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Evaluation of PV generation potential on parking lots in Dalarna County, Sweden

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SERC Centrum för solenergiforskning Solar Energy Research Center

HÖGSKOLAN DALARNA

MASTER THESIS

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Abstract

Solar energy production is increasing constantly in the world, and with that urge the necessity to find areas that cannot be used for agricultural purposes, such as parking lot areas.

The aim of this work is to estimate the total amount of energy that can be produced through photovoltaic modules mounted in solar carport systems on parking lots in Dalarna County, Sweden.

The study is performed in three parts. First, evaluate the total parking lot area in the whole county, using OpenStreetMap as geographic database and QGIS to compile and filter the data. Second, create a base case project in the parking lot area at Kupolen shopping mall in Borlänge using SketchUp and PVsyst, in order to find out how much energy per area can be produced in a year, considering near shading due to buildings and trees, as well as due to horizon profile. As a final step, perform a study in order to estimate the average percentage of parking lots in Dalarna that can be really used to generate electricity.

The results show the possibility to generate about 200 GWh/year considering all parking lot area available in Dalarna County nowadays. There are many uncertainties that must be considered, such as different solar radiation intensity, horizon profile and losses due to accumulate snow in different locations of the county, as well as different near shading due to buildings and trees. In addition, different solar carport structure and orientation according to parking lot format and software/database accuracy.

Acknowledgment

First of all, I would like to express my gratitude to my supervisor Frank Fiedler for his guidance during this project.

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Abbreviations

Abbreviation	Description
AC	Alternating current
a-Si	Amorphous silicon
BEVs	Battery electric vehicles
CdTe	Cadmium telluride
CO_2	Carbon dioxide
DC	Direct current
EU	European Union
EV	Electric vehicles
EVSPLs	Electric vehicles solar parking lots
GIS	Geographic information system
GPS	Global positioning system
JRC	Joint Research Centre
LCOE	Levelized cost of electricity
mono-Si	Monocrystalline silicon
MPP	Maximum power point
MPPT	Maximum power point tracking
O&M	Operation and maintenance
PHEVs	Plug-in hybrid electric vehicles
poly-Si	Polycrystalline silicon
PV	Photovoltaic
RCD	Residual current device
RES	Renewable energy source
SMHI	Swedish Meteorological and Hydrological Institute
STC	Standard Test Conditions

Nomenclature

Symbol	Description	Unit
A_{PLD}	Total parking lot area in Dalarna	m^2
A_{PLK}	Total parking lot area in Kupolen shopping mall	m^2
A_{SCD}	Total solar carport area in Dalarna	m^2
A_{SCK}	Total solar carport area in Kupolen shopping mall	m^2
E_{PD}	Total energy that can be produced in Dalarna	GWh/year
E_{PK}	Total energy that can be produced in Kupolen	MWh/year
E_{PPAY}	Energy produced per area in a year	$kWh/year{\cdot}m^2$
I_{sc}	Short-circuit current	A
UAC_D	Useful area coefficient for Dalarna	%
UAC_F	Useful area coefficient for Falun	%
UAC_K	Useful area coefficient for Kupolen	%
UAC_I	Useful area coefficient for IKEA	%
V_{oc}	Open-circuit voltage	V

1 Introduction

With technological development, associated with the need to reduce carbon dioxide (CO_2) emissions responsible for the greenhouse effect, society faces a new challenge, which is how to generate and store electricity from renewable sources.

Moreover, due to this same awareness of CO_2 emission reduction, new alternatives were created regarding transportation, including electric vehicles (EV). As a consequence of this exchange of combustion engines with electric motors, is necessary to increase electricity production from renewable sources, such as solar energy. On Figure 1.1, it can be seen the evolution of photovoltaic (PV) installations and also EV sales, consisted of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), in the world from 2008 to 2021 [1].

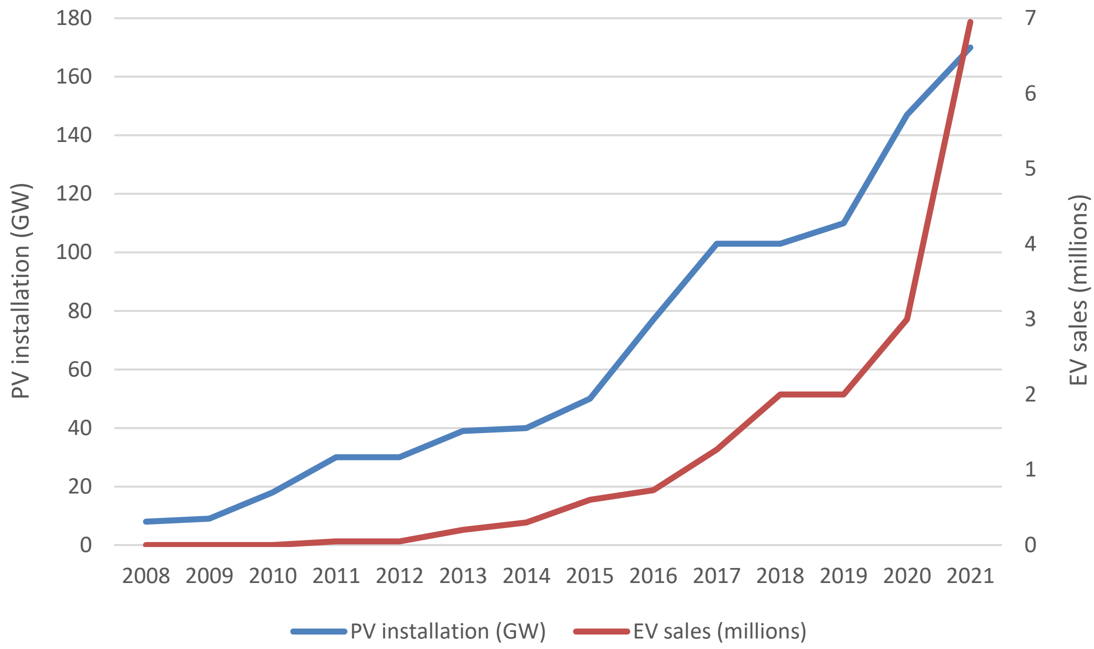


Figure 1.1 Evolution of PV and EV annual growth 2008-2021 [1].

The renewal of the vehicle fleet in Sweden from combustive engine to EV is taking place in an accelerated manner. It can be seen from Figure 1.2 the evolution of EV market share rising about 43% in a 10-year period, from 2012 to 2021 [2].

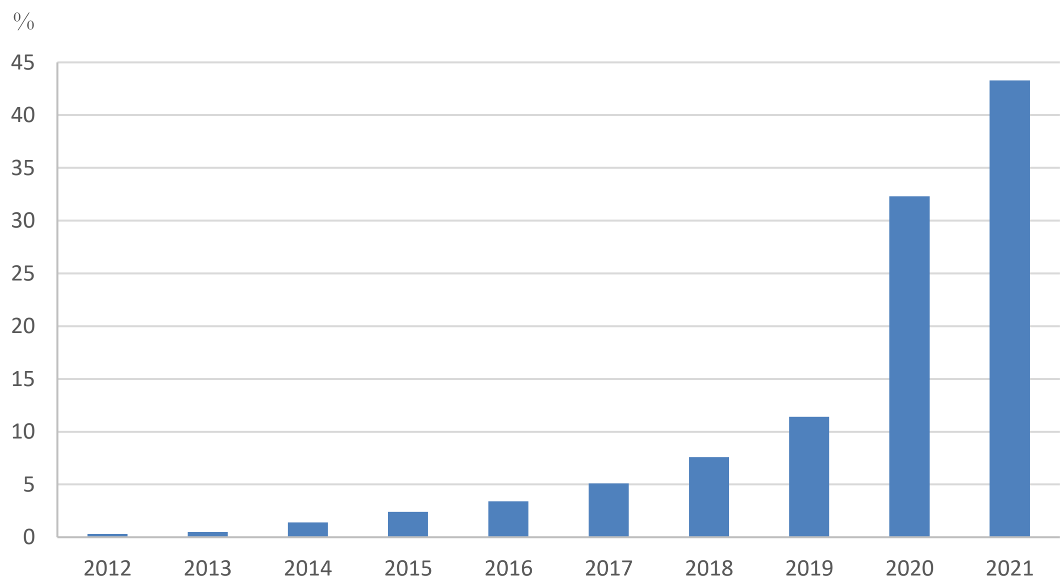


Figure 1.2 EV cars sales share in Sweden 2012-2021[2].

As a way to help in this process of exchanging the generation of energy from fossil fuels to renewable sources, the use of parking lot areas to obtain energy through PV systems could be an alternative. In addition, it makes it possible to increase the number of electric charging stations, thus customers can charge their cars while they do their shopping or just walk around retailers' facilities [3].

The cumulative installed grid-connected photovoltaic (PV) power has grown from only 250 kW in 2005 to 1107 MW in 2020 [4]. As the cost of implementing photovoltaic systems decreases, the use of PV solar modules to obtain energy is becoming increasingly popular [5].

1.1 Purpose

The purpose of this thesis consists in perform a study of the solar energy potential on parking lots in the whole county of Dalarna, considering factors that certainly influence in this potential, such as space for cars and people circulation, shadow due to buildings and trees, as well as losses in power generation caused by accumulation of dirt and snow. In other words, the idea is to evaluate how much electricity could be possible to obtain by covering parking lot areas in Dalarna with solar PV carport systems.

1.2 Method

The methodology used in order to achieve the purpose of the thesis is based on the following steps:

- Literature research
- Find out the total area on parking lots in Dalarna using mapping and filter tools, such as OpenStreetMap and QGIS
- From a PV system designed in PVsyst (base case) in both parking lots of Kupolen shopping mall in Borlänge, find out how much energy can be produced per area in a year, considering near shading due to buildings and trees, as well as shading due horizon profile (using a web tool called Suncurves), soiling and snow losses
- Evaluate the approximate percentage of a parking lot that can be really used to generate energy using parking lots, using area measurement tools from QGIS, PVsyst, Google Earth and Earth Point
- Find the total energy that could be possible to generate on parking lots in Dalarna through solar carport systems from the information in the three previous steps

1.3 Previous work

As previous work can be mentioned ten studies with relevant information regarding generation of electricity using solar PV carport systems in parking lots.

Nunes et al. [6] evaluated the use of solar carports systems in order to charge electric vehicles, making a discussion about the technical, environmental and financial outcome concerning the development of parking lots. Their work also states that electric vehicles solar parking lots (EVSPLs) may be public or private and can be installed everywhere. Also, mentioned as a benefit the shade provided by solar modules´ coverage, reducing vehicle temperature, as well as painting damage and cracked parts inside the cars. The results revealed that solar carports promote the adoption of electric vehicles, improve the local economy and enable the use of space to be used for energy production, especially in situations where there is competition for land.

Deshmukh and Pearce [3] analyzed the energy related aspects of developing EV charging stations using solar PV carports constructed on the parking infrastructure of large retailers, making a case study of three Walmart Supercenter in California, United States. The study is based on the idea these companies have larger parking lot areas, having a substantial potential of raising PV carports. In addition, other potential benefits were taken in consideration, such as reducing of heat island effect and increase the customers´ comfort in rainy days. Their research provides a detailed investigation into the energy-related aspects of developing EV charging stations powered from solar PV carports built on the parking lot infrastructure of large-scale retailers. The results of their study demonstrate that store owners can increase sales and by consequence their profit by providing free PV-EV charging for their consumers, through four mechanisms:

- Increasing the comfort of their customers by providing shading in summer and precipitation, increasing store selection
- Provide a clear mode of green consumerism, increasing also store selection
- Provide an incentive for the rapidly growing class of EV and PHEV owners to preferentially shot at the store
- Increase the time shopping and thus money spent by EV and PHEV owners at the store to enable more charging.

Lindberg et al. [7] investigated the idea that implement utility-scale PV parks in Sweden could result in a successful implementation, due to the fact that these facilities are close to becoming economically viable, due to costs reduction. Since the problem of site selection is, to a large extent, spatial, GIS are used in most cases in the analysis. The results highlighted that the proposed methodology could function as a tool in the dialog between utility companies, municipalities, PV companies, landowners and other stakeholders in order to find resources and efficient locations for PV parks.

Farahmand et al. [8] evaluated how to increase profit related to energy production on parking lots through solar carports, by investigating the effects of different PV panel technologies on energy production. The study was made considering four different PV technologies: monocrystalline silicon (mono-Si) and polycrystalline silicon (poly-Si), as well as thin-film technologies, such as amorphous silicon (a-Si) and cadmium telluride (CdTe). The results demonstrated, based on the evaluation of efficiency and performance, as well as considering different weather conditions and scenarios, that mono-Si is the more suitable option for use in parking lots, comparing to poly-Si technology. Also, a-Si and CdTe were not considerable suitable for solar carport applications.

Umer et al. [9] discussed the design and optimization of solar carports for maximum power generation in Bahawalpur, Pakistan, considering effect of shading of nearby trees and buildings and how to avoid it or reduce it using solar design software, such as HelioScope [10]. An economic analysis, as well as an optimization and selection of a solar carport model was performed considering the different types of double row carport – monopitch, duopitch and barrel-arch. The results shown that, for the same parking lot capacity and at the same location, for a maximum generation of solar energy, the monopitch carport structure is the best to choose, followed by duopitch carport, with 93% of monopitch´s production value and for last barrel-arch, with 80% of monopitch´s result.

Pawluk et al. [11] analyzed the impact of snow accumulation in regions with snow events on PV systems regarding production of electricity, examining snow impact estimation techniques, as well as identify strategies to reduce the impact of snow accumulation. Also, estimation techniques for electricity generation loss due to snow cover were summarized. In addition, ten mitigation methods were identified as having the potential to reduce the impact of snow on PV systems and were discussed qualitatively. The results provide information to system designers and operators about how to manage the effect of snow on PV systems, through mitigation methods, such as:

- Increasing overnight tilt angle: during night, through tracking PV systems, it is possible to increase the slope without any consequences regarding energy production, leading to a more rapid snow sliding.

- Reflection on back: considering snow has an albedo from about 0.8 to 0.6, and the bare soil about 0.2, in installations on flat roofs or ground mounting, if it is possible, keep enough space between rows in order to get snow on the floor under the modules. According to measurements performed by Powers et al. [12], due to a higher intensity of reflected irradiance on the back surface of the module, the melting or sliding process of accumulated snow on the front part will be faster.
- Surface coatings: reduce the impact of snow cover on PV modules by reduction of friction.

2 Theory

In order to provide a better overview, a basic theory about some important features will be discussed. The first one is an introduction to solar carports, followed by a comparative between PV modules technologies and for last a parallel of different inverter concepts.

2.1 Solar carports

Also called solar canopies, are responsible for obtaining the solar energy to be later transformed into electric energy.

According to Nunes et al. [6], solar carports can have different formats and are basically divided in three configurations according to the situation and customer´s need, such as:

- Groups of two rows of parking spaces: also called monopitch carport [9], the layout of solar carports is angled parking spaces, with tilt angle from 5° to 10° [9], covered by solar modules.
- Parking lot almost entirely covered: also called long span [3], is ideal to maximize PV coverage, including the driving aisles where the electric charge stations are located, providing a greater energy yield.
- Solar carport with tracking system: also called "solar tree", is a less common configuration, usually designed for 4 to 6 parking spaces.

Independent of the configuration used, the parking lots can be on-grid or off-grid, being the first one much more common, due to the fact that grid access is provided. Eventually an additional power, such as wind source or battery storage, is also involved.

In addition, Umer et al. [9] classified solar carports in two main structures:

- Single row carport: as its name says, it is the simplest structure regarding solar carports, with the purpose of covering only one row of cars.
- Double row carport: the structure is used because it is necessary a smaller supporting structure for parking a larger number of vehicles, and can be divided in monopitch, duopitch and barrel arch.

All double row carport structures can be seen on Figure 2.1 adapted from [9].

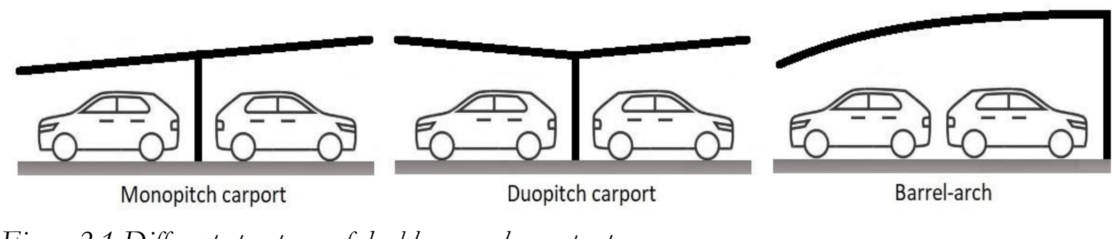


Figure 2.1 Different structures of double row solar carports.

- Monopitch: has a single surface slope, which has the same slope angle at a given time. The tilt angle of the rooftop remains from 5° to 10°.
- Duopitch: also called back-to-back [13] or inverted [3] , has two rows of roofs facing each other, making a valley running in both of them.
- Barrel-arch: has a curved shape which has different tilt angles at each point.

2.2 PV modules

As a fundamental part of solar power generation, PV modules are divided into different technologies, which will be highlighted into two parts as follows. In the first part, will be related the differences between different PV modules technologies, while in the second part, will be made an explanation about half-cut technology.

2.2.1. PV modules technologies

Photovoltaic modules can be basically divided into 4 types:

- Monocrystalline silicon (mono-Si)
- Polycrystalline silicon (poly-Si)
- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)

The last two ones are thin-film solar cell technologies, thus are not quite suitable for parking lot operations due to low efficiency. On the other hand, the first two ones are the most efficient technologies that could be suitable to use in solar carports [8].

The main differences regarding structure and efficiency between these four technologies can be seen on Table 2.1 [8] [14] [15].

Table 2.1 Specification for different solar cell technologies.

Cell type	***Structure***	***Efficiency***
Monocrystalline silicon	• Manufactured from pure semiconducting material with less defects or impurities in the silicon crystalline structure • Complicated production procedure • Higher price comparing with other technologies	17-23%
Polycrystalline silicon	• Manufacturing process is simpler than the monocrystalline ones • More cost-effective • More defects in the crystalline structures	15-18%
Thin-film solar modules	• Can be flexible if it is necessary	13-17%

2.2.2. Half-cut PV modules

Since 2017, the production of half-cut cells is growing, due to its advantage over the conventional modules. While the standard modules are usually manufactured with 60 or 72 cells in series, the half-cut modules normally come with 120 or 144 half-sized cells.

In addition, due to the fact that the module is shared in six parts instead three, if eventually some part of the module is shaded, only one-sixth of module will stop to produce energy, against one-third in a conventional one.

In a half-cut PV module the input current is divided by two, with the main purpose of decrease resistive losses, leading to a better efficiency, as well as longer lifetime due to a lower degradation of the module. A better explanation for that can be seen in the Figure 2.2.

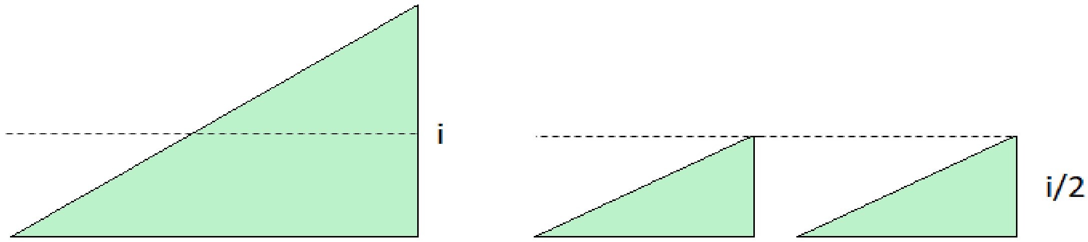


Figure 2.2 Electrical losses comparing a conventional and a half-cut module.

The electrical losses can be calculated by:

$$P_{loss} = i^2 \times R$$ *Equation 2.1*

Where *i* stands for the current in the cell and *R* the total resistance of the PV module. Thus, according to Figure 2.2 and Equation 2.1, the electrical losses in a half-cut module reduce to only 25% comparing to a conventional one.

As main improvements due to reduced resistive losses regarding modules with half-cut technology compared with the conventional ones, can be mentioned:

- Superior performance
- Durability and lifetime increased
- Lower working temperature

2.3 Inverters technology

Similar to PV modules, inverters are also fundamental components in a PV system. Responsible for converting direct current (DC) generated on PV modules into alternating current (AC) in order to fulfil client´s demand and/or send electrical energy to the grid, they also have other important functions, such as:

- After making the conversion from DC to AC, it synchronizes the AC current with the grid
- Optimize the production of energy through Maximum Power Point Tracking (MPPT)

Inverters have the important function of disconnecting the PV system from the grid in case of maintenance, through a technology called ant-islanding protection, which basic principle consists in constantly evaluate if the grid is energized and, in case of de-energization, the inverter disconnects the PV source from the grid in a very short time interval (order of milliseconds).

There are different possible connections between PV modules and inverters, with similar characteristics already mentioned, as well as some particularities that differ each other.

According to Čorba et al [16] the possible configuration are classified as:

- Multi-string inverter
- Micro inverter
- String inverter
- Central inverter

On Figure 2.3, it can be seen all possible configuration connection, adapted from [16].

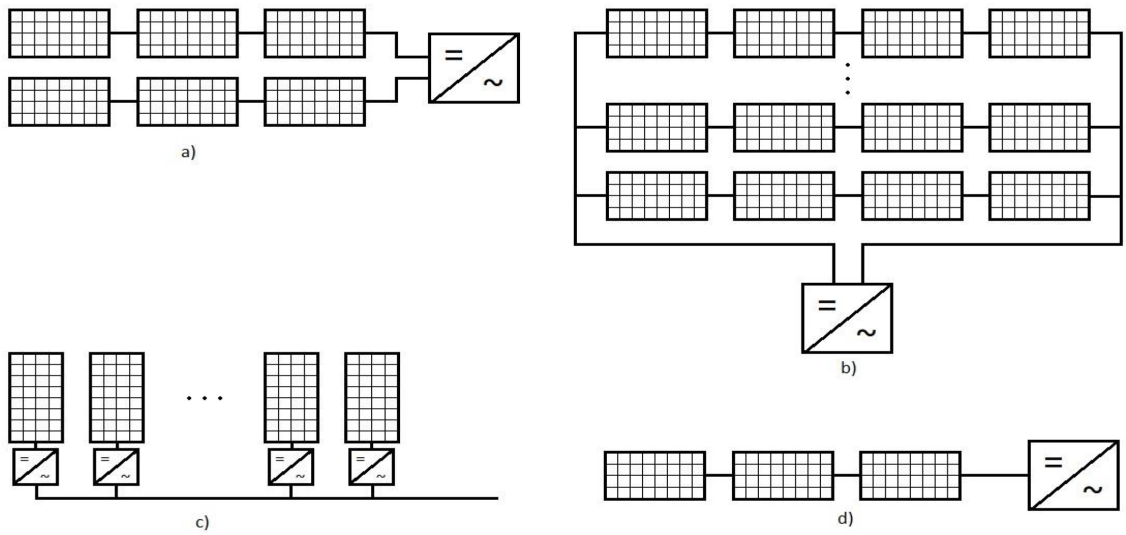


Figure 2.3 Different connection configuration: a) Multi-string inverter, b) Central inverter, c) Micro inverter, d) String inverter

Although there are the four configurations already mentioned, the two most commonly used are string inverter and central inverter, where some differences can be highlighted by:

- Central inverters: as its name says, centralizes the power produced by the plant, in a range usually from 500 kW to 2.5 MW per power block [17].
- String inverters: uses a distributed architecture instead centralized, where the power block consists of smaller inverters for every array.

In Table 2.2 is described the main differences between connections using central and string inverters [18].

Table 2.2 Comparison between central inverters and string inverters technologies [18] .

Central inverters	***String inverters***
• Centralized architecture • May require DC combiners • Physically larger, higher nominal power per unit • Longer strings and generally higher voltages (1000 V – 1500 V) • Generic/high level energy optimization only • Single point of failure (significant power loss if a string goes down) • Harder to service (requires niche technical expertise) • Less expensive overall SEK/W	• Distributed/modular architecture • May require AC combiners • Physically smaller, lower nominal power per unit • Shorter strings and generally lower voltages (600 V – 1000 V) • More granular energy optimization • No single point of failure (some power loss if a string goes down) • Easier to service (do not require niche technical expertise) • More expensive overall SEK/W

In order to give a better overview, more details of both technologies will be discussed in the next two chapters.

2.3.1. String inverters

String inverters convert less power for fewer modules, so in contrast to a central inverter, if one string fails, the whole array´s energy is not lost, being only the power from the failed string. Besides that, due to the fact that they are electrically connected to a smaller part of a PV array, in the case of maintenance, it is possible to turn off only one single inverter instead lose the power of the whole section.

On the other hand, due to the complexity of lots of string connected on many inverters, the system response is slower comparing to central inverters. In other words, as more devices used, more latency in the control system.

2.3.2. Central inverters

As already mentioned on Table 2.2, central inverters are less expensive that string overall for large utility-scale installations. Also, they respond much faster to controls when compared to string inverters, due to the fact that the command will be send for only one component, instead lots of them, having as consequence a lower latency.

On the other hand, fixing central inverters requires technical operations and maintenance (O&M) expertise, making more complex and expensive the maintenance process. In addition, even when only a small part of the array has a problem, it is necessary to turn off the entire power block.

3 Methodology

The aim of this chapter is to cover in detail the important features that were considered in the simulation and as consequence obtaining the final result. It is important to emphasize that in any simulation, and here is not different, uncertainties will always occur, which will be discussed in detail in Chapter 5 – Discussion.

3.1 Technology tools

In order estimate how much energy can be obtained through solar energy using solar carports in parking lots in Dalarna, it was necessary to use six different softwares. The purpose of using each one of them, as well as their different functions, will be explained in the following.

3.1.1. OpenStreetMap

OpenStreetMap [19] is a collaborative online tool built by a community of volunteer contributors in order to create a free editable geographic database of the world. Its database consists of streets and local data, as well as building polygons where cities are mapped according to different categories or functions, like stadiums and buildings, as well as facilities, such as hospitals and parking lots.

The geodata underlying the maps is considered the primary output of the project, and users may collect data using manual survey, global positioning systems (GPS) devices, aerial photography, and other free sources, or use their own local knowledge of the area.

The data from OpenStreetMap can be used in various ways including production of paper maps and electronic maps, geocoding of address and place names, and route planning [20].

3.1.2. QGIS

QGIS [21], is an online free tool which main purpose is getting access to OpenStreetMap data in a geographic information system (GIS) format.

A GIS creates, manages, analyzes, and maps all types of data. Also, connects these data to a map, integrating location data (where things are) with all types of descriptive information (what things are like there). The benefits include improved communication and efficiency as well as better management and decision making [22].

In other words, through the integration of QGIS and OpenStreetMap, it is possible to obtain an amount of material and, using specific layers and tools, also allowed to find out specific information, such as the total area covered by a particular layer, for example.

3.1.3. PVsyst

PVsyst [23] is a software package for the study, sizing and data analysis of complete PV systems, including both grid-connected or stand-alone systems, with or without storage. As its database, include extensive meteorological data and also complete PV components, being a very popular tool for large and utility-scale solar installations. In addition, if it is necessary, it also provides a detailed economic evaluation using real component prices, additional costs and investment conditions.

The design process in PVsyst is composed of two phases:

- Preliminary design: is a rapid estimation tool, being perfect for pre-sales on tender stage, due to the fact that it can be created in minutes
- Project design: it is a second step where the preliminary design is improved, after the tender become an order, and in this improvement includes for example

increase the attractiveness of the project, as well as include details, such as detailed shading and losses due to snow and dust.

As meteorological data, it includes data from Meteonorm [24] and NASA [25], but it is possible also to create a synthetic hourly weather file, if it is necessary for specific simulation purposes.

As components data, PVsyst provides a huge equipment library, including thousands of PV modules, inverters, batteries and generators, using real information from manufacturer´s datasheets, being also possible to import data for a special component directly for a specific project.

3.1.4. SketchUp

SketchUp [26] is a 3D modeling computer program for a range of drawing and design applications where, working in parallel with OpenStreetMap or Google Earth including functionalities such as drawing layout and surface rendering, it make it possible to model a specific area or even an entire city.

The program is currently available as a web-based application as free version. However, there is also a paid version called SketchUp Pro, where there is also and option for place the model within Google Earth.

3.1.5. Suncurves

Suncurves [27], like SketchUp, works in sync with PVsyst and it is an online tool responsible for evaluating the shading from to horizon effect, due to the presence of mountains around the evaluated place. The user only needs to choose the location.

As a second use, it can be mentioned the possibility to compute accurate sunrise and sunset times for every day of the year, taking the terrain into account. In addition, the user can also see what the terrain looks like in a 360-degree panoramic view from the chosen location, as well as the sun path for anytime.

3.1.6. Google Earth

Google Earth [28] is a computer program that accesses satellite, aerial imagery and topography over the internet to represent the Earth as a three-dimensional globe. Distributed by the American company Google, it is available in a browser-based version or to download for free.

3.1.7. Earth Point

Earth Point [29] is a tool for Google Earth where one of the main function is make it possible to calculate area of one or multiple polygons, allowing after to export this information to an Excel file in a spreadsheet format.

3.2 Boundary conditions

In this chapter will be discussed the main conditions of the project, including location with respective solar radiation data, as well as factors that influenced in the modeling, such as shading and snow and soiling losses.

3.2.1. Location

This project is located in Dalarna, one of the 21 counties in Sweden, as location can be seen on Figure 3.1 [19].

Figure 3.1 Dalarna County, Sweden.

In order to achieve the purpose of the thesis, the initial procedure started using two software with the aim to obtain the total area of parking lots of all cities in Dalarna, which are distributed over 15 municipalities, as it can be seen on Figure 3.2 [30].

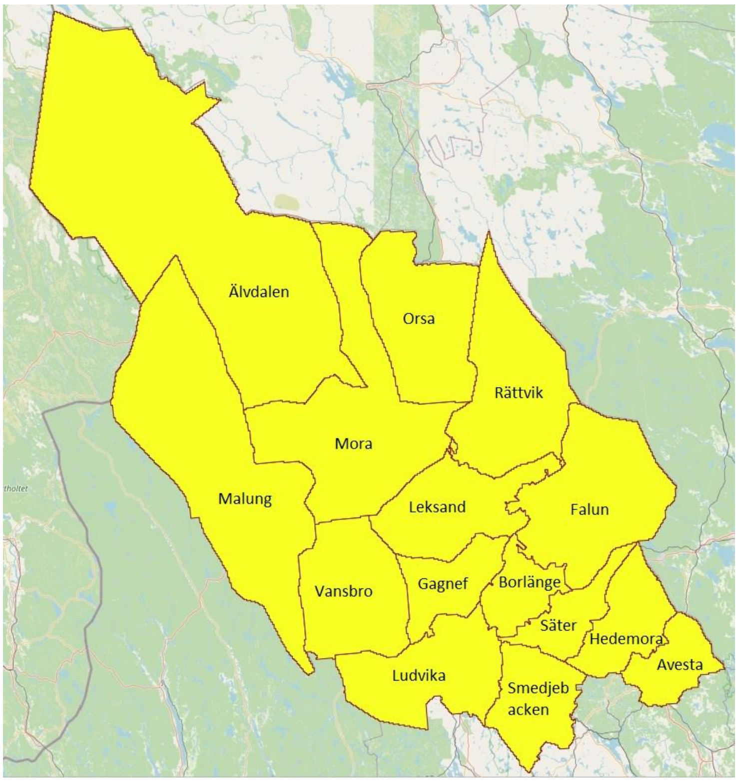


Figure 3.2 List of municipalities of Dalarna County [30].

The first one is called OpenStreetMap [19], already introduced on Chapter 3.1.1. An example of how detailed can be a region mapped in it, the area around Kupolen shopping mall in Borlänge is shown on Figure 3.3.

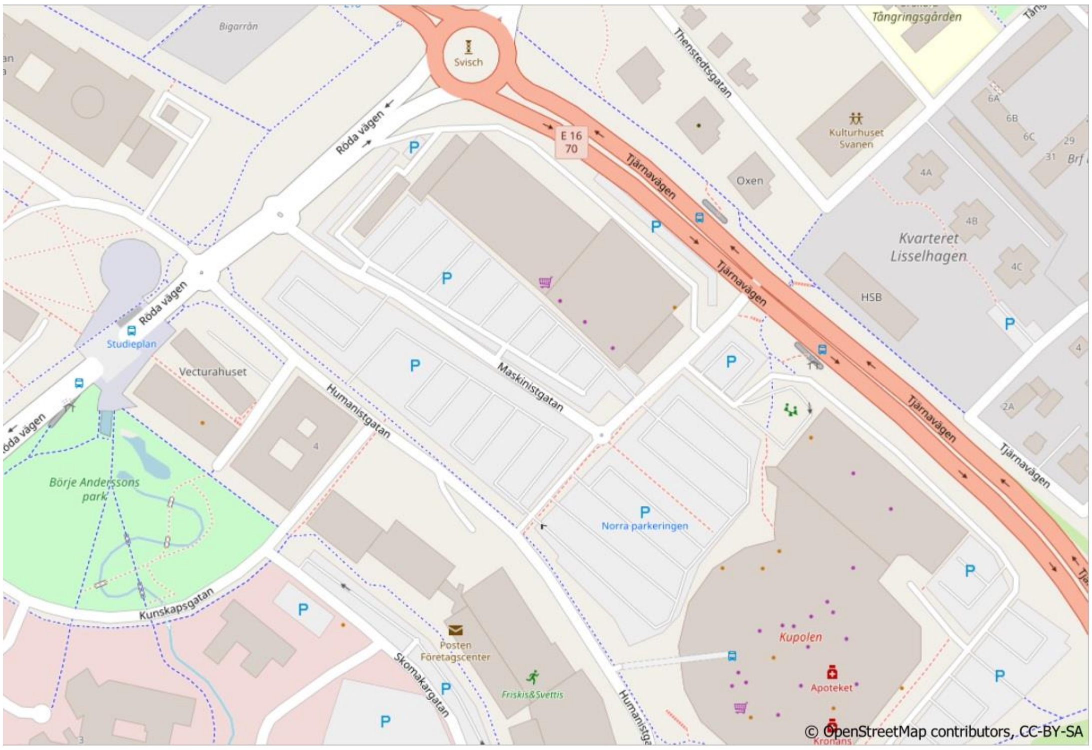


Figure 3.3 Region around Kupolen shopping mall in Borlänge using OpenStreetMap [19].

The second free software is called QGIS [21], that it was also already introduced on Chapter 3.1.2., which main purpose is getting access to OpenStreetMap data in a GIS format.

An example of using QGIS in parallel with OpenStreetMap can be verified on Figure 3.4.

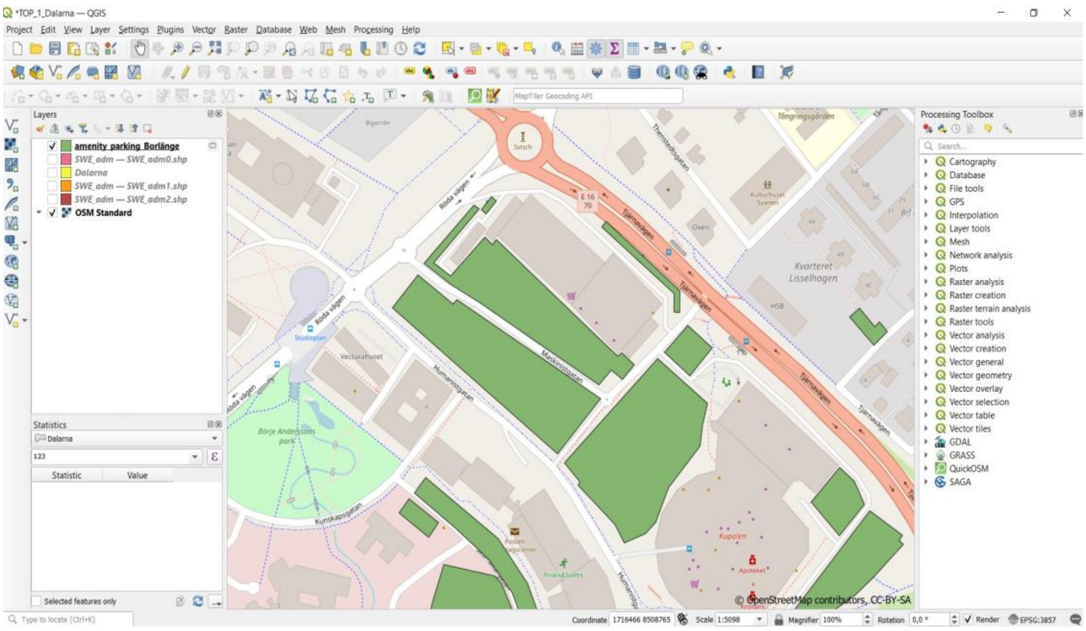


Figure 3.4 Same area as Figure 3.3 using a parking lot layer in QGIS [21].

3.2.2. Solar radiation data

With the aim of estimate how much energy can be generated on parking lots in Dalarna, one of the main factors to be considered is the solar radiation data. On Figure 3.5, it can be seen from two different sources the average global radiation in Sweden in kWh/m^2.

The first one is from SMHI [31] and the second one is from Join Research Centre from European Commission (JRC) [32].

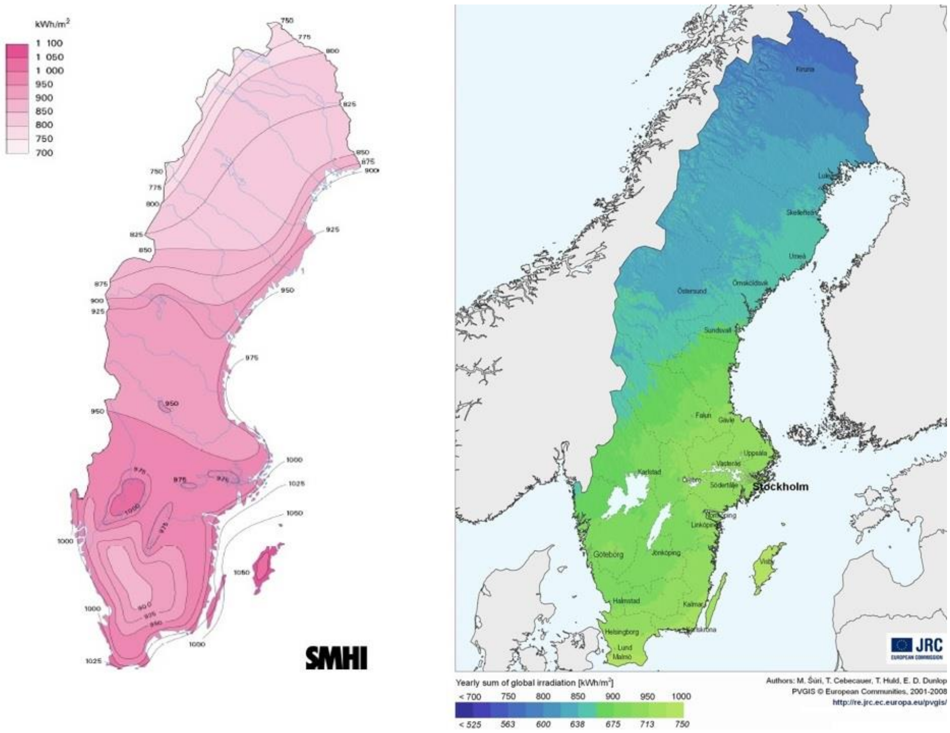


Figure 3.5 Global irradiation data in Sweden according to SMHI and JRC.

As it can be verified on Figure 3.5, the global radiation in both maps for Dalarna varies from 900 to 950 kWh/m^2.

3.2.3. Shading

In order to have a more precise value of the total energy that can be obtained in parking lots in Dalarna, it was necessary to consider shading. To achieve that, a model that will be explained in detail in the following chapters was developed, considering two different factors relevant regarding shading.

The first one is the shading due to the trees and buildings that naturally occurs at most of PV installations, especially in parking lots, which are usually located in urban areas. However, a second factor, that is shading due to the horizon where the terrain and mountains can influence on PV generation, was also considered.

The respective sun-path diagram with the horizon effect for the model designed in Suncurves [27], already introduced in the Chapter 3.1.5, can be seen on Figure 3.6.

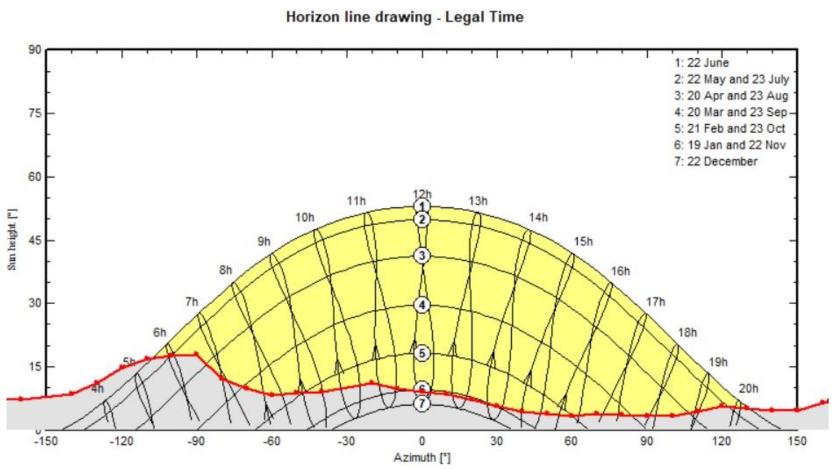


Figure 3.6 Sun-path diagram with horizon effect integrated for Borlänge.

3.2.4. Soiling and snow losses

After considering shading effect due to buildings and trees, as well as due to the mountains around Borlänge, as a last step it is necessary to estimate soiling losses.

As a default value, usually is considered 3% due to sand and dust [11] [33]. However, in Sweden, this value will be higher, due to snow losses. That said, it is clear that losses due snow cannot be neglected. Due to fact that there is no Swedish standard related to that, it was necessary to use Norwegian data. On Table 3.1 can be seen snow and soiling losses for a tilt from 15° to 25° for the region of Lillehammer, in Norway, extracted from Norwegian Standard NS3031-2016 [34].

Table 3.1 Snow and soiling losses in the region of Lillehammer, Norway [34].

Tilt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
15° to 25°	50%	50%	50%	20%	2%	2%	2%	2%	2%	2%	20%	50%

The region of Lillehammer Kommune in Norway was chosen due to the fact that it has a similar climate and it is located at similar latitude to Dalarna County, about 61° N [35]. In addition, the tilt values from 15° to 25° were chosen because they are the closest ones provided on Norwegian Standard NS3031-2016 to the values used in solar carports in general.

3.3 Municipalities parking lot area

Working in QGIS, the main layer regarding Sweden and its municipalities was taken from DIVA-GIS [36]. The Swedish layer map [37] with Dalarna highlighted in red color can be seen on Figure 3.7.

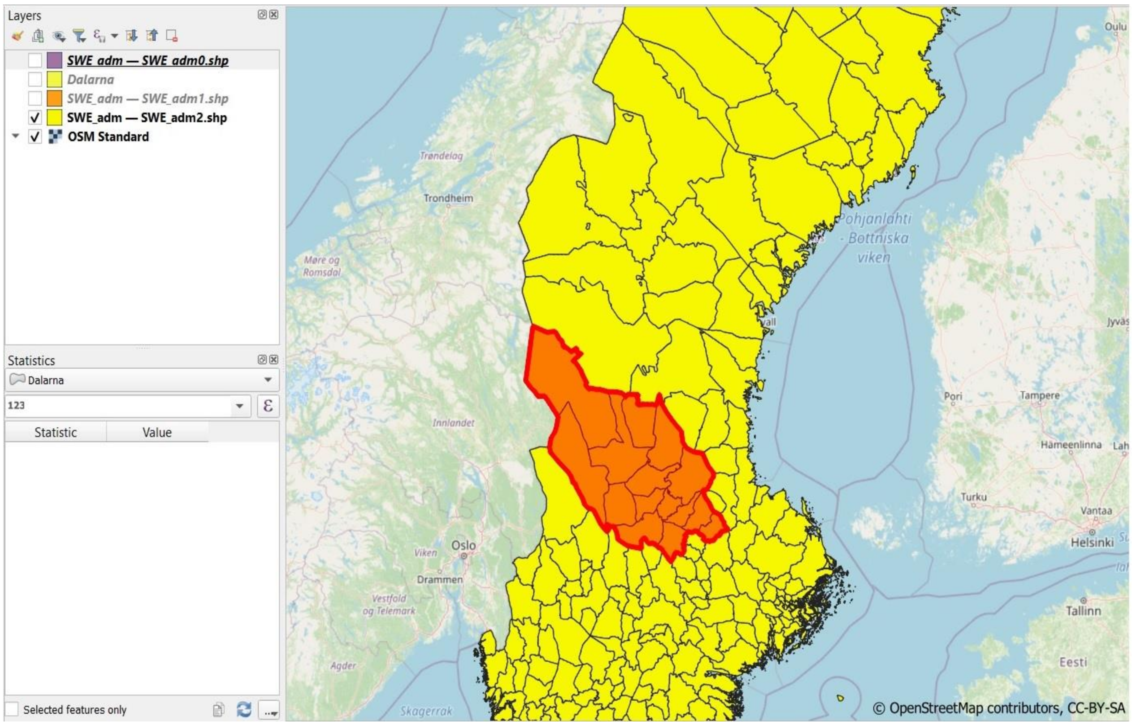


Figure 3.7 Swedish layer with its municipalities.

With the purpose to find out the total area covered by parking lots in Dalarna County, it was made a number list with all 15 municipalities according to the Figure 3.2 that can be verified on Table 3.2.

Table 3.2 List of municipalities in Dalarna County.

Region	***Municipalities***
1	Borlänge
2	Falun
3	Avesta
4	Ludvika
5	Mora
6	Hedemora
7	Leksand
8	Orsa
9	Malung
10	Smedjebacken
11	Rättvik
12	Säter
13	Vansbro
14	Älvdalen
15	Gagnef

Using QGIS working with layers through OpenStreetMap, all parking lot areas were mapped for every municipality. To achieve that, for all 15 municipalities, it was created filters in QGIS, as it can be verified on Figure 3.8 under the name "intersection", selecting only the specific layer regarding every municipality (in this case Borlänge) inside the main Dalarna County layer.

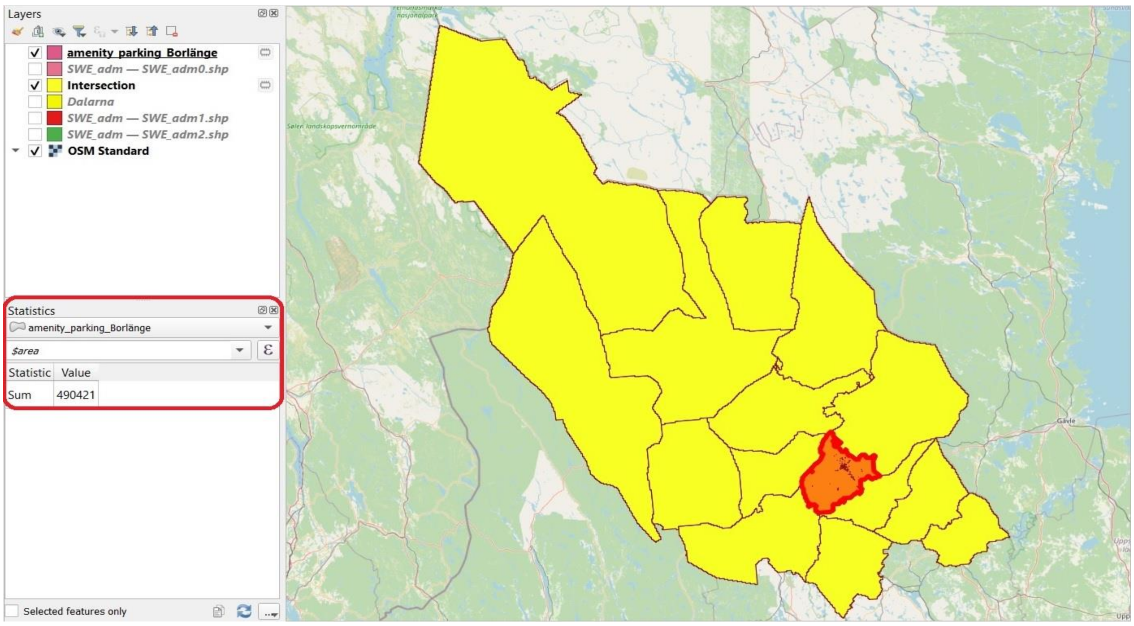


Figure 3.8 Region 1 – Borlänge with a parking lot area of 490421 m².

The total area of the municipality, shown on small black spots, was calculated using a QGIS tool and it is highlighted in a red rectangle of every figure, where which number is the area represented in square meters.

In order to cover the whole county, it was created one layer for each one of the municipalities, giving 15 layers in total. The main layer, now in yellow color, it is Dalarna County itself, and every municipality is shown in red color.

The final result for every municipality, with its respective location and area is demonstrated on Appendix A.

3.4 Base case system design

Following the stages of the project methodology, the next step will be explaining how the system was designed, taking into account the choice and dimensioning of PV modules and inverters, as well as detail the system layout.

3.4.1. PV modules

As modules, it was chosen the brand Jinko Solar [38] due to a good relation quality and price. In addition, in order to obtain the maximum power possible and keep the project with a popular PV module size, it was chosen a 400 W mono-Si PV module with 72 cells. Besides that, due to the benefits already mentioned on Chapter 2.2.2, the chosen modules have half-cut technology.

In addition, more features can be highlighted, such as [38] :

- High efficiency, up to 20.38%, due to half-cell structure
- Good low-light performance, with advanced glass and cell surface textured design
- Severe weather resilience, with a wind load of 2400 Pascal and snow load of 5400 Pascal
- Product warranty of 12 years and linear power warranty of 25 years.

With all features described, the essential information regarding the module JKM400M-72H in Standard Test Conditions (STC) it is highlighted on Table 3.3 [38].

Table 3.3 Summary of PV module specification in STC conditions [38].

Manufacturer	Jinko Solar
Model	Mono-Si JKM400M-72H
Maximum peak power	400 W
Open-circuit voltage (Voc)	49.8 V
Short-circuit current (Isc)	10.38 A
Module efficiency	19.88%
Temperature coeficiente of Voc	-0.29%/°C
Voc (-15°C)	55.5 V

The PV module datasheet can be found on Appendix C.

3.4.2. Inverters

Just as PV modules, inverters are important components in a solar plant, which choice is based on the type and size of the installation, as already mentioned in Chapter 2.3. In this project, it was decided to work with the model SHP100-20-PEAK3 [39], that is a 100 kW output AC inverter from the manufacturer SMA [40].

The biggest advantage of this model is that, with only 98 kg of weight and dimensions of 830 mm height and 770 mm width [39], it can deliver 100 kW AC and also it has a maximum power point (MPP) voltage of 1000 V. In addition, it was chosen due to some features already mentioned on Chapter 2.3, such as:

- Distributed architecture, so if one string fails, the energy of the entire block will not be lost
- In the case of maintenance, the energy will still be produced in the rest of the plant
- Technical expertise not required, having as a consequence easier and cheaper maintenance
- Physically smaller and lighter.

The main inverter specifications are emphasized on Table 3.4 [39] and the complete information can be found on Appendix D.

Table 3.4 Summary of inverter specification [39].

Manufacturer	SMA
Model	Sunny Highpower SHP100-20-PEAK3
Maximum power output	100 kW AC
Maximum input voltage	1000 V
Maximum input current	180 A
Rated grid frequency	50 Hz
MPP voltage range	590 V to 1000 V
Maximum efficiency	98.8%

3.4.3. Base case system layout

After detailed the PV modules as well as the inverters used in the project, the next step consists in explain the system layout.

That said, with the purpose of determining a more accurate value of the total area available for generating electricity, as well as how much energy per year can be generated through solar carports in this useful area, it was created a model in SketchUp [26], already introduced on Chapter 3.1.4, of the region around Kupolen shopping mall, in Borlänge.

The idea behind that is, after to find out the values already mentioned, to extrapolate this relation for the whole county, giving a more realistic value. The model was created taking in consideration buildings and trees already existing in the area nowadays and is shown on Figure 3.9.

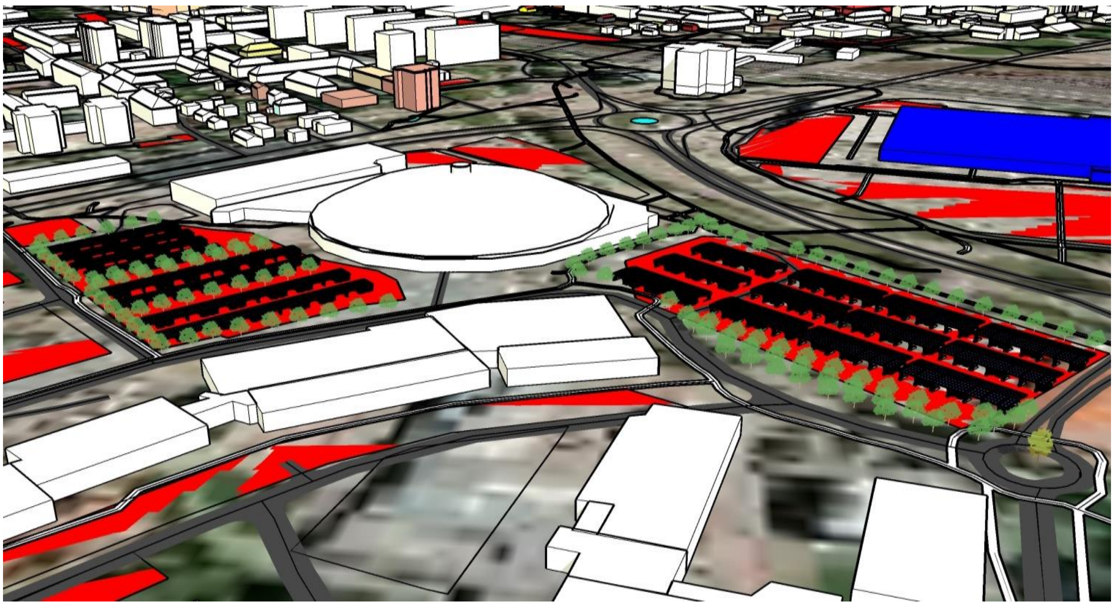


Figure 3.9 SketchUp model of Kupolen shopping mall area.

As solar carport structure, it was used a single row model as demonstrated on Figure 3.10.

Figure 3.10 Solar carport structure used on Kupolen´s parking lot model.

However, in the second Kupolen´s parking lot, it was used duopitch carport model, according to Figure 3.11.

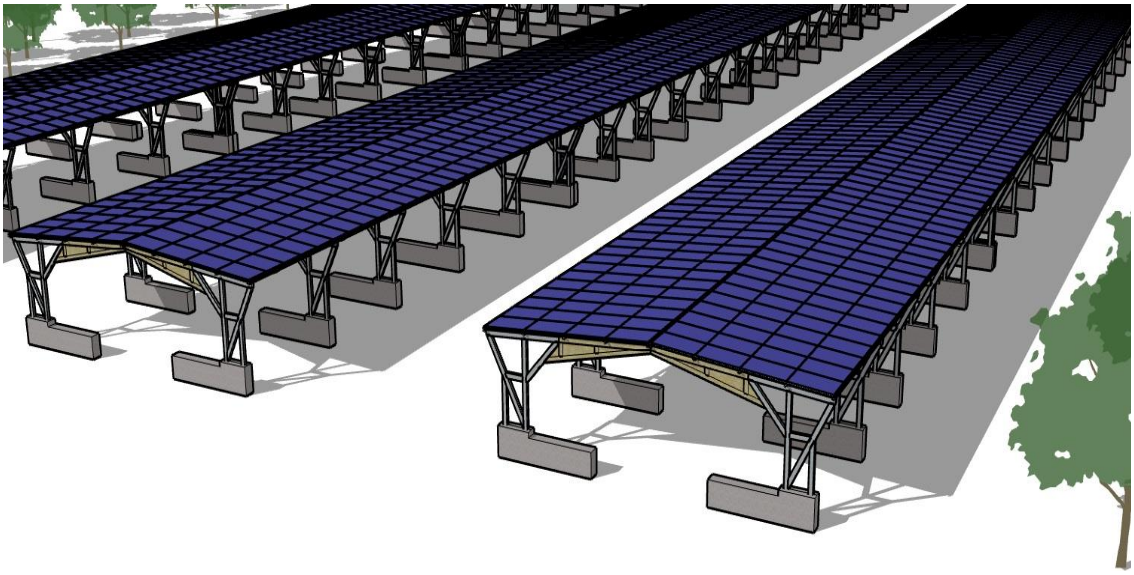


Figure 3.11 Second solar carport structure used on Kupolen´s parking lot model.

In addition, the "v inverted" format was chosen instead of "v", like the duopitch carport in the Figure 2.1, due to the high accumulation of snow in winter season.

However, due to the fact that the original project in SketchUp have too many details, including all buildings around Kupolen, even the ones that are not relevant to evaluate shading, a simplified version was developed in PVsyst using its own tools. The simplified model used to simulate the project can be seen on Figure 3.12.

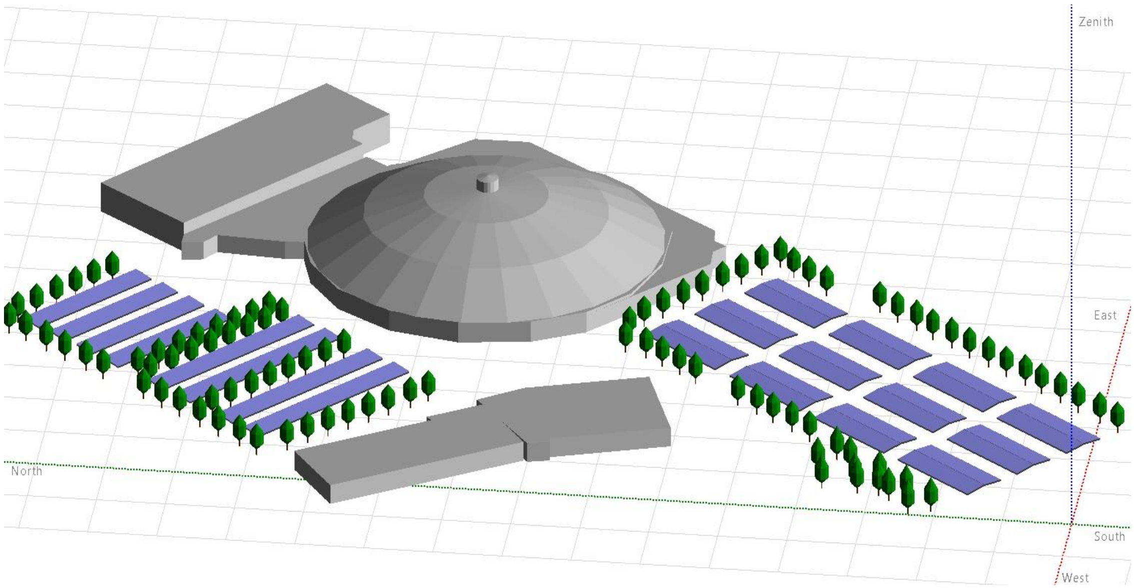


Figure 3.12 Simplified model around Kupolen shopping mall area in PVsyst.

The idea behind that is to keep to relevant building in order to consider shading, as well as the trees, where these ones were designed using PVsyst tools. The system was divided into three parts, as it can be check on Figure 3.13.

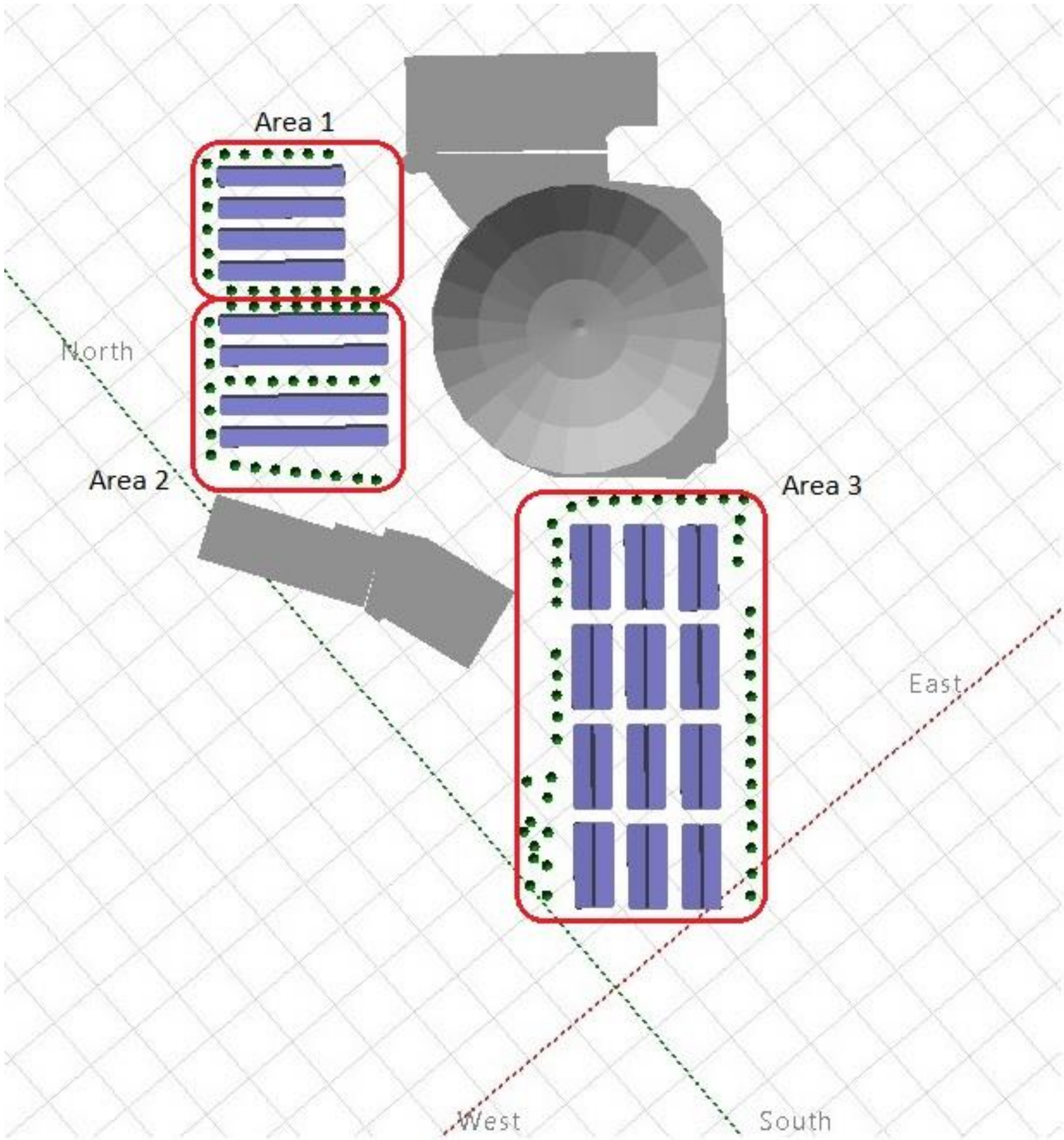


Figure 3.13 Top view of simplified model in PVsyst.

As it can be seen in Figure 3.13, the system was divided into three areas whit different configurations, where in all of them was considered -15°C for a worst case scenario regarding calculation of maximum PV modules in series for each string. According to PV module manufacturer [38], the module JKM400M-72H has Voc (-15°C) = 55.5 V and Isc = 10.38 A, considering that the inverter Sunny Highpower SHP100-20-PEAK3 has a maximum MPP voltage range of 1000 V and a maximum input current of 180 A [39], it can be concluded that the maximum of 18 PV modules can be connected in series for each string, as well as a maximum of 16 strings can be connected in parallel in each inverter.

The first area (Area 1) consists of 4 arrays of 4 strings with 54 modules in series, giving 864 modules in total, being necessary 3 inverters. The schematic can be seen on Figure 3.14.

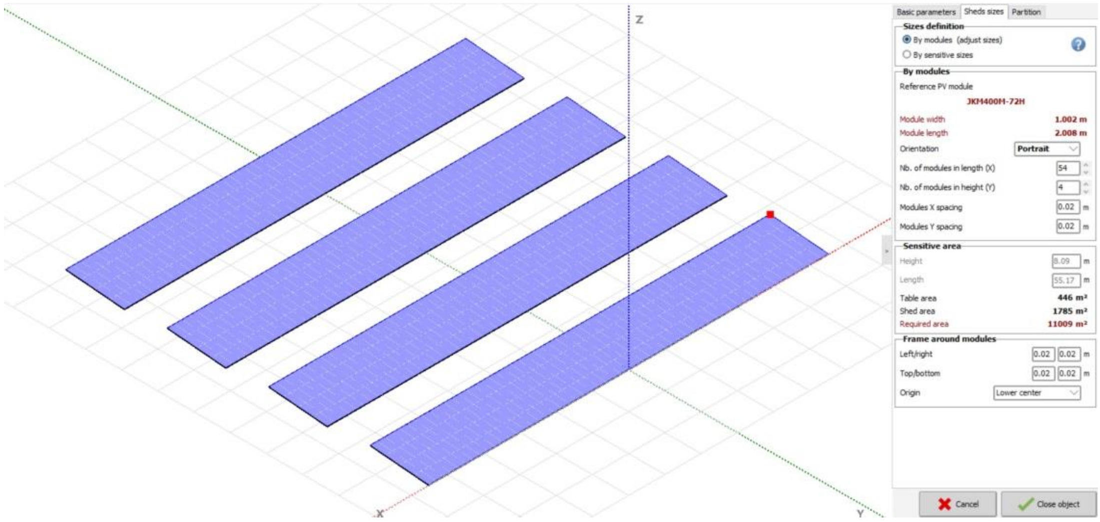


Figure 3.14 Set of PV modules representing Area 1 region.

The second one (Area 2) is formed also by 4 arrays with 4 strings each but now with 72 modules in series, giving 1152 modules in total, being necessary 4 inverters. Due to the trees in the middle of parking lot and limitations in PVsyst, it was necessary to build two separate set of PV modules, as can be seeing in Figure 3.15.

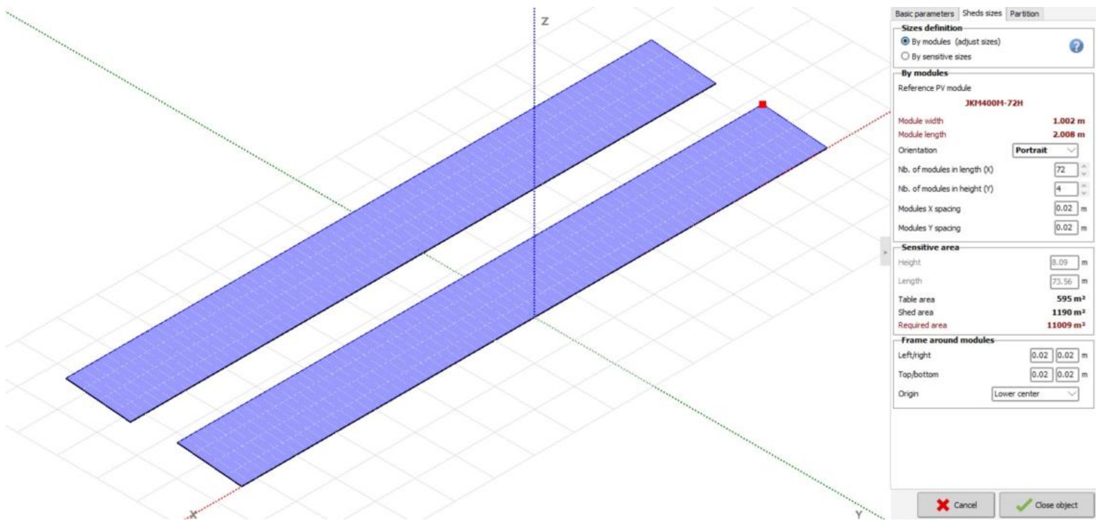


Figure 3.15 Set of PV modules representing Area 2 region.

In the third part (Area 3), there are 24 arrays of 36 modules in series and 4 strings each, giving 3456 modules in total, being necessary 12 inverters, as it can be seeing in Figure 3.16.

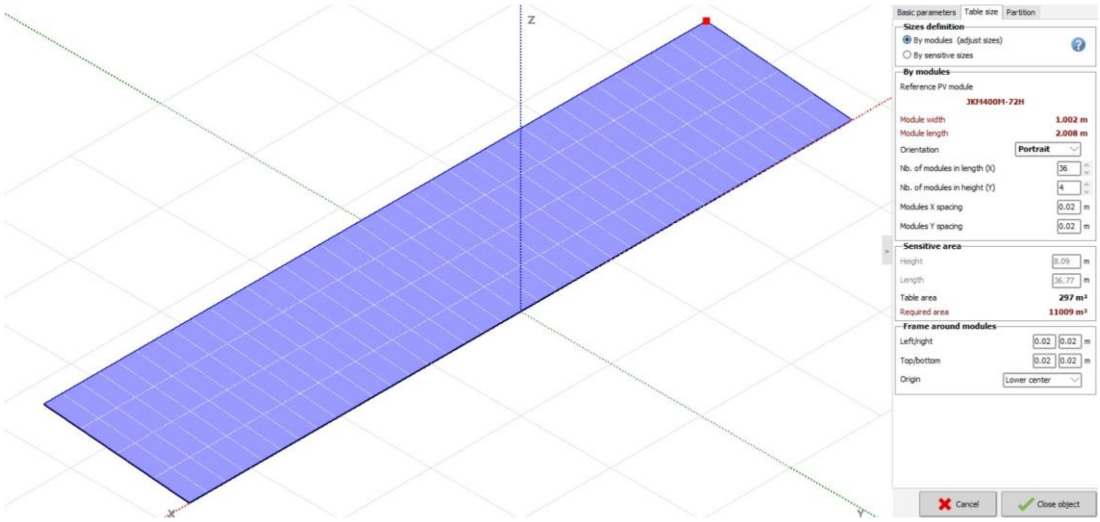


Figure 3.16 Set PV modules representing Area 3 region.

3.5 Evaluation of useful parking lot area to produce energy

The total parking lot area found for every municipality and for Dalarna County itself mentioned in the Chapter 3.3 and Appendix A cannot be consider in its totally useful to generate electricity, due to the fact that some area must be reserved for pedestrians, trees and car circulation.

In order to achieve the purpose already mentioned, first the total area of the two main parking lots in Kupolen shopping mall were measured using area QGIS tool, giving the individual values of 11466 m^2 and 13876 m^2 and by consequence, the total value of 25342 m^2, as it can be seen in Figure 3.17.

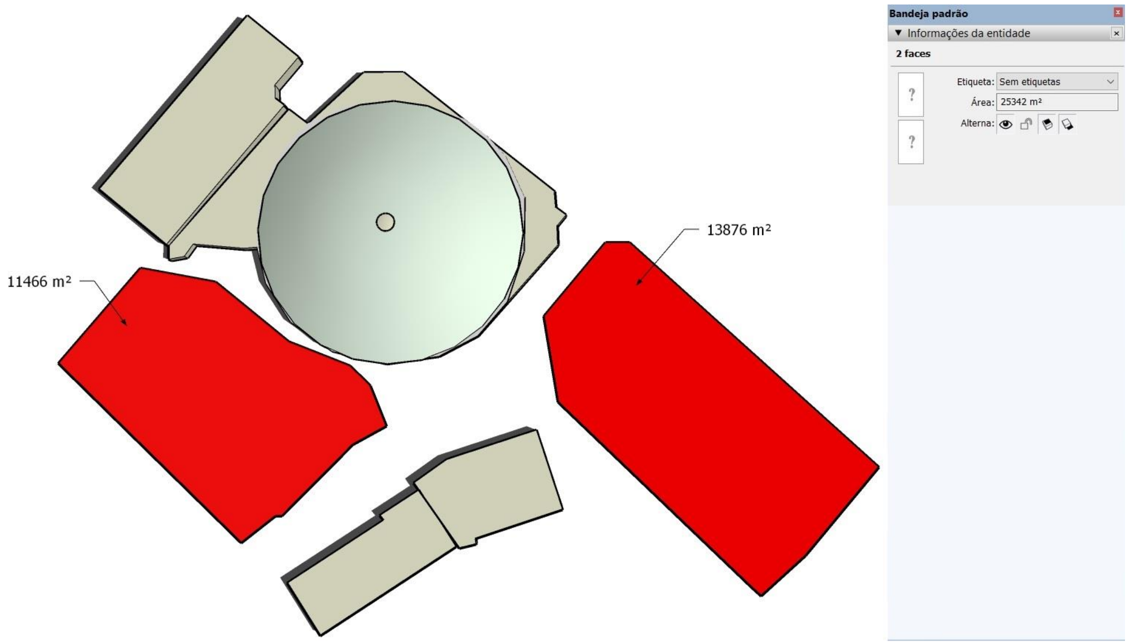


Figure 3.17 Kupolen shopping mall parking lot with a total area of 25342 m².

The next part consists in take in consideration the area occupied by the solar carports. To accomplish that, it was used a similar resource, but now in PVsyst [23]. This was necessary due to the fact that the size varies according to the model and, in big string and arrays, this difference can make a big difference. As already mentioned on Chapter 3.4.3, there are three different PV modules groups (Area 1, Area 2 and Area 3) with three different total area used by the solar carports.

The total area of the whole solar carport system, estimated in PVsyst and demonstrated from Figure 3.14 to Figure 3.16 under "Table area" can be verified on Table 3.5

Table 3.5 Total area composed by solar PV modules.

Group	***Total area*** [m²]
Area 1	446 x 4 = 1784
Area 2	595 x 4 = 2380
Area 3	297 x 24 = 7128

According to Figure 3.17, the total parking lot area of the system model in Kupolen shopping mall is 25342 m^2. In addition, the total useful area covered by solar carports can be found doing the sum of the three areas already mentioned on Table 3.5, so:

$$A_{SCK} = 1784 + 2380 + 7128 = 11292 \text{ m}^2$$

Where A_{SCK} is the total solar carport area of Kupolen shopping mall, in that case 11292 m^2.

The percentage of the area covered by solar carports can be calculated by:

$$UAC_K = \frac{A_{SCK}}{A_{PLK}} \qquad \textit{Equation 3.1}$$

Where UAC_K is the useful area coefficient and A_{PLK} stands for the total parking lot area of the simulation model at Kupolen shopping mall.

$$UAC_K = \frac{11292}{25342} \approx 0.45 \rightarrow 45\%$$

However, in order to get a better overview of the useful area that can be used to generate electricity through solar carports, it was made more two parking lot analysis. The first one was the parking lot on Falun city centre, in the bus central station area, and the second one was in IKEA´s parking lot, in Borlänge.

The first area analyzed on QGIS was the parking lot area on Falun´s city centre and, as it can be seen on Figure 3.18, with a total area of approximately 9390 m^2.

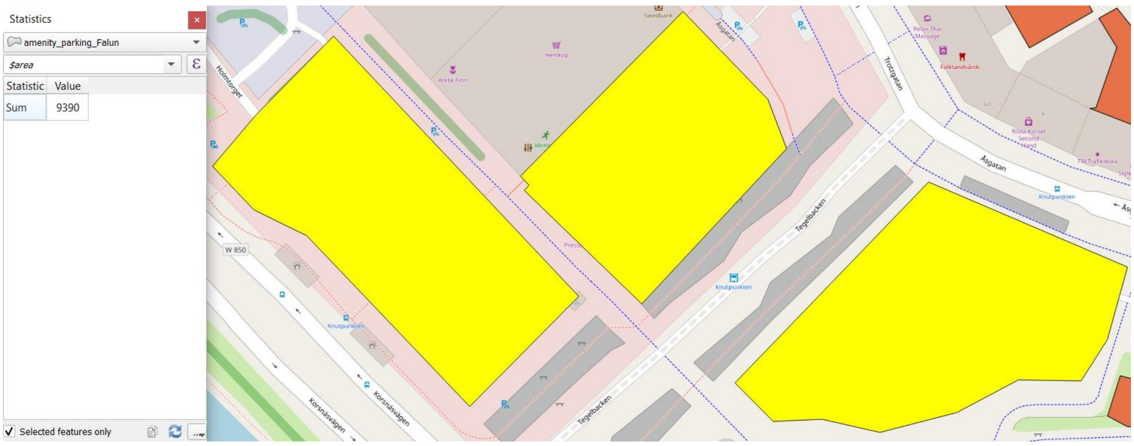


Figure 3.18 Parking lot area on Falun´s city centre.

In order to find the useful area, it was used area measurement tool of Google Earth integrated with Earth Point. The respective area of each block, as well as the total useful area can be verified on Figure 3.19.

Name	Area (m2)
1	339
2	150
3	201
4	492
5	611
6	297
7	116
8	134
9	123
10	80
11	52
12	84
13	155
14	72
15	74
16	65
Total	3045

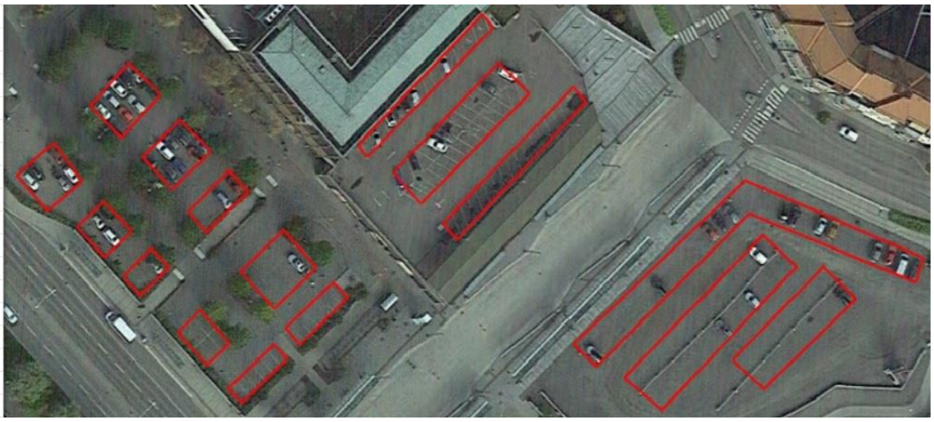


Figure 3.19 Useful parking lot area on Falun´s city centre.

According to Figure 3.19, the total useful area is 3045 m^2. That said, the percentage can be calculated by:

$$UAC_F = \frac{3045}{9390} \approx 0.32 \rightarrow 32\%$$

The analysis on second area was made at the same way of the first one. As it can be seen in Figure 3.20, the total area of IKEA´s parking lot in Borlänge using QGIS is 35797 m^2.

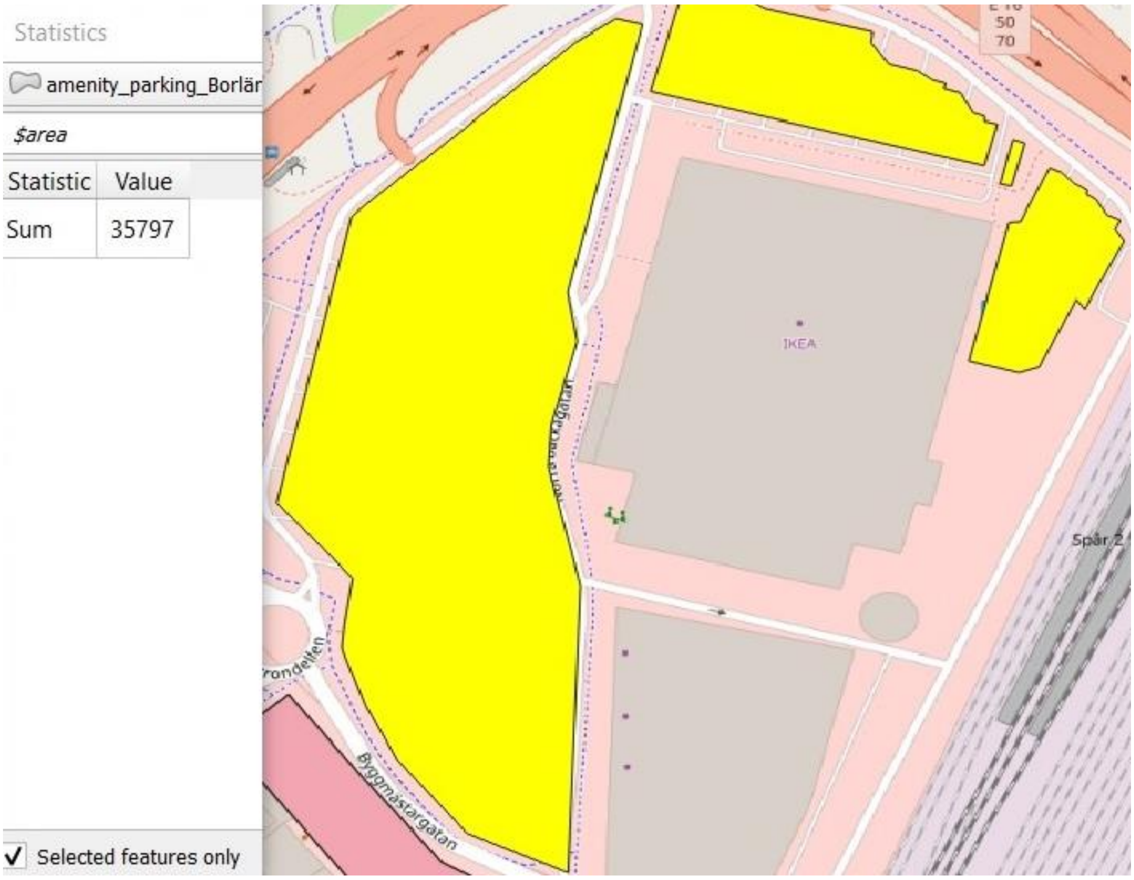


Figure 3.20 Parking lot area on IKEA in Borlänge.

Also, keeping the same method used in the first analysis through Google Earth and Earth Point, the whole useful area was mapped and it can be check on Figure 3.21.

Name	Area (m2)
I1	483
I2	719
I3	515
I4	92
I5	222
I6	361
I7	354
I8	354
I9	403
I10	333
I11	257
I12	510
I13	257
I14	162
I15	327
I16	563
I17	447
I18	213
I19	445
I20	849
I21	872
I22	1.552
I23	1.027
I24	1.011
I25	1.022
I26	1.015
I27	1.314
I28	973
I29	718
I30	1.098
I31	111
I32	680
I33	705
I34	513
I35	388
Total	20865

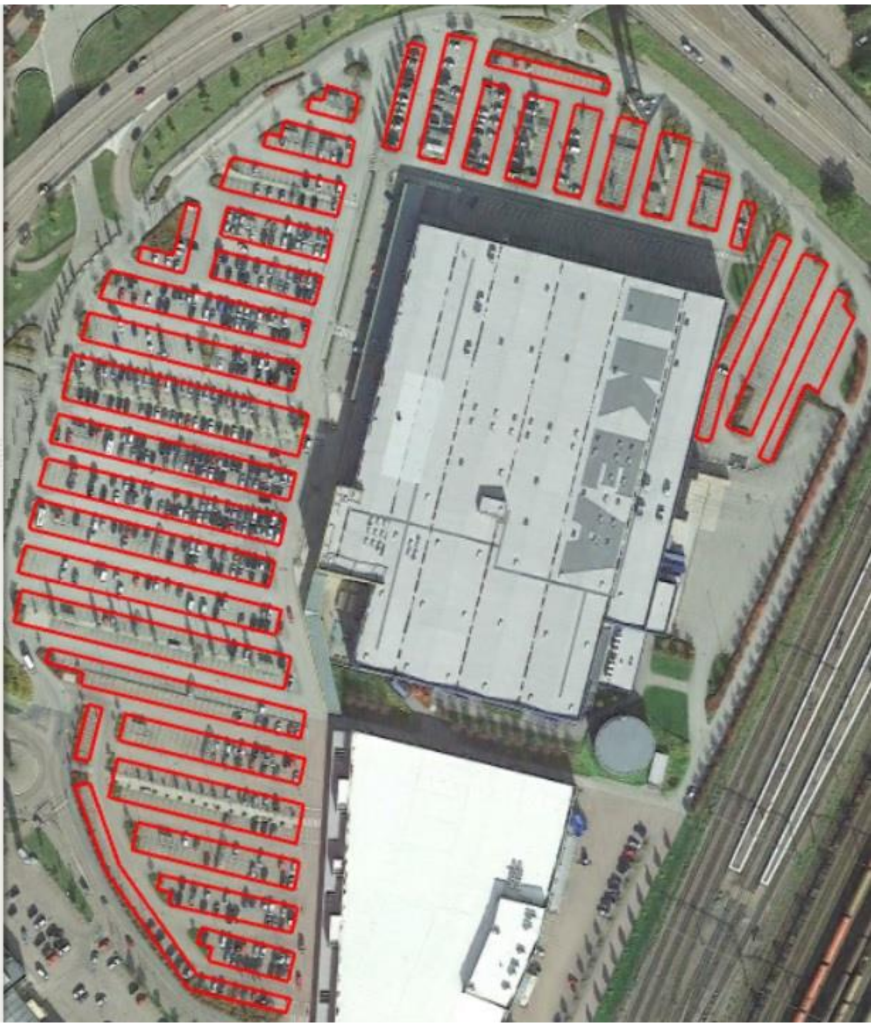


Figure 3.21 Useful parking lot area on IKEA in Borlänge.

According to Figure 3.21, the total useful area is 20865 m^2. That said, the percentage can be calculated by:

$$UAC_I = \frac{20865}{35797} \approx 0.58 \rightarrow 58\%$$

As it can be seen in the three areas studied, it was found three different useful area to generate energy on parking lots. However, for estimation purposes, it will be consider the average value of these three measurements, that said:

$$UAC_D = \frac{11292 + 3045 + 20865}{25342 + 9390 + 35797} \approx 0.50 \rightarrow 50\%$$

As expected, there are uncertainties regarding the real average percentage of a parking lot that can be used to generate electricity in Dalarna, that will be discussed on Chapter 5.

4 Results

The following will report the results regarding total parking lot area found in Dalarna, the annual energy generated by the base case model in Kupolen, the usable parking lot area for generating electricity and, as a main purpose of the thesis, present the total amount of energy that could be possible to produce in parking lots in Dalarna.

4.1 Total parking lot area in Dalarna

The result of the total parking lot area of all municipalities can be seen on Figure 4.1

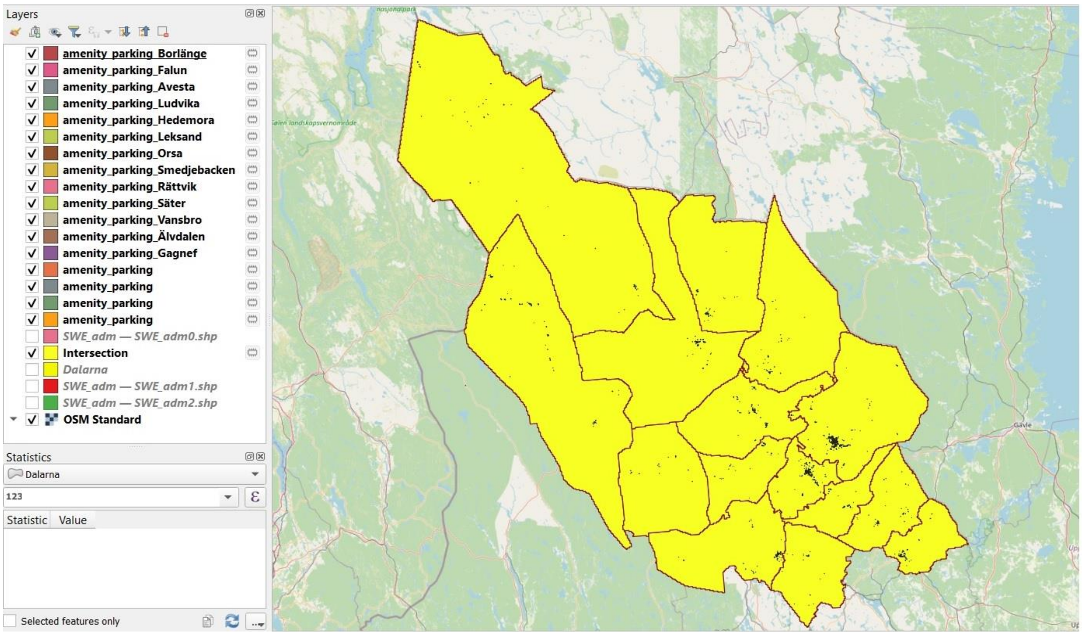


Figure 4.1 Total parking lot area in Dalarna County.

The area of every municipality according to Appendix A, as well as the total area consisted by all 15 municipalities can be verified on Table 4.1.

Table 4.1 Parking lot area for all municipalities in Dalarna County.

Region	***Municipalities***	***Parking lot area* [m²]**
1	Borlänge	490421
2	Falun	640124
3	Avesta	193738
4	Ludvika	190997
5	Mora	141312
6	Hedemora	86524
7	Leksand	210199
8	Orsa	98831
9	Malung	301150
10	Smedjebacken	29340
11	Rättvik	113874
12	Säter	51522
13	Vansbro	29608
14	Älvdalen	107719
15	Gagnef	37005
Total		2722364

As it can be seen from Figure 4.1 and Table 4.1, most of the parking lot area is concentrated to Borlänge and Falun, the two municipalities with the highest population in Dalarna [30].

4.2 Annual energy produced by the base case model

After finding out the usable area to produce electricity, as well as designed the system, the purpose now is to determine how much energy per area in kWh/m^2 can be generated. In order to achieve that, it was simulated in PVsyst the model demonstrated on Figure 3.12.

With all factors considered, in order to make a simulation as close as possible to the reality, the result of PVsyst simulation in the base case attached on Appendix B - B1 can be summarized in Table 4.2.

Table 4.2 Summarized results for simulation of Kupolen base case model on PVsyst..

PV system total size	5472 modules x 400 W = 2189 kW
Global horizontal irradiation	934 kWh/m^2
Losses due to horizon	3.4%
Losses due near shading	2.7%
Energy injected into the grid	1571 MWh
Specific yield	1571000 kWh/2189 kW = 718 kWh/kW

As it can be seen on Table 4.2, the total energy that can be produced in a year in Kupolen shopping mall is about 1.6 GWh. Also, the global horizontal irradiation considering yearly base is 934 kWh/m^2 and the losses due to horizon, as well as near shadings such as buildings and trees are about 3.4% and 2.7%, respectively. In addition, on the opposite of standard projects where soiling losses are considered 3% [11] [33], the soiling losses due to snow in Borlänge area are about 10%. The results of PVsyst simulation can be seen on Appendix B.

4.3 Usable parking lot area to generate electricity

In order to find out an approximate number that better represent the useful parking lot area that can be used to generate electricity, it was realized the procedure described on Chapter 3.5. The idea behind this is to use the value found for one parking lot and extrapolate for the whole county.

That said, the total parking lot area in Dalarna that can be used by solar carport to generate electricity can be calculated by:

$$A_{SCD} = A_{PLD} \cdot UAC_D \qquad \text{Equation 4.1}$$

Where A_{SCD} is the total parking lot that can be covered by solar carports in Dalarna and A_{PLD} is the total parking lot area found in Dalarna, according to Table 4.1.

In order to find the total useful area that can be covered by parking lots in Dalarna, it is necessary to consider UAC_D factor and, according to Chapter 3.5, this number for estimation purposes will be consider 0.5. That said, A_{SCD} can be estimated by:

$$A_{SCD} = 2722364 \times 0.5 = 1361182 \text{ m}^2$$

As it was already said on Chapter 3.5, the uncertainties regarding UAC_D factor, and consequently A_{SCD} , will be discussed in Chapter 5.

4.4 Possible energy production in parking lots in Dalarna

After simulation in the parking lot of Kupolen shopping mall and considering the useful area to generate electricity described on Chapter 4.3, as well as the PVsyst simulation result shown on Table 4.2, it is possible to generate about 1.6 GWh/year in an area of 11292 m^2. That said the energy production per area in a year in the simulation model can be calculated by:

$$E_{PPAY} = \frac{E_{PK}}{A_{SCK}} \qquad \textit{Equation 4.2}$$

Where E_{PPAY} is the energy produced per area in a year, E_{PK} is the annually energy produced by the solar power plant in Kupolen shopping mall and A_{SCK} is the total area covered by solar carports at the same place, according to Equation 4.2

$$E_{PPAY} = \frac{1571000 \frac{\text{kWh}}{\text{year}}}{11292\ \text{m}^2} \approx 139 \frac{\text{kWh}}{\text{year} \cdot \text{m}^2}$$

That said, and considering the total parking lot area in Dalarna that can be used to generate electricity through solar carports is about 1361182 m^2 according to Equation 4.1, the total energy that can be possibly produced in Dalarna can be demonstrated by:

$$E_{PD} = E_{PPAY} \cdot A_{SCD} \qquad \textit{Equation 4.3}$$

Where E_{PD} is the total energy that can be produced in all parking lot area in Dalarna in one year.

$$E_{PD} = 139 \frac{\text{kWh}}{\text{year} \cdot \text{m}^2} \cdot 1361182\ \text{m}^2 \approx 189 \frac{\text{GWh}}{\text{year}}$$

The uncertainties around this final result will be discussed on Chapter 5.

5 Discussion

The purpose of this chapter is to discuss about PV module chosen process, the methodology used in the project and also uncertainties related to it.

5.1 PV module technology

As it was shown in Chapter 2.2.1, mono-Si PV modules are more suitable to use in solar carports due to a higher efficiency compared to a poly-Si PV modules, having as a consequence a higher output energy produced for the same solar parking lot area.

In addition, half-cut modules improve solar system performance due to lower resistive losses, leading to a higher efficiency, increasing energy output. Besides that, due to the fact the current through the module is divided by two, half-cut modules have lower degradation, leading to a longer lifetime.

Although there is few studies on the subject, the idea of implementing bifacial PV modules in solar carport systems is developing. The structures can be offered in single row or double row carport model, in both monopitch or duopitch formats [41] [42]. Analytic and empirical studies have shown that use of bifacial modules can potentially increase system yield by at least 10% over a fixed latitude tilt monofacial array [43].

5.2 Methodology

The method used was initially based only on information found in the base case model made on Kupolen shopping mall in Borlänge. However, during the project, it was clear the necessity to make more studies in other places to get better results.

Based on that, due to the big area of Dalarna County, considering that in the north could have less solar radiation, and also the fact that there is a meteorological station in the location of Idre Fjäll, with Meteonorm data in PVsyst, it was decided to simulate the same model there in order to compare with Borlänge. Besides that, Idre Fjäll is a place in higher altitude than Borlänge, so it was expected to find less influence from the mountains in the horizon profile, as it can be verified on Figure 5.1. In total, it was made eight simulations, represented by B1 to B8 in Appendix B, where different scenarios were assumed in both places in order to see the impact of different solar radiation and horizon profile, as well as losses in electricity production due to snow.

Regarding UAC_D, more study apart from the base case was also made. Using satellite pictures from Google Earth and calculating the total parking lot area through Earth Point, two more parking lots were evaluated, improving the coefficient. However, in order to make UAC_D with a more precise value, is necessary more evaluation on different parking lots.

The method to find out losses due to shading, both nearby due to the buildings and trees, as well as due to the horizon profile, have also limitations. Only one model was made in SketchUp due to limitations in time and also in resources.

5.3 Uncertainties on energy generation

As expected, the final value presented on Chapter 4.4 of 189 GWh/year cannot just be trusted as an exact final result, due to the fact that there are many uncertainties related to how to find the total energy that can be produced on parking lots in Dalarna, such as:

- Location due to different incident global radiation
- Different location, having different near shading due to buildings and trees
- Different horizon profile for every parking lot
- Different soiling losses according to municipality location in Dalarna
- Parking lot profile with different useful solar carport area
- Solar carport structure with different roof formats, tilt angle and orientation
- Software and database accuracy

5.3.1. Solar radiation

As it can be seen on Figure 3.5, the global radiation in both maps for Dalarna varies from 900 to 950 kWh/m^2 according to SMHI and JRC [31] [32].

In the base case, on Kupolen shopping mall´s parking lot in Borlänge, the average annual global radiation value used by PVsyst was 934 kWh/m^2. On the other hand, in a second simulation of the same model made in a location in the northwest of Dalarna called Idre, using Meteonorm data from Idre Fjäll weather station, this same value was slightly reduced to 925 kWh/m^2, representing a difference in the yield lower than 1%.

Both simulations, for Borlänge and Idre Fjäll can be verified on Appendix B.

5.3.2. Near shading

As one source of uncertainty, losses due near shading will be different for every parking lot, due to the fact that the position or quantity of buildings and trees will also be different. In the ideal case, should be done a simulation of model for every parking lot in Dalarna, considering the buildings and trees around it, like it was made in the base case on Kupolen´s shopping mall, in Borlänge. However, this solution is not feasible and very costly, so to evaluate how much energy can be produced on parking lots through solar carports in Dalarna, it was decided to work with the value found in the model simulated in the base case, with near shadings around 3.5%.

5.3.3. Horizon profile

As one source of uncertainties, the horizon profile is usually different for every locality, due to the fact that the terrain around them is different. In the Figure 5.1 it can be seen a parallel between the horizon profile in Borlänge, already mentioned on Figure 3.6 and the horizon profile of the same project simulated in the location of Idre.

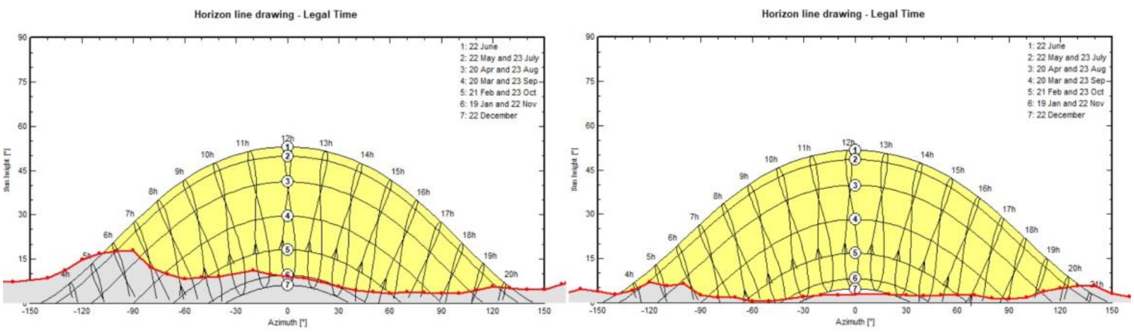


Figure 5.1 Sun-path diagram with horizon effect integrated for Borlänge (left) and Idre (right).

As it can be seen in simulations, losses due horizon can change in a large range. In Borlänge, according to PVsyst simulation, the horizon losses was about 3.4% while in Idre, in the same project, the horizon losses was only about 0.4%. In Appendix B can be found the diagram losses for both Borlänge and Idre location.

5.3.4. Snow losses

In general, PVsyst has a default value of 3% for soiling losses. However, in the northern hemisphere, especially on Nordic countries, the snow effect over PV modules cannot be neglected. That said, it was necessary to find some information regarding snow losses, but there is no such data in Sweden, being necessary to use data from Norway - Norwegian Standard NS3031-2016.

The city with information available which snow data is more similar do Dalarna is Lillehammer, located on latitude 61° N, so it can be assumed similar weather do Dalarna. The results shown losses in electricity production due to snow in the order of 10%.

5.3.5. Parking lot profile

The format of every parking lot, as well as the components within them, such as trees, crosswalks and space for car circulation, affect the percentage of useful area that can be used to generate electricity through solar carport systems.

According to Chapter 3.5, in the base case was found a useful area of 45% at Kupolen shopping mall´s parking lot. However, on IKEA´s parking lot it was found the value of 58% and, on the other hand, in the parking lot on Falun´s city centre this value is 32%.

In the ideal case, the evaluation of useful parking lot area must be done in all parking lots in Dalarna, in order to have the correct UAC_D. However, for estimation purposes, it was considered to use the average value of the three simulations done and described on Chapter 3.5, giving a value of approximately 50% of parking lot area that can be considered useful to generate energy.

5.3.6. Solar carport structure and orientation

The structure of a solar carport, as well as its tilt angle and orientation, are another source of uncertainties. Due to the lower costs, double row carports are more suitable format comparing with single row carports, being possible cover a larger amount of cars with only one central structure [9]. That said, monopitch and duopitch structures, like in the Figure 2.1, have easier installation, lower cost and can produce more energy compared to barrel-arch structures, which have bigger structure and roof with format in curve [9].

Regarding tilt angle, in both monopitch and duopitch structures, this one must be between 5° to 10°. Beyond 10°, in monopitch structures starts to make visual impacts and reduces shade to cars and in duopitch structures one side starts to reflect in the other side of the structure [9].

Related to orientation, in situations where the parking lot profile allows to put the solar carport structure south-oriented, the best option are monopitch structures, due to the fact that more electricity can be generated with this format comparing to duopitch structures at the same location [9]. However, in situations where is necessary east-west orientation, the most suitable format is duopitch structures and, considering a large amount of accumulated snow in Sweden in winter season, instead “v” format, like duopitch carport in the Figure 2.1, the most suitable is the “inverted v” format.

5.3.7. Software and database accuracy

On Meteonorm database, the calculation of uncertainty of global radiation are based on three points [44]:

- Uncertainty of ground measurements
- Uncertainty of interpolation
- Uncertainty of the splitting into diffuse and direct radiation and inclined planes

The overall uncertainty is composed from the three sources of uncertainties mentioned and, for global radiation stands at around +/- 10%, being larger in latitudes above 55° N in Northern Europe [44][45].
Regarding PVsyst, according to its validations, after analyze several installations in Geneva in a period of 3 years, designed using the straightforward simulation and normalizing the results to the real monthly irradiation, the yearly results were within +/- 5% [46].

6 Conclusions

Nowadays, one of the major challenges in the generation of electricity through PV modules, is to find out areas that cannot be used for food-production purposes, such as the surface of landfills and parking lot areas. In addition, Sweden had a consumption of electricity of 14380 kWh per capita in 2021, being the second highest value in all European Union (EU), with approximately 2.2 times higher than EU average, behind only of Finland, with 16210 kWh per capita [47].

In 2020, the total of 160898 GWh of electricity was produced in Sweden, where 1035 GWh was generated through PV systems, representing about 0.64% of the amount [48]. Besides that, the total electricity consumption in Dalarna in the same year was 6152 GWh [49]. The value of 189 GWh/year found represents the consumption of eleven days in Dalarna considering equally distributed consumption.

Considering the fact that there are 138033 EVs registered in Sweden in 2021, including both BEVs and PHEVs [50] and, for estimation purposes, assuming 10000 km/year for every car, as well as a consumption of 164 Wh/km of an average model, such as Volkswagen ID.3 [51], the total consumption of EV in Sweden in 2021 was about 226 GWh. That said, if all parking lot area in Dalarna was covered by solar carports, the electricity produced could supply about 83% of all EV car fleet consumption in Sweden.

Despite not being the main focus of this study, PV solar modules and inverter configuration were also evaluated, being considered to use mono-Si with half-cut cell PV modules, in addition to multi-string inverters with distributed architecture instead central inverters. For both, PV modules and inverters, as well as system design, due to the fact that the costs of PV modules and systems are continuously dropping [33] and these facilities are close to becoming economically viable [7].

Considering all uncertainties already discussed on Chapter 5, even being hard to determine, it can be considered a total uncertainty of +/- 10% of the total amount of electricity that could be generated through solar carports on parking lots in Dalarna.

Large parking lots have a great potential for generating electricity through solar carport systems, contributing to electrical power services oriented to support local loads or for export to the grid. In addition, as the cost of PV installations is dropping, these areas can stimulate important investments. In addition, a store that uses solar carport systems on parking lots today, as well as EV chargers, it is viewed as an environmentally friendly store, having as a consequence a competitive advantage, which economical impact could also be a suggestion for a future work.

Store owners could increase profit from providing free solar electricity charging stations for their customers through incentives, such as increase comfort for shading and precipitation, provide a clean energy, encouraging green consumerism, in addition to increase the time shopping [3].

In fact, due to the green consumerism effect, a store that owns a power generation trough a solar carport system with EV charging can be seen as a “green store”, and the customers will be encouraged to be part of it. In addition, even if the owners of EV and PHEV cars would not choose the store for environmental reasons, they will do it for the free charging incentive.

7 Future work

As future work, could be highlighted many improvements, starting with more simulations on parking lots using PVsyst and modeling programs, such as SketchUp, in order to get more data related to losses due shading from constructions and trees. In addition, with the aim to increase the data and improve the accuracy related to losses due to horizon profile, more simulations in different locations are also suggested.

Regarding to parking lots profile, it was made three simulations in order to get an average coefficient of useful area that can be used to generate electricity, and for increasing the accuracy it will be also suggested more simulations with different parking lots. As more simulations are made, more accurate the coefficient will be.

Concerning soiling and snow losses, it is important try to find Swedish data referred to it, preferably if this data was classified by county. Also, at the moment, there is not much research with focus on evaluate solar carports systems using bifacial modules, so a theoretical and/or experimental study could be suggested.

Related to the system in general, a study using a base case could be done considering energy storage, as well as an economical evaluation, in order to analyse feasibility by estimating the levelized cost of electricity (LCOE) and payback period. Also, research could be done in the design itself, such as cabling layout and protection in both DC and AC side, earthing, lightning, overcurrent and short-circuit protection systems using residual current devices (RCD), fuse and circuit-breakers, alongside with the mechanical assembly part, with quick connections on DC side, rails and clamping roof system.

References

[1] "Snapshot of Global PV Markets 2022," *IEA-PVPS*. https://iea-pvps.org/snapshot-reports/snapshot-2022/ (accessed Aug. 31, 2022).

[2] "Global EV Data Explorer – Analysis," *IEA*. https://www.iea.org/articles/global-ev-data-explorer (accessed Jan. 23, 2022).

[3] S. Deshmukh and J. Pearce, "Electric Vehicle Charging Potential from Retail Parking Lot Solar Photovoltaic Awnings," *Renew. Energy*, vol. 169, Jan. 2021, doi: 10.1016/j.renene.2021.01.068.

[4] "Annual reports Archive," *IEA-PVPS*. https://iea-pvps.org/annual-reports/ (accessed Apr. 26, 2022).

[5] "Trends in PV applications 2021," *IEA-PVPS*. https://iea-pvps.org/trends_reports/trends-in-pv-applications-2021/ (accessed May 11, 2022).

[6] P. Nunes, R. Figueiredo, and M. C. Brito, "The use of parking lots to solar-charge electric vehicles," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 679–693, Dezembro 2016, doi: 10.1016/j.rser.2016.08.015.

[7] O. Lindberg, A. Birging, J. Widén, D. Lingfors, and A. Birging, "PV park site selection for utility-scale solar guides combining GIS and power flow analysis: A case study on a Swedish municipality," *Appl. Energy*, vol. 282, p. 116086, Jan. 2021, doi: 10.1016/j.apenergy.2020.116086.

[8] M. Farahmand, S. Javadi, s. M. B. Sadati, H. Laaksonen, and M. Shafie-khah, "Optimal Operation of Solar Powered Electric Vehicle Parking Lots Considering Different Photovoltaic Technologies," *Clean Technol.*, vol. 3, pp. 503–518, Jun. 2021, doi: 10.3390/cleantechnol3020030.

[9] F. Umer, M. S. Aslam, M. S. Rabbani, M. J. Hanif, N. Naeem, and M. T. Abbas, "Design and Optimization of Solar Carport Canopies for Maximum Power Generation and Efficiency at Bahawalpur," *Int. J. Photoenergy*, vol. 2019, p. e6372503, Feb. 2019, doi: 10.1155/2019/6372503.

[10] "HelioScope: Advanced Solar Design Software." https://www.helioscope.com/ (accessed Feb. 13, 2022).

[11] R. E. Pawluk, Y. Chen, and Y. She, "Photovoltaic electricity generation loss due to snow – A literature review on influence factors, estimation, and mitigation," *Renew. Sustain. Energy Rev.*, vol. 107, pp. 171–182, Jun. 2019, doi: 10.1016/j.rser.2018.12.031.

[12] L. Powers, J. Newmiller, and T. Townsend, "Measuring and modeling the effect of snow on photovoltaic system performance," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 000973–000978, Jun. 2010, doi: 10.1109/PVSC.2010.5614572.

[13] A. S. Alghamdi, A. S. Bahaj, and Y. Wu, "Assessment of Large Scale Photovoltaic Power Generation from Carport Canopies," *Energies*, vol. 10, no. 5, Art. no. 5, May 2017, doi: 10.3390/en10050686.

[14] "Our Technology." https://www.firstsolar.com:443/en/Modules/Our Technology (accessed Aug. 06, 2022).

[15] "JinkoSolar announces 23.01% efficiency for n-type monocrystalline panel," *pv magazine International*. https://www.pv-magazine.com/2021/01/12/jinkosolar-announces-23-01-efficiency-for-n-type-monocrystalline-panel/ (accessed Aug. 06, 2022).

[16] Z. Corba, V. Katic, B. Dumnic, and D. Milicevic, "In-grid solar-to-electrical energy conversion system modeling and testing," *Therm. Sci.*, vol. 16, Jan. 2012, doi: 10.2298/TSCI120224069C.

[17] T. Morlan, "String Versus Central Inverters for Solar PV Projects." https://blog.norcalcontrols.net/string-versus-central-inverters-solar-pv (accessed May 23, 2022).

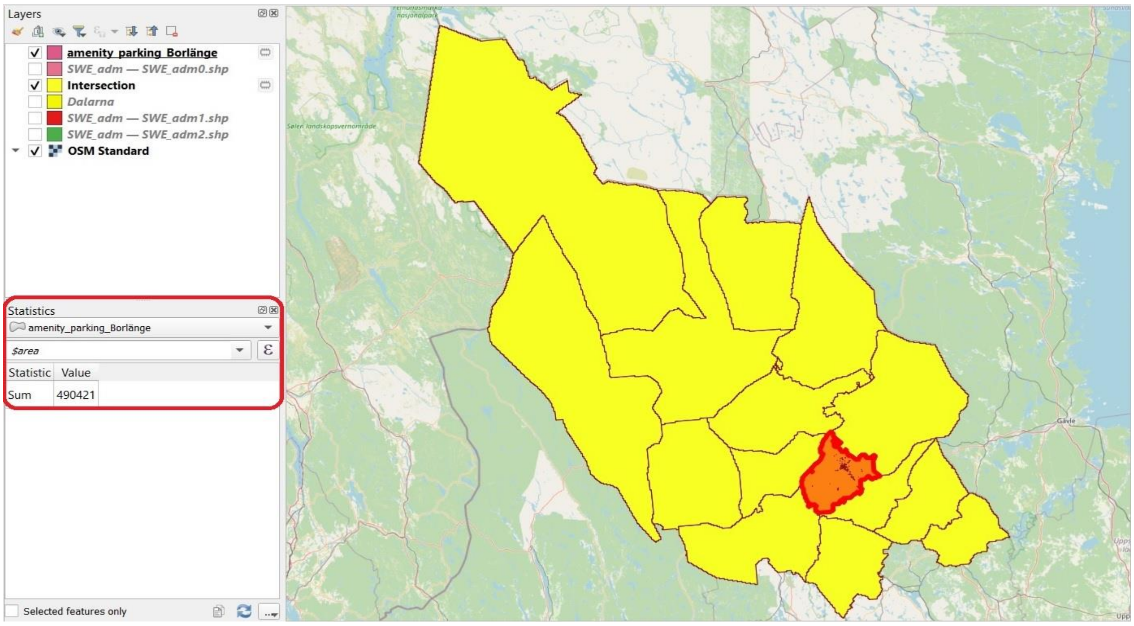
[18] "Central Inverter vs String Inverter," *RENVU Solar*. https://www.renvu.com/Central-Inverter-vs-String-Inverter (accessed May 23, 2022).

[19] "OpenStreetMap," *OpenStreetMap*. https://www.openstreetmap.org/ (accessed Jan. 23, 2022).

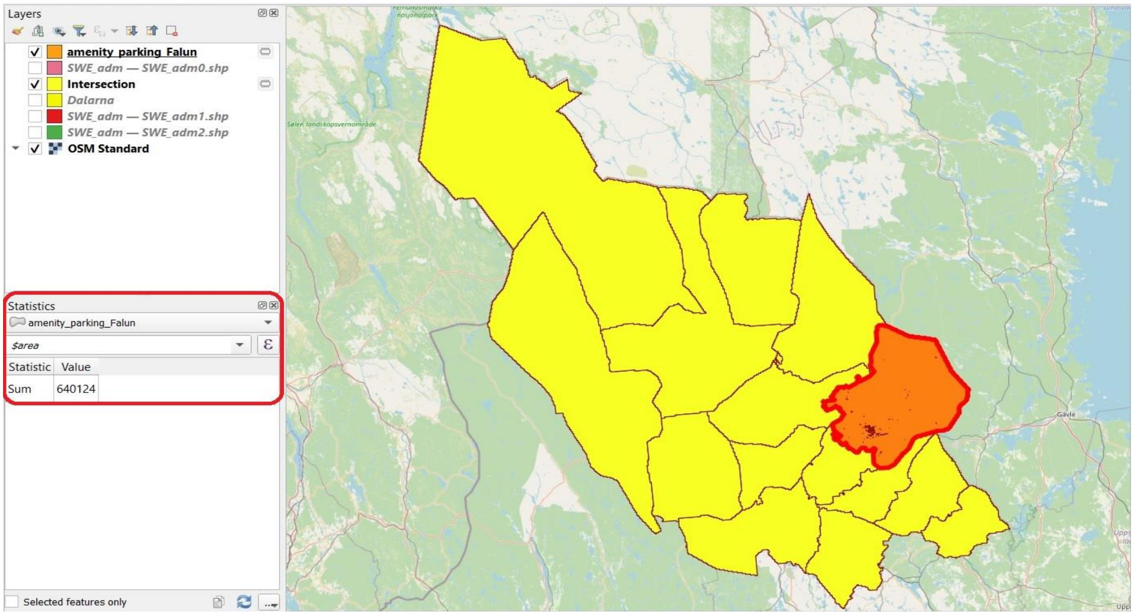
[20] G. Maier, "OpenStreetMap, the Wikipedia Map," *REGION*, vol. 1, no. 1, Art. no. 1, Dec. 2014, doi: 10.18335/region.v1i1.70.
[21] "Welcome to the QGIS project!" https://qgis.org/en/site/ (accessed Jan. 23, 2022).
[22] "What is GIS? | Geographic Information System Mapping Technology." https://www.esri.com/en-us/what-is-gis/overview (accessed Feb. 21, 2022).
[23] "Home," *PVsyst*. https://www.pvsyst.com/ (accessed Apr. 06, 2022).
[24] "intro - Meteonorm (de)," *Meteonorm (en)*. https://meteonorm.com/en/ (accessed May 14, 2022).
[25] K. Mohr, "Data Products | Earth." https://earth.gsfc.nasa.gov/climate/data (accessed May 14, 2022).
[26] "3D Design Software | 3D Modeling on the Web," *SketchUp*. https://www.sketchup.com/page/homepage (accessed Feb. 13, 2022).
[27] "Accurate Sunrise and Sunset Times Accounting for Terrain," *Suncurves*. https://www.suncurves.com/en/ (accessed Apr. 02, 2022).
[28] "Visão geral," *Google Earth*. https://www.google.com/intl/pt-BR/earth/ (accessed Aug. 31, 2022).
[29] "Tools For Google Earth." https://www.earthpoint.us/ (accessed Jul. 14, 2022).
[30] "Dalarna County," *Wikipedia*. Dec. 10, 2021. Accessed: Feb. 15, 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Dalarna_County&oldid=1059601148
[31] "Search | SMHI." https://www.smhi.se/en/search?query=global+solar+radiation&submitButton= (accessed Apr. 06, 2022).
[32] "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission." https://re.jrc.ec.europa.eu/pvg_tools/en/#MR (accessed Feb. 06, 2022).
[33] M. van Noord, T. Landelius, and S. Andersson, "Snow-induced PV loss modeling using production-data inferred PV system models," *Energies*, vol. 14, no. 6, 2021, Accessed: Apr. 13, 2022. [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-54703
[34] "SN/TS 3031:2016." https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=859500 (accessed Apr. 13, 2022).
[35] "Forside - Lillehammer kommune." https://www.lillehammer.kommune.no/ (accessed Apr. 20, 2022).
[36] "DIVA-GIS | free, simple & effective." https://www.diva-gis.org/ (accessed Feb. 26, 2022).
[37] "Download data by country | DIVA-GIS." https://www.diva-gis.org/gdata (accessed Feb. 26, 2022).
[38] "Jinko Solar-半片技术." https://www.jinkosolar.com/en/site/halfslice (accessed May 17, 2022).
[39] S. S. T. AG, "Sunny Highpower PEAK3." https://www.sma.de/en/products/solarinverters/sunny-highpower-peak3.html (accessed Jun. 02, 2022).
[40] S. S. T. AG, "SMA Solar Technology AG - Inverter & Photovoltaics solutions." https://www.sma.de/en.html (accessed Jun. 02, 2022).
[41] "Carport," *Opsun*. https://opsun.com/en/bifacial/carport/ (accessed Aug. 17, 2022).
[42] "Gridpartity: A solar carport that seems to float in the air - GW News," Jan. 28, 2020. https://www.gw-news.eu/products/gridpartity-solar-carport-seems-float-air (accessed Aug. 17, 2022).
[43] J. Stein, D. Riley, M. Lave, C. Hansen, C. Deline, and F. Toor, "Outdoor Field Performance from Bifacial Photovoltaic Modules and Systems," Sep. 2017.
[44] S. C. Müller and J. Remund, "Solar Radiation and Uncertainty Information of Meteonorm 7," *26th Eur. Photovolt. Sol. Energy Conf. Exhib.*, pp. 4388–4390, Oct. 2011, doi: 10.4229/26thEUPVSEC2011-5BV.2.61.

[45] J. Remund and S. C. Müller, "Validation of the Meteonorm Satellite Irradiation Dataset," *35th Eur. Photovolt. Sol. Energy Conf. Exhib.*, pp. 1760–1762, Nov. 2018, doi: 10.4229/35thEUPVSEC20182018-6BV.1.4.
[46] "Validations." https://www.pvsyst.com/help/validations.htm (accessed Jul. 19, 2022).
[47] "Leading electricity consumers in Europe 2021," *Statista*. https://www.statista.com/statistics/1262218/per-capita-electricity-consumption-europe-by-country/ (accessed Aug. 15, 2022).
[48] "Electricity supply and use 2001–2020 (GWh)," *Statistiska Centralbyrån*. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/energy/energy-supply-and-use/annual-energy-statistics-electricity-gas-and-district-heating/pong/tables-and-graphs/electricity-supply-and-use-20012020-gwh/ (accessed Aug. 15, 2022).
[49] "Startsida," *Energiintelligent Dalarna*. https://www.energiintelligent.se/ (accessed Aug. 15, 2022).
[50] "Plug-in electric vehicles in Sweden," *Wikipedia*. Aug. 03, 2022. Accessed: Aug. 15, 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Plug-in_electric_vehicles_in_Sweden&oldid=1102131335
[51] "Volkswagen ID.3 Pure Performance," *EV Database*. https://ev-database.org/car/1127/Volkswagen-ID3-Pure-Performance (accessed Aug. 15, 2022).

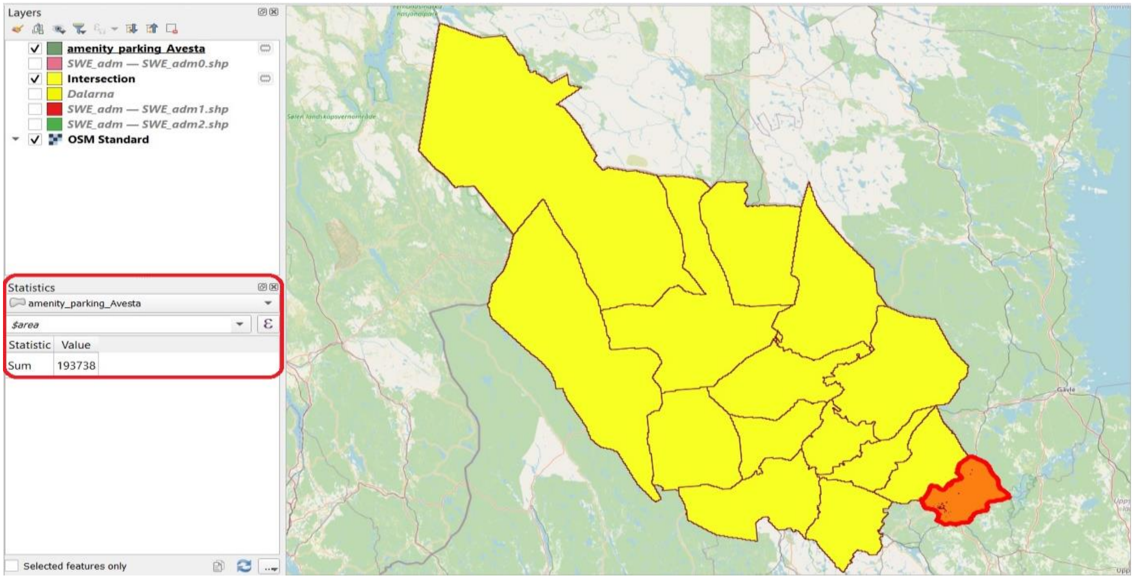
Appendix A Parking lot area by municipality



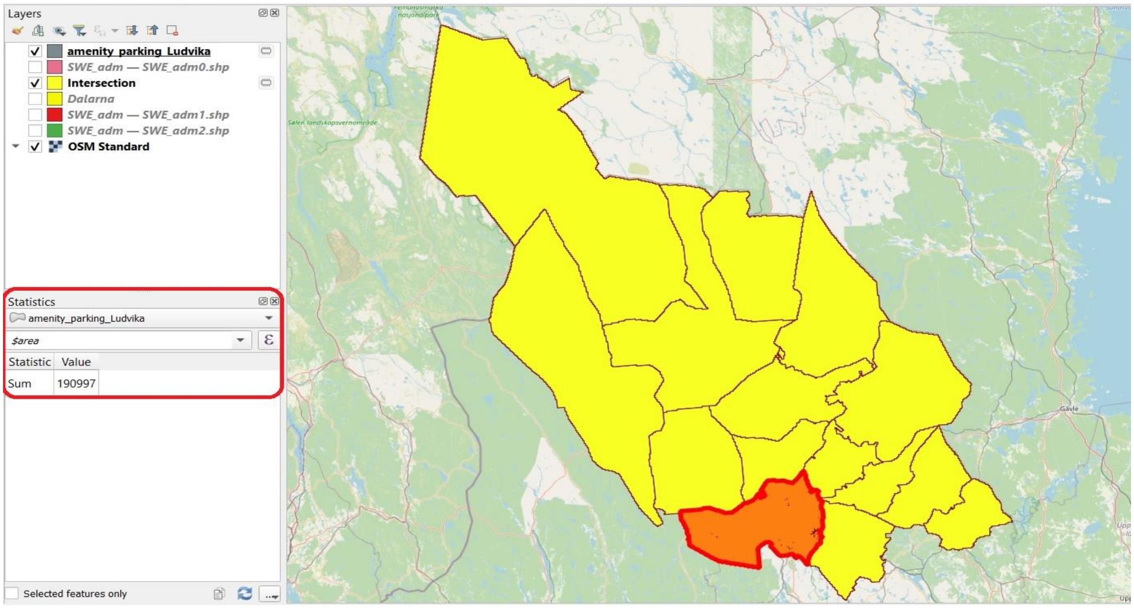
Region 1 – Borlänge with a parking lot area of 490421 m².



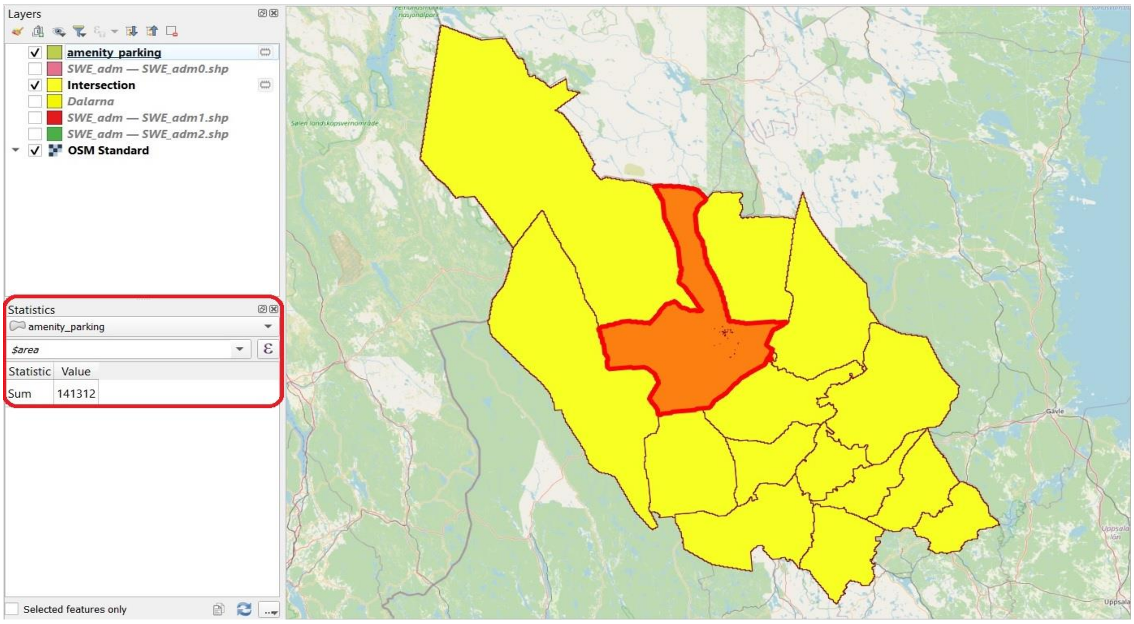
Region 2 – Falun with a parking lot area of 640124 m².



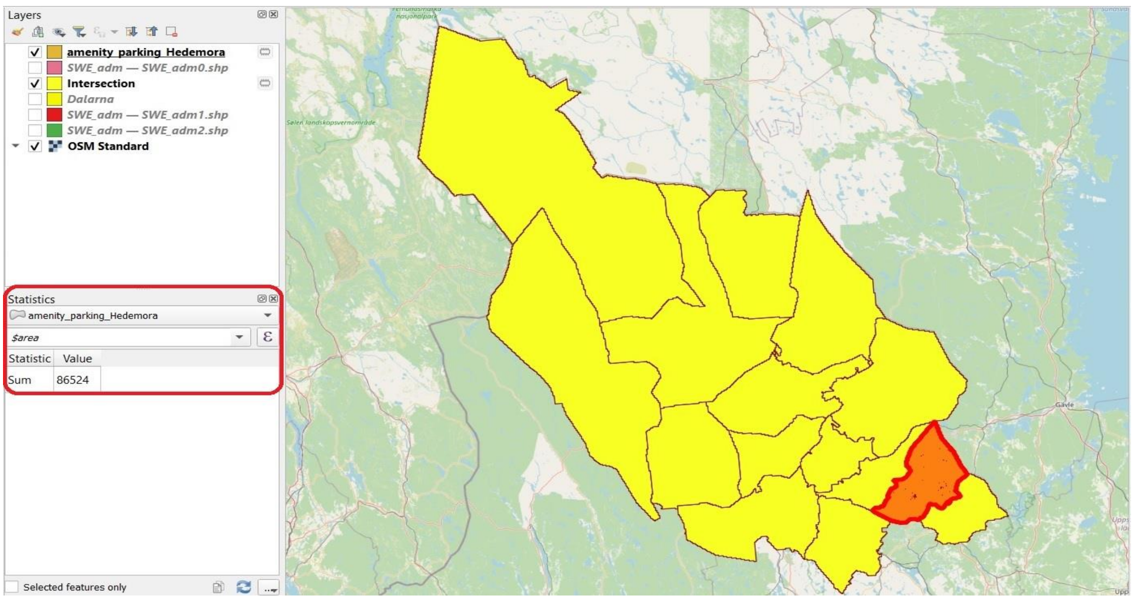
Region 3 – Avesta with a parking lot area of 193738 m².



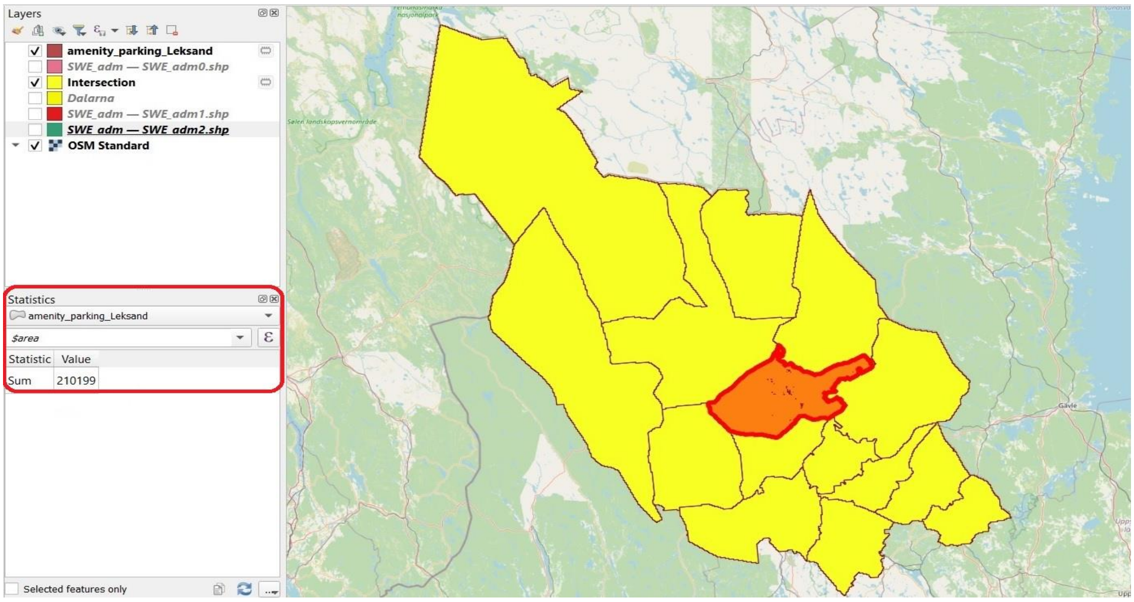
Region 4 – Ludvika with a parking lot area of 190997 m².



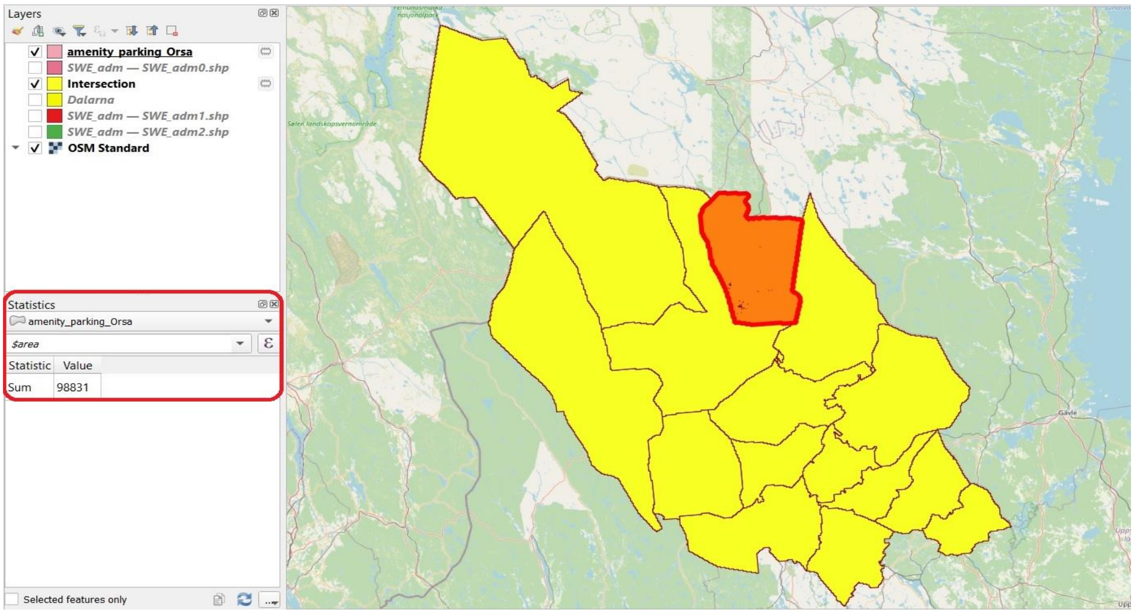
Region 5 – Mora with a parking lot area of 141312 m².



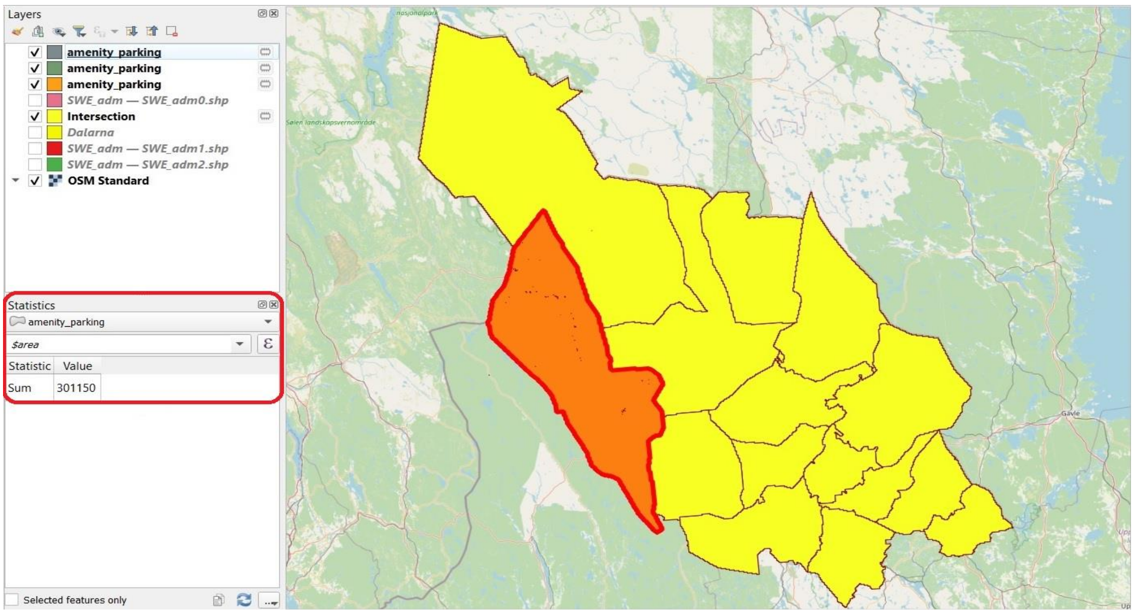
Region 6 – Hedemora with a parking lot area of 86524 m².



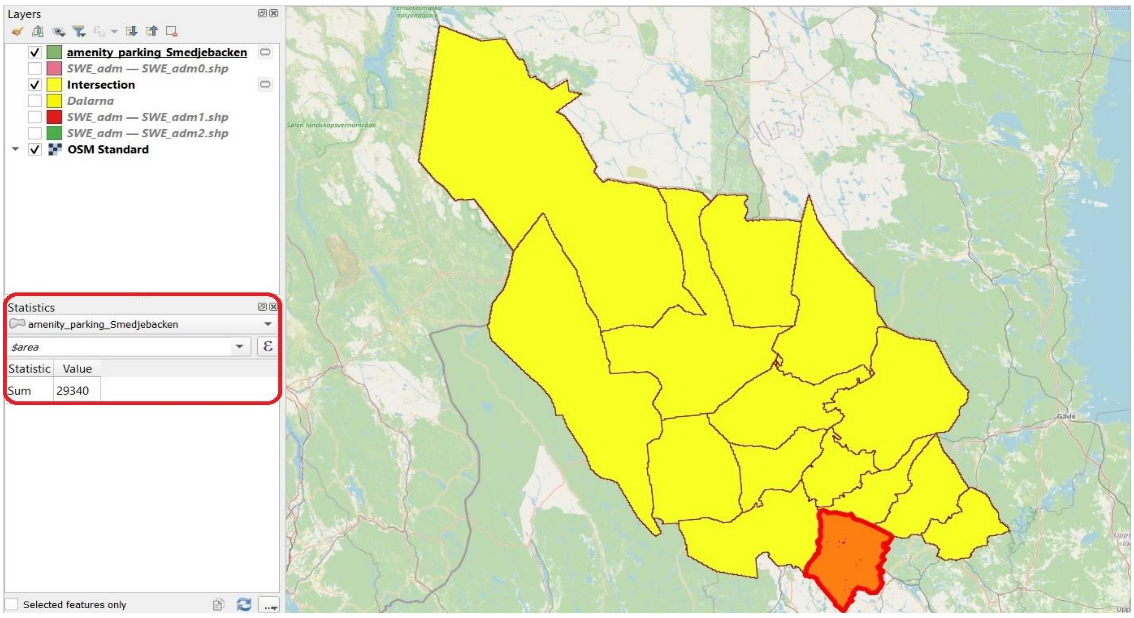
Region 7 – Leksand with a parking lot area of 210199 m².



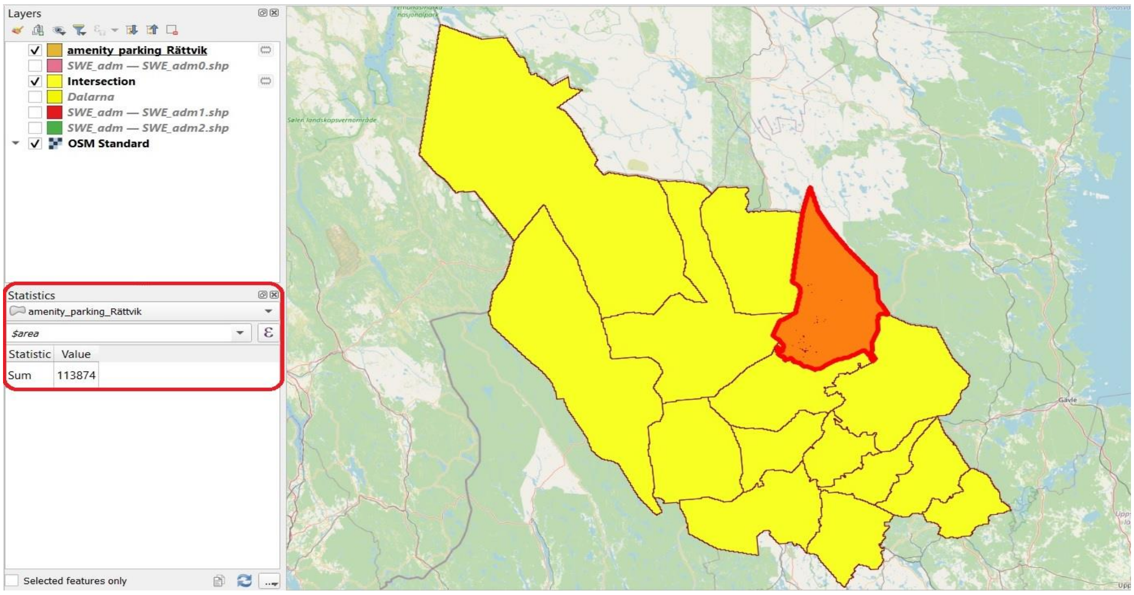
Region 8 – Orsa with a parking lot area of 98831 m².



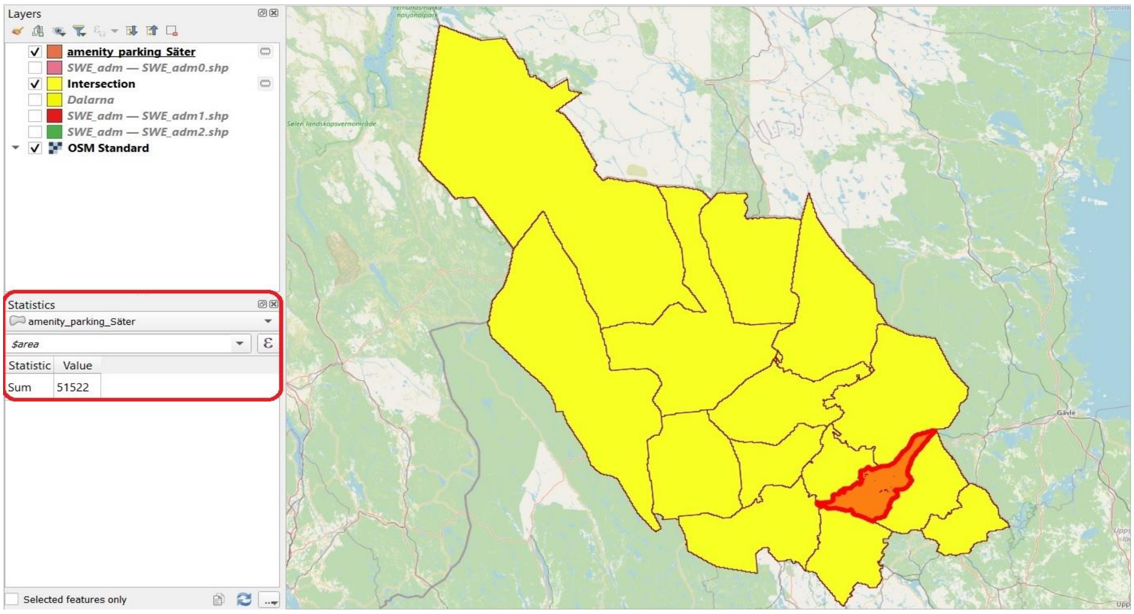
Region 9 – Malung with a parking lot area of 301150 m².



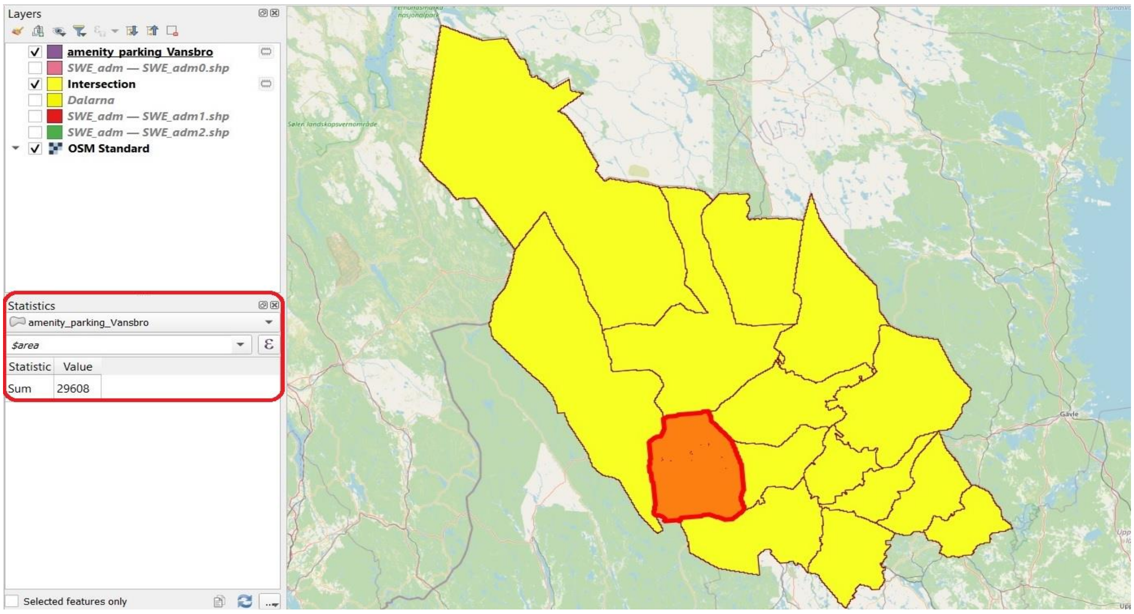
Region 10 – Smedjebacken with a parking lot area of 29340 m².



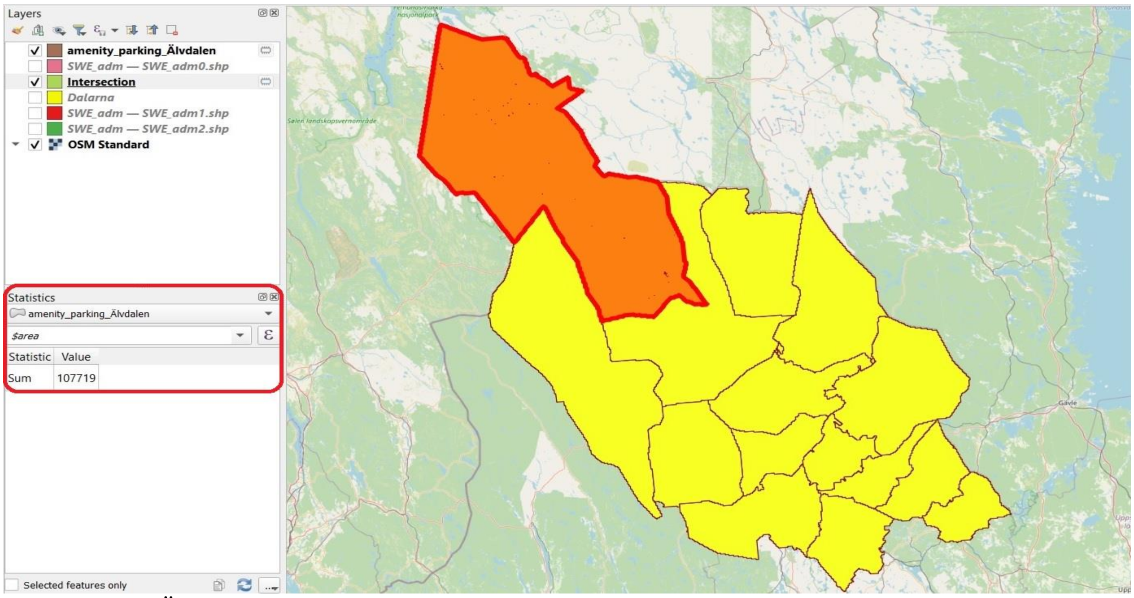
Region 11 – Rättvik with a parking lot area of 113874 m².



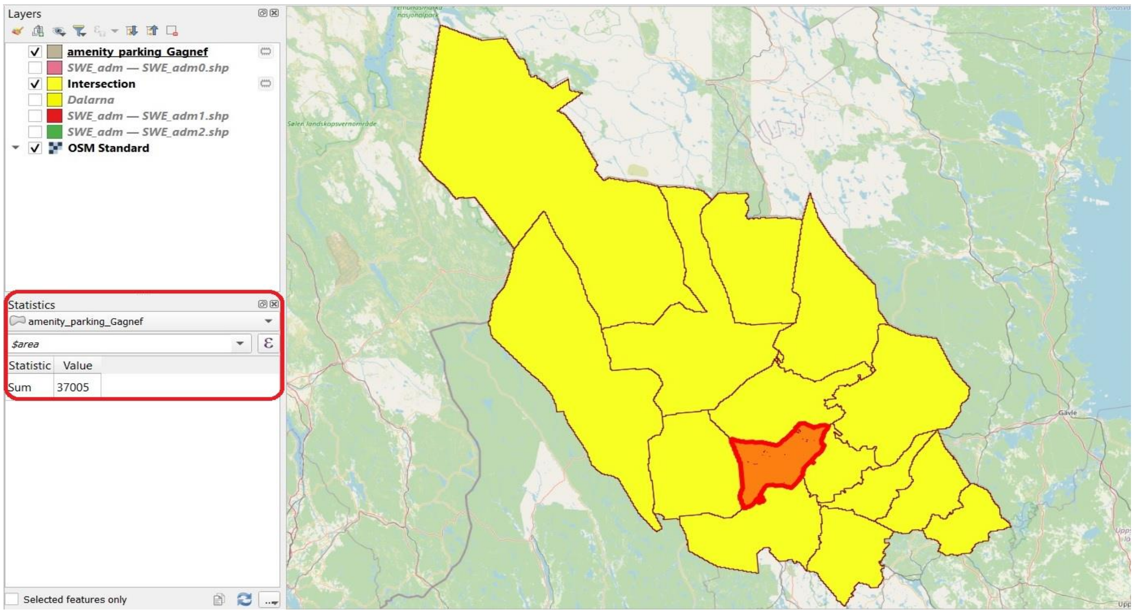
Region 12 – Säter with a parking lot area of 51522 m².



Region 13 – Vansbro with a parking lot area of 29608 m².



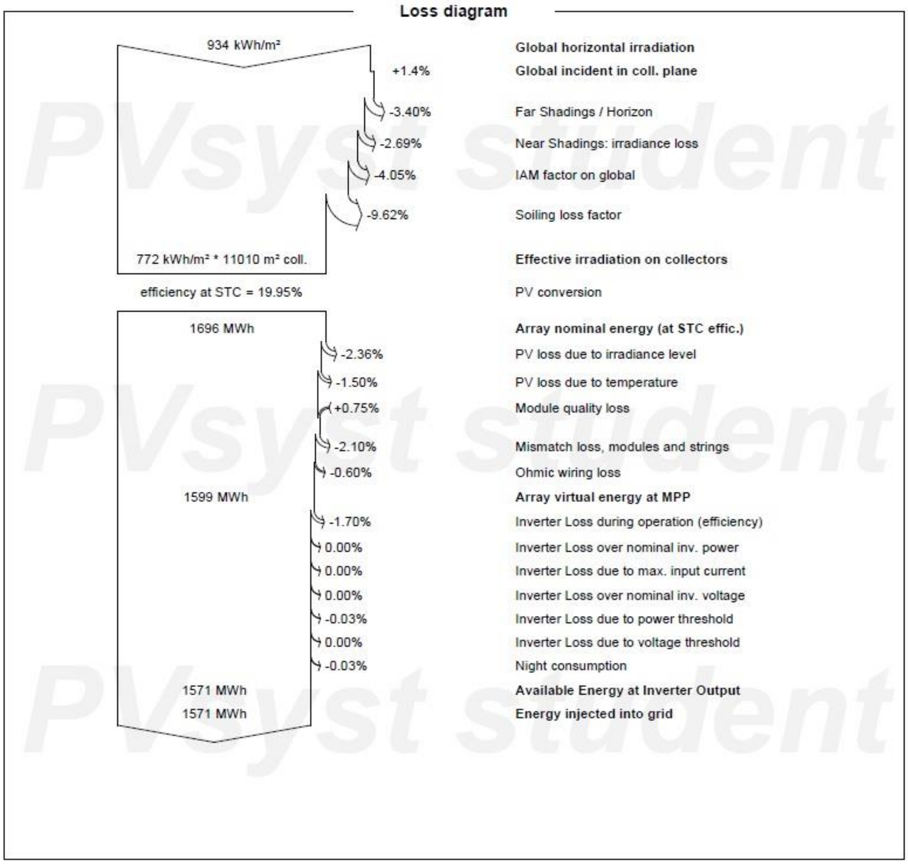
Region 14 – Älvdalen with a parking lot area of 107719 m².



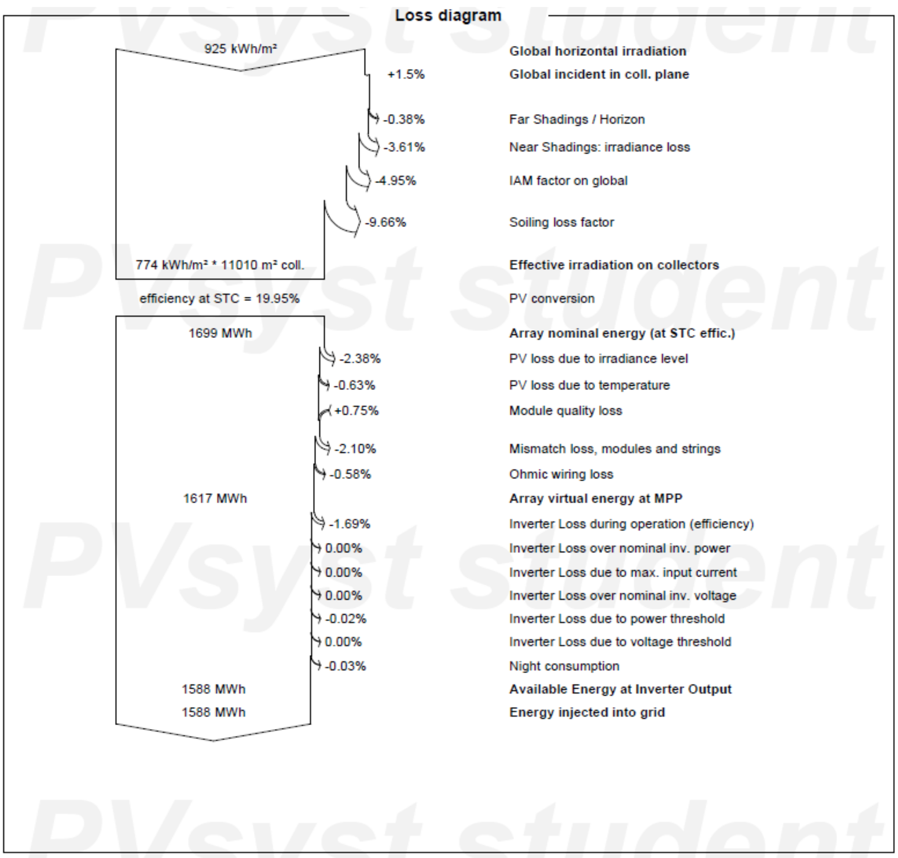
Region 15 – Gagnef with a parking lot area of 37005 m².

Appendix B PVsyst simulation results

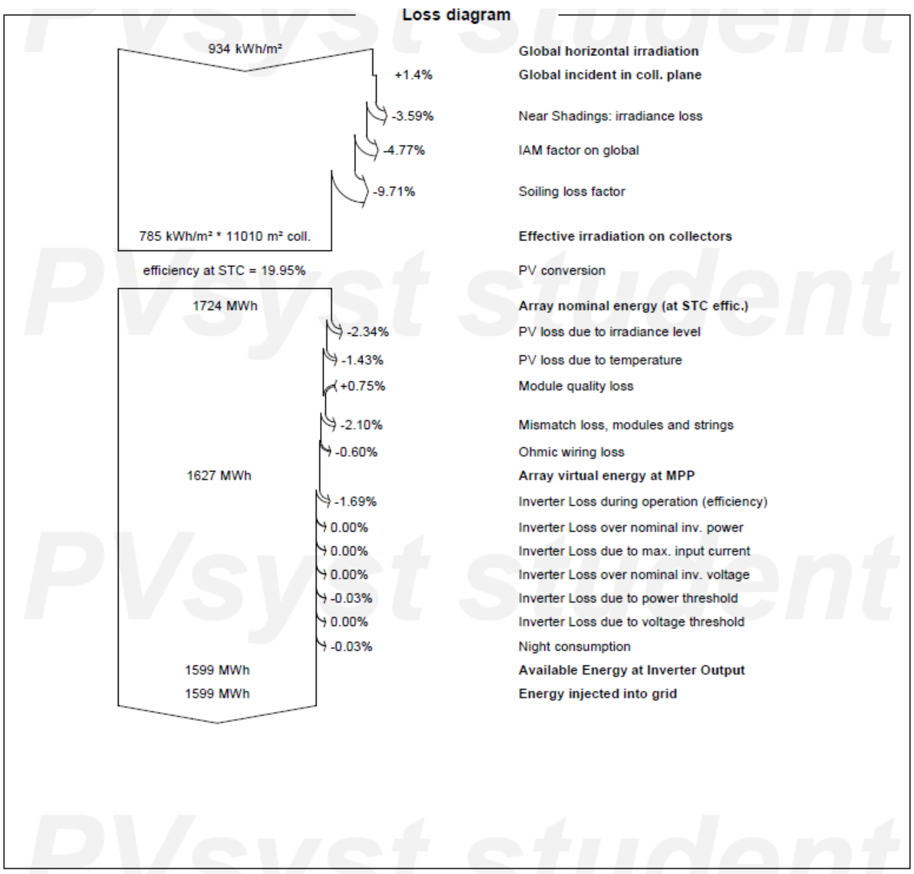
B1 Whit horizon profile / whit snow losses (Borlänge - base case)



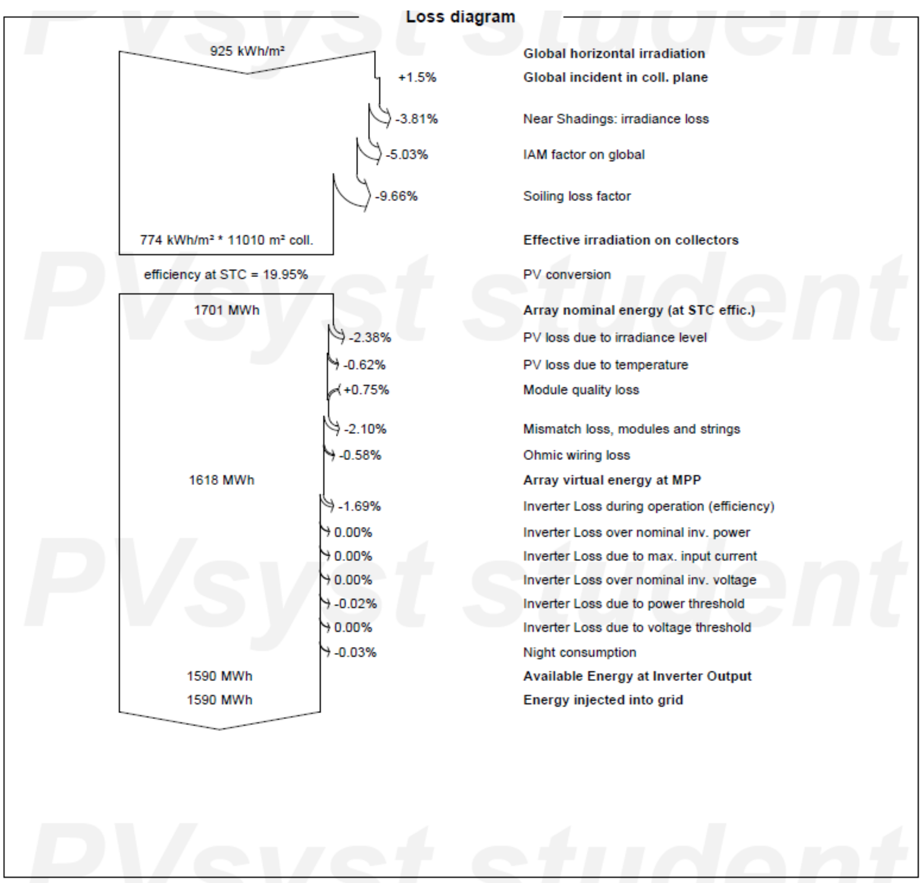
B2 Whit horizon profile / whit snow losses (Idre Fjäll)



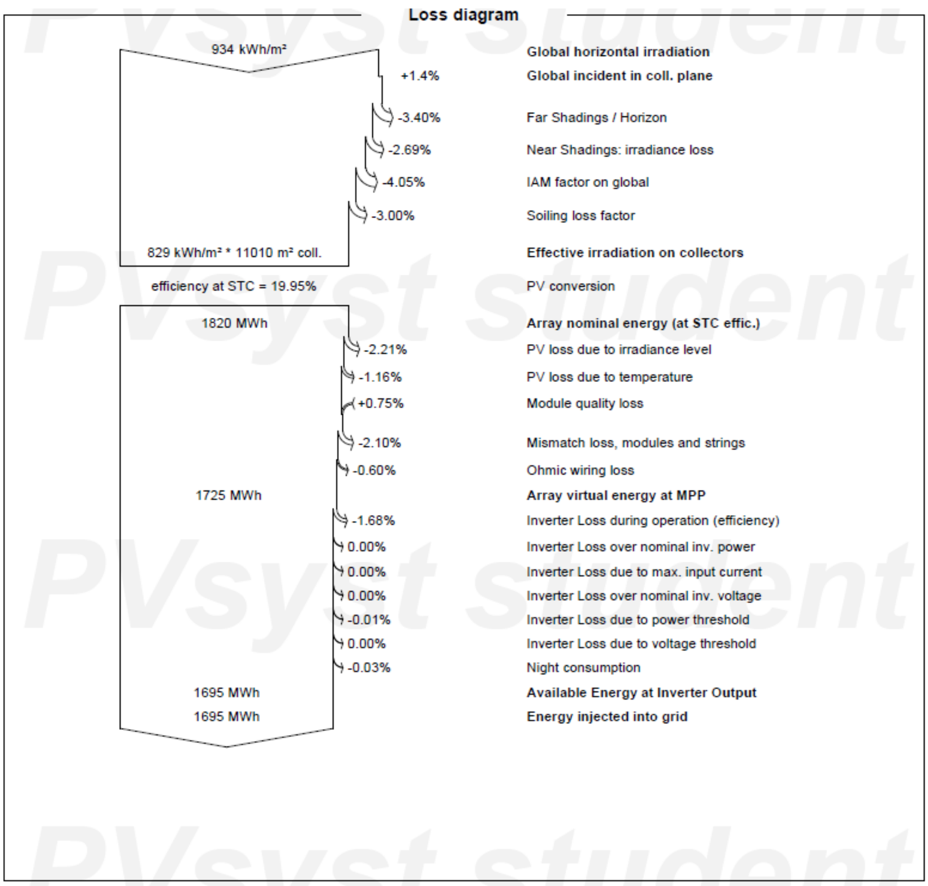
B3 Without horizon profile / whit snow losses (Borlänge)



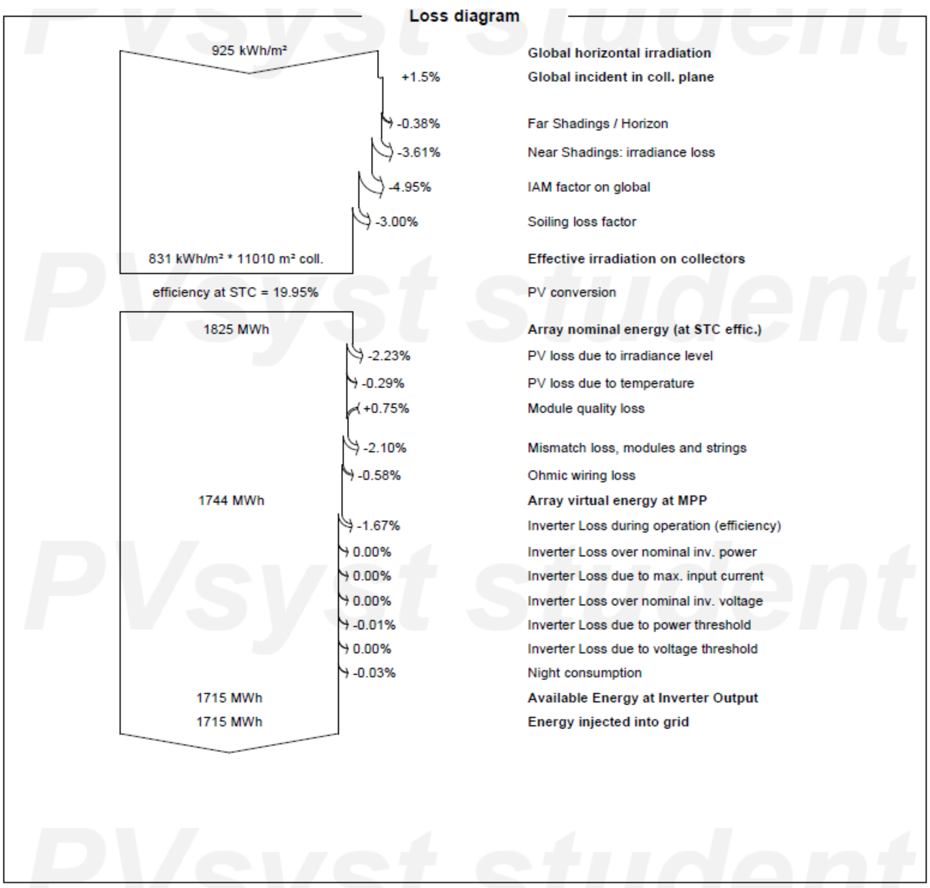
B4 Without horizon profile / whit snow losses (Idre Fjäll)



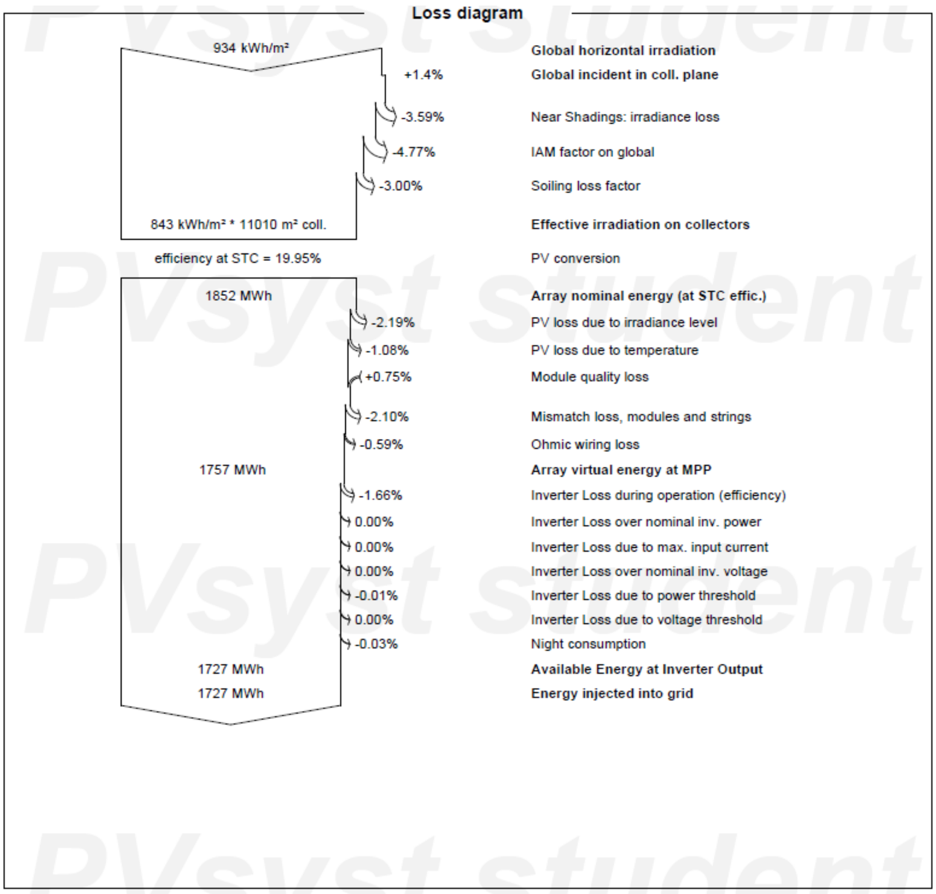
B5 Whit horizon profile / without snow losses (Borlänge)



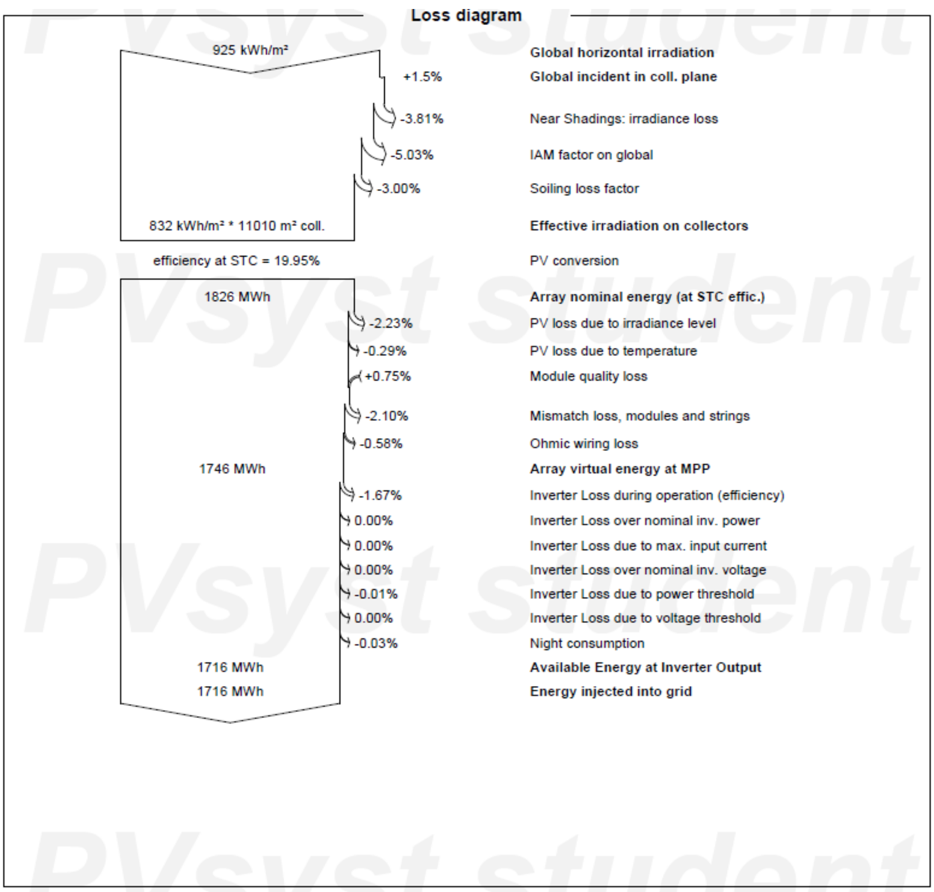
B6 With horizon profile / without snow losses (Idre Fjäll)



B7 Without horizon profile / without snow losses (Borlänge)



B8 Without horizon profile / without snow losses (Idre Fjäll)



Appendix C PV module datasheet

SPECIFICATIONS

Module Type	JKM390M-72H JKM390M-72H-V		JKM395M-72H JKM395M-72H-V		JKM400M-72H JKM400M-72H-V		JKM405M-72H JKM405M-72H-V		JKM410M-72H JKM410M-72H-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	390Wp	294Wp	395Wp	298Wp	400Wp	302Wp	405Wp	306Wp	410Wp	310Wp
Maximum Power Voltage (Vmp)	41.1V	39.1V	41.4V	39.3V	41.7V	39.6V	42.0V	39.8V	42.3V	40.0V
Maximum Power Current (Imp)	9.49A	7.54A	9.55A	7.60A	9.60A	7.66A	9.65A	7.72A	9.69A	7.76A
Open-circuit Voltage (Voc)	49.3V	48.0V	49.5V	48.2V	49.8V	48.5V	50.1V	48.7V	50.4V	48.9V
Short-circuit Current (Isc)	10.12A	8.02A	10.23A	8.09A	10.36A	8.16A	10.48A	8.22A	10.60A	8.26A
Module Efficiency STC (%)	19.38%		19.63%		19.88%		20.13%		20.38%	
Operating Temperature (℃)	-40℃~+85℃									
Maximum System Voltage	1000/1500VDC (IEC)									
Maximum Series Fuse Rating	20A									
Power Tolerance	0~+3%									
Temperature Coefficients of Pmax	-0.35%/℃									
Temperature Coefficients of Voc	-0.29%/℃									
Temperature Coefficients of Isc	0.048%/℃									
Nominal Operating Cell Temperature (NOCT)	45±2℃									

Appendix D Inverter datasheet

Technical Data	Sunny Highpower 100-20	Sunny Highpower 150-20
Input (DC)		
Max. PV array power	150000 Wp	225000 Wp
Max. input voltage	1000 V	1500 V
MPP voltage range / rated input voltage	590 V to 1000 V / 590 V	880 V to 1450 V / 880 V
Max. input current / max. short-circuit current	180 A / 325 A	180 A / 325 A
Number of independent MPP trackers	1	1
Number of inputs	1 or 2 (optional) for external PV array junction boxes	
Output (AC)		
Rated power at nominal voltage	100000 W	150000 W
Max. apparent power	100000 VA	150000 VA
Nominal AC voltage / AC voltage range	400 V / 304 V to 477 V	600 V / 480 V to 690 V
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 66 Hz	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 66 Hz
Rated grid frequency	50 Hz	50 Hz
Max. output current	151 A	151 A
Power factor at rated power / displacement power factor adjustable	1 / 0 overexcited to 0 underexcited	
Harmonic (THD)	< 3%	< 3%
Feed-in phases / AC connection	3 / 3-PE	3 / 3-PE
Efficiency		
Max. efficiency / European efficiency	98.8% / 98.6%	99.1% / 98.8%
Protective devices		
Ground fault monitoring / grid monitoring / DC reverse polarity protection	● / ● / ●	● / ● / ●
AC short-circuit current capability / galvanically isolated	● / –	● / –
All-pole-sensitive residual-current monitoring unit	●	●
Monitored surge arrester (type II) AC / DC	● / ●	● / ●
Protection class (according to IEC 62109-1) / overvoltage category (as per IEC 62109-1)	I / AC: III; DC: II	I / AC: III; DC: II
General Data		
Dimensions (W / H / D)	770 mm / 830 mm / 444 mm (30.3 in / 32.7 in / 17.5 in)	
Weight	98 kg (216 lbs)	
Operating temperature range	−25°C to +60°C (−13°F to +140°F)	
Noise emission (typical)	< 69 dB(A)	
Self-consumption (at night)	< 5 W	
Topology	transformerless	
Cooling method	OptiCool, active cooling, speed-controlled fan	
Degree of protection (according to IEC 60529)	IP65	
Max. permissible value for relative humidity (non-condensing)	100 %	
Features / function / accessories		
DC connection / AC connection	Terminal lug (up to 300 mm^2) / Screw terminal (up to 150 mm^2)	
LED indicators (Status / Fault / Communication)	●	
Ethernet interface	● (2 ports)	
Data interface: SMA Modbus / SunSpec Modbus / Speedwire	● / ● / ●	
Mounting type	Rack mounting	
OptiTrac / Integrated Plant Control / Q on Demand 24/7	● / ● / ●	
Off-grid capable / SMA Fuel Save Controller compatible	● / ●	
Warranty: 5 / 10 / 15 / 20 years	● / ○ / ○ / ○	
Certificates and approvals (selection)	IEC/EN 62109-1/-2, VDE-AR-N 4110/4120, IEC 62116, IEC 61727, EN 50549, C10/11, CEI 0-16, G99/1 (>16A), PO 12.3, ABNT NBR 16149	
● Standard features ○ Optional features – Not available Data at nominal conditions Status: 10/ 2020		
Type designation	SHP 100-20	SHP 150-20