internal ID of Nominatim database.
- OSM type – refers to an object in OSM.
- Bounding box – a vector of geographical coordinates of an object's corner.
- Latitude and longitude – geographic coordinates of object's centroid.
- Display name – full address separated by comma.
- GeoJSON – full geometry by geographic coordinates.
- etc.

```
[
    {
        "place_id": 165982557,
        "licence": "Data © OpenStreetMap contributors, ODbL 1.0. https://osm
.org/copyright",
        "osm_type": "way",
        "osm_id": 307772355,
        "boundingbox": [
          …
        ],
        "lat": "59.399924999999996",
        "lon": "24.656535007628918",
        "display_name": "8, Teaduspargi, Teaduspark Tehnopol, Mustamäe linna
osa, Tallinn, Таллин, Уезд Харьюмаа, 12618, Estonia",
        "class": "building",
        "type": "yes",
        "importance": 0.33100000000000007,
        "address": {
          "house_number": "8",
          "road": "Teaduspargi",
          "commercial": "Teaduspark Tehnopol",
          "suburb": "Mustamäe linnaosa",
          "city": "Tallinn",
          "municipality": "Таллин",
          "county": "Уезд Харьюмаа",
          "postcode": "12618",
          "country": "Estonia",
          "country_code": "ee"
        },
        "geojson": {
          "type": "Polygon",
          "coordinates": [
            …
          ]
        }
    }
  ]
```

Figure 4.4 Example of JSON output of Nominatim API.

In the web application after user enters the address of interest, it is then passed to Nominatim API. A GeoJSON data returned by the API includes geographic coordinates of the polygon and coordinates of the object's centroid (Figure 4.4).

While Nominatim API is used for finding a location of interest and centering the map on it. There is a necessity for finding a corner coordinates of the building user requested. These will be used in calculation of a rooftop area.

OSM provides a good solution for this – Overpass API. Based on request by street and house number Overpass returns a GeoJSON data which includes the geographic coordinates of a building's corners. Considering the scale of the current project, it was decided to restrict the search area for Overpass API to include only the city of Tallinn, Estonia.

When the user requests a certain address, this is sent as a query to Overpass API, which then returns a GeoJSON data. For rooftop area calculation a "geometry" property of a returned object is necessary. It contains the set of latitudes and longitudes which describes the geometry of the building. As an example, if user searches for "Teaduspargi 8" the set of coordinates as in Figure 4.5 is returned.

```
"geometry": [
    { "lat": 59.3997380, "lon": 24.6571030 },
    { "lat": 59.3997290, "lon": 24.6559790 },
    { "lat": 59.4001120, "lon": 24.6559670 },
    { "lat": 59.4001180, "lon": 24.6567700 },
    { "lat": 59.4002800, "lon": 24.6567650 },
    { "lat": 59.4002820, "lon": 24.6570860 },
    { "lat": 59.3997380, "lon": 24.6571030 }
  ]
```

Figure 4.5 An example array of geographic coordinates.

Then obtained array is passed for area calculation. Estimation of rooftop area is conducted through another JavaScript library Turf.js. It accepts geographic coordinates as input and returns the area in square meters.

The array of coordinates in Figure 4.5 will result a value of 3041.88 m² which is taken as an approximate rooftop area for selected building. The importance of this value is determined by the fact that it is used for peak power calculation which affects the output for PV power yield.

4.2.2 Map box component

The Map box component requires latitude and longitude coordinates to find the object and center the map on it. The required parameters are passed from Main Component. Current component is responsible for presenting the online interactive map on the user interface. The interactive map (Figure 4.6) was created using the JavaScript library Leaflet.js and was retrieved from OSM platform.

Figure 4.6 Interactive map created with Leaflet.js.

4.2.3 Calculations component

This component is responsible for output of optimal and custom results supported by the graph of monthly energy output. Component requires latitude and longitude coordinates in order to pass it to PVGIS API, estimated area of a rooftop which is passed to Rooftop PV Potential Estimator for peak power calculation and the GeoJSON data obtained from Overpass API.

This component has two sub-components that describe two options available for PV power output calculation: calculation with optimal parameters and calculation with custom parameters.

To get the PV power output with optimized parameters user only needs to enter address data. The main parameters, such as latitude and longitude, rooftop area and PV

technology, are determined automatically and passed to PVGIS API which in response returns a JSON data containing calculated optimal results.

Table 4.1 Input parameters for optimized calculation.

Input parameters for optimized calculation	
Location	Latitude
	Longitude
Meteo-data	Radiation database
Mounting system	Slope
	Azimuth
PV module	Technology
	Peak power
	System loss

The radiation database of choice as it was mentioned in previous sections is "PVGIS-SARAH".

Slope and azimuth are calculated automatically by PVGIS.

PV technology of choice is c-Si.

Peak power is calculated by formula described in previous sections.

System loss – 14%.

The response from the PVGIS API are output parameters that describe PV power output monthly and yearly.

Table 4.2 Output parameters of optimized calculation.

Variable	Description	Units
E_d	Average daily energy production from the given system	kWh/d
E_m	Average monthly energy production from the given system	kWh/mo
H(i)_d	Average daily sum of global irradiation per square meter received by the modules of the given system	kWh/m2/d

H(i)_m	Average monthly sum of global irradiation per square meter received by the modules of the given system	kWh/m2/mo
SD_m	Standard deviation of the monthly energy production due to year-to-year variation	kWh

From the obtained data from PVGIS API it is possible to retrieve a yearly PV power output. Next, the total installation cost for PV system is calculated using the given value for rooftop approximate area and a constant value for a cost of a panel per square meter which equals to 41 €/m^2.

To calculate the payback period of a proposed PV system, there are three variables that are necessary, these are: total installation cost of a PV system, yearly PV power output and electricity price. The total installation cost value is calculated as mentioned previously, yearly PV power output can be retrieved from PVGIS API response and average electricity price for Estonia is retrieved from the data provided by Nord Pool and for 2020 year it is equal to 33.69 €/MWh. As a result, there are several parameters that are passed to user interface and presented to a user.

Table 4.3 Parameters passed to user interface.

Parameter	Description	Units
Address	Street and house number, only parameter that is required to be given by user.	-
Peak power	Represents systems or modules power production at 1000 W/m2 solar irradiance.	kWp
Yearly PV energy production	Average annual energy production from the given system.	MWh/y
Total installation cost	Total cost of a PV system for a given area	€
Payback	The period in which it is possible to return investments made for system installation	Years

Cost of a panel	Cost of a PV panel per square meter	€/m2
Electricity price	Average electricity price	€/MWh
Estimated area	Estimated rooftop area suitable for PV system installation	m2
Slope	Angle from a horizontal perspective of the PV panels	Degrees
Azimuth	The direction from where the sun rays descend.	Degrees
PV technology	Technology used to produce the PV module.	c-Si, CIS, CdTe

In calculations with custom parameters sub-component the calculation logic is almost the same as in the case with optimized parameters. The distinguishing point between these components is in the customizability of some of the parameters.

If in the calculation with optimized parameters user can input only one parameter which is address, in this component web application allows to alter the values for a number of parameters. This might be the case if user has more descriptive data and wants to get more precise output. In this component the following parameters are read-only:

- Peak power
- Yearly PV energy production
- Total installation cost
- Payback period

The values for these parameters cannot be changed manually by user, however these can be changed based on the respective dependencies on the parameters that can be altered. The parameters that can be customized are as follows:

- Cost of a panel
- Electricity price
- Estimated rooftop area
- Slope
- Azimuth
- PV technology

The output data is supported by the graph in Figure 4.7 which represents monthly energy output of a PV system in kWh.
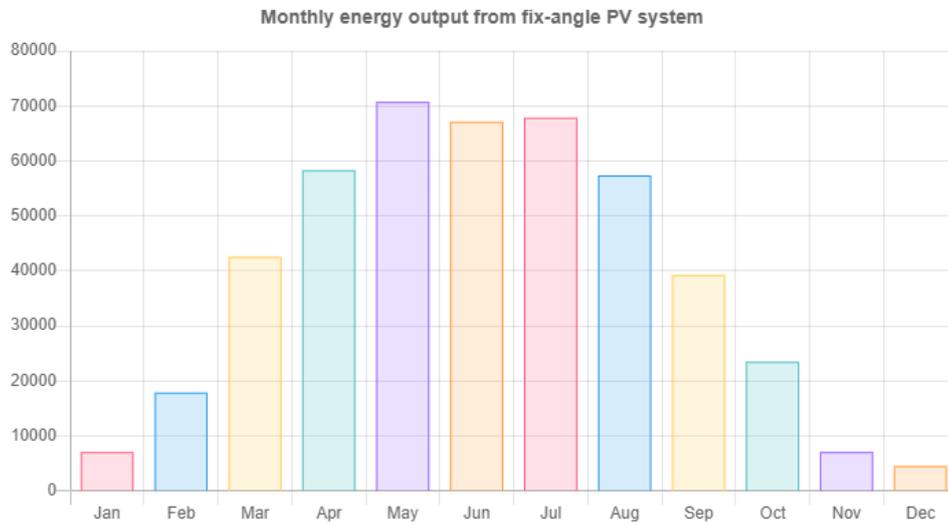
Figure 4.7 Monthly energy output in kWh.

5 Results

In this section results for the web application will be presented. The output for calculation with optimal parameters will be presented and compared with the output of calculation with custom parameters.

The monthly energy output graph will be presented for all types of PV technologies considered in this study. For user, in order to get optimized results, it is only necessary to enter the address of the building of interest. Further, the web application will present a yearly PV power output, total installation cost of the system and the payback period in years. These parameters will be supported by other helper parameters described in previous sections.

For presenting purposes, it was decided to provide a test address to web application and observe the results. Test address: Akadeemia tee 3, Tallinn, Estonia.

Table below shows the results for the building under a given address and Figure 5.1 presents monthly energy output for this test case:

Table 5.1 Output results for optimized calculation.

Parameters	Values	Units
Address	Akadeemia tee 3	-
Peak power	558.19	kWp
Yearly PV energy production	500.27	MWh
Total installation cost	134621.86	€
Payback	8	years
Cost of a panel	41	€/m2
Electricity price	33.69	€/MWh
Estimated area	3283.46	m2
Slope	42	degrees
Azimuth	3	degrees
PV technology	c-Si	-
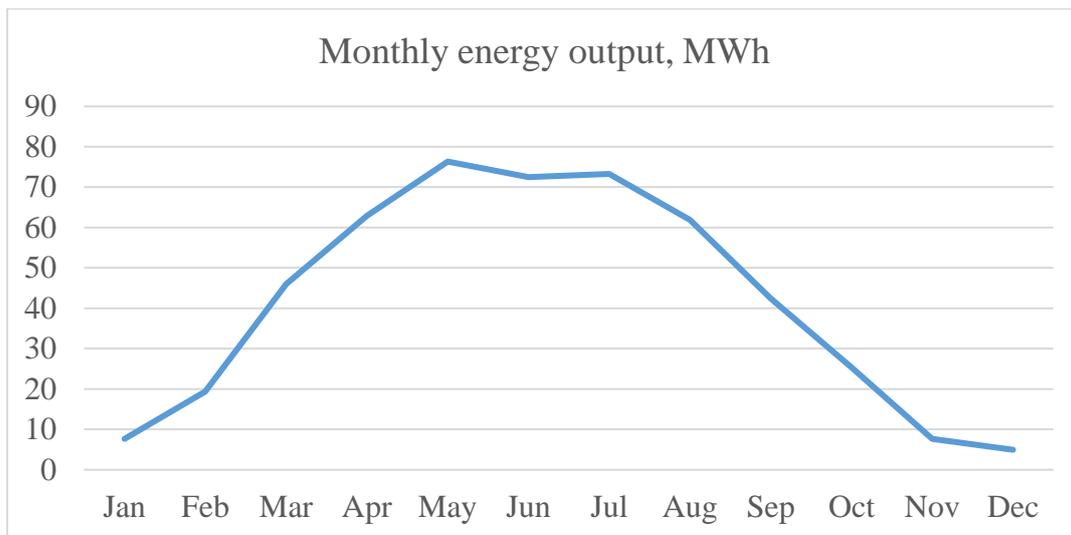
Figure 5.1 Monthly energy output for the test case.

The default values for cost of a panel, electricity price, estimated area, slope, azimuth, and PV technology were explained in previous sections. Mentioned parameter are customizable and if user has a necessity to alter the value web application allows this. For presenting purposes, the values for customizable parameters for the same address and location has been changed.

Table 5.2 Input parameters for customized calculation.

Parameters	Values	Units
Cost of a panel	50	€/m2
Electricity price	45	€/MWh
Estimated area	3000	m2
Slope	40	degrees
Azimuth	2	degrees
PV technology	c-Si	-

As it can be seen in table above, the input parameters have been changed and when these passed to the web platform, the following data is resulted in Table 5.3.

Table 5.3 Output parameters for c-Si module.

Parameters	Values	Units
Address	Akadeemia tee 3	-
Peak power	510	kWp
Yearly PV energy production	457.02	MWh
Total installation cost	150000	€
Payback	7	years

In the previous sections it was mentioned that based on the PV technology of the solar panels, the prices differentiate.

Considering that all the input parameters are identical as in Table 5.2, except of the cost of a panel and PV technology the yearly PV energy output will be different as well as the payback period for each type of solar panel. The prices for each solar panel are as follows:

- c-Si – 41 €/m^2
- CIS – 176.8 €/m^2
- CdTe – 82.5 €/m^2

The output comparison can be observed in Figure 5.2 as monthly and in Figure 5.3 as yearly.
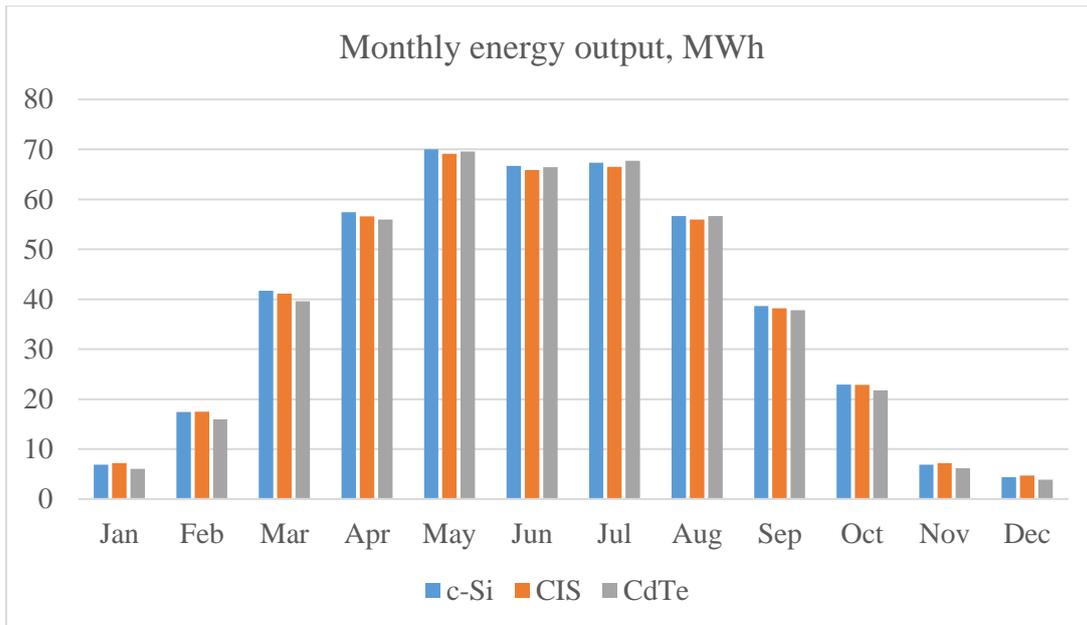
Figure 5.2 Monthly energy output for three types of PV technology.
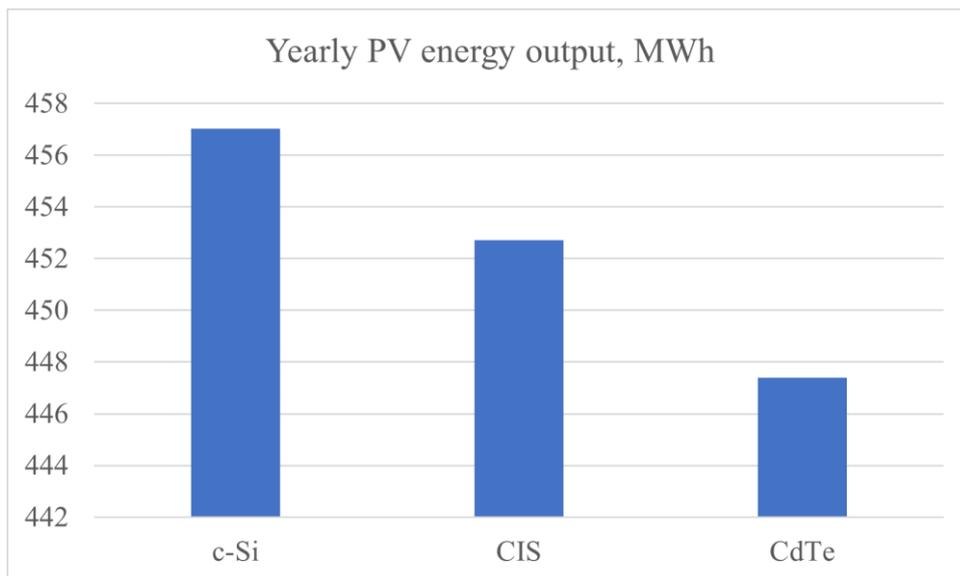
Figure 5.3 Yearly PV energy output for three types of PV technology.

From the above figures it can be seen that in average yearly PV power yield for c-Si solar panels outperforms two other types of PV technologies. This is true for the payback period also. Because of the lower price panels made from c-Si are faster in return of investments. The c-Si is the most researched type of a PV technology and the most used.

6 Conclusion

The increasing popularity of rooftop PV panels worldwide requires developments of tools for estimating installation potential. The web application for rooftop PV potential estimation developed through this study has the aim to simplify the average user's intention for investigation of a building's rooftop PV power output and the payback period of such solar PV system. This goal is motivated by the fact that most of the tools available and studies conducted requires a certain background knowledge about the topic and in order to output a proper result, requires a set of parameters that might bring a complexity for an average user.

The proposed solution can present PV energy output and corresponding data results by only requiring the address of the building. Other parameters that are necessary for input in other tools in this solution are determined automatically through a number of methods. This approach eliminates additional input complexity for a user by providing optimal parameters based on the geographic data. As a result, there is a simple tool which gives an overview of a PV potential for a rooftop and helps in decision making. The web application also supports the customization and the result can be modified based on the user's provided parameters, this approach gives a flexibility for the mentioned web tool.

Here are some recommendations that may be implemented in future studies in order to improve web tool's performance:

- Add more locations. Currently web tool is available only for Tallinn, Estonia. However, it has a potential to cover more locations.
- Consider roof shapes. In this work this is compensated by altering slope and azimuth angles. Pre-calculated roof shape's angles have a potential to give a higher precision for PV energy output.
- Optimize calculated results by determining amount of PV panels that can fit the given rooftop considering orientation in space, size and distance between panels.
- Add support for tracking PV systems.
- Consider off-grid systems.

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