

École polytechnique de Louvain

Handling of 3D data of UCLouvain buildings and computation of the solar energy production potential

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0.1 Abbreviations

<i>gCO₂eq</i>	Gram of carbon dioxide equivalent
kWh	Kilowatt-hour
kWp	Kilowatt-peak
kWh/y	Kilowatt-hour per year
PICC	Projet Informatique de Cartographie Continue
LIDAR	Light Detection And Ranging
ZEB	Zero Energy Building
NZEB	Near Zero Energy Building
REC	Renewable Energy Community
PV	Photovoltaic
BIPV	Building Integrated PV
BAPV	Building Added PV
QGIS	Quantum Geographic Information System
LST	Local Solar Time

Chapter 1

Introduction

1.1 Energy context

Analyzing the energy mix for electricity production in European countries, we realize that Belgium's situation is halfway between France's and Germany's. France relies mainly on nuclear power, which alone produces around 69% of the country's electricity while relying little on fossil fuels, which account for only around 7% in 2021 [1]. Germany, on the other hand, is developing electricity production using renewable energies such as wind power (22%), solar power (10.4%), and biomass (7.5%), but still produces around 44% of its electricity using fossil fuels (lignite, hard coal, and natural gas) in 2022 [2]. Between the two, Belgium is developing its electricity production with renewable energies, but still produces 23.4% with natural gas and 46.1% with nuclear energy in 2022 [3]. Belgium has therefore developed its electricity production proportionally less from renewable sources than Germany and produces more polluting electricity than France on average because of the important proportion of electricity produced with natural gas (Electricity produces on average $124 [gCO_2eq/kWh]$ ¹ in Belgium compared with $43 [gCO_2eq/kWh]$ in France over the last 12 months [4]). Even though Belgium produces more renewable energy than France and cleaner energy than Germany, the country must continue its efforts in the ecological transition in order to contribute to the achievement of carbon neutrality in the European Union before 2050 [5]. To succeed, the country will need a major energy transition. UCLouvain and in particular the project of Energy Transition Laboratory are dedicated to this transition.

One of the key objectives of UCLouvain Energy Transition Lab is to assess the solar potential of non-residential buildings to cover the electrical needs of the inhabitants of Louvain-La-Neuve. A preliminary study concluded that around 25% of those needs could be covered with these buildings alone. The solution to achieve this result would be to use building integrated photovoltaic (BIPV) and building applied photovoltaic (BAPV). This master thesis is part of this process and aims to help achieve this objective. The chapters depict the potential production of solar energy using PV panels on academic buildings in Louvain-La-Neuve with various models.

The UCLouvain is currently in the middle of its energy transition towards carbon neutrality. The goals of this transition are firstly to reduce by 60% the CO_2 emissions before 2030 in comparison with 1990 and secondly to reach carbon neutrality by 2035 [6]. Reaching this target necessitates, among others increasing the deployment of renewable energy sources including PV panels.

1.2 State of the art

This section summarizes the different works and publications related to the topic of this master thesis. The first half of the articles focuses on the case of Louvain-La-Neuve and the second half focuses more on the maths used

¹ $1 [gCO_2e]$ means $1 [g]$ of CO_2 equivalent, so it means that the amount of gas emitted will have the same global warming effect as $1g$ of CO_2 . Most of the time, if it is not specified, the impact is calculated for the 100 years following the emission.

to calculate the output of the panels based on their position and the sun's trajectories in the sky.

Work of the "Service des études du patrimoine immobilier"

Even though the subject is fairly recent, there are already various studies in this field. The "Service des études du patrimoine immobilier" has conducted a study about the roof surfaces of some academic buildings and parking lots of Louvain-La-Neuve. The selection of edifices used for this study is distinct from the one that we used for this master thesis. However, it may be interesting to look at the data obtained from the study to compare them with our data. For roof areas, the study obtained a total of 16 991 [m²] and 2 613 [m²] for the Leclerc car park alone. Based on these areas, the author calculates a total of 6 225 panels. However, the assumptions made for the surface areas and powers of the panels are different. In the end, the installed power is estimated at 1 741.23 [kWp]². It should be noted that this study mentions the possibility of using car parks, but only provides surface area measurements for one of them. A brief mention is made of the use of two fields for the installation of PV panels, without going into further detail about the potential installation.

Master thesis of B. Dardenne and X. de Liedekerke

Regarding this from a civil engineering point of view, it could be worthwhile to design a lightweight steel or wooden structure to cover parking lots with PV panels. This can offer shade during summer for the cars and provide electricity without using more space. This might also provide electricity for the plug-in stations for electric cars that are going to be more frequent in the future. In the civil engineering department of UCLouvain, some studies are looking for wooden structures to support PV panels. One example is the study of Xavier de Liedekerke de Pailhe and Benjamin Dardenne [7]. This is a master thesis in the Civil Engineering department and its name is "Conception et optimisation de structures agrivoltaïques via modélisation paramétrique". This work details the technical aspects of log-based structures for supporting PV panels over agricultural fields. This kind of solution can also be used to cover parking lots in Louvain-La-Neuve. It could also be interesting to study the possibility to create a steel or hybrid structure to set on the parking lots of Louvain-La-Neuve.

Master thesis of M. Deboot

Louis Deboot for the "Louvain School of Management" has also written a study about the possibility of a PV project in Louvain-La-Neuve [8]. This work goes more into the economic details of this kind of project.

The first part of the master thesis discusses the physics of the panels, how they transform solar energy into electricity, and how it is possible to compute the production with data on the irradiance of the sun. This part also explains the state of the art in terms of PV panel recycling in Belgium.

Then, the author explains the legal framework of solar energy in Belgium. The "Green certificates" that the Wallon region offers for the new installation of PV panels are described in detail. These certificates contribute significantly to the development of solar energy for private investors. The author really describes the different possible cases of installations and the rules for "Green certificates". This section also depicts three investment patterns for the private installation of PV panels. The first possibility is the investment from own funds. The second is the bank loan. The last one is the third-party investor. Each solution has its own advantages and disadvantages. The first is the economical optimum but it presents more drawbacks than the two other solutions.

In the case of UCLouvain, the Renewable Energy Community (REC) in which a project such as the installation of photovoltaic panels could be included is yet another case of investment. In the latter case, UCLouvain would

²kWp means kilowatt-peak, it is the power produced under standard conditions. The conditions require an irradiance of 1000W/m², a temperature of 25°C, and other conditions.

own the panels but would not consume the electricity produced. We can imagine that UCLouvain's investment would have the advantage of economies of scale by directly installing thousands of panels. We can also assume that the economic risks would also be low for UCLouvain, given the current trend in energy prices. Indeed, if UCLouvain were to offer low-cost electricity, it would be in the interest of many inhabitants to enter the REC corresponding to the panels on the academic buildings.

Another discussion of this work explains why the co-generation system and the installation of PV panels are complementary. The two co-generation plants of the UCLouvain are plants that produce heat and electricity at the same time from gas. Thanks to this hybrid production it has good efficiency and is inexpensive. The idea behind the use of both co-generation and PV panels is to produce heat and electricity during winter with co-generation and to produce most of the electricity with PV panels during summer when we do not need the heat of the co-generation. In this work, the question of solar production is explained in the case where the electricity produced is used directly to meet the energy demands of UCLouvain. However, in our work, we will be looking primarily at the impact of this production on the inhabitants of Louvain-La-Neuve, and then at what the impact might be for the university.

In terms of results, the master thesis suggests the installation of 5 150 panels on the University's roofs, for a total of 1.5 [MWp] of installed power. This would cost an estimated 1 660 023 [€]. For this, the author takes a price of 144 [€] and 46 [€] for the price of panel and support, respectively. Installation, cables, and inverters must also be taken into account. We can use the cost assumptions made here as a basis for estimating the costs of the installations we are discussing in this work.

The last and most developed part is about the description of three PV investment scenarios previously described in Louvain-La-Neuve. The economic aspect is detailed with precise data about net values, internal rate of return, pay-back, etc.

In general, this work was a useful source of information because it explains various topics directly related to the economic aspects of PV such as the "Green certificates", the different possible investments, or the cost for a given reduction of CO_2 .

Report of EnergyVille about Leuven

EnergyVille³ made a study about PV panels in Leuven in November 2020 [9]. The first discussion of the work just after the selection of the building, is the assumptions made for the usable surfaces of the facades and roofs. This discussion is relevant for this master thesis because we had to make the same kind of assumptions during the work.

During the main section of this article, the authors explain the computations that lead from the solar irradiance values in Leuven to the potential production of solar energy using BIPV on the different buildings of Leuven.

Another discussion explains the relation between the potential production of electricity and the consumption by districts. Some graphs show the number of buildings that should be fitted with PV panels in order to produce a certain percentage of the city's consumption. These graphs show four possibilities depending on the kind of surfaces we take into account.

Finally, the detailed results gave a benchmark to compare the results found for Louvain-La-Neuve. It is also interesting to compare the differences between the proportion produced by the facades and the roofs for the two cities.

³It is a collaboration between KULEuven, VITO, imec, and UHasselt that works in the field of intelligent energy systems and sustainable energy.

Study about PV in Lisbon

Thanks to the decreasing cost of panels, there is an increased interest in the use of PV panels with vertical (such as facades) or at least non-optimal inclination. Some estimations say that these surfaces could increase solar energy production by 10 to 15% for the city of Lisbon (considering the situation in 2019) [10].

The study of the "Universidade de Lisboa" explains the modeling used to compute the potential production of solar energy in Lisbon. It describes a shadow algorithm that can compute accurately the shadowing of an obstacle on a facade of a roof for a certain position of the sun in the sky. The algorithm computes the shadow for each hour of the year and then determines the "sky viewing factor". This factor corresponds to the proportion of the sun's positions in the sky for which a certain part of a building is illuminated by the sun. It is always between 0 and 1. The study represents the sky as a hemisphere. This hemisphere is divided into equiangular subdivisions. These subdivisions are comparable to the subdivisions of the earth in degrees of longitude and latitude but applied to a hemisphere representing the sky. They chose different angles for the division to go from a small number of possible positions for the sun in the sky to a bigger number. This factor gives a clear idea of how useful a surface would be to produce electricity with BIPV. However, the further we are from the equator, the less relevant this factor is. Indeed, if we consider a sky factor at the equator, it is relevant because the sun azimuth⁴ is equiprobable. However, for further latitudes north, the sun is mainly positioned in the south, west, or east direction and it is the opposite in the southern hemisphere.

The concept of "diffuse irradiance" is also mathematically developed in this paper. They mathematically describe the influence of this irradiance on solar production.

Finally, the last part shows the results of their research and the outputs giving an appreciation of the potential production of the different portions of facades of the buildings inside the city of Lisbon. Then, there is an analysis of the correlation between the computed and measured values of the production.

Integration of SURFSUN3D into a GIS-based application

This paper is an introduction to the use of SURFSUN3D in a GIS-based program [12]. During the first couple of pages, the authors describe some of the existing solar models that use 3D or 2.5D⁵ to compute solar data for surfaces. The methodology and the implementation of SUNSURF3D are then developed. The procedure is described in figure 1.1.

⁴The azimuth angle in this master thesis corresponds to the orientation angle from the south. It means that the south direction has a 0[°] azimuth angle, the west is +90[°], the east is -90[°] and the north is +180[°]. In general, the azimuth angle is always between -179[°] and +180[°]. This description is used by the European Commission in the Photovoltaic Geographical Information System [11].

⁵2.5D is an intermediate vision between 2D and 3D, it could be described as a set of 2D layers with different heights. For example, if we wanted to represent a 10m high house on a certain surface, there would be a layer at the ground level everywhere around the house and another layer 10m above the first one with the dimensions of the roof. However, this method has a lack of information about the surfaces of the facades.

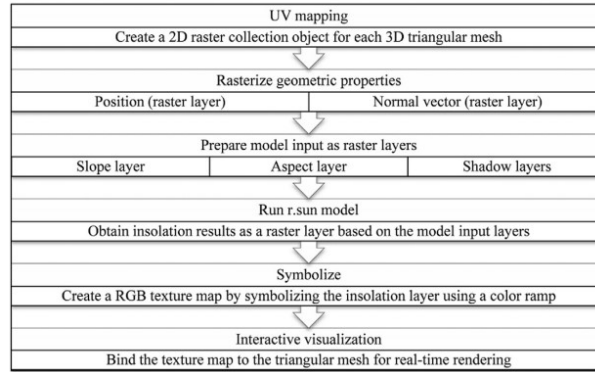


Figure 1.1: Working methodology of SURFSUN3D from [13]

After the description of all the methods used, the authors show the results for some of the buildings in Boston. The results are displayed with a color code. The green and red colors are for low and high irradiance zone, respectively. They also criticize the results given by the computation. This method gives good results and can be used with a variety of different inputs such as LIDAR data.

Estimations of PV potential in Namur and Lyon

Namur, the capital city of Wallonia, has developed a web platform that has modeled the buildings of the city. It is publicly available to anyone. There is the possibility to visualize the potential solar energy production or the approximated level of irradiance of a facade or a building. The color of a given surface corresponds to a PV potential [14].

The city of Lyon has also developed an interface dedicated to the estimation of the potential PV production. The website is a tutorial that explains and popularizes the steps to compute the potential of any building in the center of the city. The results are directly shown via a 3D colored map. The colors represent the potential of a given surface [15].

Computation of solar flux on the building by ray-tracing

The second section of this paper [16] explains the ray-tracing method using ArchiWIZARD Esquisse. The principle is quite simple. We follow the path of a given ray backward. Going from a target to the sky. The ray does not stop when it meets another surface because it can either bounce, diffuse or transmit when it reaches a surface. Then, we continue with the possible rays. This process allows us to get a precise idea of the irradiance that would reach a given point for a given solar orientation.

The following sections are more focused on giving an example of an application for this ray-tracing method. It gives convincing results for a simple example. The measures on-site, the reference software, and the ArchiWIZARD Esquisse have remarkably close results.

Study on the consolidation of PV in Wallonia

As a first step, this paper [17] explains the current PV situation in Wallonia and Brussels. Then, the authors give some values for solar radiation. There is also a description of the model used to derive the PV final production from solar irradiances. The following figure 1.2 shows how much an azimuth or a pitch angle influences the final production of a panel. In this case, the azimuth angle corresponds to the deviation from the south, with one difference: for an east-facing panel, the azimuth angle is considered to be negative, whereas for a west-facing panel, it is positive. The pitch angle is a synonym of the tilt angle.

		Tilt angle [°]									
		0	10	20	30	40	50	60	70	80	90
Deviation from South [°]	0	68	85	94	99	100	99	94	87	77	64
	10	68	85	94	98	100	98	94	86	76	64
	20	68	85	93	96	98	97	92	85	75	63
	30	68	84	92	95	96	94	90	83	73	62
	40	68	83	90	92	93	91	87	80	70	59
	50	68	82	87	89	89	86	82	75	66	56
	60	68	81	85	86	85	82	77	70	62	52
	70	68	79	82	82	79	76	71	65	57	49
	80	68	77	79	77	75	71	66	60	53	44
	90	68	75	75	73	69	65	60	53	46	39

Figure 1.2: PV Production factors from [17]

Then, a computation of the production of a reference installation is made and it finds an annual production of 995 [kWh/kWp] for an installation in Uccle facing south and with a pitch angle of 35[°]. This result is compared to the results measured in reality thanks to statistical tools.

The last part concerns the energy pay-backs, the reduction of CO_2 resulting from the installation, and some other economical aspects for the case of Wallonia and Brussels. This part was useful to understand more of the economic aspects behind the PV panels in the region of Louvain-La-Neuve.

1.3 Goals of the research

The goal of this master thesis is to analyze the potential benefits of installing solar panels on the roofs and facades of UCLouvain's academic buildings. The energy produced can be used for the need of the university but it will more likely be used to reduce the carbon footprint of the inhabitants of Louvain-La-Neuve and create a renewable energy community (REC). This electricity can reduce the carbon footprint of residents in two ways. Firstly, supplying solar-generated electricity to the residents of Louvain-La-Neuve reduces the carbon footprint of their existing electricity consumption. Secondly, this additional electricity production can be used to transition domestic consumption from fossil fuels to cleaner electricity. It can for example be switching from gas heating to heat pumps, or from gas cooking to electric cooking.

If we look at the statistics of 2020, we can see that in Belgium, 44.1% and 41.5% of space heating is provided by natural gas, oil, and petroleum product respectively. For water heating, 51.8% of the energy used comes from gas. And 27.6% of cooking in the country is made using gas [18]. These households' consumption account for 27% of the final energy consumption⁶ in the EU [19]. It represents an important CO_2 production.

The main goal of this master thesis is to quantify the photovoltaic (PV) potential production and the potential carbon reduction that can result from these installations. This work also tries to provide helpful information for the authorities to discuss future energy investments in Louvain-La-Neuve.

The first part of this study focuses on the computation of the roof and facade surfaces as well as a first estimation of the production of the panels on the roofs and facades with the PICC data. It provides a good order of magnitude of the potential use of the facades. The data gives an upper bound for the future PV potential production.

⁶Final consumption describes all energy in its final form (electricity, car fuel, etc.), whether it is used for transport, heating, etc.

The second part goes more into the details of the potential installation of PV panels on academic roofs with the LIDAR data. The computation is made by taking into account the shades of the obstacles around the panels. It also considers the production at different hours of the day to compute the yearly production. The results are, therefore, closer to reality than the previous section.

Part three develops the energy implications of such an installation for the inhabitants of Louvain-La-Neuve. To do so, we use load duration curves, as well as production indices such as the "self-consumption" rate and the "self-sufficiency" rate.

1.4 Introduction to the different uses of PV

1.4.1 BIPV and BAPV

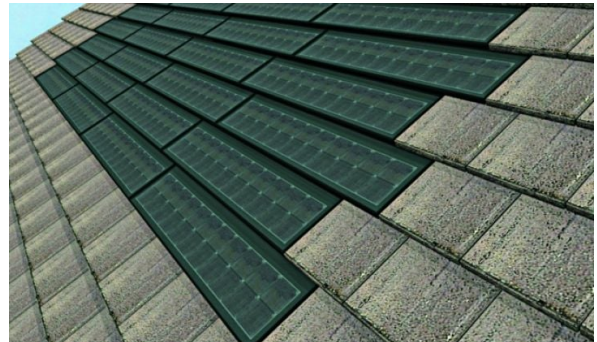
Building-integrated photovoltaic is the use of PV panels as construction material. This material can be directly integrated into facades or roofs. For example, some panels can be used to replace roofing slates or brick cladding. In the absence of these panels, another material would have to replace them to ensure certain properties such as water-tightness and this would generate additional costs. The initial investment cost is then reduced for the BIPV panels [20]. Moreover, BIPV panels come in a range of colors, making them easy to integrate aesthetically into buildings. This aspect is explained in the next section about the AGC technologies1.4.2.

The building-applied photovoltaic is different from the BIPV because the panels are added after the construction. The majority of the panels used nowadays are BAPV but there is sometimes confusion between the two in the literature. This technology is generally installed on roofs, but it can also be installed on facades. However, the unattractive appearance of the panels is often disturbing on facades.

For the academic buildings in Louvain-La-Neuve, it would be a BAPV in most cases, as the aim is not to rebuild all the buildings in the town. However, in the case of the towers on Place Croix du Sud, renovation work is planned. The facades of the towers need to be rebuilt, and this can involve replacing conventional materials with BIPV panels. This specific case will be discussed in chapter 3.



(a) BAPV on a roof from [21]



(b) BIPV as tiles [22]

Both technologies present some interesting advantages. The first one is that it produces on-site electricity. It then reduces the losses due to transmission from the production site to the consumption site. In the case of this master thesis, there would still be a certain distance between the electricity production sites and consumers, but the distance would still remain small. This technology also avoids taking extra space outside of the city to produce electricity.

1.4.2 AGC facade PV technology

AGC is an industrial group implanted in Louvain-La-Neuve, producing glass for the automotive and construction industries. The group also conducts research in the field of photovoltaics. One of the aims of this research is to develop BIPV panels that are visually close to building materials. It was in this context that we contacted Mr. Olivier Mal, who works on BIPV research for AGC. This section is based on discussions we had with him about their PV panel technologies.

First, there are a number of points that differentiate conventional PV panels from those developed by AGC. Where conventional panels use modules with a glass/polymer back sheet structure, AGC panels use glass/glass modules. Both technologies use silicon cells to generate electricity. Each of their panels can have customized dimensions to adapt to the geometry of a building, whereas the dimensions of traditional panels are fixed. It is not just the dimensions of their panels that can vary, but also the colors and shapes.



Figure 1.4: Example of colored BIPV panels [23]

In most cases, AGC works with small series, meaning that the dimensions of their projects are generally between 100 and 10 000m². These series are exclusively intended for commercial projects (in opposition to residential projects). In its current state, this kind of BIPV is more expensive than conventional BAPV. Nonetheless, this additional cost can be at least partially offset by the savings made on materials. In terms of lifespan, AGC technologies are guaranteed for 20 to 25 years. Even if the company is open to innovating technologies such as second or third-generation panels, the current lifespan of these panels is shorter and not sufficient for BIPV applications.

In general, BIPV supports conventional PV and technologies that reduce energy consumption, such as heat pumps and insulation. Often, the space available on the roof for conventional PV is not sufficient to achieve NZEB⁷ or ZEB⁸. In this case, the use of BIPV on the facade allows the lateral surfaces of the building to be used efficiently.

From a financial point of view, these panels cost between 225 and 350 [€/m²] depending on the customer's needs. They can be more expensive if the PV modules are integrated into double or triple-insulating glazing. However, prices are influenced by the batch size to produce. Larger quantities mean lower costs. The future should see the arrival of larger and larger projects, which will have the effect of increasing automation, thereby lowering prices. In terms of installation techniques, the only difference with a conventional facade is the need to integrate cable routing.

⁷Nearly Zero Energy Building

⁸Zero Energy Building



Figure 1.5: Example of flat glass including PV cells from [23]

Chapter 2

Analysis of rooftops and facades with PICC data

2.1 Introduction to software and data used

2.1.1 QGIS

QGIS also known as Quantum Geographic Information System is an open-source software that has a large variety of applications. Its primary use is map creation and manipulation. From data such as Google Maps, the user can create maps and obtain data such as surface area, elevation, and sinking data. In this part of the work, QGIS was used primarily for length and area measurements. It can generate 2D or even 3D maps. The software provides a lot of tools and packages that give various possibilities for the users. The selection, measurement, and manipulation of the features on the map are accessible without extensive training. The data used to create the maps of Louvain-La-Neuve are PICC data. We only had access to the data of Louvain-La-Neuve. However, thanks to public data, we can also create maps on the scale of a house, a village, a country, or even the entire world. In QGIS, conventional orientation is used, which means that the north is at the top of the map.

QGIS is a software program that works with an overlay of layers. Each layer can contain different information. Layers can be vector layers, raster layers, mesh layers, etc. For this first analysis, we use vector layers exclusively, as we only need polygons, lines, and points.

For this section, we mainly used the "Field calculator" to get some quick data about the buildings of Louvain. We also created new layers to get the length of the facades easily.

2.1.2 WalOnMap

WalOnMap is an online platform developed by the SPW ("service publique de Wallonie") that contains a large number of maps of the entirety of Wallonia. There are maps from various times going from 1777 to nowadays. This platform also gives the possibility to switch views between satellite images, IGN, Google Maps, etc. Street view is also available. There is the possibility to measure distances and surfaces as well.

Another useful option is the addition of complementary data available directly on WalOnMap or uploaded from an external source. For example, the data from the PICC is relevant to this study. The advantage of this platform is that the data sets are regularly updated. All this is freely available.

2.1.3 PICC

The PICC or (Projet Informatique de Cartographie Continue) is a 3D map of the entire Wallonia. It gives a great deal of information such as the height of the terrain, the height of the roofs, or the horizontal surfaces of the roofs. The project has three-dimensional measurements of the buildings with a precision of under 25cm. There is also information about the assignments of the buildings. We mainly used this data for the first part of our master thesis.

The PICC data has been compiled from various sources. The first source is the use of aerial photos by private companies to reconstruct tridimensional models. Although data is lacking, it can be assumed that the model used is multi-view stereo. Secondly, we have also used modern data from the Walloon region. Finally, company surveys were also used for the PICC data.

2.2 Selection of the buildings

For this part of the master thesis, the data used are the PICC 2019 data and we manipulated them with QGIS. This data set as well as the CaBu 2020 were provided by Baptiste Delhez doctoral student with Pr. Defourny from the Earth and Life Institute in the Bio-engineering faculty of UCLouvain. The CaBu is a data set rather similar to the PICC. To make the selection between these two possibilities, we investigated the small differences directly in QGIS. After a closer look, we noticed some slight differences for some buildings. The PICC is more accurate for some places like the "Place des sciences" which is considered a constructed area for the CaBu. So even though the CaBu data are more recent than the PICC data, we chose to use the PICC.

The PICC data form the base layer from which we have worked for this section. Using QGIS, we were able to manipulate this layer to make various selections and manipulations. The first operation was to select only the buildings of Louvain-La-Neuve. In order to do this, we draw the boundaries of the 8 districts of Louvain-La-Neuve and we removed the remaining buildings, most of which were located in Ottignies. Here are the names of the districts.

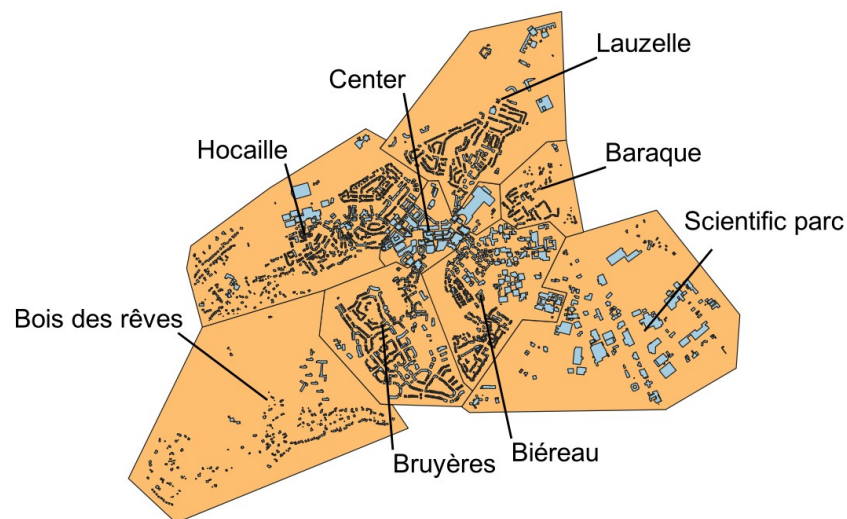


Figure 2.1: Districts of Louvain-La-Neuve

1. Baraque

2. Biéreau
3. Bois des rêves
4. Bruyères
5. Center
6. Hocaille
7. Lauzelle
8. Einstein scientific park

Figure 2.1 is an overall view of the city.

Then, thanks to the attribute table, we found the purposes of the buildings. We selected only the academic buildings of the city. We then chose to remove some buildings such as the primary and secondary school to focus on purely academic buildings of the UCLouvain. In the end, there were only three districts with academic buildings: Biéreau, Center, and Hocaille. Figure 2.2 shows the global map with only the academic buildings.

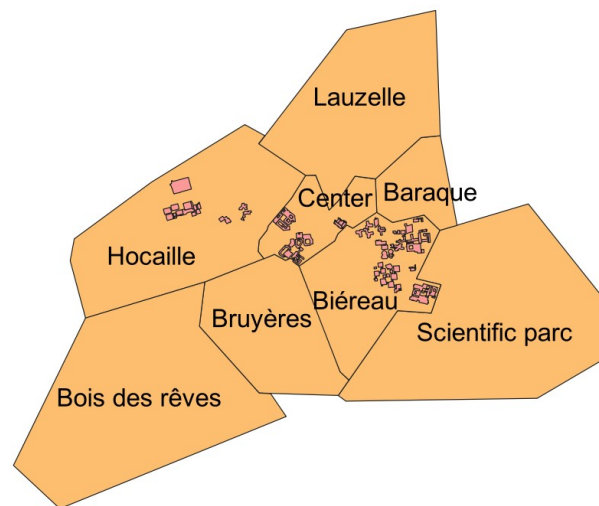


Figure 2.2: Districts of Louvain-La-Neuve

After this, we listed the buildings by district. Some of the large buildings such as the main building of the Blocry were divided into smaller parts. The final look of the Hocaille district is represented in figure 2.3.

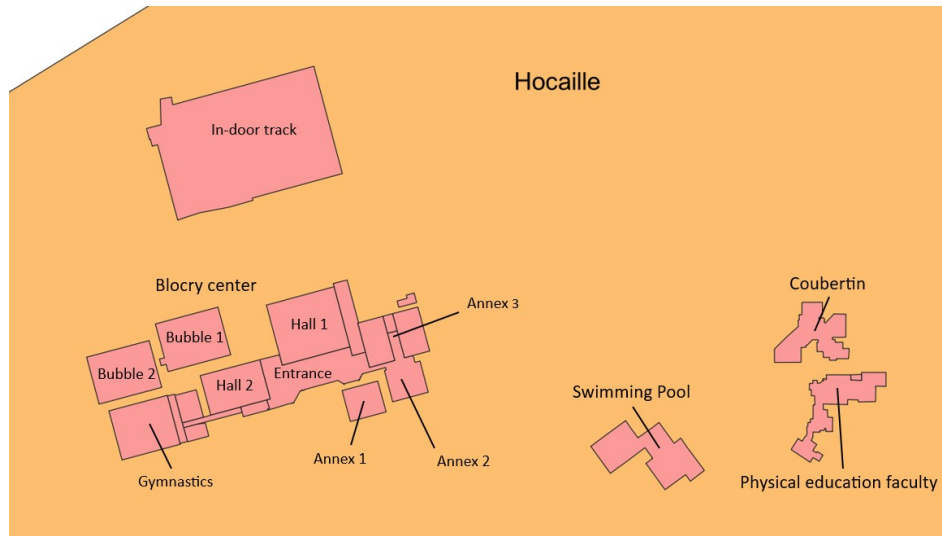


Figure 2.3: Denomination of the buildings in the Hocaille district

The center district is visible in figure 2.4.

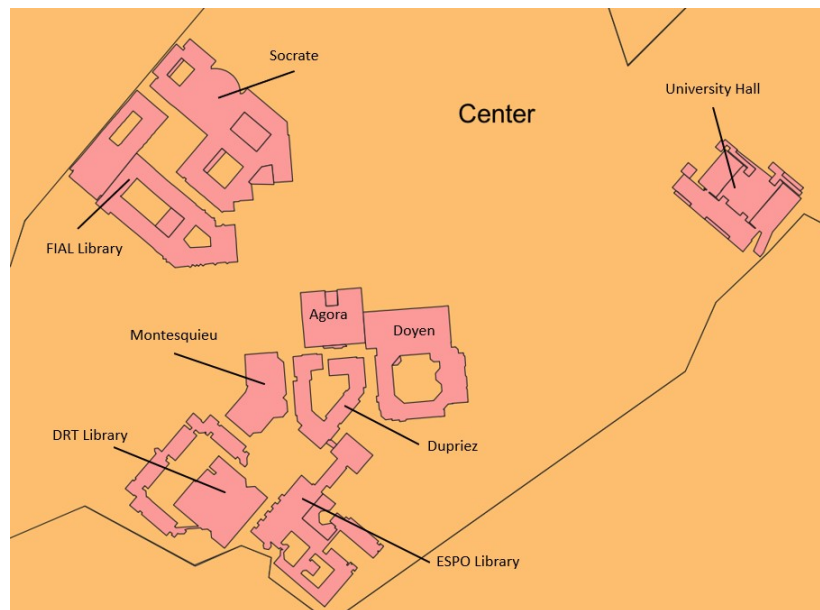


Figure 2.4: Denomination of the buildings in the Center district

Finally, the Biéreau district map is divided into two parts for the representation here. The northern part is visible in figure 2.5 and the southern part is in figure 2.6.

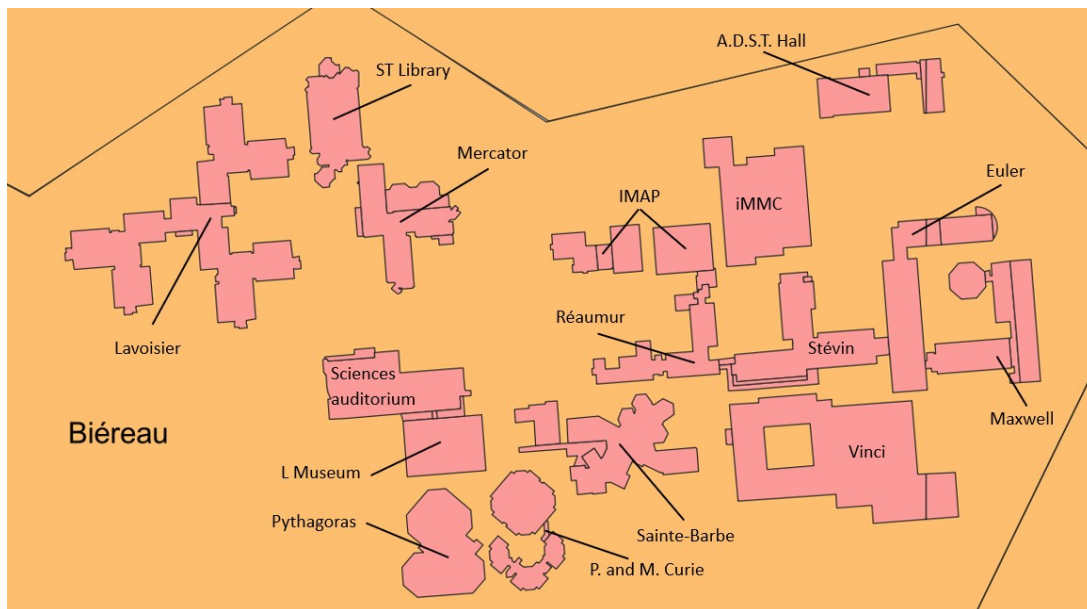


Figure 2.5: Denomination of the buildings in the northern part of the Biéreau

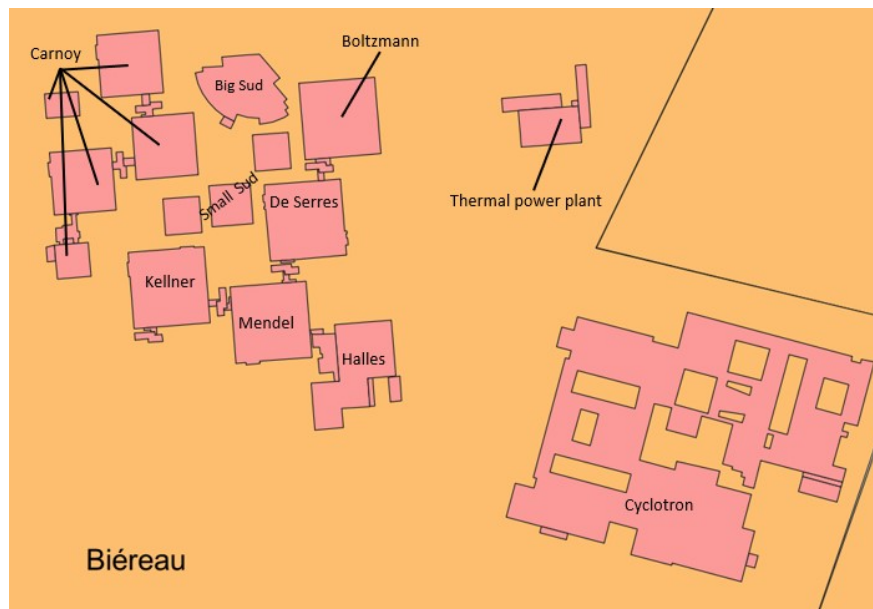


Figure 2.6: Denomination of the buildings in the southern part of the Biéreau

We decided to make different layers for each district of the city to have data about each of them. The QGIS project consists of 4 layers for this part. There is a layer for each district containing academic buildings (Biéreau, Center, Hocaille) and a final layer that shows the boundaries of each district. Once the academic buildings had been selected, it was important to remove those unsuitable for the installation of PV panels. For example, we removed the greenhouses from the Faculty of Agronomy. Finally, a selection of buildings suitable for the installation of PV panels is obtained.

In the end, the remaining buildings represent a small fraction of the buildings in their respective district. For the Biéreau, academic buildings are located on 99 out of the 610 surfaces (16%). For the center, it is 27 out of the 156 (17%) surfaces and for the Hocaille district, it is even less as it is 22 out of 1 159 (2%). However, it represents a large surface as we will see in the next subsection.

2.3 Measurements of surfaces

After the selection of the academic buildings, we can calculate all the surfaces that we need to measure in order to determine the PV potential production. First, assumptions are made about the usability of the surfaces.

- We consider 1m² PV panels.
- From the previous assumption, we know that surfaces with a width or a length smaller than 1m are not taken into account.
- The roof surfaces are assumed flat and horizontal. The difference between the horizontal equivalent surfaces and the pitched surface is not really important as the majority of the academic buildings have flat roofs in Louvain (especially in the Biéreau district¹). Moreover, a coefficient will be used in the section about the potential production to take this difference into account.
- The facades are considered flat vertical surfaces. In the large majority of the facades, these assumptions are true or the facades offer equivalent surfaces.

Due to these assumptions, we consider the surfaces as a good order of magnitude rather than precise and accurate estimations.

To calculate the roof surfaces, we can use the "Field calculator" to add the perimeter and the area data for each feature of the layer. Then, we used the "Statistical summary" to get the sum of the areas of the different layers. It is also possible to use the selection tool to get the area of a given building. These tools were especially useful for the areas but not very efficient for the perimeters as some areas are part of a larger building or have adjoining buildings.

To find the right surfaces for the facades, it is not enough to multiply the perimeter with a global width. For a large number of buildings, the bottom of the top of facades are not flat and the height might differ from one section to another. Moreover, the presence of fused buildings makes some surfaces inoperable. This is the reason the decision was made to find the width of each portion of the facades of the buildings and then multiply it by the mean height of the section. To achieve this, we had to use the QGIS tool "Polygons to lines" which splits the polygons from a given layer into a new layer that only contains lines. From these lines, we can use the "Explode lines" tools that broke the lines into individual segments. The segments were saved in the layers "Exploded". From these layers, we used the labels tool to create a new label for each line that show the length of it. Thanks to this, the measure of the length of the lines of the facades directly appeared on the layer in QGIS as represented in figure 2.7. Sometimes, it is necessary to zoom in on a facade to see its length if it is smaller than a few meters.

¹22/26 or 85% of the academic buildings in this district have exclusively flat roofs.

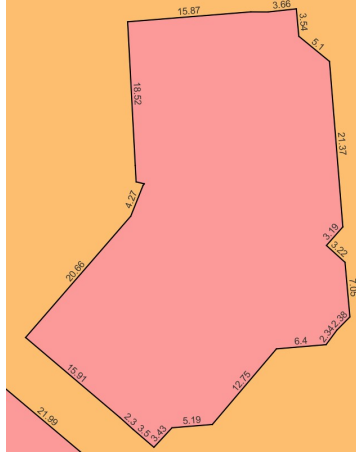


Figure 2.7: Overhead view of the Montesquieu building with the length of the facades segments

Then, we used available data on WalOnMap and in the point layer of the 2015 version of the PICC to get the height of each facade segment manually. It would have been possible to automatically get the mean height of the segments from the QGIS layers. However, the large number of irregular cases made it difficult to implement and get accurate results. Among the irregular cases, we can mention a few examples:

- New buildings are not present on the 2015 points cloud so there is no data about the height
- Some surfaces joined together so it would count twice the area of the surface when in reality neither of the surfaces are exploitable.
- Awnings, covered courtyards, and elements like this would count as part of the buildings with facades. However, in reality, these surfaces cannot be covered with panels.

For all these reasons, the decision was made to manually compute the height of the surface segments of the academic buildings. This was very time intensive but gave more representative and qualitative results.

For the measurement of the facade surfaces, we decided to use 4 different orientations (North, South, West, and East). The northern orientation is between $] - 179^\circ, -135^\circ[\cup]135^\circ, 180^\circ]$, east is between $] - 135^\circ, -45^\circ]$, south is between $] - 45^\circ, 45^\circ]$ and finally, west is between $]45^\circ, 135^\circ]$. Note that for the computation of the solar potential production, we are going to consider a mean value of production on the entire interval, not the single value corresponding to the mean azimuth of the interval.

2.3.1 Results

First of all, thanks to the analysis of the overhead views of the city of Louvain-La-Neuve we can say that with a total of 5 593 buildings in the city², the roofs represent a total surface of around 770 000 [m²]. If we only consider the academic buildings this time, the total is around 150 000 [m²]. This means that the academic buildings account for 19.5% of the roof surfaces even if they only account for 3.6% of the buildings in the city.

The results for the Biéreau district are displayed in figure 2.1. Each building has a total facade surface and the last row summarises the total surface for each orientation and for the roof surfaces.

²The total of 5 593 includes all the districts (Baraque, Biéreau, Bois des rêves, Bruyères, Center, Hocaille, Lauzelle, and Einstein Scientific park)

Biéreau	North [m ²]	East [m ²]	South [m ²]	West [m ²]	Total facades [m ²]	Roof surfaces [m ²]
Cyclotron	3 328.38	3 658.82	3 540.34	2 733.23	13 260.76	12 491.10
Lavoisier	1 860.95	2 098.50	2 210.61	2 387.11	8 557.16	4 558.14
ST Library	642.29	1 076.83	653.08	853.68	3 225.88	1 365.29
Mercator	742.48	1 008.64	740.99	1 016.69	3 508.79	1 756.26
Sciences auditorium	1 113.22	557.28	615.79	459.41	2 745.70	2 021.73
L Museum	368.34	442.43	894.36	441.96	2 147.09	1 137.69
Pythagoras	401.80	335.69	423.35	361.78	1 522.63	1 703.43
P. and M. Curie	732.46	760.80	678.93	769.40	2 941.58	1 317.40
Sainte-Barbe	1 044.74	984.12	1 181.13	878.12	4 088.10	2 333.62
Réaumur	973.07	882.94	977.88	813.76	3 647.64	1 282.27
IMAP	940.65	839.81	917.26	863.32	3 561.04	1 479.64
iMMC	491.31	680.92	494.23	674.43	2 340.88	2 442.39
A.D.S.T. Hall	481.97	322.79	474.53	269.99	1 549.28	1 121.35
Euler	639.79	660.22	641.01	618.28	2 559.29	1 947.64
Maxwell	969.39	789.63	939.82	816.22	3 515.06	1 973.92
Stévin	803.63	404.72	750.04	474.35	2 432.75	2 035.14
Vinci	1 235.98	932.66	1 434.37	978.81	4 581.82	4 880.92
Big Sud	422.19	439.25	735.12	494.23	2 090.80	1 168.17
Small Sud	415.01	448.46	450.18	415.76	1 729.40	1 119.70
Carnoy	2 046.61	2 005.66	1 847.21	2 003.76	7 903.24	3 853.61
Boltzmann	761.76	803.15	731.05	805.14	3 101.10	1 597.81
Kellner	978.66	898.03	938.96	1 021.88	3 837.53	1 671.32
Mendel	899.99	925.25	966.22	844.06	3 635.53	1 590.37
Halles	396.92	414.25	423.71	400.61	1 635.49	1 714.13
De Serres	763.80	780.40	662.80	794.80	3 001.80	1 544.44
Thermal power plant	234.22	214.54	247.04	258.72	954.51	965.46
Total Biéreau	23 689.59	23 365.77	24 569.99	22 449.49	94 074.84	61 072.94

Table 2.1: Summary of the surfaces for the Biéreau district

While doing this, we also classified each roof into 3 categories. Roofs can either be "flat", "pitched" or "pitched and flat". This classification is going to help in the potential production steps.

The results for the district Hocaille are presented in table 2.2. The 0 values can be explained :

- The 0 for the facade surfaces means that the part of the building is totally adjoining another building on this side.
- The 0 for the roof surface of "Annex 2" comes from the fact that the roofs of this part and of the "Entrance" are represented as a single surface. Then, it was measured all at once.
- For the case of the buildings called the "bubbles", it was decided to only consider the roof surfaces as the facades of the buildings are pitched. That is the reason the facade surfaces are set to 0.
- For "Bubble 1", the total surface is divided into four parts. Each of them has a different pitch angle and the total energy production is computed by considering the irradiance value of each of them.

- For "Bubble 2", the computation is a bit more difficult. The decision was made to assume a partial coverage of the surface such as the one presented in figure 2.8. However, it is important to note that due to the lack of information, the 3D geometry of the bubble is not totally accurate.

Hocaille	North [m ²]	East [m ²]	South [m ²]	West [m ²]	Total facades [m ²]	Roof surfaces [m ²]
In-door track	1 490.27	1 023.14	1 525.84	1 051.74	5 090.99	10 204.30
Bubble 1	/	/	/	/	/	1 721.63
Bubble 2	/	/	/	/	/	1 671.79
Hall 1	724.99	345.94	359.42	439.79	1 870.14	2 879.55
Gymnastics	769.70	381.96	921.17	407.52	2 480.35	2 498.11
Hall 2	378.67	105.41	261.30	285.89	1 031.27	1 484.02
Entrance	59.52	/	430.27	/	489.79	2 823.26
Annex 1	92.60	80.26	92.60	80.26	345.72	630.81
Annex 2	/	99.90	126.24	87.62	313.76	/
Annex 3	394.35	403.51	37.18	/	835.04	1 442.77
Swimming Pool	404.24	376.03	297.23	453.92	1 531.41	1 936.49
Coubertin	506.47	494.10	543.39	374.61	1 918.57	1 366.94
Physical education faculty	981.52	910.10	998.05	684.95	3 574.63	1 514.55
Total Hocaille	5 802.34	4 220.34	5 592.71	3 866.28	19 481.67	30 174.22

Table 2.2: Summary of the surfaces for the Hocaille district

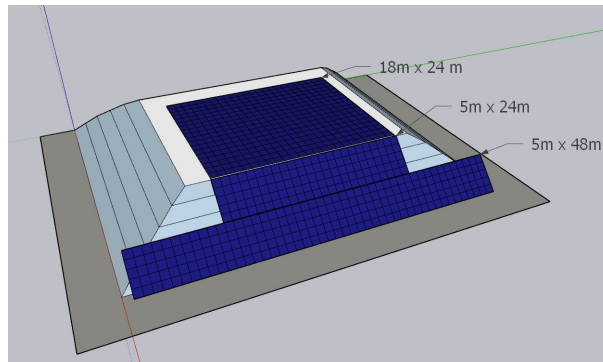


Figure 2.8: 3D model of the PV coverage used on the "Bubble 2" from a southern point of view

The idea behind this repatriation is to use the top to install flat panels that cover 25% of the surface with flat panels and the southern wall with pitched panels. The pitched panels are divided into two parts with a width of 23.66[m] and 47.32[m] that are cropped to 24[m] and 48[m]. The other lengths are also rounded. However, it should be noted that the installation of such panels would require structural reinforcement such as a light steel structure due to the stresses that the structure would withstand [24]. This additional structure would increase the investment cost which reduces the profitability.

The table 2.3 shows the results for the Center district.

Center	North [m ²]	East [m ²]	South [m ²]	West [m ²]	Total facades [m ²]	Roof surfaces [m ²]
University Hall	2 058.30	2 368.44	1 401.02	2 075.92	7 903.68	3 352
Socrate	1 683.30	1 167.93	2 038.71	1 935.69	6 825.63	5 335
FIAL Library	2 011.51	1 466.82	2 381.91	1 382.74	7 242.98	4 701
Montesquieu	128.27	425.48	341.79	218.25	1 113.80	1 447
Doyen	753.05	1 125.86	953.60	931.93	3 764.45	3 238
DRT Library	2 147.04	1 672.34	2 330.36	1 519.41	7 669.15	3 413
Durpriez	450.42	958.14	517.73	863.93	2 790.22	1 602
Agora	375.78	232.13	354.39	477.74	1 440.04	1 516
ESPO Library	1 847.00	1 748.14	1 710.04	1 591.23	6 896.41	3 451
Total	11 454.68	11 165.28	12 029.53	10 996.83	45 646.33	28 055

Table 2.3: Summary of the surfaces for the Center district

The following table summarizes the total surfaces available for every district.

Districts	North [m ²]	East [m ²]	South [m ²]	West [m ²]	Total facades [m ²]	Roof surfaces [m ²]
Biéreau	23 689.59	23 365.77	24 569.99	22 449.49	94 074.84	61 072.94
Hocaille	5 802.34	4 220.34	5 592.71	3 866.28	19 481.67	30 174.22
Center	11 454.68	11 165.28	12 029.53	10 996.83	45 646.33	28 055.00

Table 2.4: Summary of the surfaces for districts

2.4 Potential production

Now that all the measurements are done, the model that will be used to describe the electrical production can be discussed. In order to do this, there will be a distinction between three different types of surfaces. The first one is the flat roof. It requires a special installation where we have pitched rows separated from one another to optimize the surface without adding gigantic structures. The second surface is the pitched roof where we assume a full coverage of the surface with PV panels. The last surfaces are the facades. For this surface, we will discuss and compare the coverage with a standard panel or with a BIPV produced by AGC. After this, there will be a conclusion about the total production taking all surfaces into account.

To get data about solar production in Louvain-La-Neuve, we used the website of the European Commission [11]. The solar radiation database used is the PVGIS-SARAH2. For the set-up, we consider standard Si-cell panels with a peak power of 0.30 [kWp] for 1 [m²]. We assume a system loss of 14% which corresponds to the losses between the power production and the power delivered to the grid. All the panels have a slope and azimuth angle that depends on the location. Once we know the orientation of a surface, we can compute the yearly PV energy production that takes into account the system losses, the losses due to the angle of incidence, the temperature, and the low irradiance difference³. It also considers the positive spectral effect.

2.4.1 Flat roofs

For flat roofs, in the first time, we determined the best settings for the rows to optimize production and minimize the shadowing between the rows. Two parameters are required, the first one is the spacing between the rows and the second is the pitch angle of the panels. After searching the literature, what emerged is that the parameters depend sensibly on the latitude of the installation. After looking for information, we found a recommended minimum spacing for cities in the United Kingdom [25]. The city of Plymouth is located at a latitude of 50.3° while

³The low irradiance difference represents the difference between the standard irradiance and the effective irradiance

the city of Louvain-La-Neuve is at a latitude of 50.67° so the values for the spacing are close. The data for a panel $1\text{m} \times 1.675\text{m}$ in landscape orientation⁴ in the English city are written in the following table.

Pitch angle $[\circ]$	Minimum spacing [m]
20	1.359
25	1.661
30	1.940

Table 2.5: Minimum spacing in relation to the pitch angle between rows for 50.3° latitude

When we talk about spacing here, we consider the distance between the foot of one row to the foot of the next one. Even if the literature gives us a recommended value for the spacing, we have calculated the potential output for different spacing and inclination angles. For the spacing, we considered four cases, 1m , 1.5m , 2m and 2.5m . For each case, we took into account different angles. For the 1m spacing, we assumed flat panels, for the 1.5m and 2m spacing, we considered 20° , 25° and 30° . And finally, for the 2.5m , we considered 20° , 25° , 30° , and 35° because the wider spacing means that larger angles can be considered.

Thanks to the information provided by the European Commission [11], we can get the global irradiance data for each hour in a year for given orientation settings, the latitude and longitude values of Louvain-La-Neuve, and the solar height. We decided to orientate the panels with an azimuth angle of 0° (facing south) and we considered four different pitch angles: 0° , 20° , 25° , and 30° . For the latitude and longitude, we took 50.670°N , 4.615°E which corresponds to the Place de l'Université of Louvain-La-Neuve. The database is the same as before (PVGIS-SAHARA2) and we decided to select the most recent year available which is 2020.

Then, we obtained three spreadsheets. Each line of the spreadsheets corresponds to an hour in the year 2020 for which there is the global solar irradiance on the plane $[\text{W}/\text{m}^2]$, the sun height [degree], the air temperature $[\text{C}^\circ]$, and the wind speed $[\text{m}/\text{s}]$. Thanks to the use of Python and the "openpyxl", we can do a small code A.1 to find the fraction of sunlight that reaches a row of panels located behind another row. In order to compute the loss of energy due to shadowing, we take five "checks points" equally spread all over a panel. For the check points, we are going to check each hour to see if the sun is high enough so that the check point is no longer in the shade. The configuration for a 2m spacing is represented on the figure 2.9.

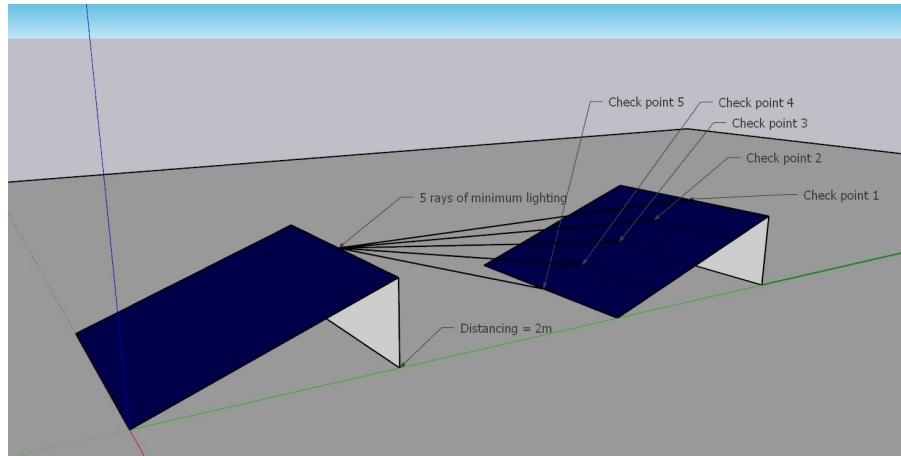


Figure 2.9: Configuration of the "check points" of a panel with 2m spacing

⁴Landscape orientation means that the row has a diagonal length of 1m

Once we know the position of our check points, we can calculate the minimum sun elevation angles for each configuration. This elevation angle corresponds to the angle between the "ray of minimal lighting" (that goes from the top of the previous panel row to a given check point) and the horizontal surface. It is expressed in degree. We find the following angles.

Pitch angle [°]	Spacing [m]	CP 1 [°]	CP 2 [°]	CP 3 [°]	CP 4 [°]	CP 5 [°]
20	1.5	0	3.84	9.37	17.78	31.30
25	1.5	0	4.72	11.36	21.07	35.40
30	1.5	0	5.56	13.21	23.87	38.44
20	2	0	2.76	6.34	11.12	17.78
25	2	0	3.39	7.74	13.42	21.07
30	2	0	4.01	9.08	15.52	23.86
20	2.5	0	2.15	4.79	8.09	12.29
25	2.5	0	2.65	5.86	9.83	14.80
30	2.5	0	3.13	6.90	11.47	17.05
35	2.5	0	3.55	7.76	12.77	18.74

Table 2.6: Minimum solar elevation for the lighting of the check points (CP)

As we can see, the minimum elevation for check point 1 is 0 because we consider the solar rays to be parallel. The spacing of 1[m] with a pitch angle is not in the previous table as all the elevation angles would be 0[°]. As the minimum solar elevation for the lightning of check point 4 for a tilt angle of 20 [°] is 11.12 [°], all the solar positions with lower elevation angles do not illuminate check point 4. These positions are all the positions of the solar curves inside the red rectangle in figure 2.10. The general figure represents the solar curves corresponding to the latitude and longitude of Louvain-La-Neuve. The horizontal axis of the figure represents the solar azimuth⁵ and the vertical axis represents the solar elevation in [°]. The blue curves represent the solar positions (Elevation and azimuth angles) for the 20th or 21th of each month. The red curves represent the hours of the day. In the case of these curves, in order to maintain the same definition of time, the convention is that noon corresponds to the moment when the sun is directly south. This time is called "Local Solar Time" or LST. Using these curves, we can find out the exact position of the sun in the sky at a given time of year. These curves will be used to analyze the LIDAR data in the next chapter.

⁵It is important to note that depending on the source of information, the azimuth angle might have different definitions. In this case, the information provided by the University of Oregon considers that the north is at 0[°] of azimuth angle and the south and 180[°]. However, the European Commission considers the south as 0[°] and the north as 180[°] azimuth. The azimuth angle is sometimes also called "Hour Angle" or HRA.

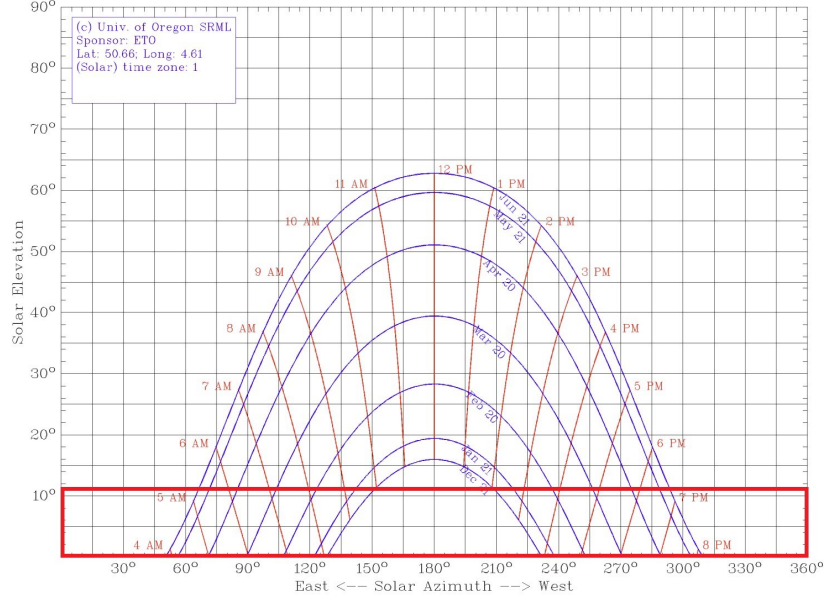


Figure 2.10: Solar curves of Louvain-La-Neuve and shaded positions for check point 4 (pitch angle: 20 [°] and spacing of 2[m]) form [26]

Thanks to these angles, we can check if the elevation angle is large enough to reach the check points. If it is the case, the global irradiance is added to a total that represents a modified irradiation that reaches the point during a year. To give an example, on the 1st of September, at 6:10 a.m., the data provided indicates that the elevation angle is 11.14[°] and the global irradiation is 83.51[W/m²]. In this case, the sunlight reaches check points 1 to 4 if the pitch angle is 20[°] and the spacing is 2[m], so we add the 83.51[W/m²] to the sum corresponding to these check points. Once we have the total for each check point and for each angle, we can compute a mean value for the three angles. In order to do this, each point is weighted with a coefficient. The check points 1 and 5 are given a coefficient of 1/8 because they are at the edge of the panels and the check points 2 to 4 are given a weight of 1/4 the result is summarized in the following equation.

$$Mean = \frac{sum_{cp1} + 2sum_{cp2} + 2sum_{cp3} + 2sum_{cp4} + sum_{cp5}}{8} \quad (2.1)$$

The sum_{cpi} corresponds to the sum of the global irradiation that reached the check point number "i". Once we have a mean, we can divide it by the value of the sum_{cp1} to know the percentage of the sunlight that really reaches a row of panels hidden behind another row. The results can be found in the following table 2.7.

Array pitch[°]	Spacing[m]	Mean irr[W/m ²]	Fraction received[-]	Yearly PV prod[kWh]	Fract*Prod[kWh]
0	1	/	1	896.08	896.08
20	1.5	1 222 346.27	0.877	1 028.45	901.54
25	1.5	1 189 703.34	0.839	1 047.72	879.27
30	1.5	1 154 826.42	0.806	1 061.33	855.09
20	2	1 358 191.36	0.974	1 028.45	1 001.73
25	2	1 360 858.81	0.960	1 047.72	1 005.77
30	2	1 353 033.55	0.944	1 061.33	1 001.85
20	2.5	1 372 920.89	0.984	1 028.45	1 012.59
25	2.5	1 379 198.57	0.968	1 047.72	1 014.68
30	2.5	1 374 441.30	0.958	1 061.33	1 016.57
35	2.5	1 345 921.02	0.968	1 069.27	1 035.55

Table 2.7: Production results for the different pitch angles

The third column corresponds to the results of the equation 2.1 for the three pitch angles. The fourth one is the ratio between the mean and the sum for check point 1 of every angle. The fifth column is Yearly production for an installation of 1 [kWp] without any shadowing from the rows⁶. The last column is the product of the third and fourth rows. Note that for the spacing of 1[m], we do not calculate the ratio because the rows do not shade each other.

When we look at these results, we see that the ideal situation for optimizing power production is one where the spacing is 2.5[m] and the angle of inclination is 35[°]. However, an arrangement like this requires more surface area than an arrangement with a spacing of 1.5[m] or 2[m]. If we divide the production that takes shadow into account by the spacing of the lines, the most optimal arrangement corresponds to the case where the spacing and the angle are 1.5[m] and 20[°]. The corresponding yearly production is 601.03[kWh]. That for 2[m] and 25[°] becomes 502.88[kWh], that for 2.5[m] and 35[°] becomes 414.22[kWh] and that for 1[m] remains 896.06[kWh].

It is therefore assumed that the optimal situation corresponds to the case where a flat roof is totally covered with horizontal panels. However, it is necessary to maintain a certain angle of inclination so that the panels do not accumulate dust, snow, or even water, which can reduce panel output or even damage them in some cases. It should be noted that an angle of inclination means using a light structure to lay the panels. This represents an additional cost but guarantees better wind resistance. Therefore, we choose to use a spacing of 2[m] and a tilt angle of 25[°] because it is a good compromise for having a sufficient slope to guarantee good production with each panel as well as efficient self-cleaning. We have made this choice even if another analysis of these results can lead to the choice of another configuration. It depends on the importance we attach to each of the parameters.

Now that the optimal pitch angle and row spacing are known, we can write the formula that will give the yearly PV production as a function of the surfaces available. This is the equation 2.2.

$$E = \frac{S * P * r * c}{d} \quad (2.2)$$

E : Yearly PV energy production [kWh]

S : Surface of the roof [m²]

P : Yearly PV energy production for a 1 [m²] panel of 0.30 [kWp] with an azimuth angle of 0[°] and a pitch angle of 25[°] in [kWh]

d : Spacing between the rows of panels

r : Fraction of irradiance received [-]

c : Coefficient that accounts for the potential shadowing of a portion of the roofs.

⁶The data are provided by the European Commission [11]

For our situation, $d = 2[\text{m}]$, $P = 1\,047.72[\text{kWh}]$, $r = 0.96[-]$ and $c = 0.8 [-]$ so the equation becomes $E = \frac{S \cdot 1047.72 \cdot 0.96 \cdot 0.8}{2} = 402.32 * S [\text{kWh}]$. The idea behind the "c" coefficient is not to give an exact value but rather to be able to give a good order of magnitude for the potential production. This ratio is an estimation made after analyzing the potential obstruction and self-shadowing of the sun for the roofs. After this, we apply the formula to all the flat roofs and the results are available in the section 2.4.6.

2.4.2 Pitched roofs

The computation for the pitched roofs is more specific because almost every roof has different azimuth and pitch angles so the yearly PV production for $1[\text{m}^2]$ can vary significantly. However, for one given orientation, the computation is more straightforward. The equation used is represented in the equation 2.3.

$$E = S * P * c \quad (2.3)$$

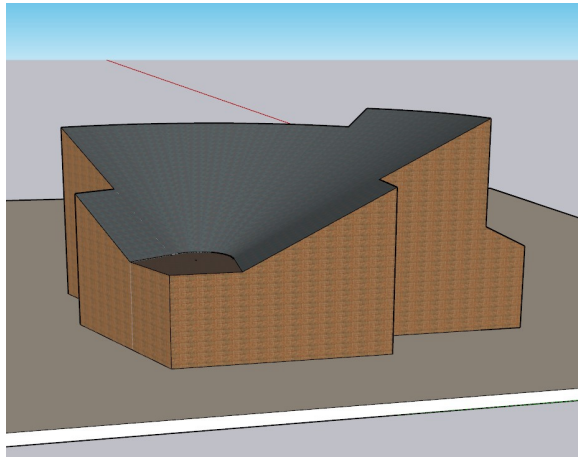
E : Yearly PV energy production [kWh]

S : Surface of the roof [m^2]

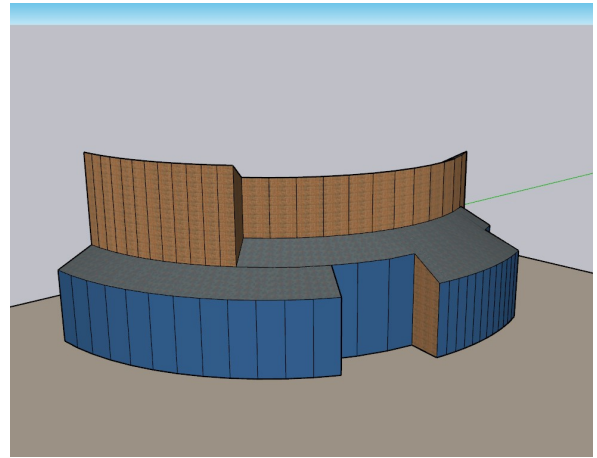
P : Yearly PV energy production for a $1 [\text{m}^2]$ panel of $0.30 [\text{kWp}]$ with the corresponding azimuth and pitch angle in [kWh]

c : Coefficient that accounts for the potential shadowing of a portion of the roofs.

We apply this to all the different pitched sections of the roofs. If some roof productions are quick to compute (the museum L for example, only has one azimuth and one pitch angle), some demand a more detailed approach. The building housing the large "Sud" auditoriums has a specific roofing with pitched circle arcs shown in the 3D view 2.11.



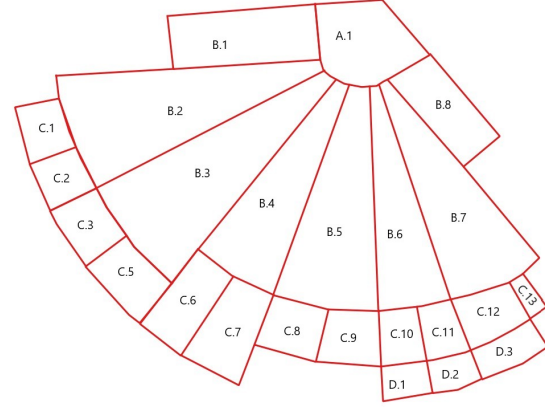
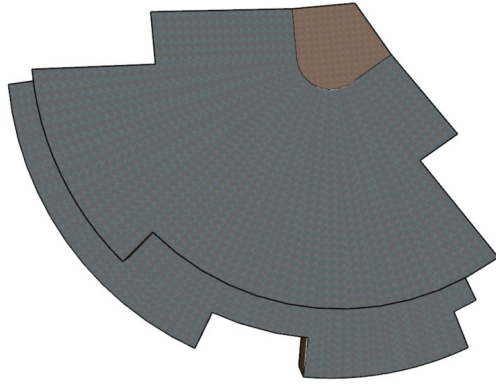
(a) View for the north



(b) View for the south

Figure 2.11: 3D model of the "Big Sud" auditorium building

To get a good result for this kind of roof, we divided the roofs into sections and got the azimuth angle and pitch angle of every sub-sections of the roof. The distribution of the section is shown in figure 2.12.



(a) Zenithal view of the "Big Sud" auditorium building

(b) Distribution of the sub-sections of the roofing

Figure 2.12

Thanks to this distribution, we can assume that the sub-section of B, C, and D are all parallelograms for which we can find a single azimuth and pitch angle. The sub-section A.1 is not pitched, it is considered flat.

The rest of the roofs with pitched sections are also divided into several sub-sections to get more accurate results. Some buildings like the "FIAL library" have complex roofing but all the surfaces can be divided into smaller ones with constant slope and orientation. The results for all the roofs are found in section 2.4.6.

2.4.3 Facades with standard Si-cells PV

We consider two possibilities for the facades, the first one uses standard Si-Cells like the one used in the previous section about roofs. So, in order to compute the potential production, we have to find four average production values for the four orientations of facades possible (North, West, South, and East). The facades of Louvain have all sorts of orientations, this is the reason we calculate a weighted average based on three orientations. The equation 2.4 expresses the average yearly production that will be used for all the facade surfaces facing this direction.

$$P_{mean} = \frac{P_{Az-45} + 2 * P_{Az} + P_{Az+45}}{4} \quad (2.4)$$

P_{mean} : Mean yearly PV production for the chosen orientation

P_{Az} : Yearly PV production for the cardinal point corresponding to the orientation (N, W, S, E)

P_{Az-45} : Yearly PV production for the azimuth angle equal to the orientation $-45[^\circ]$ (NE, SE, SW, NW)

P_{Az+45} : Yearly PV production for the azimuth angle equal to the orientation $+45[^\circ]$ (NE, SE, SW, NW)

We finally find the following values for the 4 possible facade orientations for a $0.3 \text{ [kWp]} \text{ } 1\text{[m}^2\text{]}$ panel.

Yearly production [kWh/y]	Facing North	Facing East	Facing South	Facing West
Vertical surfaces	83.49	156.16	220.42	156.81

Table 2.8: Average yearly productions for the four different facades orientations

We can see considerable differences between the orientations. The south orientation almost produces three times more than the north. We can conclude that facades facing north have significantly smaller potential than the three other orientations, which explains why they are excluded in some analyses in the article about the BIPV

in Leuven [9]. After doing so, we can write the formula used to compute the potential production of the facades.

$$E = S * P * c \quad (2.5)$$

E : Yearly PV energy production [kWh]

S : Surface of the facades [m²]

P : Yearly PV energy production for a 1 [m²] panel of 0.30 [kWp] for the corresponding orientation [kWh]

c : Reduction coefficient

The reduction coefficient accounts for the shadowing due to the surrounding buildings, the surfaces taken by doors, windows, and other elements. The article about Leuven [9] considered a 0.8 coefficient, however, the architecture of Louvain-La-Neuve is far more recent than the architecture of Leuven. This means that on average, the surface of windows is larger in Louvain-La-Neuve. Moreover, due to the complex architecture, some facade surfaces are covered by a canopy making it totally or partially unusable. These are the reasons why we choose a reduction coefficient of 0.6 for the buildings of Louvain-La-Neuve. We know that because of this, the results will not be an exact measurement, but as said previously, the main goal of this chapter is to provide an order of magnitude for the production estimations. Now that the reduction coefficient is known, we can apply the formula to all facade surfaces.

2.4.4 Facades with AGC BIPV

In the sequence of discussions with Tanguy Timmermans and Olivier Mal of AGC, we concluded that using European Commission data to calculate panel production is the closest thing to reality. This is because various of AGC's studies are confidential and cannot be shared publicly. Mr. Timmermans mentioned some of the studies but admitted that the assumptions were sometimes very simplistic and that the results are therefore probably not as useful as the European Commission data. For these reasons, we consider the production of AGC panels to be equal to that of conventional PV panels. However, conventional panels are not suitable for electricity production in a vertical configuration. In reality, AGC panels are therefore more efficient in this type of application. This means that panel production estimates are a lower bound than actual production. That said, we will consider a production of 14.77 [GWh] for the facades and 12.72 [GWh] if we include the north-facing facades. Here, it should be remembered that the appeal of AGC panels also lies in their aesthetic appearance, which makes it possible to use panels that blend in better with facades than conventional ones.

2.4.5 Lake of Louvain-La-Neuve

Nowadays, some lakes are partially covered with flat PV panels. One example is the artificial lake of the Alqueva dam in southeast Portugal 2.13, visited in the frame of Civil Engineering travel. This configuration presents various advantages. Firstly, one would be that it does not use space that can be used for other purposes to produce electricity. Secondly, would be that during drought in summer, it reduces the evaporation of the water contained in the lake because the panels cover the surface reducing the water-to-air interface and it also reduces the amount of solar energy that reaches the surface of the lake. In this section, we will briefly discuss the potential use of PV panels on the surface of the lake of Louvain-La-Neuve.



Figure 2.13: PV panel at the Alqueva dam in Portugal (Personal picture)

The measurements of the city's lake give a total surface of around 50 000[m²], and if we remove the parts covered with plants, large stones, or technical devices, the surface drops to around 41 000[m²]. We can now see how to compute the potential production of the lake. To do this, we use the following formula 2.6.

$$E = S * P * c \quad (2.6)$$

E : Yearly PV energy production [kWh]

S : Surface of the lake [m²]

P : Yearly PV energy production for a 1 [m²] horizontal panel of 0.30 [kWp] in [kWh]

c : Coefficient that accounts for the potential shadowing.

We can consider a coefficient $c = 0.9$ because the surface of the lake is not really prone to shadowing during the year as the sides of the lake are often clear except in the northern direction. The value of P in this case is 268.64 [kWh]. The equation 2.6 becomes $E = 241.78 * S$ [kWh]. In the next section, we will discuss the potential production for different coverage fractions of the lake.

2.4.6 Summary of the results

Now that all the computations are explained, we can look at the results found for the potential of the different surfaces. All the precise results are found in the appendix A.2 and the summary of the results is available in the following tables.

Results for the roofs

Districts	Biéreau	Hocaille	Center	Total
PV production in [MWh/y]	7 853.15	3 887.99	4 488.12	16 229.26

Table 2.9: Yearly PV roof potential production for the academic buildings of Louvain-La-Neuve

We can see that the Biéreau district produces an amount of energy almost equal to the sum of the production of the Center and the Hocaille district. The total is a bit more than 16.23 [GWh].

Results for the facades

Districts	Biéreau	Hocaille	Center	Total
facades north [MWh/y]	1 186.64	290.65	573.78	2 051.07
facades east [MWh/y]	2 189.31	395.43	1 046.16	3 630.90
facades south [MWh/y]	3 249.49	739.66	1 590.96	5 580.11
facades west [MWh/y]	2 112.12	363.75	1 034.62	3 510.49
Total [MWh/y]	8 737.56	1 789.49	4 245.52	14 772.57

Table 2.10: Yearly PV facades potential production for the academic buildings of Louvain-La-Neuve

The total production for the facade is 14.77 [GWh]. If we do not consider the facades facing north, the total drops to 12.72 [GWh].

Results for the lake

For the lake, we consider different fractions of lake coverage. The results are presented in the table below.

Fraction	Surface [m ²]	Production [MWh/y]
Total surface	48 095	10 465.6
Surface without obstacles	40 897.7	8 899.4
75%	30 673.3	6 674.6
50%	20 448.9	4 449.7
25%	10 224.4	2 224.9

Table 2.11: Yearly PV facades potential production for the academic buildings of Louvain-La-Neuve

We can see that for a coverage of 25%, the production is 2.22 [GWh], this is a significant value compared to the values found for the roofs and for the facades.

2.4.7 Comparison to the household consumption

In this section, we are going to compare briefly the results found in the previous section with the household of Louvain-La-Neuve. On the 31st of December 2021, the population of the municipality of Ottignies-Louvain-La-Neuve was 31 339 [27] and the locality of Louvain-La-Neuve counted 10 503 inhabitants. According to Engie [28], the average yearly electricity consumption of a Belgian citizen is 1.66 [MWh]. If we only consider the roofs, the 16 229[MWh] can cover the consumption of almost 9 800 inhabitants of Louvain-La-Neuve, which represents almost the entire population of Louvain-La-Neuve. This result would be achieved by ensuring loss-free storage and distribution throughout the year.

However, we must keep in mind that this is the official population that does not count all the students that live five days a week in the city. Moreover, the main goal of the Transition Energy Lab is to decarbonize the households' consumption and this is about the heating of the houses, the cooking, and the replacement of the actual electricity consumption with solar electricity. Indeed, nowadays, 1[kWh] of electricity emits on average 124 [gCO₂e] in Belgium in 2023 while the production 1 [kWh] with PV panels emits on average 36 [gCO₂e] [4].

Moreover, in the section 1.3, we said that the majority of heating and cooking in Belgium still uses fossil fuels. According to the French "Agence de la transition écologique", the heating of a 1[m²] surface of a house during a year emits on average 6 [kgCO₂e]⁷ if it is heated with electricity, 38 [kgCO₂e] if it is with gas and 53

⁷These are averages for different house types. These figures vary according to the insulation of the house, its orientation in relation to the sun, and the technology used to supply heat from electricity, gas or heating oil.

$[kgCO_2e]$ if it is with heating oil [29]. This shows that the transition from gas to electricity saves on average 32 $[kgCO_2e]$ per year and 47 $[kgCO_2e]$ for the same transition from heating oil. It should be noted, however, that heating oil is forbidden as a fuel in Louvain-La-Neuve, even for residents. All student accommodation is equipped with electric cooking facilities and all areas are heated either directly or indirectly with gas. To the best of our knowledge, however, no identical data are available for residents' homes.

If we now consider the surface of the facades, they produce enough electricity for the consumption of 8 899 inhabitants if we take all four orientations and 7 950 inhabitants if we remove the facades facing north. Regarding the lake, for every fourth of the lake covered with panels, 1 340 inhabitants would be theoretically provided with electricity. If we consider total coverage, the production would then be enough for 5 361 inhabitants.

It is also important to keep in mind that these numbers represent an upper bound. In reality, there is an offset between electricity consumption and PV production. During daylight in summer, the demand is lower than in winter but the PV production is larger and nowadays, we do not have the perfect technology to store this electricity efficiently.

In conclusion of this section, we can say that the PV installations on the roofs and facades of the academic buildings in Louvain-La-Neuve can theoretically provide enough electricity to cover the electricity demand of 18 676 inhabitants if we consider every surface and 17 727 inhabitants if we exclude the facades facing north.

Chapter 3

Analysis of rooftops with LIDAR data

3.1 Introduction

In the previous chapter, we gave an estimate of the surface areas that can be used to install PV panels. However, even if these calculations give a good order of magnitude, with the coefficients used to take shading into account, we lack precision in the analysis of surface areas. This section remedies this by providing a more detailed analysis of potential installations on the roofs of academic buildings. The data collected during a flight of an aircraft equipped with LIDAR sensors forms the basis for the analyses in this chapter. With this data, we can determine more precisely the usable surfaces. In this way, we can establish the potential solar electricity production of Louvain-La-Neuve's academic buildings. We then analyze and compare these results with those obtained previously.

3.1.1 Lidar

LIDAR or "Light Detection And Ranging" is a measurement method comparable to RADAR that uses electromagnetic waves instead of sound to measure distances. It is a remote measurement technique based on analyzing the properties of a beam of electromagnetic waves sent back to its transmitter. The distance is then measured from the time taken for the beam to reach the object and return to its source. LIDAR has various applications other than topography, such as meteorology, environmental sciences, seismic sciences, etc. Using this technique, it is possible to reconstruct three-dimensional models of surfaces. This is what was done recently at Louvain-La-Neuve.

3.1.2 Lidar data in QGIS

The three-dimensional models recreated using LIDAR data are referred to as DSM, DTM, and DHM. DSM stands for Digital Surface Model, DTM for Digital Terrain Model, and DHM for Digital Height Model. DSM is a representation of the elevation of all visible relief elements, whether man-made or natural. DTM represents all exclusively natural elements to give a three-dimensional model of the terrain to which human structures such as roads or buildings can be added. Finally, DHM gives the height of all man-made elements. This is the result of subtracting the heights of the DSM and the DTM.

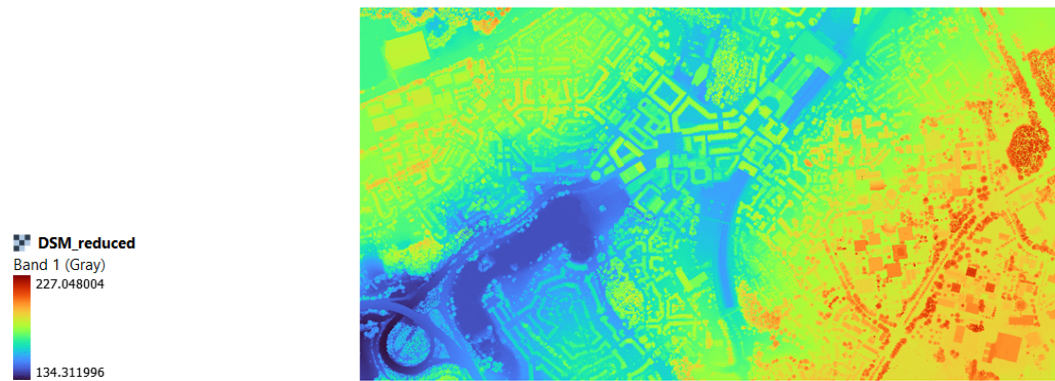


Figure 3.1: Digital surface model of the city of Louvain-La-Neuve

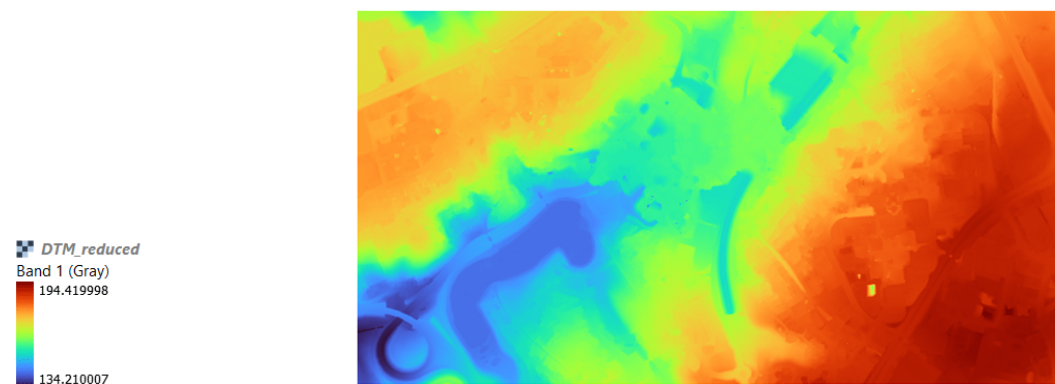


Figure 3.2: Digital terrain model of the city of Louvain-La-Neuve

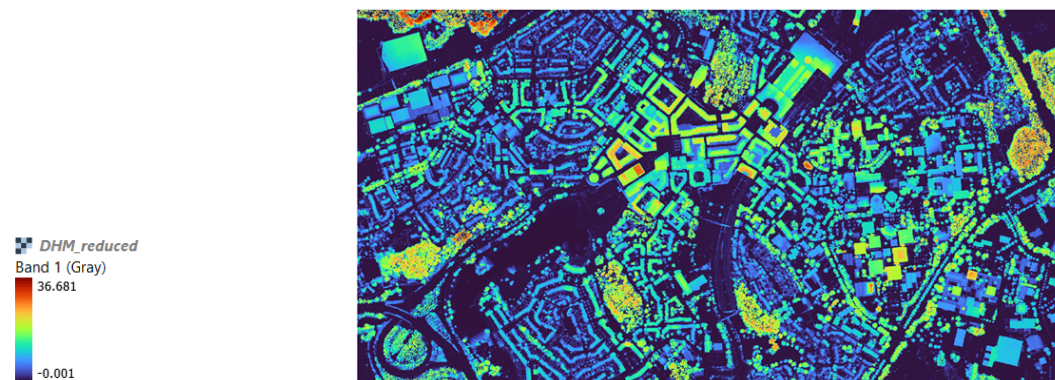


Figure 3.3: Digital height model of the city of Louvain-La-Neuve

A brief analysis of the DTM reveals a number of particular details relating to the special case of Louvain-La-Neuve. For example, at the level of the Institute of Modern Languages, the DSM is not at the level of the railway tracks but at the level of the slab that passes in front of the entrance to the Institute. The same applies to other areas where the pedestrian slab overhangs roads or railway lines.

The three three-dimensional models were supplied to us by the Earth and Life Institute in the Bio-engineering faculty of UCLouvain in the same way as the PICC data. These three data sets can be used in the form of raster files that can be manipulated in QGIS. Rasters are made up of a matrix of pixels (also known as cells), each containing a value for a feature of the surface. This value may represent height, humidity, shading, or other data. In our case, a raster cell measures 50[cm] on each side. The three-dimensional models are height measurements but later in this thesis, we are going to use other data than height. For example, the DSM ranges in height from 134 [m] to 227[m]. The highest point is the top of the Cyclotron antenna and the lowest point is the road that passes along the bottom of the lake. The DTM has the same lowest point at 134[m] but does not rise above 194[m]. For this work, we will be using the DSM layer, as it takes into account not only the topography of the terrain but also the geometry of the buildings.

To help us analyze the roofs of Louvain-La-Neuve, we used data from the PICC, which gave us an implementation of the roofs of the academic buildings. The layout of these buildings can be seen in image 2.2.

3.2 Measurement of the potential production

3.2.1 Solar curves for the determination of the production

In order to determine the production potential of PV panels, we thought about a model that can give us a good estimate of the production of each surface, whatever its orientation. To do this, we used the solar curves corresponding to the latitude and longitude of Louvain-La-Neuve. We have calculated the points of intersection of the curves corresponding to the 21st or 20th of each month and the curves corresponding to the hours. This gives 83 azimuth-pitch pairs, which correspond to the positions of the sun in the sky at specific times. Most of the positions correspond to two times of the year since the sun's trajectory in the sky is identical on 21st January and 21st November, 21st May and 21st July, etc. Only on the days of the summer and winter solstices do the sun's trajectories correspond to just one day of the year. The angle pairs obtained are shown in the appendix table A.3. The figure 3.4 represents the solar curves of Louvain-La-Neuve.

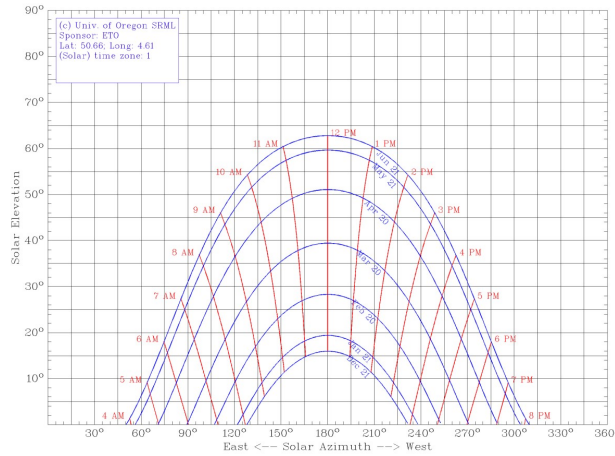


Figure 3.4: Solar curves of the city of Louvain-La-Neuve

Now that we know the positions of the sun at various times of the year, we can find the fraction of irradiance that each surface of the academic buildings receives for each position of the sun in the sky. Once we have these values, we can weigh them by the maximum irradiance that can be received for each position of the sun in the sky. In this way, we will obtain a weighted average that will give us the fraction of the production of a panel placed on

a fixed surface compared to a panel that is permanently oriented perpendicular to the sun's rays. This procedure is developed further in section 3.3. To find the fraction of irradiance received by the surfaces of the academic buildings at each point in time, we are going to use the QGIS "Hillshade" package.

Hillshade package

Hillshade is a QGIS package that uses data from a raster and various parameters to create a new raster where the data is no longer a height but a fraction of the sunlight received by the surface. This fraction is expressed as a value ranging from 1 to 255. The value 1 represents total obscurity and the value 255 represents maximum illumination corresponding to a surface perpendicular to the direction of the light source's rays. The Hillshade parameters are the position of the light source (in our case the sun) with an elevation angle in the sky and an azimuth angle, as well as the ratio between the horizontal and vertical distances if this is different from 1 to 1. In our case, the ratio between the horizontal and vertical distances is 1 to 1 and the positions of the sun are those determined by the solar curves. The angles are all given in degrees and the south is considered to have an azimuth angle of 180°. Image 3.5 shows the result of Hillshade's calculations on the DSM raster for the sun's position in the sky at 12:00 on April 20.



Figure 3.5: Hillshade raster for DSM and solar position of the 20th of April at 12:00 and zoom in on the buildings in Place de la Croix du Sud

If we analyze this type of image, we notice certain characteristics. The resulting raster is not binary, with shadows at 1 and bright areas at 255. The angle of the surfaces influences the value of the Hillshade raster. The more perpendicular a surface is to the sun's rays, the higher the raster value. This will enable us to obtain useful coefficients for measuring surface production. We can see, for example, that the roof of the large auditorium building on the Croix du Sud faces north, resulting in a lower irradiance fraction.

We then calculated Hillshade rasters for each position of the sun in the sky found using the solar curves with the DSM raster. The result is 83 different rasters that can be analyzed for building roofs. To analyze these rasters, we used the polygons giving the building implementations and merged them into a single layer. Once we had the polygon layer and the various rasters, we can use the "Zonal statistics" function. This function calculates a whole series of statistics from a raster layer for each polygon in a vector layer. These statistics include the mean value, maximum value, minimum value, and standard deviation of the zones delimited by the polygons. In our case, we have calculated the averages for each building for each Hillshade raster.



Figure 3.6: Hillshade raster of the 20th of April with the building location polygons

The results of these averages were then tabulated, bearing in mind that the positions of the sun in the sky in months other than December and June correspond to two separate times of the year. This table is available in the appendix A.4.

From the coefficients we have obtained, we want to calculate a weighted average of the irradiances received by each surface over the course of a year. To do this, we will multiply the coefficients found above by the irradiances received by a panel that is permanently oriented ideally to receive maximum irradiance. Such a panel is one that can adjust its azimuth angle and inclination at any time. Once again, the European Commission provides data for such panels. We have therefore taken the document gathering the data of a pivoting double-axis panel from 2005 to 2020. Each line of this document contains information corresponding to one hour of this period. In the same way, as we used Python code to extract data for choosing the optimum angle and spacing for our PV panels, we have extracted irradiance data for each of the hours of interest in our study. The Python code is available in the appendix A.5. With this code, we directly calculate the 16-year average of the irradiance received by the double-axis pivoting panels for each moment of interest in the year. These irradiances are displayed in table A.6. The European Commission's data is given in hours and 10 minutes, but our data on the sun's position in the sky is at the exact hour. However, during a period of ten minutes, the sun elevation and azimuth angle do not change significantly. In fact, in 10 minutes, the sun's elevation and azimuth angle do not change drastically. So, we are going to take these data as presented.

Once we have this data, we can apply the formula to obtain an overall average for each academic building.

$$F = \frac{\sum_{i=1}^{142} c_i I_i}{\sum_{i=1}^{142} I_i 255} \quad (3.1)$$

F : Average fraction of the sum of the optimum irradiances¹ received by the academic building [-]. Its value is always within the range [0;1].

i : the index corresponding to a time of year [-]. For example, $i=1$ corresponds to 8 a.m. on January 21 and $i=142$ corresponds to 3 p.m. on December 21.

C_i : The coefficient that averages the Hillshade raster value over the building surface corresponding to time "i" in the year [-]. Since the maximum coefficient is 255, we have multiplied the denominator by 255.

I_i : Irradiance received by a double-axis panel in Louvain-La-Neuve at the time of year i [W/m²].

¹the sum of optimal irradiances corresponds here to the sum of all irradiances received by a panel with double pivoting axis.

We obtain a coefficient for each building. These coefficients are shown in the table 3.1. The maximum value is 0.53 and it corresponds to the Swimming pool building. This is because the pool building has large, south-facing roofs. The lowest value is 0.3 for Museum L, whose roof faces due north.

Buildings	Fraction [-]	Buildings	Fraction [-]	Buildings	Fraction [-]
IMMC	0.51	IMAP	0.50	Mendel	0.51
Pythagoras	0.49	Réaumur	0.49	De Serres	0.50
L Museum	0.30	A.D.S.T. Hall	0.50	Cyclotron	0.49
Dupriez	0.43	Euler	0.51	Thermal plant	0.49
DRT Library	0.44	Maxwell	0.48	University Hall	0.46
Monstequieu	0.48	Stévin	0.50	Doyen	0.49
Coubertin	0.48	Vinci	0.50	Agora	0.46
Swimming Pool	0.53	Sainte-Barbe	0.50	ESPO Library	0.46
Indoor track	0.51	P. and M. Curie	0.50	FIAL Library	0.44
Hall 2	0.49	Sciences	0.51	Socrate	0.46
Annex 1	0.50	Small Sud	0.49	Physical education	0.49
Bubble 2	0.47	Carnoy	0.51	Gymnastics	0.50
Bubble 1	0.51	Kellner	0.51	Annex 2	0.49
Mercator	0.49	Halles	0.48	Annex 3	0.48
ST Library	0.48	Big Sud	0.43	Hall 1	0.49
Lavoisier	0.47	Boltzmann	0.50	Entrance	0.52

Table 3.1: Table of fractions of the optimal irradiance for each building.

If we multiply this coefficient by the average annual production of a $1[m^2]$ double-axis pivoting panel, we obtain the average production of a $1[m^2]$ panel on the roof of the given academic building. Then we multiply the value obtained by the available roof surface. This gives an initial value for the number of MWh produced per year by each building. These results are shown in the table 3.2

Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]
IMMC	531.02	IMAP	313.23	Mendel	342.82
Pythagoras	352.70	Réaumur	259.81	De Serres	325.45
L Museum	145.15	A.D.S.T. Hall	238.82	Cyclotron	2 592.48
Dupriez	292.17	Euler	422.14	Thermal plant	201.69
DRT Library	636.38	Maxwell	404.04	University Hall	661.77
Monstequieu	296.51	Stévin	440.33	Doyen	672.25
Coubertin	276.48	Vinci	1 046.63	Agora	297.60
Swimming Pool	433.15	Sainte-Barbe	492.85	ESPO Library	677.70
Indoor track	2 223.84	P. and M. Curie	277.12	FIAL Library	877.51
Hall 2	280.84	Sciences	441.24	Socrate	1 049.11
Annex 1	133.99	Small Sud	232.92	Physical education	316.19
Bubble 2	330.61	Carnoy	830.65	Gymnastics	535.56
Bubble 1	369.69	Kellner	359.33	Annex 2	188.65
Mercator	368.26	Halles	350.43	Annex 3	297.26
ST Library	275.93	Big Sud	215.58	Hall 1	595.94
Lavoisier	910.38	Boltzmann	341.90	Entrance	453.73

Table 3.2: Table of the potential production in [MWh/y] for a direct analysis

In this table, we can note the high production of roofs such as the indoor athletics track or the cyclotron, which have a larger-than-average surface area.

We refer to our analysis here as "direct analysis" because this analysis is correct insofar as the entire surface of the roofs is covered with panels that all have the same azimuth angle and angle of inclination as the roofs in question. However, this means that we are covering roofs even in areas where panels would have extremely low production. Furthermore, in the case of Louvain-La-Neuve's many flat roofs, as we have seen, it is more cost-effective to install PV panels in rows with an angle of inclination of 25[°]. For this reason, the following sections deal with the analysis of shadow zones and the case of flat roofs.

3.2.2 Shadows

In order to find areas that are too often shaded, we used the raster calculator. The idea is to set a threshold that differentiates between light and shade in the calculated Hillshade rasters. Next, we choose what we define as an area unsuitable for the installation of PV panels. To do this, we choose the maximum fraction of time an area can spend in shadow. Beyond this value, the area is considered unusable.

To choose the threshold, we looked at the different raster results and deduced two main things. Firstly, when the sun's angle of elevation is low, it is difficult to distinguish clearly between shadow and light. This is why we only consider positions of the sun in the sky where the elevation is greater than 25[°]. Secondly, on these rasters, shadow areas almost always have a raster value of less than 50/255. This value may seem arbitrary, but it is a good compromise. Moreover, it is difficult to give a threshold that is the result of a calculation rather than a trial-and-error method. A lower value would have classified illuminated areas as shadows, and a higher value would have done the opposite.

This threshold now allows us to calculate shadows for all rasters. We can then use these shadows to make an average that gives a score to each pixel in our raster. The higher the score, the more often the pixel is in the light, and the lower the score, the more often it is in the shadow. We then need to choose a tolerance that determines the limit score separating pixels in the raster that are in an unusable zone because they are too shaded from those that are usable. This calculation is expressed in general terms by the formula 3.2 for each pixel of the raster layer.

$$S = (\sum_i^n (s_i > 50)) > T * n \quad (3.2)$$

S : binary value that determines whether the pixel is a light or dark area. It can only be equal to 0 or 1 [-].

i : index corresponding to a given Hillshade raster.

n : number of Hillshade raster layers to consider [-].

s_i : Value of the Hillshade raster i [-].

T : The tolerance value. It is in the range [0;1].

The output of this formula is a Boolean value. In other words, if a statement is true, it takes on a value of 1, and if it is false, a value of 0. This is how we end up with a raster layer consisting solely of pixels with a value of 0 or 1.

In the end, we obtain several raster layers depending on the tolerance chosen. For example, the figures 3.7 and 3.8 are the layers for a tolerance of 75% and 80%. In other words, an area is considered to be in shadow if it spends more than 25% or 20% of its time in shadow.

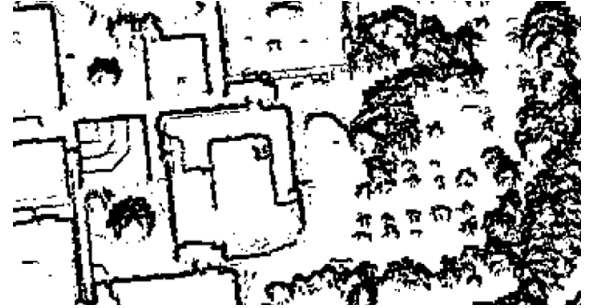


Figure 3.7: Shadow raster for a tolerance of 75% and a zoom on the roof of the De Serres building

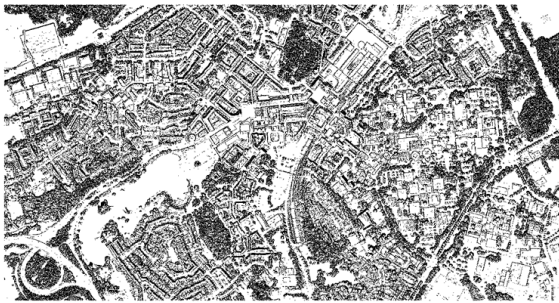


Figure 3.8: Shadow raster for a tolerance of 80% and a zoom on the roof of the De Serres building

We can see on the raster which areas are to be considered as shadows. Next, using the Zonal Statistics tool, we can calculate the fraction of the implementation area of each of the academic buildings that we consider usable. This fraction of the area corresponds to the average value of the raster found on the buildings' implementation polygons.

At first glance, it seemed that the roofs contained areas considered to be outliers. However, after overlaying the shadow raster with the aerial photographs, the supposed outliers turned out to be either vegetation on the edges of the buildings or H.V.A.C. (Heating, Ventilation, and Air Conditioning) installations on the roofs. Our model, therefore, has no outliers in the areas corresponding to roofs.

Therefore, we multiply the areas of the buildings by their usable fraction to find out the area that can actually be covered with panels. The use of these shading zones makes it possible to eliminate areas corresponding to roofs sloping towards the north, northeast, and northwest. The coefficients are shown in the appendix A.7. For the Dupriez building, the usable surface has been reduced by 54% for a tolerance of 80%, excluding the roof part facing northern directions.

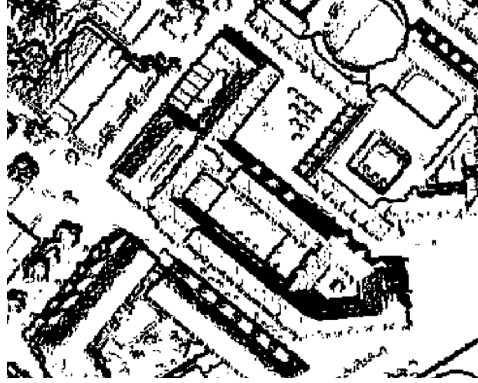
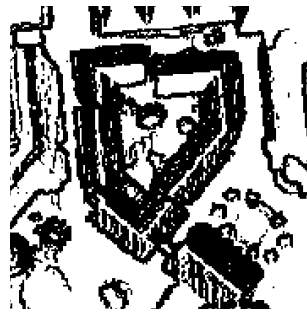


Figure 3.9: Result of the shadow raster for a tolerance of 80% on the FIAL Library

The coefficients for tolerances of 75% and 80% are those which, after analysis, give the most consistent results as we can see in figure 3.9. A lower tolerance does not rule out north-facing parts of the roof, while a higher tolerance results in shaded areas on usable parts of the roof. This result is visible on the figure 3.10. For the remainder of this master thesis, we will take into account the results for the 80% tolerance in order to be able to compare the final results. This tolerance is strict enough to exclude badly oriented parts of the roof without excluding usable parts.



(a) Tolerance of 60%



(b) Tolerance of 90%



(c) Aerial view

Figure 3.10: Result of the shadow raster tolerances too high and too low

The outliers visible in these photos are due to the accuracy of the DSM layer measurements, which are of the order of 12[cm]. This can lead to different results for two pixels located on the same roof slope. However, these outliers are much less frequent for the 80% tolerance. Note that while in our considerations we calculate production for panels of 1 [m²], the areas used here are considered to be completely covered by PV panels. This implies the use of panels smaller than 1 [m²] to cover the entire surface. While AGC offers panels with customized dimensions, most of the panels have standard dimensions such as 1[m] × 1[m] or 1.6[m] × 1[m]. To find the maximum number of panels that can fit in an area, we either have to do a lot of trial and error or use mathematical reasoning like that used for the maximum number of squares within a given large square. Article [30] summarizes the state of knowledge on this subject in 2009. There are a number of research subjects trying to find a method that gives the maximum number of panels that can fit into a given area. However, this research is beyond the scope of this master thesis. We can use Lagrange multipliers to determine the optimal arrangement of panels on a given roof. It should be noted that some of the areas too small to install PV panels are included in the shaded areas and therefore not in the usable areas.

3.2.3 Flat roofs

In the case of academic buildings with flat roofs, the calculation of potential production requires more steps than for sloping roofs. In this case, as we have seen, the panels must be arranged in pitched rows. In the case of Louvain-La-Neuve, we opted for rows 2m apart, with an angle of inclination of 25[°]. However, if we could look directly at the fraction of light received by pitched roofs to calculate the production of panels that would be put on them, in the case of flat roofs, the panels are not oriented in the same way as the roof, so the fraction of irradiance received is different.

One solution would be to manually add the panels to the DSM layer, in order to obtain a layer on which the geometry of the panels would be respected (inclinaison of the surface and presence of the volume that can create shade between the rows). In our case, we consider two flat roofs (one modern and one older) and then generalize the results to the other flat roofs. For the modern roof, we have taken the building with the most recent re-roofing, the De Serres building. For the older roof, we took the roof of the Mendel building. What is more, these two buildings have similar geometries and are located side by side. The results obtained here can also be used when renovating the other towers on Place Croix du Sud.

Before adding these panels to the roofs, we must first determine the arrangement in which we want to install our panels on both roofs. We have chosen to do as most flat roofs are done, i.e. in rows parallel to the south-facing facade of the buildings². We then fill in the roofs row by row, keeping the same spacing and not placing any panels on the shaded areas discussed in the "shadows" section 3.2.2. Here, we have chosen to install the panels so that they avoid the 80% tolerance shadow zones. The proposed installation of panels also takes into account the presence of major features such as those on the De Serres building, chimneys and the building's ventilation systems. The installation for the two buildings can be seen in the image 3.11. The slight offset for the De Serres building is due to the fact that the aerial photograph was not taken from the zenith. It will be seen later that the panels are well positioned in relation to the DSM raster data. The point here is to use an aerial photo of the two buildings to illustrate what the installation of panels would look like.



(a) Tower De Serres



(b) Tower Mendel

Figure 3.11: Chosen installation of PV panels on the roof of the towers considering shade areas

Given that the panels have a slope of 25[°], the width of our polygons is $\sin(25) = 0.91$. The length of the rows is an integer number of meters. The number of PV panels per 1 [m²] is then 490 and 531 for De Serres and Mendel respectively. We are going to use this layer of polygons, which represents the implementation of the panels, to add this geometry to the DSM raster. To do this, we use the "polygon to line" function to split the polygons into lines. The result is a layer of polylines. Next, we use the "explode lines" function. At this stage, we delete all the lines that are not the bases or crests of the PV panels. We then use the QChainage plugin to create points along our lines. This function allows us to automatically create a point at the beginning and end of each line. The evolution of the different layers for the tower De Serres can be seen in the images 3.12.

²They have an azimuth angle of 4[°] or 5[°] depending on the part of the roof.

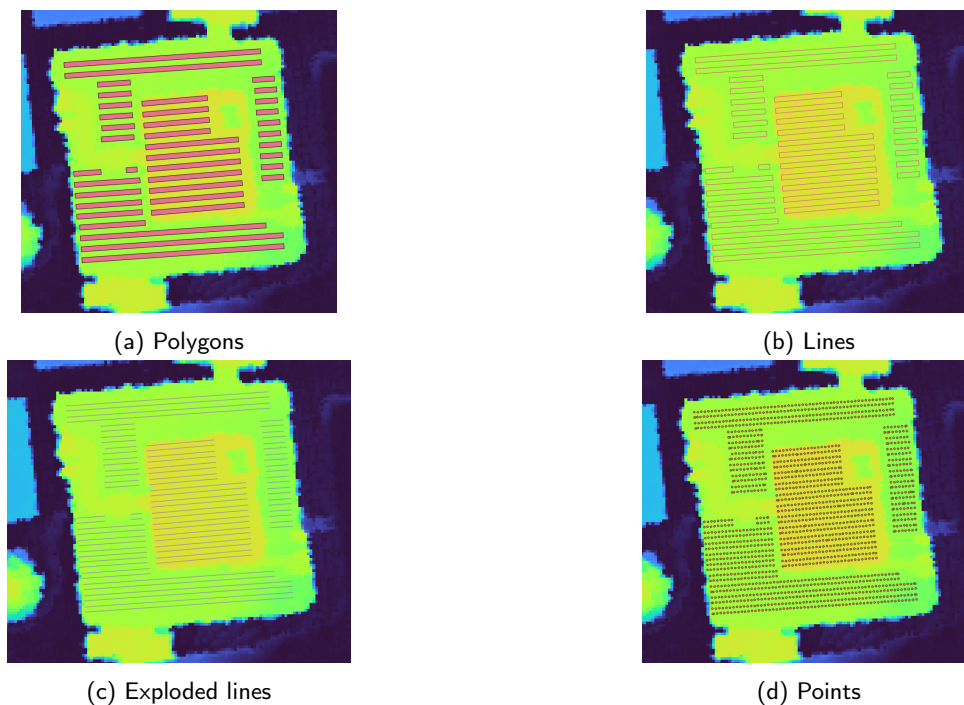


Figure 3.12: Evolution of the layers for the tower De Serres

To make it easier to create the raster we are adding points all over the place along the edges of the roofs. These points will help the raster creation function to understand how to treat the edges of the raster. Our points layer will then be used as the basis for creating the raster panel groove. To do this, we need to give our points a height. We need to create a new height attribute for our points. We then need to select all the ridge points, choose the height attribute and give them a value of 42, which corresponds to the height of the ridges in [cm] ($\cos(25) = 42$). We then reverse the selection in QGIS to give a height of 0 [cm] to the points at the foot of the panels and those delimiting the roofs.

The TIN Interpolation function will then use these points to create a raster that includes the geometry of the panels. This function needs the points layer we have just created and an attribute from which it can interpolate. In our case, this is the height of the panels. We can then choose the type of interpolation, which in our case is linear. We then select the area over which we want to interpolate the point layer and save the result in a new raster layer. The result is the image 3.13. The result is not aesthetically pleasing, but the important thing is that the relief of the panels is clearly visible.

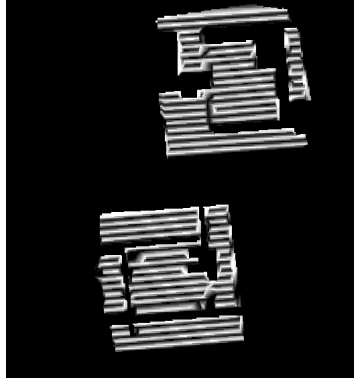


Figure 3.13: Raster of the panels' geometry (De Serres tower is on top and Mendel tower is at the bottom)

To add this new raster to the DSM raster, we use the raster calculator. Since the panel raster is in [cm], we ask the calculator to sum the DSM raster values and $1/100$ of the panel geometry raster values for each pixel in the area. This produces a raster with the geometry of the buildings and the trees in addition to the rows of panels 3.14.

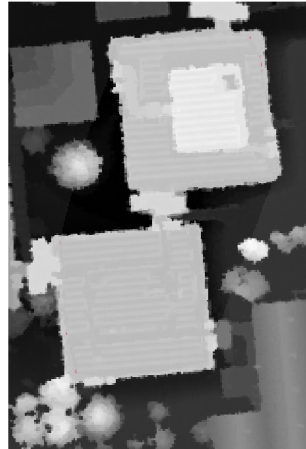


Figure 3.14: Raster of the towers with the panels

We now apply the same analysis as for pitched roofs 3.1. In this way, we obtain fractions for PV panels installed directly on the two roofs. We obtain a fraction of 0.643 for the Mendel building and 0.641 for the De Serres building. These fractions are higher than the fractions obtained for sloping roofs. As a reminder, the best fraction was 0.53 for the swimming pool. This difference is explained by the fact that in our case of flat roofs, we only use panels facing south and inclined at an angle that ensures good production. The towers' potential electricity production is then 145.04 [MWh/year] and 133.52 [MWh/year] for the Mendel and De Serres towers, respectively. We can therefore see that, despite similar dimensions for the two roofs, De Serres tower has lower productivity. If we take the ratio of the production of the roofs to their total surface area, we see that the De Serres model gives a productivity equal to 95% of the productivity of the Mendel model. The renovation has created more relief, reducing the space available for the installation and increasing shading, which inevitably reduces potential production. However, it is clearly preferable to have a building with modern energy standards but slightly lower production than an older building with slightly higher production.

What we refer to hereafter as the Mendel model and the De Serres model, are the consideration for roofs or flat parts of roofs an electricity production per $[m^2]$ unshaded equivalent to that obtained from the calculations

made for the addition of panels on the roof of the Mendel tower and the De Serres tower respectively.

We are now applying the results found to the other flat roofs of academic buildings. In this way, we will obtain production for panels installed in inclined rows and not flat. We will consider the case where the flat roofs are like the Mendel and the case where they are like the De Serres. For flat roofs, we will consider the same productivity per [m²] as for the Mendel and De Serres towers. For mixed roofs (with both flat and pitched sections), we multiply the productivity by the steep roof fraction before adding the production of the flat section as if it were a flat roof in its own right. The formula used for the flat and mixed roofs is generalized by the formulas 3.3 and 3.4 respectively.

$$E_{Flat} = \frac{S_{Flat} E_{Ref}}{S_{Ref}} \quad (3.3)$$

E_{Flat} : Yearly PV energy production of the flat roof [kWh]

S_{Flat} : Surface of the flat roof [m²]

E_{Ref} : Yearly PV energy production of the roof of one of the reference buildings (Mendel or De Serres) [kWh]

S_{Ref} : Surface of the roof of the reference building [m²]

$$E_{Mix} = \frac{E_{Sh}(S_{Tot} - S_{Flat})}{S_{Tot}} + E_{Flat} \quad (3.4)$$

E_{Mix} : Yearly PV energy production of the mixed roof [kWh]

E_{Sh} : Yearly PV energy production of the building without differentiating flat sections [kWh]

S_{Tot} : Total surface of the roof of the building [m²]

S_{Flat} : Surface of the flat sections of the roof [m²]

E_{Flat} : Yearly PV energy production of the flat sections computed as in 3.3 [kWh]

The electricity production results from the installation of the panels on the roofs of the Mendel and De Serres towers will be referred to as "results from the Mendel model" and "results from the De Serres model" respectively. These results are detailed in the following section.

3.3 Potential production of the roofs

In this section, we will analyze the production results and compare them with those obtained previously. We express the results obtained with a direct analysis that takes account of shadow zones with the two tolerances mentioned. Then we give the calculations made for flat roofs in order to obtain the final results. The results are shown here by district, but detailed tables can be found in the appendices A.8 and A.9. Only the results for the final two situations are detailed for each building in figure 3.15. However, the table below summarizes the production status of academic building roofs according to the calculation methods used.

Districts	Biéreau	Hocaille	Center	Total
PV Production for analysis 1 in [MWh/y]	12 712.91	6 435.93	5 460.99	24 609.82
PV Production for analysis 2 in [MWh/y]	10 949.96	5 631.07	3 628.42	20 209.45
PV Production for analysis 3 in [MWh/y]	8 335.25	4 375.53	3 336.33	16 047.11

Table 3.3: Yearly PV production of the districts for the different methods

In Table 3.3, we can see that production becomes progressively lower as the methods become more complex. This is to be expected, as each new method removes areas of the plant that would otherwise be unsuitable for consumption, thus reducing potential production. For method 1, this is the sum of the table 3.2. This method

does not take into account the presence of unusable shaded areas, nor the fact that flat panels on flat roofs are not recommended. Method 2 uses the calculations made to determine the shadow zones. Areas such as roofs that face too far north, or areas that are too often shaded by relief, are excluded. Then, for method 3, all flat roof sections are equipped as described in chapter 2. It is therefore consistent to see a reduction in production here too, given that we set up rows of panels every two meters to guarantee good production for each panel. Placing panels in rows every two meters reduces the number of panels for a given surface area. However, rows have the advantage of producing more electricity per panel, and therefore more electricity for a given investment. What is more, these rows can be cleaned themselves, as mentioned previously. For these methods, we can mainly use the potential annual production value of 16.05 [GWh/y].

- Analysis 1 : Direct analysis as described previously (Detailed results are available in table 3.2)
- Analysis 2 : Without shadowing for a tolerance of 80% (Detailed results are available in appendix A.8)
- Analysis 3 : Without shadowing for a tolerance of 80% and flat roofs equipped as in chapter 2 (Detailed results are available in appendix A.9)

Now, we look at the results obtained if the flat roofs or flat parts of roofs are covered in the same conditions as for the De Serres Tower and the Mendel Tower. We analyze both cases because roofing a roof like that of the Mendel Tower gives a fairly high estimate of production, given the lack of relief or objects providing shade. On the other hand, the case of the Mendel Tower gives a slightly lower productivity per [m²] of the roof, due to the presence of relief and H.V.A.C. elements on the roof. These two models also allow us to compare a relatively old building with a recently renovated one. The tables A.10 and A.11 in the appendices show the results for each building and table 3.4 summarizes production by district for these two cases.

Districts	Biéreau	Hocaille	Center	Total
PV Production with Mendel in [MWh/y]	5 335.34	2 912.37	3 005.20	11 252.91
PV Production with De Serres in [MWh/y]	5 144.74	2 807.08	2 981.86	10 933.68

Table 3.4: Yearly PV production of the districts without shadows for a tolerance of 80% flat roof with flat roofs equipped as the model of the Mendel and De Serres tower

These data confirm that, as was the case in the chapter results, the Biéreau district has much higher production than the Hocaille and Centre districts, which are relatively close in terms of production.

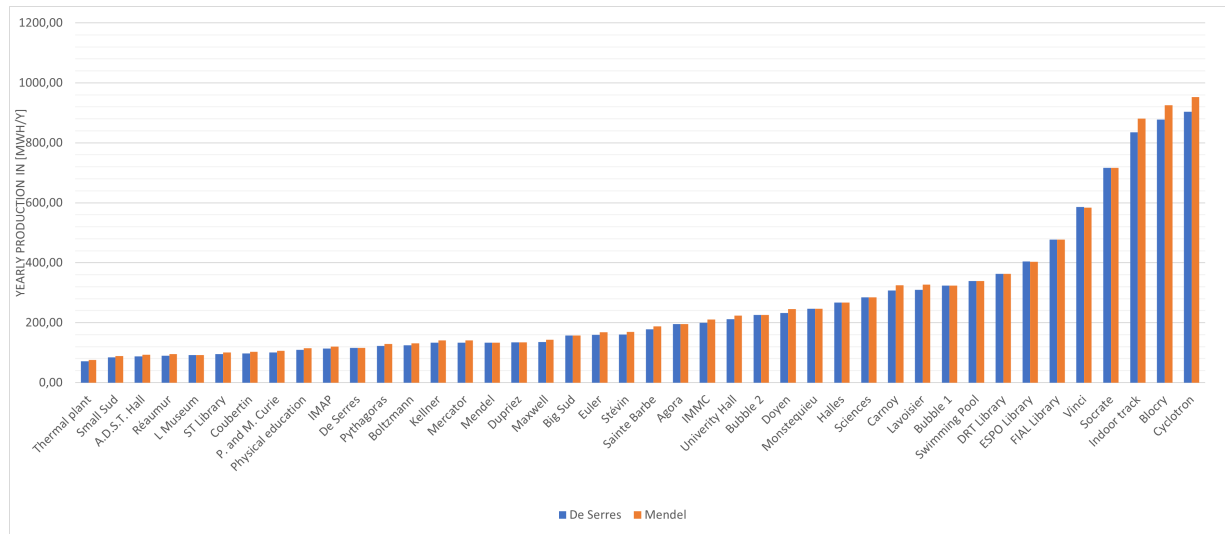


Figure 3.15: Column chart of the annual potential production of every building in [MWh/y]

Graph 3.15 shows the potential annual production of each of the buildings in Louvain-La-Neuve. Note that the "Blocry" building is made up of several parts. Indeed, during the measurements, we divided the Blocry into sets of parts to simplify the measurements and avoid errors. The Blocry, therefore, comprises the following buildings: Annexe 1, Annexe 2, Annexe 3, Hall 1, Hall 2, Entrance, and Gymnastics. With this modification, we can see that four buildings have significantly higher production than the others. These are the Socrate, the Indoor Track, the Blocry, and the Cyclotron. Between them, they represent 2 614 [MWh/y] for the De Serres model and 2 659 [MWh/y] for the Mendel model. In both cases, this represents around 24% of the total yearly potential production of the academic buildings. This result is directly linked to the fact that these buildings have a large roof surface area. The average building output is 260.33 [MWh/y] for the De Serres case and 267.93 [MWh/y] for the Mendel case. Buildings such as Museum L and the thermal power plant also have a lower output than other buildings. It is therefore less attractive to equip them with solar panels. We also notice that for each building the Mendel model gives a higher production. The only exception is the Mendel and De Serres buildings for which we choose to keep the results found in the respective models.

We can therefore deduce that renovation of the towers around Place de la Croix du Sud would slightly reduce the potential production of solar energy. However, these renovations are necessary to improve the energy performance of the buildings and thus reduce the amount of energy required to heat them. In addition, the reduction in production is minor. The difference in production between the Mendel and De Serres models is very small for some buildings, such as the Socrate. This is because these buildings have very few if any, flat roof surfaces.

3.3.1 Comparison to the household consumption

As mentioned above, the average annual electricity consumption in Belgium is 1.66 [MWh] per person [28]. We can therefore relate the results found to this consumption. It should be noted here that we are considering an optimal situation where electricity can be stored indefinitely and without loss. In reality, this is not the case and we need to compare the load curves with the production curves as a function of the time of year or day. If we assume perfect and abundant storage, we obtain that the annual potential production of electricity on the roofs of the academic buildings of UCLouvain can produce enough electricity to provide 6 788 and 6 586 people for the Mendel and De Serres model, respectively. If we consider 2.46 people per household in the Walloon Brabant [31], this represents 2 759 and 2 677 households, respectively. This represents 69% and 67% of the city's residents, respectively. This figure relates solely to the electricity consumed by residents. This would be produced by

emitting only 22% of the amount of $[CO_2e]$ needed to produce the same amount of electricity with the current Belgian energy mix [4]. This is mainly due to gas-fired power stations, which emit 515 $[gCO_2e/kWh]$, compared with just 36 $[gCO_2e/kWh]$ for solar power.

3.3.2 Comparison of the results

Now that we have results for the analysis with the LIDAR data and the PICC data, we can compare the results. Figure 3.16 compares the results obtained for roofs using LIDAR with the De Serres model and PICC data. We have chosen to use the De Serres model here to simplify the graphs and make them easier to read. In addition, this model is more representative of the future of flat roofs on academic buildings.

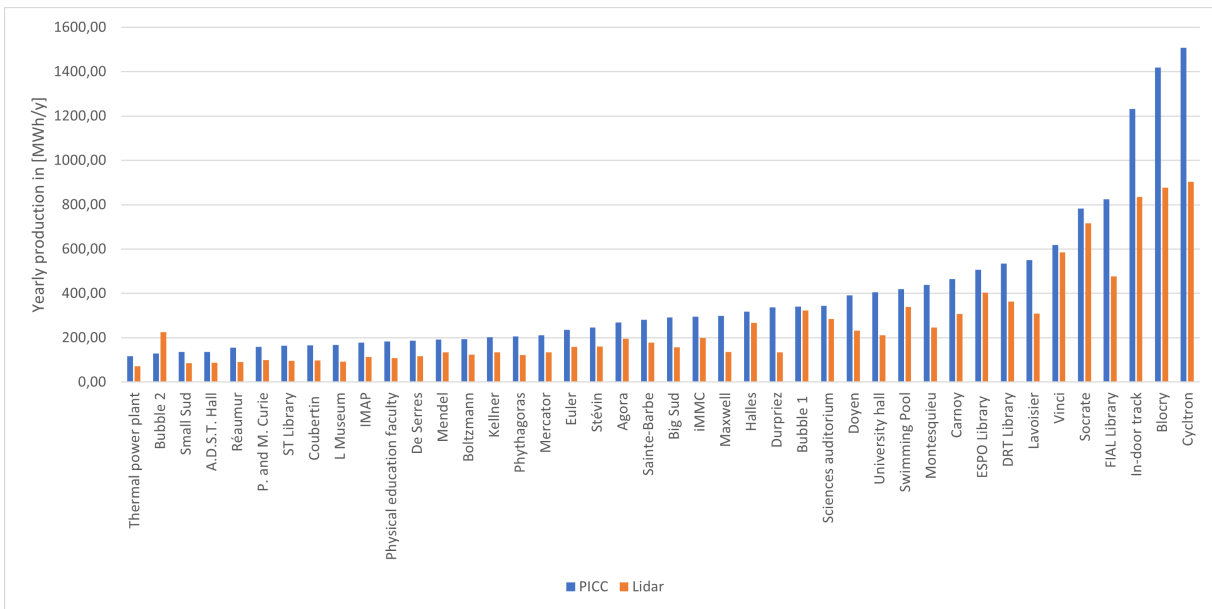


Figure 3.16: Yearly production for De Serres model with LIDAR data and for PICC

The graph shows that the PICC results are higher than the LIDAR results in most cases. On average, the LIDAR results are equivalent to 67% of the PICC results. This difference clearly shows that the results we found for the PICC overestimate potential production. Even though we used a coefficient to take account of shading and roof elements such as chimneys and H.V.A.C. systems, these coefficients are too low. If we had used a coefficient of 0.6 instead of 0.8, we would have obtained results closer to those obtained with LIDAR.

The case of "Bubble 2" is different, in that we imagined a particular panel coverage as in image 3 for the PICC data. In the case of the LIDAR data, however, we assumed total coverage, as in the case of fully sloping roofs. In reality, in this case, the model proposed for the PICC is more realistic. Indeed, on this type of bubble, the installation of panels on the north-facing facade does not appear to be cost-effective. For some buildings, production is halved between the PICC and the LIDAR, as is the case for the "Dupriez" or "University Hall" for example. In the first case, the reduction is explained by the removal of the north-facing roof parts with the shadow model. The second is due to the reduction in luminosity caused by the significant relief in the roof. The different parts of the flat roof shade each other. The models developed here are efficient for both flat and pitched roofs.

In terms of overall results, potential roof production drops from 16.23 $[GWh/y]$ with PICC data, to 10.93 $[GWh/y]$ with the De Serres model for LIDAR data.

3.3.3 Results considering the facades and the lake

If we retain the figure of 10.9 [GWh/y] obtained with the LIDAR data for the De Serres model, we can add the potential production of the facades and the lake, found thanks to the PICC. As a reminder, if we covered 25% of the surface of the lake of Louvain-La-Neuve with PV panels, the production would be 2.22 [GWh/y] and the facade production would be 12.72 [GWh/y]. In total, we obtain 25.84 [GWh/y]. This is enough electricity to supply 15 566 inhabitants or 6 327 households assuming perfect and abundant storage. This is more than the current population of Louvain-La-Neuve, but just under half of the population of the Ottignies-Louvain-La-Neuve. Not only could this production be used to decarbonize the electricity consumed by the inhabitants of Louvain-La-Neuve, but it could also be used to electrify several applications, such as heating homes, cooking with electricity, or powering electric vehicles.

3.4 Estimated cost of installation

In this section, we give a brief estimate of the cost of installing these panels on academic buildings. These estimates are based on the price analysis made by Mr. Deboot in his master thesis. This is only an estimate, not a detailed calculation. In 2018, at the time of Louis Deboot's master thesis, the price of a 1[m²] PV panel was 144 [€]. For flat roofs, the price of panel support is 46 [€]. This price is the result of a calculation made by the electrician company "Briatte". It should therefore be noted that the results presented below do not take into account inflation between 2018 and 2023.

3.4.1 Estimation for the roofs

In the case of academic buildings, if we put solar panels with the same density as on De Serres tower's roof on all flat roofs and cover sloping roofs as described above, then we get a total of 58 254 roof panels, of which 24 886 are installed on flat roofs. According to our assumptions, this corresponds to an installed capacity of 17.47 [MWp]. The amount of cable is calculated as being directly proportional to the number of panels. The number 42 refers to the number of roofs, bearing in mind that the different parts of the "Blocry" are counted as a single building. The total price for these roof-mounted panels was calculated as in the table 3.5.

Item	Quantity	Unit price [€]	Total price [€]
PV panels 1[m ²] and [0.3kWc]	58 254	144	8 388 576
Support for panels on flat roofs	24 886	46	1 144 756
Cables	1	818 723	818 723
Remote monitoring box	42	2 400	100 800
Decoupling relay	42	7 500	315 000
Display for instantaneous production and cumulative CO2	42	1 234	51 828
Building site installation	42	4 400	184 800
Restoration of roof waterproofing	42	5 500	231 000
Earthing and equipotential bonding	42	600	25 200
Total investment			11 260 683

Table 3.5: Estimation of the total price of the roof installation

We took the maximum parameters into account but there is a lack of information about some cost categories. We therefore note that this price estimate does not take all aspects into account, and therefore gives a low estimate. However, as the size of the installation is very large, economies of scale are to be expected. It is a

hefty sum, but it would enable us to produce a large quantity of electricity and thus greatly decarbonize the city of Louvain-La-Neuve.

3.4.2 Estimation for the facades

For facades, we can consider two cases. The first is the use of conventional PV panels such as those used on roofs, and the second is the use of BIPV panels such as those produced by AGC. In the case of conventional panels, we consider only the cost of the panels and the supports for each panel. The other costs are associated with a building and are taken into account in the case of roofs. In the case of AGC's BIPV panels, Mr. Mal tells us that these panels cost between 225 and 350 [€/m²]. He also points out that this price decreases with the number of panels requested. We can therefore consider 250 [€/m²] as an acceptable value. The tables 3.6 and 3.7 summarize the prices for the two cases. If we consider only facades facing south, west, or east and if we multiply the total surface by the 0.6 coefficient used previously, we obtain a total surface of 70 953 [m²]. According to our assumptions, this corresponds to an installed capacity of 21.28 [MWp].

Item	Quantity	Unit price [€]	Total price [€]
PV panels 1[m ²] and [0.3kWc]	70 953	144	10 217 232
Support for panels on flat roofs	70 953	46	3 247 278
Total investment			13 464 510

Table 3.6: Estimation of the total price of the facade installation with classical PV

Item	Quantity	Unit price [€]	Total price [€]
PV panels 1[m ²]	70 953	250	17 738 250
Total investment			17 738 250

Table 3.7: Estimation of the total price of the facade installation with AGC BIPV

In both cases, the price is higher than for roof-mounted panels. What is more, for conventional panels, rooftop production is not only more productive but also cheaper than facade production, even though facade panels have a good output. This means that the priority in terms of investment should be the roofs, followed ideally by facades.

3.4.3 Estimation for the lake

As far as floating panels are concerned, price data are not very plentiful. However, article [32] provides an analysis of prices for installation in Australia. The study gives prices for 3 200 panels. We can adapt this to 10 224 panels covering 25% of the lake surface. We round the number of panels to make complete rafts. We then consider 10 200 panels or 3.06 [MWp]. This gives the results shown in the table 3.8.

Item	Quantity	Unit price [€]	Total price[€]
PV panels 1[m ²]	10 200	131.25	1 338 750
Raft carpentry	510	1 250	627 500
Pipes	2 040	250	510 000
Cable and inverter	1	446 250	446 250
Site preparation	1	95 625	95 625
Work (hour)	9 562	13.33	127 461
Total investment			3 145 586

Table 3.8: Estimation of the total price of the floating installation

It is important to bear in mind that these are figures for Australia in 2017. The evolution over the years as well as the differences in labor or material prices. This, therefore, gives an order of magnitude but not an exact value for Belgium.

3.4.4 Global estimation

All in all, if we take into account the price of the panels on the roof, facades, and lake, we obtain a total price of 32 million [€] for AGC BIPV panels and 27 million [€] for conventional panels. These costs are high, but in the current energy context and with the energy transition underway, this investment would make sense and would probably be profitable after a few years.

Chapter 4

Energy implications for Louvain-La-Neuve

4.1 Household and university electricity consumption

To be able to look at the impact of the solar installation described in the previous chapters, we need to use household electricity consumption data for Louvain-La-Neuve and the University. These data were provided by Aurélia Hernandez, research assistant at IMMC (Institute of Mechanics, Materials and Civil Engineering). University data is from 2019 and household data is from 2021. The university's electricity consumption for 2019 is around 27 [GWh] and that of Louvain-La-Neuve households is around 25[GWh] for 2021. It is presented in tabular form, with each line representing a quarter-hour of the year. For each quarter-hour, the fraction of annual electricity consumption is indicated. With this data and the total annual electricity consumption data for households and the university, we can calculate the consumption for each hour of the year. We can then plot the annual consumption profile of the city's inhabitants and the University. The Python code A.12 produces the following two graphs.

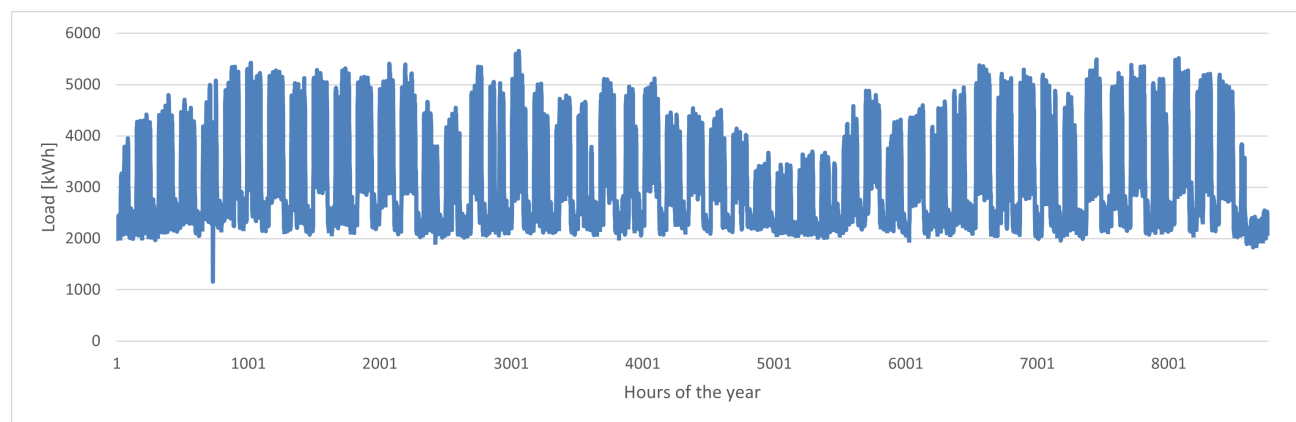


Figure 4.1: UCLouvain's load curve

When we look at this curve, we can see a number of particularities. The curve for UCLouvain is between 2 and 6 [MWh] per hour during the year, except for a 3-hour period on January 31. We can imagine that this much lower consumption than the rest of the year probably corresponds to a special event, such as the reboot of UCLouvain's servers. Another particularity of this curve is the fact that weekends are marked by a decrease in consumption. This represents the weekly life of the university. The month of August, and especially July,

also corresponds to a decrease in consumption. The daily average consumption then lowers from 4 [MWh] to 3 [MWh]. There is also a drop in the April and December vacations.

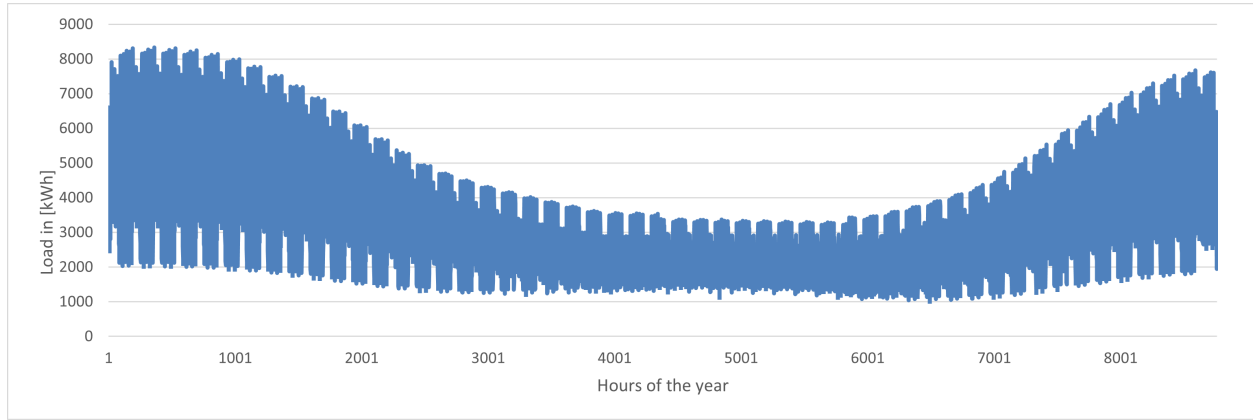


Figure 4.2: Louvain's household load curve

Hourly household consumption, on the other hand, is smoother and more in line with the seasons. In winter, consumption rises sharply, while in summer it falls sharply. In the case of households, hourly consumption does not fall below 1 [MWh] and only goes above 8 [MWh] for a few days in winter. Weekends are also marked by a drop in household electricity consumption.

Since these data are expressed in terms of hourly consumption throughout the year, the photovoltaic electricity production data found in the previous chapters must be transformed to obtain hourly production. To do this, we transform the data found with LIDAR for roofs and the data found with PICC for facades.

4.2 PV production during the year

We will begin by analyzing the annual production of roofs and then move on to facades.

4.2.1 Roof PV production and load curves

For rooftop production, we will reuse the fractions of the optimal irradiances as well as the irradiances received by the dual-axis pivoting panels to find the rooftop production for each hour of the year. For rooftop production, we will reuse the fractions of the optimal irradiances as well as the irradiances received by the dual-axis pivoting panels to find the rooftop production for each hour of the year. To keep annual production constant, we will take an average according to the formula 4.1.

$$E_i = \frac{c_i I_i E_{tot}}{\sum_{j=1}^{142} c_j I_j} \quad (4.1)$$

E_i : Hourly production of PV panels installed on the building's roof in [kWh]

i : One hour of the 20th or 21st day of a month of the year [-]

c_i : Fraction of the optimal irradiance perceived during hour "i" [-]¹

I_i : Mean irradiance received by a double axis pivoting panel during hour "i" [W/m²]²

¹the fractions used for flat surfaces correspond to the fraction of the De Serres buildings. These fractions, therefore, correspond to inclined rows of panels.

²Here, we average the irradiance obtained at these times between 2005 and 2020.

E_{tot} : Total production of PV panels installed on the building throughout the year [kWh]

Repeating this for each building, we then obtain the production of the buildings at all hours of the day corresponding to the blue curves on the Louvain-La-Neuve solar curves. Next, we assume that production at a given hour on a given day can be found by making a linear approximation between production for that hour on the previous reference day and production for that hour on the following reference day. The reference day is the day corresponding to the blue curves on the solar curves (21st January, 20th February, etc.). For example, if we want to obtain the production on April 8 at 10 a.m., we will make a linear approximation between the production on March 20 and April 20 at 10 a.m. This is calculated using the formula 4.2

$$E_h = \frac{(E_a(\Delta t - d) + E_p d)12}{365\Delta t} \quad (4.2)$$

E_h : Production of PV panels of a building during hour "h" of the year (h in [1;8760]) [kWh]

E_a : Production of the panels during the previous reference day during the same hour of the day as E_h multiplied by the number of days in the month [kWh]

Δt : Number of days between the previous reference day and the next reference day

d : Number of day between the day of E_h and the day of E_a

E_p : Production of the panels during the next reference day during the same hour of the day as E_h multiplied by the number of days in the month [kWh]

The presence of 12/365 allows the number of days in the year to increase from 12 to 365, contributing to a yearly production that remains constant. Where before, one day's production acted as an average for all days of the month, here each day brings its own production.

This gives us the hourly output of each building. We then add them together to obtain the hourly output of all academic buildings combined. These results are summarized in a large vector of 8 760 productions expressed in [kWh]. The code for this computation can be found in the appendix A.13. From this vector, we can plot the hourly electricity production of academic buildings over a typical year 4.3. Figure 4.4 is a zoom on the month of January where we see the production dropping to zero when the sun is down. With the electricity generated by the rooftop panels and the consumption of the university and households, the first comparison we make is to examine the load curves for two days in each month of the year. Here we choose the 20th and 21st of each month. These curves are shown below.

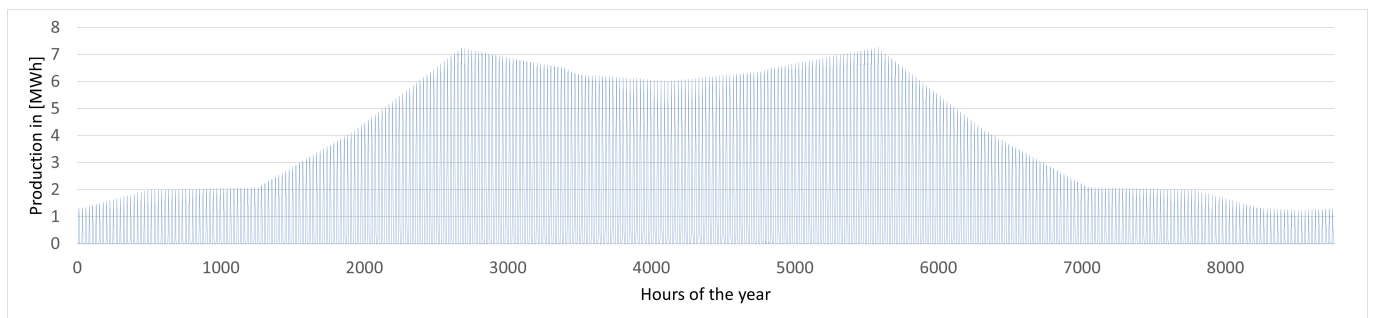


Figure 4.3: Hourly PV production of the roofs of the academic buildings

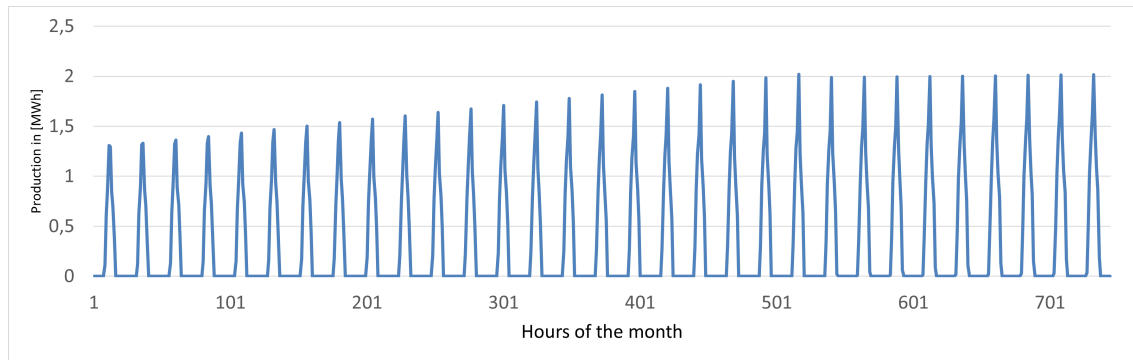


Figure 4.4: Hourly PV production of the roofs of the academic buildings in January

This last graph provides a better understanding of how the hourly production graph is constructed. We can see that until the sun rises, production is logically zero. The linear nature of the maximum daily productions (production peaks at 12:00) of UCLouvain roofs comes from the fact that we make a linear approximation between two reference days. In addition, the fact that the irradiance values we used above are 16-year averages means that the results we have found are a good estimate of the distribution of production in a typical year. Contrary to the consumption graphs, production from rooftop panels returns to zero every night.

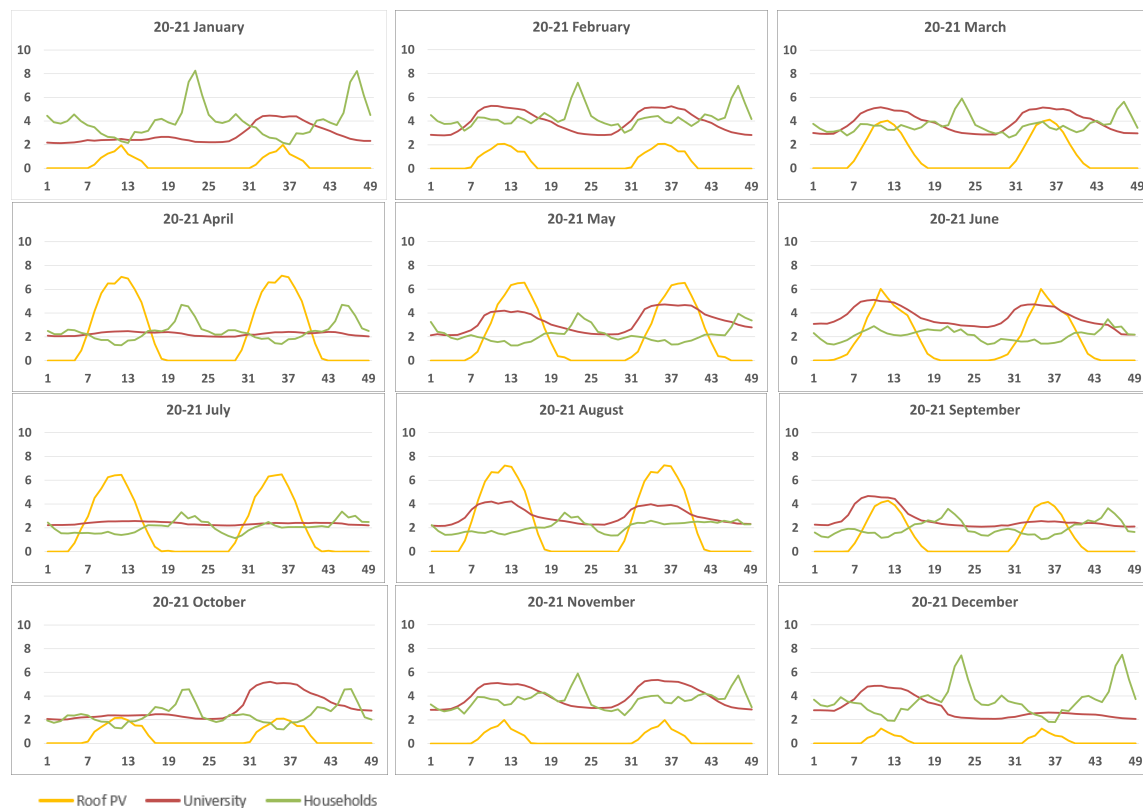


Figure 4.5: Load curves of the roof production compared to the consumption of UCLouvain and Louvain's households in [MWh]

Days of low demand for the university correspond either to public holidays or weekend days. From April to

September, the production curve regularly exceeds the consumption curves. In some cases, such as April or July, the production curve at midday is close to university and household consumption combined.

4.2.2 Facade PV production and load curves

The reflection used to obtain hourly production from facade-mounted solar panels differs from the reflection used for roof-mounted panels. Whereas the method used for roof-mounted panels was designed to determine hourly production on specific days in order to approximate other days, the method for vertical panels uses direct hourly data from vertical panels to determine production. The principle is that production is proportional to the irradiance received by a panel. Based on this observation and irradiance data from the European Commission, we can average panel production for each hour. To do this, we will use a weighted average of three-panel orientations. For west-facing panels, for example, we take a weighted average of the output from panels facing northwest, west, and southwest. In this case, north-facing facades are not taken into account, given their low production. The following formula summarizes the calculation of hourly panel output.

$$E_h^o = \frac{(I_h^{o+45} + 2I_h^o + I_h^{o-45})E_{tot}^o}{\sum_{h=1}^{8760}(I_h^{o+45} + 2I_h^o + I_h^{o-45})} \quad (4.3)$$

E_h^o : Production at hour "h" for panels facing direction "o"³ [kWh]

I_h^o : Global irradiance on the inclined plane for hour "h" and orientation "o"⁴ [W/m²]

I_h^{o+45} : Global irradiance on the inclined plane for hour "h" and orientation "o" plus 45° (For south it is south-west, for west, it is north-west, etc.) [W/m²]

I_h^{o-45} : Global irradiance on the inclined plane for hour "h" and orientation "o" minus 45° (For south it is south-east, for west, it is south-west, etc.) [W/m²]

E_{tot}^o : Total production of the panels facing in the "o" direction [kWh]

Then all we need to do is add up the production of the east, south, and west panels to obtain the total hourly production of the facades of the university buildings. The code used for this calculation is available in appendix A.14. If we look at the individual outputs, we can see that the output of the west-facing panels is higher in the evening and lower, or even zero, in the morning, while the opposite is true for the east-facing facades. We can therefore logically say that equipping buildings that are heavily used in the morning will be more directly useful on the eastern facades, whereas a building used mainly in the afternoon and evening will benefit more from the installation of panels on the western facades. The fact that we have used global irradiance data means that the facade production calculated here is highly subject to changes in the weather. Significant increases are sometimes followed by drastic decreases, which can probably be explained by the presence or absence of clouds in front of the panels.

Now that we have the hourly output of the facade panels, we can compare their output with the load curves of the university and households for two days each month. Here are the curves for the 20th and 21st of each month of the year. The significant variations in production from facade panels are clearly visible in the following graphs.

³Orientation "o" can either be west, south or east as we exclude facade facing north here due to the low production.

⁴We have taken the irradiance data for 2020.

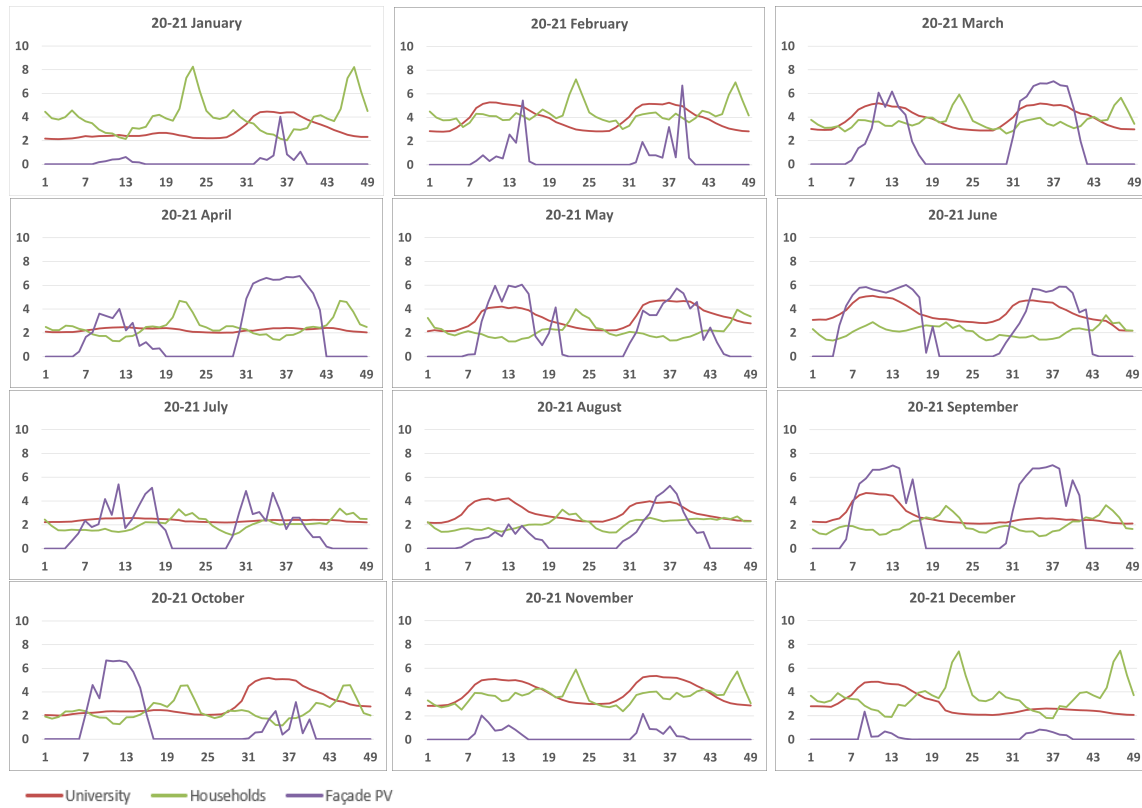


Figure 4.6: Load curves of the facade production compared to the consumption of UCLouvain and Louvain's households in [MWh]

The following curves show the comparison between the cumulative production of roofs and facades and the consumption of the university and the households.



Figure 4.7: Load curves of the roof and facade production compared to the consumption of UCLouvain and Louvain's households in [MWh]



Figure 4.8: Load curves of the total of the roof and the facade production compared to the total consumption of UCLouvain and Louvain's households in [MWh]

Graphs representing five curves (University's consumption, households' consumption, roof production, facade production, and total production) simultaneously are available in appendix A.15.

4.3 Load duration curves

With all the production and consumption data thus obtained, we calculate load duration curves for the case of households or for the case of UCLouvain. Load duration curves are curves in which the demands for each hour of the year are sorted from the largest to the smallest. The result is a descending load curve for all hours of the year. To plot them, we take the hourly consumption data and sort them from highest to lowest, to obtain the first curve corresponding to the absence of solar panels. To obtain the other curves in the graph, we take the hourly consumption data and subtract hour by hour the production of the panels (either from the roofs or facades, or both at the same time). In fact, we consider the electricity generated by the panels as negative demand. Once this subtraction has been made, we can sort the values. Negative values correspond to PV production in excess compared to consumption.

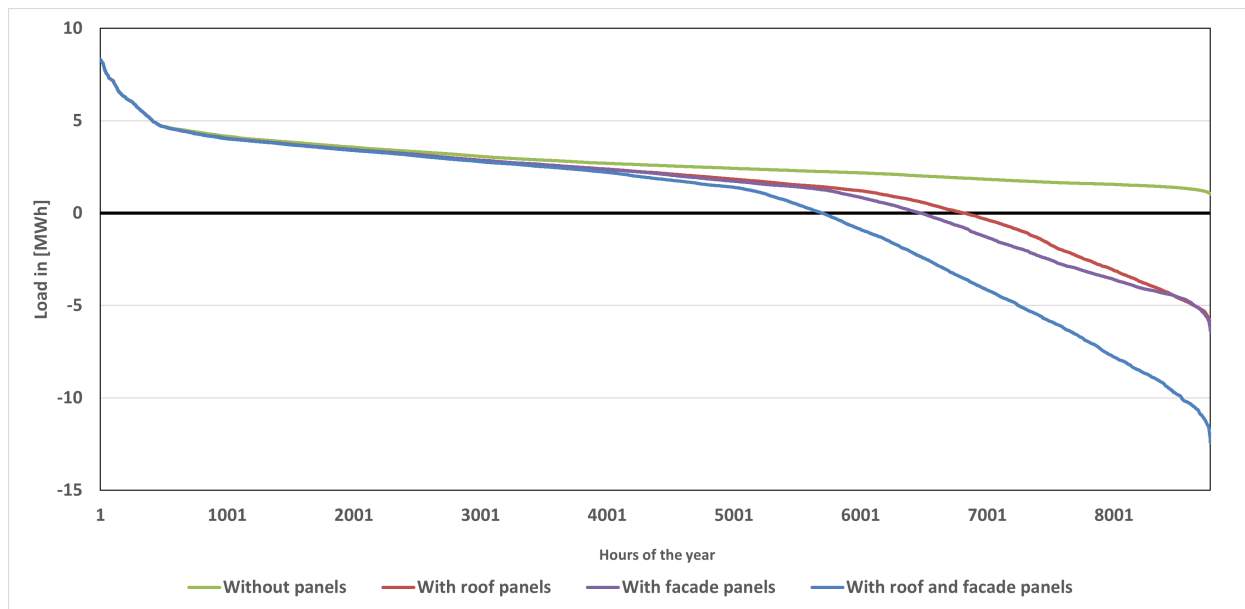


Figure 4.9: Households' load duration curves with different PV installations

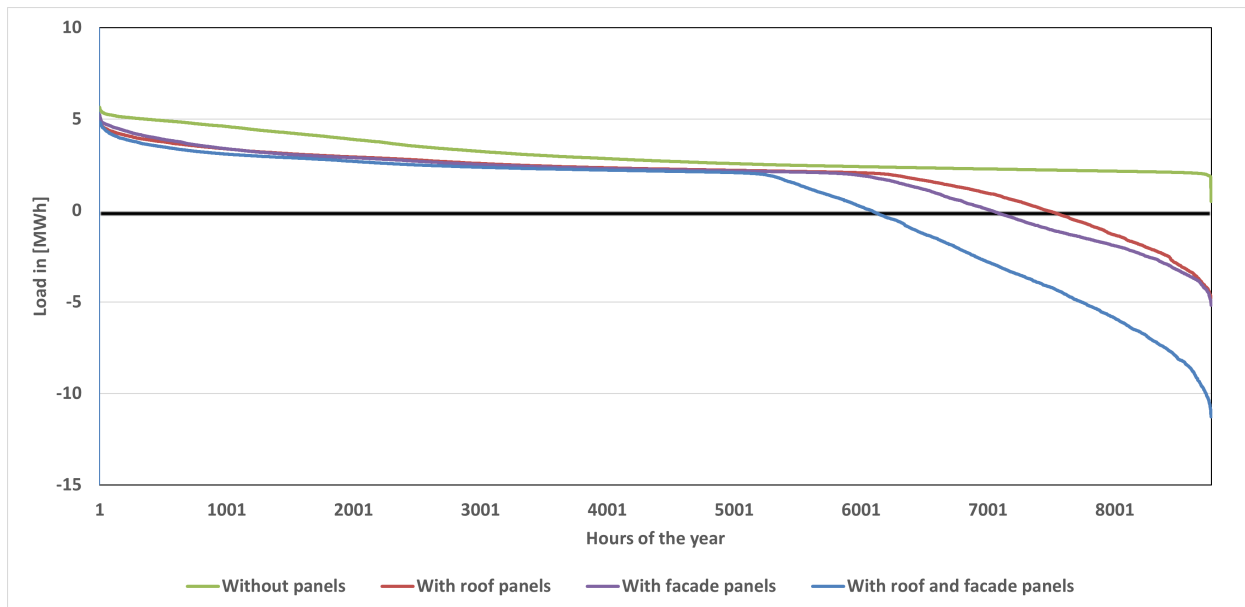


Figure 4.10: UCLouvain's load duration curves with different PV installations

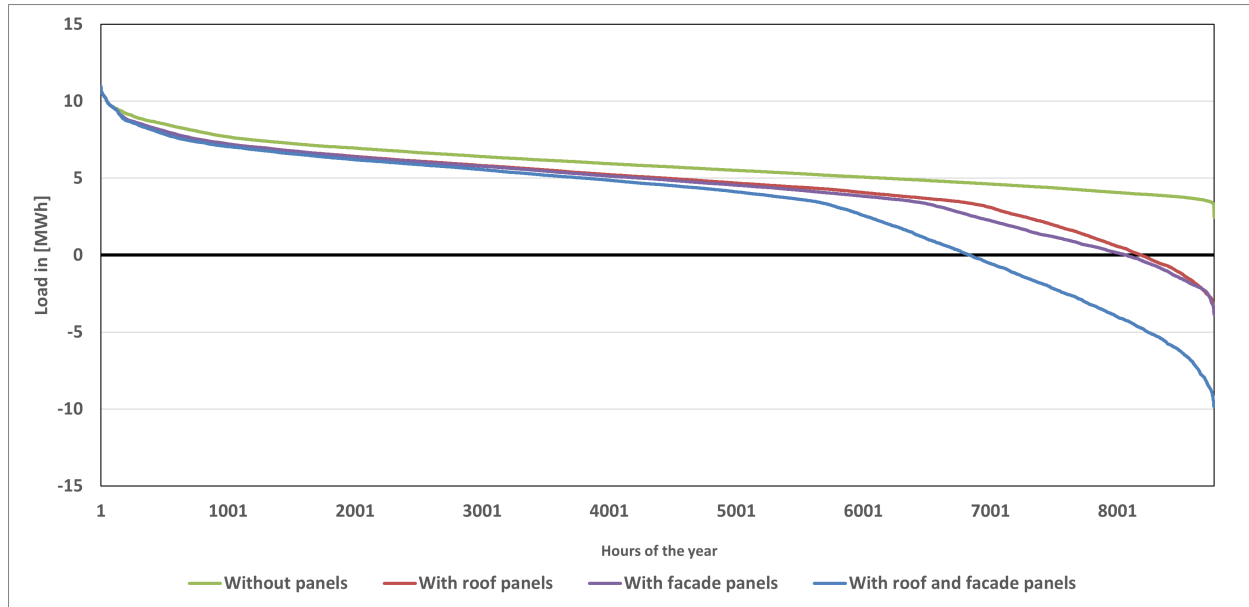


Figure 4.11: Load duration curves for UCLouvain and households combined with different PV installations

Characteristic point values are shown in the tables 4.1, 4.2 and 4.3.

When we plot the load duration curve corresponding to the presence of the panels, we see that it crosses the x-axis. We can then see how many hours lie to the left and right of this point, and if we relate this number to the total number of hours in the year, we obtain the fractions of time when consumption exceeds production and the fraction of time when production exceeds consumption, respectively. These percentages of time where the production overcomes the consumption and the potential re-injection are shown below.

Cases	Negative fraction	Re-injection [MWh]	Minimum [MWh]	Maximum [MWh]
Without panels	/	0	1.025	8.330
With roof panels	0.221	4 934	-5.943	8.330
With facades panels	0.198	6 191	-6.361	8.330
With facades and roof panels	0.350	15 607	-12.409	8.330

Table 4.1: Potential network re-injection for the households

Cases	Negative fraction	Re-injection [MWh]	Minimum [MWh]	Maximum [MWh]
Without panels	/	0	0.505	5.655
With roof panels	0.147	2 302	-4.780	4.870
With facades panels	0.261	3 250	-8.186	5.242
With facades and roof panels	0.305	11 389	-11.284	4.842

Table 4.2: Potential network re-injection for UCLouvain

Cases	Negative fraction	Re-injection [MWh]	Minimum [MWh]	Maximum [MWh]
Without panels	/	0	2.458	10.971
With roof panels	0.065	697	-3.360	10.971
With facades panels	0.079	856	-3.855	10.971
With facades and roof panels	0.219	6 723	-9.826	10.971

Table 4.3: Potential network re-injection for UCLouvain and households combined

Network re-injection data correspond to electricity produced in excess when the generation curve exceeds the demand curve. This is the area between the x-axis and the part below 0 of the load duration curves. This excess electricity can be used to supply other homes just outside of Louvain-La-Neuve. In the case of households, the fraction of time when production exceeds demand is almost equivalent for roofs only and facades only. However, if we look only at these two scenarios, we see that the amount of electricity fed back into the grid is greater in the case of facade-only installations. In the case of UCLouvain, the amount of electricity fed back into the grid is significantly lower. This can be explained by the fact that the university's daily consumption peak coincides with the photovoltaic electricity production peak. On the other hand, peak household electricity consumption occurs in the evening, at a time when panel output is low, or even zero, depending on the season. It would therefore be interesting, especially in the case of households, to find a solution for storing part of the electricity so that it can be reused at times of peak demand. One storage solution is pumped storage, as practiced at the Plate Taille dam on the Eau d'Heure lakes. However, this solution is less easy to implement in the vicinity of Louvain-La-Neuve.

There are other indicators of interest here including self-consumption and self-sufficiency. Self-consumption represents the fraction of electricity directly consumed by the university or its residents. It is the production from which excess electricity is deducted. It can also be computed as the total PV production minus the Re-injection divided by the total PV production. Self-sufficiency then represents the proportion of self-consumption in total annual consumption. These indicators can be expressed in terms of percentages.

Cases	Self-consumption [%]	Self-sufficiency [%]
With roof panels	55	24
With facades panels	51	26
With facades and roof panels	34	32

Table 4.4: Households' self-consumption and self-sufficiency

In the household table, we can see that if panels are installed on roofs or facades, the self-consumption rate rises above 50 %. However, we can see that combining these two types of production significantly reduces the rate of self-consumption. Combining the two, therefore, generates a large amount of excess electricity to be re-injected into the network. However, this solution covers almost a third of household demand.

Cases	Self-consumption [%]	Self-sufficiency [%]
With roof panels	79	32
With facades panels	74	35
With facades and roof panels	52	45

Table 4.5: UCLouvain's self-consumption and self-sufficiency

In the case of the university, this coverage rises to 45% in the case of roof and facade panels, even though this also reduces the self-consumption rate. We can therefore see that increasing the number of panels and, above all, choosing different surfaces increases the self-sufficiency rate, but reduces the self-consumption rate. On the other hand, combining these panels with electricity generated independently of the sun's irradiance, as is the case

with wind turbines, can increase the self-consumption rate. However, this kind of solution is beyond the scope of this work.

Cases	Self-consumption [%]	Self-sufficiency [%]
With roof panels	94	20
With facades panels	93	23
With facades and roof panels	72	33

Table 4.6: UCLouvain and households combined self-consumption and self-sufficiency

In the last case, we can see that most of the electricity produced is consumed directly by the university and households. However, the self-sufficiency rate remains low. In this configuration, re-injections into the network are low, but demand is not sufficiently covered.

4.4 Environmental impact

Using the figures determined above, we analyze the impact that the installation of these panels could have on the city of Louvain-La-Neuve's greenhouse gas emissions. The first calculation we can make is that if all the electricity generated by the panels is consumed, then the 23.65 [GWh] are produced while emitting 36 [gCO_2e/kWh] instead of 124 [gCO_2e/kWh], which is the average for Belgium. This means that emissions amount to 851 [tCO_2e]⁵ instead of 2 933 [tCO_2e], a 71% reduction in greenhouse gases. And if we consider only the self-consumed portion of electricity (8.04 [GWh] for households and 12.26 [GWh] for the university), the drop is proportionally identical. We go from 997 to 289 [tCO_2e] and from 1 520 to 441 [tCO_2e], respectively.

As far as heating is concerned, we know that student apartments in Louvain-La-Neuve are all heated directly or indirectly with gas. We also know that, while all these apartments use electricity for cooking, some are connected to mains gas. So, we can now imagine using the electricity that would be fed back into the grid to see how many households can use this surplus electricity to switch their cooking and/or heating to electric solutions. Since the average surface area of residential buildings in Louvain-La-Neuve is 235.45 [m^2] according to the QGIS data we have, and knowing that the average consumption of an aérothermal heat pump is 51 [$kWh/(m^2 \cdot year)$] [29], we can deduce that this represents consumption of $235.45 \cdot 51 = 12\,007.95$ [$kWh/year$]. This means that the 15 607 [MWh] re-injected into the system can theoretically be used to convert 1 300 homes from gas heating to heat pump heating. In practice, heat pumps are likely to consume less when the sun is producing a lot of electricity, as the sun also heats homes directly. Assuming that households switch from gas heating to an aérothermal heat pump powered by solar electricity, each household would go from an average of 8 947 [$kgCO_2e$]⁶ per year to 432 [$kgCO_2e$]⁷.

For the university, the environmental impact is lower, even though a smaller amount of electricity is fed back into the network. In fact, the university is planning a co-generation project using biomass harvested from waste disposal sites around the city. Although biomass emits an average of 230 [gCO_2e] per [kWh], this co-generation has a dual role. It produces the electricity as well as the heat required by the university. Given its dual role, this co-generation is not too emission-intensive. To achieve this result from electricity, it would have to meet electricity demands in addition to generating heat. The greenhouse gas emissions generated by such a solution are difficult to quantify at this stage. In addition, during the months of July and August, a large amount of solar-generated electricity is produced when there are few students at the university. A large amount of electricity must be fed back into the network.

⁵[tCO_2e] means ton of CO_2 equivalent.

⁶considering an emission of 38 [$kgCO_2e$] per [m^2] per year

⁷considering 12 [MWh/year] and 36 [gCO_2e] per [kWh]

We can thus see that these installations have a positive environmental impact on the households of Louvain-La-Neuve, despite the environmental cost of the life cycle of the panel. In line with the environmental objectives of Belgium, and Louvain-La-Neuve in particular, it is therefore interesting to invest in a solution such as this to decarbonize the households of Louvain-La-Neuve. Although it is probably more important to supply electricity to households than to the university, the excess electricity produced can be used directly to meet the university's needs.

Chapter 5

Conclusion

5.1 Summary

In previous chapters, we have seen how three-dimensional building models can be used to determine the benefits of installing photovoltaic panels on facades and roofs in a recent urban environment such as Louvain-La-Neuve. To do this, we went through several stages. Firstly, based on the literature on the subject, we were able to familiarise ourselves with studies relating to photovoltaic electricity production models and the installation of panels in a geographical area such as Louvain-La-Neuve. This provided us with a scientific basis for the development of our production models.

We then used the PICC data to measure the surface areas of the facades and roofs of the academic buildings concerned. Thanks to these measurements and a mathematical model based on hypotheses, we were able to give an order of magnitude for the production of each facade and roof concerned. This model has enabled us to give initial values for annual production of around 13 [GWh] for the facades and 16 [GWh] for the rooftops. This electricity can cover a significant fraction of the households' demand of the University's demand.

After this, in order to fine-tune our potential production values of the rooftops, we used a LIDAR database to calculate production at different times of the year according to the corresponding position of the sun in the sky. It seemed to us that this would give a better estimate for a town located at a latitude such as Louvain-La-Neuve than models that give production for all azimuth and elevation angles, including north azimuth angle. With this technique, we were able to manually add rows of panels on rooftops to the LIDAR data in order to directly calculate production for given panel installations. We also take into account the presence of shadow zones on roofs. In this way, we obtain more accurate production results that take into account many parameters that reduce the exploitable surface. Thanks to this more precise method, we obtain a result of around 11 [GWh] of annual roof production. We were then able to compare this production and the previously obtain facade production with the average consumption of Louvain-La-Neuve's households. Assuming perfect and abundant storage, we can cover the consumption of 6 327 households. To conclude this chapter, we briefly analyze the potential cost of such installations which is around 32 million [€] in total.

Finally, we have dedicated a chapter to the analysis of this production throughout the year. To achieve this, we modeled the hourly production of roof and facade panels. This enables us to obtain production curves that we can compare with the consumption data we have for households in Louvain-La-Neuve and for the UCLouvain. Based on this data, we have drawn up load duration curves for the various possible layouts. This enabled us to calculate the quantities of electricity re-injected into the grid, as well as self-consumption and self-sufficiency rates. If we use the electricity produced by the roof and facade panels to meet household demand, the self-consumption rate is 34% and the self-sufficiency rate is 32%. In the case of UCLouvain, these rates are 52% and 45%, respectively. On the basis of these analyses, we can discuss whether it is more interesting to use this electricity production primarily for universities or households. As described in section 4.4, we tend to favor households even though the

surplus electricity could be consumed directly by the university.

5.2 Research perspectives

We are convinced that several studies can follow from this work.

First, it would be interesting to study how a renewable energy community (REC) can be set up in Louvain-La-Neuve. The price of electricity can be established. It should be noted that the initial idea is that UCLouvain should sell low-cost electricity to private households in the city. This study can also provide more detailed and precise information on the purchase and installation prices of the panels. The conditions for joining the community would then be discussed. Common services such as charging stations for electric cars are also conceivable. All these analyses would make the installation of PV panels on university buildings even more concrete. These analyses can also be used to determine the return on investment.

With the advent of the biomass plant at UCLouvain, it would also be interesting to compare energy production curves with panel production curves. This can then be put into perspective with the university's electricity consumption. In this way, we'd have information on the energy impact of these panels in the presence of this new biomass power plant.

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Appendix A

Appendix for Chapter 2

A.1 Code used to compute the optimal tilt angle for the PV panels on flat roofs

```
1 ### Hourly production code for academic buildings in Louvain-La-Neuve ###
2 ### Code by Theo Schepers 02/08/2023 ###
3 ### Imports###
4 from openpyxl import load_workbook
5 import numpy as np
6
7 workbook = load_workbook(filename="Timeseries.xlsx")
8 workbook2 = load_workbook(filename="Timeseries_20deg.xlsx")
9 workbook3 = load_workbook(filename="Timeseries_25deg.xlsx")
10 workbook4 = load_workbook(filename="Timeseries_35deg.xlsx")
11 s = workbook.active
12 t = workbook2.active
13 u = workbook3.active
14 v = workbook4.active
15
16 r_min=10
17 r_max=8793
18
19 angles30 = [23.86, 15.52, 9.08, 4.01]
20 angles25 = [21.07, 13.42, 7.74, 3.39]
21 angles20 = [17.78, 11.12, 6.34, 2.76]
22
23 angles20_15 = [31.30,17.78,9.37,3.84]
24 angles25_15 = [35.40,21.07,11.36,4.72]
25 angles30_15 = [38.44,23.87,13.21,5.56]
26
27 angles20_25 = [12.29,8.09,4.79,2.15]
28 angles25_25 = [14.80,9.83,5.86,2.65]
29 angles30_25 = [17.05,11.47,6.9,3.13]
30 angles35_25 = [18.74,12.77,7.76,3.55]
31
32 sum_15 = np.zeros((3,5))
33 sum_25 = np.zeros((4,5))
34
35 sum_30_24=0
36 sum_30_16=0
37 sum_30_9=0
38 sum_30_4=0
39 sum_30_0=0
40
41 sum_20_18=0
```

```

42 sum_20_11=0
43 sum_20_6=0
44 sum_20_3=0
45 sum_20_0=0
46
47 sum_25_21=0
48 sum_25_13=0
49 sum_25_8=0
50 sum_25_3=0
51 sum_25_0=0
52
53 p35 =1069.27
54 p30 =1061.33
55 p25 =1047.72
56 p20 =1028.45
57
58 for i in range(10,8793):
59     a = s.cell(row=i, column=1).value
60     a= a.split(",")
61     if(a[1]!="0.0"):
62         sum_30_0 += float(a[1])
63         if(float(a[2])>=angles30[0]):
64             sum_30_24 += float(a[1])
65         if(float(a[2])>=angles30[1]):
66             sum_30_16 += float(a[1])
67         if(float(a[2])>=angles30[2]):
68             sum_30_9 += float(a[1])
69         if(float(a[2])>=angles30[3]):
70             sum_30_4 += float(a[1])
71     if(a[1]!="0.0"):
72         sum_15[2][0] += float(a[1])
73         if(float(a[2])>=angles30_15[0]):
74             sum_15[2][1] += float(a[1])
75         if(float(a[2])>=angles30_15[1]):
76             sum_15[2][2] += float(a[1])
77         if(float(a[2])>=angles30_15[2]):
78             sum_15[2][3] += float(a[1])
79         if(float(a[2])>=angles30_15[3]):
80             sum_15[2][4] += float(a[1])
81     if(a[1]!="0.0"):
82         sum_25[2][0] += float(a[1])
83         if(float(a[2])>=angles30_25[0]):
84             sum_25[2][1] += float(a[1])
85         if(float(a[2])>=angles30_25[1]):
86             sum_25[2][2] += float(a[1])
87         if(float(a[2])>=angles30_25[2]):
88             sum_25[2][3] += float(a[1])
89         if(float(a[2])>=angles30_25[3]):
90             sum_25[2][4] += float(a[1])
91
92
93 for j in range(10,8793):
94     b = t.cell(row=j, column=1).value
95     b= b.split(",")
96     if(b[1]!="0.0"):
97         sum_20_0 += float(b[1])
98         if(float(b[2])>=angles20[0]):
99             sum_20_18 += float(b[1])
100        if(float(b[2])>=angles20[1]):
101            sum_20_11 += float(b[1])
102        if(float(b[2])>=angles20[2]):
103            sum_20_6 += float(b[1])
104        if(float(b[2])>=angles20[3]):
105            sum_20_3 += float(b[1])
106    if(b[1]!="0.0"):

```

```

1207     sum_15[0][0] += float(b[1])
1208     if(float(b[2])>=angles20_15[0]):
1209         sum_15[0][1] += float(b[1])
1210     if(float(b[2])>=angles20_15[1]):
1211         sum_15[0][2] += float(b[1])
1212     if(float(b[2])>=angles20_15[2]):
1213         sum_15[0][3] += float(b[1])
1214     if(float(b[2])>=angles20_15[3]):
1215         sum_15[0][4] += float(b[1])
1216 if(b[1]!="0.0"):
1217     sum_25[0][0] += float(b[1])
1218     if(float(b[2])>=angles20_25[0]):
1219         sum_25[0][1] += float(b[1])
1220     if(float(b[2])>=angles20_25[1]):
1221         sum_25[0][2] += float(b[1])
1222     if(float(b[2])>=angles20_25[2]):
1223         sum_25[0][3] += float(b[1])
1224     if(float(b[2])>=angles20_25[3]):
1225         sum_25[0][4] += float(b[1])
1226
1227
1228 for k in range(10,8793):
1229     c = u.cell(row=k, column=1).value
1230     c= c.split(",")
1231     if(c[1]!="0.0"):
1232         sum_25_0 += float(c[1])
1233         if(float(c[2])>=angles25[0]):
1234             sum_25_21 += float(c[1])
1235         if(float(c[2])>=angles25[1]):
1236             sum_25_13 += float(c[1])
1237         if(float(c[2])>=angles25[2]):
1238             sum_25_8 += float(c[1])
1239         if(float(c[2])>=angles25[3]):
1240             sum_25_3 += float(c[1])
1241     if(c[1]!="0.0"):
1242         sum_15[1][0] += float(c[1])
1243         if(float(c[2])>=angles25_15[0]):
1244             sum_15[1][1] += float(c[1])
1245         if(float(c[2])>=angles25_15[1]):
1246             sum_15[1][2] += float(c[1])
1247         if(float(c[2])>=angles25_15[2]):
1248             sum_15[1][3] += float(c[1])
1249         if(float(c[2])>=angles25_15[3]):
1250             sum_15[1][4] += float(c[1])
1251     if(c[1]!="0.0"):
1252         sum_25[1][0] += float(c[1])
1253         if(float(c[2])>=angles25_25[0]):
1254             sum_25[1][1] += float(c[1])
1255         if(float(c[2])>=angles25_25[1]):
1256             sum_25[1][2] += float(c[1])
1257         if(float(c[2])>=angles25_25[2]):
1258             sum_25[1][3] += float(c[1])
1259         if(float(c[2])>=angles25_25[3]):
1260             sum_25[1][4] += float(c[1])
1261
1262 for l in range(10,8793):
1263     d = u.cell(row=l, column=1).value
1264     d= d.split(",")
1265     if(d[1]!="0.0"):
1266         sum_25[3][0] += float(d[1])
1267         if(float(d[2])>=angles35_25[0]):
1268             sum_25[3][1] += float(d[1])
1269         if(float(d[2])>=angles35_25[1]):
1270             sum_25[3][2] += float(d[1])
1271         if(float(d[2])>=angles35_25[2]):

```

```

172         sum_25[3][3] += float(d[1])
173         if(float(d[2])>=angles35_25[3]):
174             sum_25[3][4] += float(d[1])
175
176 mean30 = (sum_30_24+2*sum_30_16+2*sum_30_9+2*sum_30_4+sum_30_0)/8
177 mean20 = (sum_20_18+2*sum_20_11+2*sum_20_6+2*sum_20_3+sum_20_0)/8
178 mean25 = (sum_25_21+2*sum_25_13+2*sum_25_8+2*sum_25_3+sum_25_0)/8
179 ratio30 = mean30/sum_30_0
180 ratio20 = mean20/sum_20_0
181
182 ratio25 = mean25/sum_25_0
183 print("Spacing of 2m")
184 print("p*r 20")
185 print(ratio20 * p20)
186 print("p*r 25")
187 print(ratio25 * p25)
188 print("p*r 30")
189 print(ratio30 * p30)
190
191
192 mean20_15 = (sum_15[0][0]+2*sum_15[0][1]+2*sum_15[0][2]+2*sum_15[0][3]+sum_15[0][4])/8
193 mean25_15 = (sum_15[1][0]+2*sum_15[1][1]+2*sum_15[1][2]+2*sum_15[1][3]+sum_15[1][4])/8
194 mean30_15 = (sum_15[2][0]+2*sum_15[2][1]+2*sum_15[2][2]+2*sum_15[2][3]+sum_15[2][4])/8
195 r20_15 = mean20_15/sum_15[0][0]
196 r25_15 = mean25_15/sum_15[1][0]
197 r30_15 = mean30_15/sum_15[2][0]
198 print("Spacing of 1.5m")
199 print("p*r 20")
200 print(r20_15 * p20)
201 print("p*r 25")
202 print(r25_15 * p25)
203 print("p*r 30")
204 print(r30_15 * p30)
205
206 mean20_25 = (sum_25[0][0]+2*sum_25[0][1]+2*sum_25[0][2]+2*sum_25[0][3]+sum_25[0][4])/8
207 mean25_25 = (sum_25[1][0]+2*sum_25[1][1]+2*sum_25[1][2]+2*sum_25[1][3]+sum_25[1][4])/8
208 mean30_25 = (sum_25[2][0]+2*sum_25[2][1]+2*sum_25[2][2]+2*sum_25[2][3]+sum_25[2][4])/8
209 mean35_25 = (sum_25[3][0]+2*sum_25[3][1]+2*sum_25[3][2]+2*sum_25[3][3]+sum_25[3][4])/8
210 r20_25 = mean20_25/sum_25[0][0]
211 r25_25 = mean25_25/sum_25[1][0]
212 r30_25 = mean30_25/sum_25[2][0]
213 r35_25 = mean35_25/sum_25[3][0]
214 print("Spacing of 2.5m")
215 print("p*r 20")
216 print(r20_25 * p20)
217 print("p*r 25")
218 print(r25_25 * p25)
219 print("p*r 30")
220 print(r30_25 * p30)
221 print("p*r 35")
222 print(r35_25 * p35)
223
224 print("Ratio to length")
225 print("2m")
226 print(ratio25 * p25/2)
227 print("1.5m")
228 print(r20_15 * p20/1.5)
229 print("2.5m")
230 print(r35_25 * p35/2.5)
231 print("1m")
232 print(896.08)

```

A.2 Detailed potential production results with the PICC data

In this appendix are shown the detailed results for the potential production.

Buildings	Roofs	Facades N	Facades E	Facades S	Facades W	Total
Cycltron	1507,58	166,72	342,82	468,23	257,15	2742,50
Lavoisier	550,13	93,22	196,62	292,36	224,59	1356,92
ST Library	164,78	32,17	100,90	86,37	80,32	464,54
Mercator	211,97	37,19	94,51	98,00	95,65	537,32
Sciences auditorium	344,80	55,76	52,22	81,44	43,22	577,45
L Museum	168,02	18,45	41,45	118,28	41,58	387,79
Phythagoras	205,59	20,13	31,45	55,99	34,04	347,20
P. and M. Curie	159,00	36,69	71,28	89,79	72,39	429,15
Sainte-Barbe	281,65	52,33	92,21	156,21	82,62	665,02
Réaumur	154,76	48,74	82,73	129,33	76,56	492,12
IMAP	178,58	47,12	78,69	121,31	81,22	506,92
iMMC	294,78	24,61	63,80	65,36	63,45	512,00
A.D.S.T. Hall	135,34	24,14	30,24	62,76	25,40	277,89
Euler	235,07	32,05	61,86	84,78	58,17	471,92
Maxwell	297,80	48,56	73,99	124,30	76,79	621,43
Stévin	245,63	40,25	37,92	99,20	44,63	467,63
Vinci	617,88	61,91	87,39	189,70	92,09	1048,98
Big Sud	291,78	21,15	41,16	97,22	46,50	497,80
Small Sud	135,14	20,79	42,02	59,54	39,12	296,60
Carnoy	465,10	102,52	187,92	244,30	188,52	1188,37
Boltzmann	192,84	38,16	75,25	96,68	75,75	478,69
Kellner	201,72	49,02	84,14	124,18	96,14	555,20
Mendel	191,95	45,08	86,69	127,79	79,41	530,92
Halles	318,36	19,88	38,81	56,04	37,69	470,78
De Serres	186,40	38,26	73,12	87,66	74,78	460,22
Thermal power plant	116,52	11,73	20,10	32,67	24,34	205,37
Total Biereau	7853,15	1186,64	2189,31	3249,49	2112,12	16590,72
In-door track	1231,58	74,65	95,87	201,80	98,95	1702,85
Bubble 1	340,75	0,00	0,00	0,00	0,00	340,75
Bubble 2	129,55	0,00	0,00	0,00	0,00	129,55
Hall 1	347,54	36,32	32,41	47,54	41,38	505,18
Gymnastics	301,50	38,56	35,79	121,83	38,34	536,02
Hall 2	179,11	18,97	9,88	34,56	26,90	269,41
Entrance	340,75	2,98	0,00	56,90	0,00	400,63
Annex 1	76,13	4,64	7,52	12,25	7,55	108,09
Annex 2	0,00	0,00	9,36	16,70	8,24	34,30
Annex 3	174,13	19,75	37,81	4,92	0,00	236,61
Swimming Pool	419,16	20,25	35,23	39,31	42,71	556,66
Coubertin	164,98	25,37	46,30	71,87	35,24	343,75
Physical education faculty	182,79	49,17	85,27	132,00	64,44	513,67
Total Hocaille	3887,99	290,65	395,43	739,66	363,75	5677,48
University hall	404,56	103,10	221,92	185,29	195,31	1110,18
Socrate	782,14	84,32	109,43	269,63	182,12	1427,64
FIAL Library	824,33	100,76	137,44	315,02	130,09	1507,64
Montesquieu	437,98	6,43	39,87	45,20	20,53	550,01
Doyen	390,80	37,72	105,49	126,12	87,68	747,81
DRT Library	534,86	107,55	156,69	308,20	142,95	1250,26
Durpriez	337,25	22,56	89,77	68,47	81,28	599,34
Agora	269,06	18,82	21,75	46,87	44,95	401,46
ESPO Library	507,12	92,52	163,80	226,16	149,71	1139,30
Total Center	4488,12	573,78	1046,16	1590,96	1034,62	8733,63
Total	16229,26	2051,07	3630,90	5580,11	3510,49	31001,83

Figure A.1: Detailed potential production results for roofs and facades with standard SI-cells

A.3 Positions of the sun in the sky for every intersection of solar curves

Mois	4a.m.	5a.m.	6a.m.	7a.m.	8a.m.	9a.m.	10a.m.	11a.m.	12a.m.	1p.m.	2p.m.	3p.m.	4p.m.	5p.m.	6p.m.	7p.m.	8p.m.
21-Jan	0	0	0	0	2 126	9 138	15 151	18 165	19 180	18 195	15 209	9 222	2 234	0	0	0	0
20-Feb	0	0	0	1 108	9 121	17 133	23 148	27 163	28 180	27 197	23 212	17 227	9 239	1 252	0	0	0
20-Mar	0	0	0	9 102	18 113	27 127	33 143	38 161	39 180	38 199	33 217	27 233	18 247	9 258	0	0	0
20-Apr	0	0	9 82	18 95	28 107	37 121	44 138	49 157	51 180	49 203	44 222	37 239	28 253	18 265	9 278	0	0
21-May	0	7 66	16 67	25 88	34 98	43 113	52 131	57 155	60 180	57 205	52 229	43 247	34 262	25 272	16 293	7 294	0
21-Jun	2 53	9 64	18 65	27 84	37 92	46 112	54 128	60 152	63 180	60 208	54 232	46 248	37 268	27 276	18 295	9 296	2 307
21-Jul	0	7 66	16 67	25 88	34 98	43 113	52 131	57 155	60 180	57 205	52 229	43 247	34 262	25 272	16 293	7 294	0
20-Aug	0	0	9 82	18 95	28 107	37 121	44 138	49 157	51 180	49 203	44 222	37 239	28 253	18 265	9 278	0	0
20-Sep	0	0	0	9 102	18 113	27 127	33 143	38 161	39 180	38 199	33 217	27 233	18 247	9 258	0	0	0
20-Oct	0	0	0	1 108	9 121	17 133	23 148	27 163	28 180	27 197	23 212	17 227	9 239	1 252	0	0	0
21-Nov	0	0	0	0	2 126	9 138	15 151	18 165	19 180	18 195	15 209	9 222	2 234	0	0	0	0
21-Dec	0	0	0	0	0	6 140	12 152	15 166	16 180	15 194	12 208	6 220	0	0	0	0	0

Figure A.2: Positions of the sun in the sky for every intersection of solar curves

A.4 Results of the mean value of the Hillshade raster for every building

fid	Building Name	layer	NATUR CODE	Net Area	mean Opti	9-D	10-D	11-D	12-D	13-D	14-D	15-D	8-Jun	9-Jun	10-J	11-J	12-J	13-J	14-J	15-J	16-J	8-N	9-N	10-N	11-N	12-N	
1	IMMC	Bureau_PICC	SCO	2.442	191.14	35.00	57.45	114.23	73.84	70.399	58.961	36.52	21.29	45.38	68.77	80.87	85.234	81.851	70.407	47.20	22.962	21.29	45.38	68.77	80.87	85.234	
2	Pythagoras	Bureau_PICC	SCO	1.703	176.57	44.00	62.41	110.51	75.34	71.743	61.638	43.57	33.02	52.70	71.83	81.81	85.089	81.461	71.025	51.85	33.01	47.16	71.83	81.81	85.089		
3	L'Esplanade	Bureau_PICC	SCO	1.138	105.75	2.34	2.83	15.12	3.42	3.604	3.63	3.11	2.17	2.74	3.54	4.02	4.3984	4.4213	4.9103	4.06	3.315	2.17	2.74	3.54	4.02	4.3984	
4	Duprez	Centre_PICC	SCO	1.581	147.16	58.63	67.32	95.37	73.18	71.018	66.62	56.91	53.35	64.01	72.84	77.72	79.313	76.981	72.309	62.51	52.642	53.35	64.01	72.84	77.72	79.313	
5	DRT Library	Centre_PICC	SCO	3.413	152.75	48.80	60.97	92.39	68.28	66.062	60.158	47.29	40.89	54.63	67.06	72.86	74.735	73.291	67.967	55.12	42.895	40.89	54.63	67.06	72.86	74.735	
6	Monstequieu	Centre_PICC	SCO	1.447	174.52	48.42	58.31	103.70	67.49	65.224	57.729	43.26	44.74	54.39	66.25	74.10	77.552	75.565	67.764	52.32	38.185	44.74	54.39	66.25	74.10	77.552	
7	Coubertin	Hocalle_PICC	SCO	1.367	171.27	38.21	56.78	105.02	70.48	68.455	60.403	43.57	27.59	47.14	66.38	76.34	80.164	78.167	69.995	52.61	34.292	27.59	47.14	66.38	76.34	80.164	
8	Swimming Pool	Hocalle_PICC	CUL	1.536	180.53	82.48	99.18	136.86	103.96	94.806	77.785	59.91	69.70	82.42	107.09	113.45	112.95	102.9	86.274	59.87	30.108	68.70	90.42	107.09	113.45	112.95	
9	Indoor track	Hocalle_PICC	CUL	10.204	191.55	31.90	55.20	113.23	71.84	68.675	57.566	34.65	18.17	43.14	66.79	78.99	83.512	80.438	69.37	46.23	20.738	18.17	43.14	66.79	78.99	83.512	
10	Hall 2	Hocalle_PICC	BAT	1.338	181.62	37.32	57.26	109.96	72.33	69.491	59.787	41.05	26.90	47.02	67.78	78.72	82.955	80.118	70.109	50.42	30.351	26.90	47.02	67.78	78.72	82.955	
11	Annex 1	Hocalle_PICC	ANE	6.31	183.36	36.79	57.51	110.67	72.65	70.083	60.733	40.59	25.57	47.29	68.29	79.21	83.303	80.67	71.274	50.90	28.85	25.57	47.29	68.29	79.21	83.303	
12	Bubble 2	Hocalle_PICC	BAT	1.672	164.96	59.80	72.15	108.97	80.31	76.789	67.947	51.90	49.41	65.27	79.25	86.29	87.602	83.75	74.608	57.77	37.746	49.41	65.27	79.25	86.29	87.602	
13	Bubble 1	Hocalle_PICC	BAT	1.722	185.13	57.81	74.28	119.68	85.60	80.748	65.745	68.5	47.35	43.84	64.06	82.28	92.10	94.709	89.76	77.404	54.84	30.008	43.84	64.06	82.28	92.10	94.709
14	Mercator	Bureau_PICC	SCO	1.756	170.82	39.13	60.28	112.33	75.28	72.112	61.579	40.89	26.47	49.06	70.77	81.77	85.768	82.658	72.148	50.79	28.94	26.47	49.06	70.77	81.77	85.768	
15	ST Library	Bureau_PICC	SCO	1.365	172.18	45.90	65.54	112.07	79.34	75.891	65.312	45.56	33.08	54.62	74.79	85.10	88.635	85.117	74.547	54.18	32.866	33.08	54.62	74.79	85.10	88.635	
16	Lavoisier	Bureau_PICC	SCO	4.558	167.51	44.97	62.64	107.24	75.16	72.94	64.342	46.64	34.16	53.47	71.70	80.82	84.237	82.078	73.465	55.19	35.807	34.16	53.47	71.70	80.82	84.237	
17	MAP	Bureau_PICC	BAT	1.480	183.01	39.94	60.48	112.01	74.45	71.025	60.279	39.56	27.56	46.67	70.75	81.23	84.761	81.324	70.593	49.21	27.081	27.56	46.67	70.75	81.23	84.761	
18	Réaumur	Bureau_PICC	SCO	1.257	176.42	43.16	63.15	111.83	76.81	73.604	63.035	43.64	30.91	52.67	73.04	83.17	86.63	83.425	73.331	53.00	31.53	30.91	52.67	73.04	83.17	86.63	
19	A.D.S.T. Hall	Bureau_PICC	BAT	1.121	185.42	37.17	59.07	113.50	75.66	72.586	61.697	40.32	24.58	47.39	69.97	81.81	86.556	83.65	72.814	50.71	28.348	24.58	47.39	69.97	81.81	86.556	
20	Euler	Bureau_PICC	SCO	1.948	189.97	34.73	57.53	114.18	72.74	68.707	56.792	33.69	21.37	45.90	69.13	80.60	84.224	80.223	68.388	44.70	20.399	21.37	45.90	69.13	80.60	84.224	
21	Maxwell	Bureau_PICC	SCO	1.974	172.27	41.05	63.74	107.52	73.25	71.466	63.526	45.72	30.69	50.40	69.54	79.09	83.01	81.294	73.337	55.25	35.597	30.69	50.40	69.54	79.09	83.01	
22	Stein	Bureau_PICC	ANE	2.060	185.39	41.61	64.12	117.12	79.86	76.091	64.492	42.08	27.66	51.86	74.82	86.51	90.49	86.736	75.239	52.34	28.354	27.66	51.86	74.82	86.51	90.49	
23	Vinci	Bureau_PICC	BAT	4.881	186.57	34.27	57.06	112.70	73.07	70.086	59.932	36.83	20.79	45.41	68.42	79.97	84.337	81.446	70.787	48.15	23.615	20.79	45.41	68.42	79.97	84.337	
24	Sainte Barbe	Bureau_PICC	SCO	2.334	182.89	39.15	61.15	113.93	77.23	73.948	63.114	41.82	25.77	49.17	71.71	83.41	87.732	84.493	73.693	51.86	29.106	25.77	49.17	71.71	83.41	87.732	
25	P. and M. Curie	Bureau_PICC	ANE	1.317	181.53	43.67	64.03	114.51	73.67	71.093	61.538	41.63	28.00	47.06	68.26	79.89	84.125	81.341	71.281	47.55	30.702	28.00	47.06	68.26	79.89	84.125	
26	Sciences	Bureau_PICC	SCO	2.022	185.78	69.39	91.60	135.97	105.36	99.601	85.489	71.18	50.81	77.68	100.31	111.44	113.98	108.31	92.973	69.05	40.568	50.81	77.68	100.31	111.44	113.98	
27	Small Sud	Bureau_PICC	BAT	1.120	180.13	32.00	52.71	105.90	68.34	66.08	56.661	36.44	19.99	42.16	63.37	74.46	79.118	77.042	67.625	47.16	25.251	19.99	42.16	63.37	74.46	79.118	
28	Carnoy	Bureau_PICC	ANE	3.854	188.35	35.99	58.99	114.62	74.57	70.7	58.997	36.01	21.93	47.07	70.30	81.92	85.762	81.902	70.268	47.07	20.31	21.93	47.07	70.30	81.92	85.762	
29	Kellner	Bureau_PICC	ANE	1.671	181.33	34.25	57.31	113.50	73.97	69.255	57.599	34.59	20.30	45.42	68.75	80.42	84.389	80.562	68.985	45.70	20.603	20.30	45.42	68.75	80.42	84.389	
30	Halles	Bureau_PICC	SCO	1.714	174.10	47.56	67.45	104.71	67.91	65.174	59.71	51.37	45.53	55.52	66.82	74.98	78.135	75.251	67.895	58.48	46.621	45.53	55.52	66.82	74.98	78.135	
31	Big Sud	Bureau_PICC	SCO	1.168	153.35	45.96	56.48	90.45	59.41	55.803	50.753	42.67	39.88	52.63	63.26	66.457	65.375	60.885	54.834	46.17	35.838	39.88	52.63	63.26	66.457	65.375	
32	Boltzmann	Bureau_PICC	SCO	1.598	186.19	39.13	61.19	114.89	75.67	71.368	59.625	33.22	25.54	49.73	72.12	83.12	86.44	82.189	70.438	47.64	23.285	25.54	49.73	72.12	83.12	86.44	
33	Mendel	Bureau_PICC	SCO	1.590	188.51	34.46	57.45	113.67	72.87	69.025	57.43	34.50	20.70	45.75	68.96	80.44	84.256	80.437	68.885	45.73	20.592	20.70	45.75	68.96	80.44	84.256	
34	De Senes	Bureau_PICC	ANE	1.544	181.37	37.04	59.63	111.42	73.33	71.209	61.232	41.29	24.08	47.61	63.29	80.39	84.581	81.922	71.983	50.80	27.601	24.08	47.61	63.29	80.39	84.581	
35	Cyclotron	Bureau_PICC	SCO	12.491	177.45	40.86	62.22	111.28	76.86	73.702	63.688	43.35	25.52	50.70	72.20	83.04	86.796	83.706	73.737	53.30	30.359	25.52	50.70	72.20	83.04	86.796	
36	Thermal plant	Bureau_PICC	ANE	965	178.90	43.26	63.97	114.20	74.92	69.506	56.992	34.22	30.88	53.97	74.70	83.77	85.311	79.797	67.372	44.29	20.275	30.88	53.97	74.70	83.77	85.311	
37	University Hall	Centre_PICC	ANE	3.352	164.19	46.20	63.44	106.08	75.19	71.734	62.167	44.61	35.93	54.16	71.89	80.94	83.791	80.428	70.975	53.15	35.616	35.93	54.16	71.89	80.94	83.791	
38	Doyen	Centre_PICC	SCO	3.327	177.52	43.89	62.74	113.30	76.41	73.675	64.332	46.31	31.75	52.59	72.01	82.07	85.836	83.083	73.704	53.23	33.502	31.75	52.59	72.01	82.07	85.836	
39	Agnes	Centre_PICC	MAG	1.516	162.24	59.67	71.86	107.27	80.69	78.69	72.871	47.77	49.79	64.98	78.10	85.11	87.58	85.304	78.964	66.56	49.076	49.79	64.98	78.10	85.11	87.58	
40	ESPO Library	Centre_PICC	SCO	3.472	160.26	51.45	67.46	104.44	76.22	71.732	61.905	44.73	41.25	59.07	75.04	82.35	83.721	79.483	70.714	53.04	37.016	41.25	59.07	75.04	82.35	83.721	
41	FIAP Library	Centre_PICC	ANE	4.701	140.30	52.78	69.68	101.71	87.06	87.887	82.41	70.04	41.64	58.00	74.95	86.03	92.396	93.112	88.069	75.66	62.847	41.64	58.00	74.95	86.03	92.396	
42	Socrate	Centre_PICC	ANE	5.335	162.48	47.23	64.81	105.79	78.78	76.88	69.233	53.32	36.64	54.68	72.64	82.60	86.719	84.896	77.388	61.34	44.031	36.64	54.68	72.64	82.60	86.719	
43	Physical education	Bureau_PICC	ANE	1.514	180.86	39.94	60.43	114.28	82.04	79.804	70.642	51.38	30.56	52.61	74.39	86.49	91.719	88.954	86.265	49.594	30.56	52.61	74.39	86.49	91.719	88.954	
44	Gymnastics	Hocalle_PICC	CUL	2.498	185.13	38.76	60.77	114.22	75.72	72.598	61.735	40.46	27.10	49.15	72.15	82.38	86.674	83.603	72.728	50.70	27.878	27.10	49.15	72.15	82.38	86.674	
45	Annex 2	Hocalle_PICC	ANE	905	176.31	43.51	61.27	109.94	72.99	70.324	61.385	42.89	34.28	53.28	71.45	80.12	83.023	80.196	7								

[illegible]

19.J	4.Jn	5.Jn	6.Jn	7.Jn	8.Jn	9.Jn	10.J	11.J	12.J	13.J	14.J	15.J	16.J	17.J	18.J	19.J	20.J
37.07	18.49	40.643	75.96	110.80	146.38	175.16	197.09	211.33	218.02	212.7	199.46	178.13	149.71	114.26	79.29	44.42	22.32
43.59	33.40	51.909	79.75	109.15	139.51	164.34	183.45	195.55	200.71	195.21	182.66	163.16	137.90	107.27	77.50	49.12	31.46
82.87	67.32	74.534	104.82	102.80	123.16	125.69	136.38	142.73	149.40	147.74	146.11	139.17	140.09	121.61	123.25	93.42	84.30
69.87	54.41	67.052	83.68	100.64	119.97	137.67	153.24	163.56	168.48	164.65	155.37	140.62	123.63	104.87	89.34	73.46	60.83
72.31	35.81	50.634	71.28	91.88	116.06	136.65	154.47	167.51	175.51	174.55	168.19	155.29	138.52	116.07	98.65	77.19	61.50
61.25	33.40	50.843	74.10	101.75	133.11	159.16	179.48	192.87	199.14	194.43	183.28	165.58	143.20	115.26	88.99	65.73	47.65
51.31	28.50	47.186	75.51	103.81	133.75	157.74	176.14	188.27	194.66	191.24	181.61	165.16	143.23	114.37	86.99	57.69	36.70
38.41	24.60	52.259	81.21	119.13	149.57	176.39	194.02	204.16	205.72	196.49	178.8	154.31	119.86	84.15	51.67	40.41	33.98
38.48	16.49	41.421	76.84	111.47	147.06	175.70	197.74	212.14	219.02	213.88	200.86	179.70	151.61	116.21	81.28	46.09	20.94
45.85	26.98	45.79	76.07	107.19	139.91	166.17	186.62	200.33	206.95	202.23	190.22	170.84	145.20	112.77	82.47	52.08	31.42
43.17	26.72	48.174	79.78	110.58	142.84	169.01	189.93	203.57	209.76	204.29	191.43	171.33	145.41	113.12	81.35	49.88	26.72
54.32	40.71	52.564	77.27	103.30	130.86	153.47	171.55	182.95	187.69	182.01	170.05	152.01	128.70	100.66	79.17	58.93	47.65
40.77	21.36	39.378	71.80	107.16	140.92	169.39	190.26	203.67	209.30	203.4	189.55	168.24	139.26	105.20	72.34	45.92	34.61
41.75	25.47	45.608	76.68	107.27	139.24	165.61	185.48	198.23	204.10	199.39	187.44	168.15	142.43	110.57	79.57	48.31	27.87
45.02	31.43	48.401	76.36	103.09	132.37	156.90	175.55	187.56	192.68	187.69	176.12	157.83	133.88	104.88	78.95	51.15	34.18
48.61	33.31	50.546	77.73	103.53	131.77	154.81	172.11	183.14	188.44	184.3	174.24	157.62	135.37	107.63	81.97	54.58	36.72
39.59	25.78	46.158	78.54	110.45	143.42	170.05	190.10	202.69	208.18	202.73	189.94	169.60	142.74	109.71	77.98	46.20	26.20
43.64	28.89	48.297	77.68	106.63	137.11	162.39	181.39	193.50	198.83	193.71	181.81	163.08	138.34	108.07	79.16	49.87	30.72
42.34	21.39	42.699	74.57	106.54	139.96	167.61	188.63	202.91	209.87	205.38	193.18	173.28	146.60	113.59	81.62	49.13	26.93
35.94	20.48	44.004	78.81	112.52	148.05	176.20	197.49	210.94	216.60	210.57	196.69	175.39	147.17	112.10	78.20	43.35	19.84
48.80	30.72	50.061	78.66	106.47	135.51	159.03	176.96	188.86	194.87	190.97	180.71	163.80	140.97	112.21	83.72	54.90	33.79
38.70	22.07	43.502	75.13	107.33	140.49	168.52	189.29	202.72	208.58	203.22	190.18	169.71	142.29	109.44	77.61	45.51	23.89
39.57	20.25	43.199	77.44	110.25	144.02	171.20	191.91	205.57	212.11	207.11	194.76	174.75	148.07	114.40	81.10	46.91	23.39
40.10	24.87	45.288	76.55	107.25	139.50	166.31	186.81	200.29	206.41	201.39	188.85	168.96	142.45	110.08	78.45	46.81	25.77
42.92	27.61	46.819	76.92	107.73	140.31	166.98	187.52	200.81	206.96	202.09	190.01	170.48	144.62	112.23	80.10	49.09	28.46
32.38	29.04	39.079	67.28	103.70	136.20	166.15	186.18	198.64	202.27	195.18	179.62	157.40	126.42	93.54	58.71	36.60	28.33
46.15	22.72	44.247	76.65	106.49	138.92	164.79	185.54	199.47	206.90	203.12	192.21	173.57	149.25	117.15	86.55	53.44	30.70
36.91	20.26	44.215	78.18	111.44	145.83	173.76	194.91	208.43	214.28	208.39	194.83	173.60	145.74	111.48	78.44	44.36	20.45
37.08	20.40	44.406	78.83	111.99	146.42	174.01	195.14	208.60	214.52	208.7	195.26	174.12	146.51	112.03	78.99	44.71	20.75
57.00	48.60	66.63	86.32	108.98	136.27	159.95	178.00	189.36	194.37	189.02	177.15	158.45	133.80	105.06	80.41	60.51	42.17
44.65	59.54	74.573	99.16	118.10	142.04	157.77	170.80	177.34	178.83	170.64	157.06	138.04	116.37	88.93	70.41	49.32	38.00
37.42	23.24	45.98	79.14	111.67	145.38	172.71	193.29	206.24	211.62	205.35	191.47	170.18	142.59	109.07	77.24	44.62	22.38
37.41	20.23	44.474	78.95	112.29	146.74	174.46	195.65	209.18	215.10	209.19	195.71	174.60	146.85	112.49	78.35	45.03	20.73
41.24	24.58	46.675	78.66	109.32	141.30	167.09	186.83	199.70	205.72	200.88	189.15	169.99	144.20	111.99	80.55	48.27	25.30
40.46	27.95	49.543	79.49	107.94	138.32	163.24	182.42	194.83	200.39	195.49	183.63	164.77	139.53	108.53	78.16	47.34	25.66
36.30	28.66	51.649	83.92	115.07	146.57	171.10	188.99	199.19	202.20	194.53	180.33	160.11	134.70	103.46	74.75	43.43	22.50
52.96	33.74	51.622	77.19	103.19	130.03	152.18	169.09	179.92	184.83	180.73	171.07	155.46	135.37	109.34	84.28	58.46	40.74
44.28	29.24	46.802	76.79	106.79	137.72	163.02	182.52	195.44	201.56	196.8	184.9	165.97	141.00	109.98	79.68	50.37	32.59
55.26	45.04	54.843	76.34	101.17	126.92	148.68	165.75	177.39	182.66	178.13	167.1	149.96	128.20	102.67	79.11	59.76	48.73
57.28	35.18	54.335	78.37	102.99	128.11	149.11	165.48	176.54	181.85	177.88	167.88	151.70	131.57	108.06	86.41	62.46	44.94
59.52	53.08	64.433	80.19	94.52	113.79	133.30	149.21	160.47	168.34	163.97	155.86	141.80	122.87	102.83	81.42	62.71	47.05
51.98	39.54	55.637	78.88	101.49	126.56	148.34	165.67	177.26	182.77	179.02	169.28	153.69	133.31	107.78	81.60	56.91	38.92
47.08	26.17	44.05	71.71	100.20	130.84	157.97	178.74	193.12	200.28	196.89	186.07	167.82	142.56	112.05	81.50	52.92	33.21
39.29	23.40	45.864	77.82	110.79	143.90	170.83	190.85	203.70	209.47	204.22	191.54	171.20	143.99	111.19	78.49	46.00	23.07
44.76	34.12	54.344	83.18	112.79	142.27	165.84	184.23	195.87	200.38	193.99	181.08	162.16	137.84	108.14	78.92	50.56	30.13
48.55	31.88	50.35	79.80	108.55	137.94	160.86	179.03	191.96	199.41	194.25	183.57	166.10	142.38	112.24	81.70	54.13	35.73
41.54	36.64	56.742	86.67	116.28	146.74	169.56	186.83	196.84	200.18	193.71	181.79	163.04	138.56	107.45	77.71	47.73	26.83
32.43	22.68	45.149	76.90	113.75	147.81	176.76	196.76	208.67	212.07	204.01	187.91	164.58	133.09	100.19	69.33	38.84	17.88

Figure A.3: Results of the mean value of the Hillshade raster for every building

A.5 Code used to extract the mean irradiances for each time between 2005 and 2020

```
1 ### Hourly production code for academic buildings in Louvain-La-Neuve ###
2 ### Code by Theo Schepers 02/08/2023 ###
3 ### Imports###
4 from openpyxl import load_workbook
5 import numpy as np
6
7 w0 = load_workbook(filename="Timeseries_rotating_2a_2005_2020.xlsx")
8 wb0 = w0.active
9
10 Irr = np.zeros((12,24))
11
12 for i in range (10,140266):
13     a = wb0.cell(row=i, column=1).value
14     a = a.split(",")
15     date = a[0]
16     ir = float(a[1])
17
18     if(int(date[6:8])==20):
19         if(int(date[4:6])==2):
20             if(ir>0.0):
21                 Irr[1][int(date[9:11])] += ir/16
22             if(int(date[4:6])==3):
23                 if(ir>0.0):
24                     Irr[2][int(date[9:11])] += ir/16
25             if(int(date[4:6])==4):
26                 if(ir>0.0):
27                     Irr[3][int(date[9:11])] += ir/16
28             if(int(date[4:6])==8):
29                 if(ir>0.0):
30                     Irr[7][int(date[9:11])] += ir/16
31             if(int(date[4:6])==9):
32                 if(ir>0.0):
33                     Irr[8][int(date[9:11])] += ir/16
34             if(int(date[4:6])==10):
35                 if(ir>0.0):
36                     Irr[9][int(date[9:11])] += ir/16
37
38     if(int(date[6:8])==21):
39         if(int(date[4:6])==1):
40             if(ir>0.0):
41                 Irr[0][int(date[9:11])] += ir/16
42             if(int(date[4:6])==5):
43                 if(ir>0.0):
44                     Irr[4][int(date[9:11])] += ir/16
45             if(int(date[4:6])==6):
46                 if(ir>0.0):
47                     Irr[5][int(date[9:11])] += ir/16
48             if(int(date[4:6])==7):
49                 if(ir>0.0):
50                     Irr[6][int(date[9:11])] += ir/16
51             if(int(date[4:6])==11):
52                 if(ir>0.0):
53                     Irr[10][int(date[9:11])] += ir/16
54             if(int(date[4:6])==12):
55                 if(ir>0.0):
56                     Irr[11][int(date[9:11])] += ir/16
57 print(Irr)
```

A.6 Average irradiances for a pivoting double-axis panel between 2005 and 2020 for specific times

Months	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
January	0	0	0	0	105,45	214,32	240,48	246,91	333,12	211,89	181,98	157,98	0	0	0	0
February	0	0	0	55,02	263,46	268,49	272,86	307,50	302,86	283,79	248,48	308,69	196,64	0	0	0
March	0	0	52,11	231,53	367,10	449,27	533,65	523,95	531,63	497,32	457,61	362,97	288,18	179,21	0	0
May	22,97	241,07	355,80	489,74	543,52	654,02	653,38	713,05	708,19	740,18	660,54	627,17	507,59	398,75	198,29	0,92
June	81,08	191,61	226,72	323,12	371,61	487,11	557,59	672,72	572,24	508,67	507,71	538,49	515,66	430,04	274,52	142,28
July	182,64	414,86	568,57	715,92	657,16	680,57	656,27	596,32	527,43	444,54	493,32	443,82	374,89	226,02	53,22	0
August	0	64,09	243,66	439,72	602,89	645,14	616,96	649,06	508,77	480,86	595,08	492,15	403,07	253,14	115,21	0
September	0	0	266,06	544,90	649,22	695,12	736,46	742,90	757,53	682,88	657,86	555,71	473,38	157,08	0	0
October	0	0	0	221,76	311,98	325,53	385,41	421,23	389,25	420,68	338,84	306,09	130,76	0	0	0
November	0	0	0	0	175,85	260,63	240,07	302,95	366,24	287,78	276,79	180,51	0	0	0	0
December	0	0	0	0	5,38	115,26	131,89	204,54	162,64	134,20	121,45	60,16	0	0	0	0

Figure A.4: Average irradiances for a pivoting double-axis panel between 2005 and 2020 for specific times

A.7 Fraction of the buildings' area considered as usable for 75% and 80% tolerance

Buildings	$T = 75\%$	$T = 80\%$	Buildings	$T = 75\%$	$T = 80\%$
IMMC	0.96	0.94	Maxwell	0.82	0.79
Pythagoras	0.86	0.83	Stévin	0.91	0.90
L Museum	0.86	0.64	Vinci	0.92	0.91
Dupriez	0.59	0.46	Sainte-Barbe	0.90	0.88
DRT Library	0.65	0.58	P. and M. Curie	0.90	0.88
Monstequieu	0.90	0.83	Sciences	0.83	0.82
Coubertin	0.85	0.83	Small Sud	0.89	0.87
Swimming Pool	0.82	0.78	Carnoy	0.94	0.92
Indoor track	0.96	0.95	Kellner	0.94	0.92
Hall 2	0.90	0.88	Halles	0.89	0.80
Annex 1	0.88	0.84	Big Sud	0.86	0.74
Bubble 2	0.75	0.68	Boltzmann	0.92	0.90
Bubble 1	0.92	0.88	Mendel	0.94	0.92
Mercator	0.89	0.88	De Serres	0.89	0.87
ST Library	0.83	0.80	Cyclotron	0.86	0.84
Lavoisier	0.81	0.79	Thermal plant	0.87	0.86
IMAP	0.91	0.89	University Hall	0.78	0.73
Réaumur	0.85	0.83	Doyen	0.87	0.83
A.D.S.T. Hall	0.92	0.91	Agora	0.72	0.66
Euler	0.95	0.94	ESPO Library	0.71	0.65
FIAL Library	0.61	0.55	Annex 2	0.82	0.79
Socrate	0.73	0.68	Annex 3	0.82	0.77
Physical education	0.86	0.83	Hall 1	0.87	0.85
Gymnastics	0.92	0.90	Entrance	0.94	0.92

Table A.1: Fraction of the buildings' area considered as usable for 75% and 80% tolerance

A.8 Potential production in [MWh/y] without shadows for a tolerance of 80%.

Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]
IMMC	501.49	IMAP	278.67	Mendel	316.14
Pythagoras	292.27	Réaumur	214.97	De Serres	283.43
L Museum	92.38	A.D.S.T. Hall	216.58	Cyclotron	2167.99
Dupriez	134.81	Euler	398.29	Thermal plant	172.94
DRT Library	370.60	Maxwell	320.73	University Hall	483.94
Monstequieu	246.56	Stévin	396.22	Doyen	557.89
Coubertin	228.20	Vinci	952.75	Agora	195.72
Swimming Pool	338.88	Sainte-Barbe	433.59	ESPO Library	443.59
Indoor track	2105.17	P. and M. Curie	243.66	FIAL Library	478.78
Hall 2	247.26	Sciences	359.67	Socrate	716.53
Annex 1	112.53	Small Sud	203.25	Physical education	262.73
Bubble 2	225.73	Carnoy	766.00	Gymnastics	483.78
Bubble 1	323.48	Kellner	332.00	Annex 2	149.35
Mercator	323.98	Halles	279.82	Annex 3	230.00
ST Library	222.06	Big Sud	158.81	Hall 1	506.13
Lavoisier	714.75	Boltzmann	307.50	Entrance	417.85

Table A.2: Potential production in [MWh/y] without shadows for a tolerance of 80%.

A.9 Potential production in [MWh/y] without shadows for a tolerance of 80% with flat roof with flat roofs equipped as described in chapter 2

Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]
IMMC	362.44	IMAP	206.93	Mendel	230.44
Pythagoras	221.78	Réaumur	163.46	De Serres	211.33
L Museum	92.38	A.D.S.T. Hall	159.77	Cyclotron	1641.63
Dupriez	134.81	Euler	288.85	Thermal plant	130.04
DRT Library	356.41	Maxwell	246.27	University Hall	385.24
Monstequieu	246.56	Stévin	291.32	Doyen	422.18
Coubertin	177.32	Vinci	736.31	Agora	195.72
Swimming Pool	338.88	Sainte-Barbe	322.71	ESPO Library	408.67
Indoor track	1518.07	P. and M. Curie	181.99	FIAL Library	470.21
Hall 2	185.13	Sciences	259.03	Socrate	716.53
Annex 1	83.28	Small Sud	153.60	Physical education	197.84
Bubble 2	225.73	Carnoy	558.55	Gymnastics	354.63
Bubble 1	323.48	Kellner	242.64	Annex 2	112.60
Mercator	242.78	Halles	272.15	Annex 3	175.47
ST Library	172.64	Big Sud	157.99	Hall 1	384.40
Lavoisier	562.39	Boltzmann	225.87	Entrance	298.72

Table A.3: Potential production in [MWh/y] without shadows for a tolerance of 80% flat roof with flat roofs equipped as described in 2

A.10 Potential production in [MWh/y] without shadows for a tolerance of 80% with flat roof with flat roofs equipped as De Serres tower

Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]
IMMC	199.43	IMAP	113.86	Mendel	133.76
Pythagoras	122.04	Réaumur	89.94	De Serres	116.28
L. Museum	92.38	A.D.S.T. Hall	87.91	Cyclotron	903.32
Dupriez	134.81	Euler	158.94	Thermal plant	71.56
DRT Library	362.88	Maxwell	135.51	University Hall	211.98
Monstequieu	246.56	Stévin	160.30	Doyen	232.31
Coubertin	97.57	Vinci	585.57	Agora	195.72
Swimming Pool	338.88	Sainte-Barbe	177.57	ESPO Library	403.66
Indoor track	835.33	P. and M. Curie	100.14	FIAL Library	477.42
Hall 2	101.87	Sciences	284.38	Socrate	716.53
Annex 1	45.83	Small Sud	84.52	Physical education	108.86
Bubble 2	225.73	Carnoy	307.34	Gymnastics	195.14
Bubble 1	323.48	Kellner	133.51	Annex 2	61.96
Mercator	133.59	Halles	266.83	Annex 3	96.55
ST Library	94.99	Big Sud	157.31	Hall 1	211.52
Lavoisier	309.46	Boltzmann	124.29	Entrance	164.37

Table A.4: Potential production in [MWh/y] without shadows for a tolerance of 80% flat roof with flat roofs equipped as the model of De Serres tower

A.11 Potential production in [MWh/y] without shadows for a tolerance of 80% with flat roof with flat roofs equipped as Mendel Tower

Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]	Buildings	Prod. [MWh/y]
IMMC	210.38	IMAP	120.11	Mendel	133.76
Pythagoras	128.73	Réaumur	94.88	De Serres	116.28
L Museum	92.38	A.D.S.T. Hall	92.74	Cyclotron	952.88
Dupriez	134.81	Euler	167.66	Thermal plant	75.48
DRT Library	362.56	Maxwell	142.94	University Hall	223.61
Monstequieu	246.56	Stévin	169.09	Doyen	245.05
Coubertin	102.92	Vinci	584.13	Agora	195.72
Swimming Pool	338.88	Sainte Barbe	187.31	ESPO Library	403.13
Indoor track	881.16	P. and M. Curie	105.64	FIAL Library	477.22
Hall 2	107.46	Sciences	284.02	Socrate	716.53
Annex 1	48.34	Small Sud	89.16	Physical education	114.83
Bubble 2	225.73	Carnoy	324.21	Gymnastics	205.84
Bubble 1	323.48	Kellner	140.84	Annex 2	65.36
Mercator	140.92	Halles	266.75	Annex 3	101.85
ST Library	100.21	Big Sud	157.29	Hall 1	223.12
Lavoisier	326.44	Boltzmann	131.10	Entrance	173.39

Table A.5: Potential production in [MWh/y] without shadows for a tolerance of 80% flat roof with flat roofs equipped as the model of Mendel Tower

A.12 Python code to obtain the hourly electrical consumption UCLouvain and households

```

1  ### Hourly production code for academic buildings in Louvain-La-Neuve ###
2  ### Code by Theo Schepers 02/08/2023 ###
3  ### Imports###
4
5  from openpyxl import load_workbook
6  from openpyxl import Workbook
7  import numpy as np
8
9  ### Opening Excel sheets ###
10
11 workbook = load_workbook(filename="ProdV11.xlsx")
12 workbook2 = load_workbook(filename="Conso_menages_LLN.xlsx")
13 workbook3 = load_workbook(filename="Consommation_electricite_universite.xlsx")
14 p = workbook.active
15 m = workbook2.active
16 u = workbook3.active
17
18 for i in range(2,35042):
19     cu = 0
20     cm = 0
21     for j in range(4):
22         if(i+j<35042):
23             cu += float(u.cell(row=(i+j), column=4).value)
24             cm += float(m.cell(row=(i+j), column=12).value)
25     i+=3
26     celu = "C" +str((i//4)+1)

```

```

27     celm = "D" +str((i//4)+1)
28     p[celu] = cu
29     p[celm] = cm
30     workbook.save("ProdV12.xlsx")

```

A.13 Python code to obtain the hourly electrical hourly production of the roofs

```

1  ### Hourly production code for academic buildings in Louvain-La-Neuve ###
2  ### Code by Theo Schepers 02/08/2023 ###
3  ### Imports###
4
5  from openpyxl import load_workbook
6  from openpyxl import Workbook
7  import numpy as np
8
9  ### Opening Excel sheets ###
10
11 workbook = load_workbook(filename="General.xlsx")
12 workbook2 = load_workbook(filename="Conso_menages_LLN.xlsx")
13 workbook3 = load_workbook(filename="Consommation_electricite_universite.xlsx")
14 g = workbook.active
15 m = workbook2.active
16 u = workbook3.active
17
18 ### Variables ###
19
20 coef = np.zeros((48,142))
21 coef_flat = np.zeros(142)
22 area = np.zeros(48)
23 date = []
24 ir = np.zeros(142)
25 irr = np.zeros((12,16))
26 type = []
27 yprod = np.zeros(48)
28 d_prod = np.zeros((48,142))
29 h_prod = np.zeros(8760)
30
31 ### Extraction of data ###
32
33 for i in range(2,50):
34     area[i-2] = g.cell(row=i, column=5).value
35
36 for i in range(7,148):
37     ir[i-7] = g.cell(row=54, column=i).value
38     date.append(str(u[1][i-4].value))
39     for j in range(2,50):
40         coef[j-2][i-7] = g.cell(row=j, column=i).value
41
42 for i in range(16):
43     for j in range(12):
44         irr[j][i] = g.cell(row=j+56, column=i+2).value
45
46 for i in range(2,50):
47     type.append(str(g[1][155].value))
48
49 for i in range(7,148):
50     coef_flat[i-7] = g.cell(row=51, column=i).value
51     166
52 for i in range(48):
53     yprod[i] = g.cell(row=i+2, column=169).value

```

```

54
55 ### Computation of specific production ###
56 sum_i_c = 0
57
58 for i in range(48):
59     sum_i_c=0
60     if(type[i]=="F"):
61         for j in range(142):
62             sum_i_c += ir[j]*coef_flat[j]
63         for j in range(142):
64             d_prod[i][j] = ((coef_flat[j]*ir[j])/sum_i_c)*yprod[i]
65     else:
66         for j in range(142):
67             sum_i_c += ir[j]*coef[i][j]
68         for j in range(142):
69             d_prod[i][j] = ((coef[i][j]*ir[j])/sum_i_c)*yprod[i]
70
71 ### Generalisation to every hours of the year ###
72 gap = [31,30,28,31,31,31,30,30,31,30,32,30]
73 gp=30.42
74 month = 1
75 for i in range(48):
76     for d in range(365):
77         if(d<=21):#D->J
78             m=1
79             for h in range(8,17):
80                 if(h==8):
81                     h_prod[d*24+h] += d_prod[i][7]*(d+11)/gap[m-1]
82                 elif(h==16):
83                     h_prod[d*24+h] += d_prod[i][15]*(d+11)/gap[m-1]
84                 else:
85                     h_prod[d*24+h] += (d_prod[i][h-9]*(gap[m-1]-(d+11)) + (d+11)*d_prod[i][h
86 -1])/gap[m-1]
87             elif(d<=52):#J->F
88                 m=2
89                 for h in range(7,18):
90                     if(h==7):
91                         h_prod[d*24+h] += d_prod[i][25]*(d-21)/gap[m-1]
92                     elif(h==17):
93                         h_prod[d*24+h] += d_prod[i][35]*(d-21)/gap[m-1]
94                     else:
95                         h_prod[d*24+h] += (d_prod[i][h-1]*(gap[m-1]-(d-21))+(d-21)*d_prod[i][h
96 +18])/gap[m-1]
97             elif(d<=80):#F->M
98                 m=3
99                 for h in range(7,18):
100                     h_prod[d*24+h] += (d_prod[i][h+18]*(gap[m-1]-(d-52)) + (d-52)*d_prod[i][
101 h+40])/gap[m-1]
102             elif(d<=111):#M->A
103                 m=4
104                 for h in range(6,19):
105                     if(h==6):
106                         h_prod[d*24+h] += d_prod[i][69]*(d-80)/gap[m-1]
107                     elif(h==18):
108                         h_prod[d*24+h] += d_prod[i][81]*(d-80)/gap[m-1]
109                     else:
110                         h_prod[d*24+h] += (d_prod[i][40+h]*(gap[m-1]-(d-80)) + (d-80)*d_prod[i][
111 h+63])/gap[m-1]
112             elif(d<=141):#A->M
113                 m=5
114                 for h in range(5,20):
115                     if(h==5):
116                         h_prod[d*24+h] += d_prod[i][95]*(d-111)/gap[m-1]
117                     elif(h==19):
118                         h_prod[d*24+h] += d_prod[i][110]*(d-111)/gap[m-1]

```

```

115         else:
116             h_prod[d*24+h] += (d_prod[i][63+h]*(gap[m-1]-(d-111)) + (d-111)*d_prod[i
] [h+90])/gap[m-1]
117         elif(d<=171):#M->J
118             m=6
119             for h in range(4,21):
120                 if(h==4):
121                     h_prod[d*24+h] += d_prod[i][125]*(d-141)/gap[m-1]
122                 elif(h==20):
123                     h_prod[d*24+h] += d_prod[i][141]*(d-141)/gap[m-1]
124                 else:
125                     h_prod[d*24+h] += (d_prod[i][90+h]*(gap[m-1]-(d-141)) + (d-141)*d_prod[i
] [h+121])/gap[m-1]
126         elif(d<=201):#J->J
127             m=7
128             for h in range(4,21):
129                 if(h==4):
130                     h_prod[d*24+h] += d_prod[i][125]*(gap[m-1]-(d-171))/gap[m-1]
131                 elif(h==20):
132                     h_prod[d*24+h] += d_prod[i][141]*(gap[m-1]-(d-171))/gap[m-1]
133                 else:
134                     h_prod[d*24+h] += (d_prod[i][121+h]*(gap[m-1]-(d-171)) + (d-171)*d_prod[i
] [h+106])/gap[m-1]
135         elif(d<=232):#J->A
136             m=8
137             for h in range(5,20):
138                 if(h==5):
139                     h_prod[d*24+h] += d_prod[i][111]*(gap[m-1]-(d-201))/gap[m-1]
140                 elif(h==19):
141                     h_prod[d*24+h] += d_prod[i][124]*(gap[m-1]-(d-201))/gap[m-1]
142                 else:
143                     h_prod[d*24+h] += (d_prod[i][106+h]*(gap[m-1]-(d-201)) + (d-201)*d_prod[i
] [h+76])/gap[m-1]
144         elif(d<=263):#A->S
145             m=9
146             for h in range(6,19):
147                 if(h==6):
148                     h_prod[d*24+h] += d_prod[i][82]*(gap[m-1]-(d-232))/gap[m-1]
149                 elif(h==18):
150                     h_prod[d*24+h] += d_prod[i][94]*(gap[m-1]-(d-232))/gap[m-1]
151                 else:
152                     h_prod[d*24+h] += (d_prod[i][76+h]*(gap[m-1]-(d-232)) + (d-232)*d_prod[i
] [h+51])/gap[m-1]
153         elif(d<=293):#S->O
154             m=10
155             for h in range(7,18):
156                 h_prod[d*24+h] += (d_prod[i][51+h]*(gap[m-1]-(d-263)) + (d-263)*d_prod[i
] [h+29])/gap[m-1]
157         elif(d<=324):#O->N
158             m=11
159             for h in range(7,18):
160                 if(h==7):
161                     h_prod[d*24+h] += d_prod[i][36]*(gap[m-1]-(d-293))/gap[m-1]
162                 elif(h==17):
163                     h_prod[d*24+h] += d_prod[i][46]*(gap[m-1]-(d-293))/gap[m-1]
164                 else:
165                     h_prod[d*24+h] += (d_prod[i][29+h]*(gap[m-1]-(d-293)) + (d-293)*d_prod[i
] [h+8])/gap[m-1]
166         elif(d<=355):#N->D
167             m=12
168             for h in range(8,17):
169                 if(h==8):
170                     h_prod[d*24+h] += d_prod[i][16]*(gap[m-1]-(d-324))/gap[m-1]
171                 elif(h==16):
172                     h_prod[d*24+h] += d_prod[i][24]*(gap[m-1]-(d-324))/gap[m-1]

```

```

173         else:
174             h_prod[d*24+h] += (d_prod[i][8+h]*(gap[m-1]-(d-324)) + (d-324)*d_prod[i
] [h-9])/gap[m-1]
175         else:#D->J
176             m=1
177             for h in range(8,17):
178                 if(h==8):
179                     h_prod[d*24+h] += d_prod[i][7]*(d-355)/gap[m-1]
180                 elif(h==16):
181                     h_prod[d*24+h] += d_prod[i][15]*(d-355)/gap[m-1]
182                 else:
183                     h_prod[d*24+h] += (d_prod[i][h-9]*(gap[m-1]-(d-355)) + (d-355)*d_prod[i
] [h-1])/gap[m-1]
184
185     ### Write the results in production
186     workbook4 = Workbook()
187     p = workbook4.active
188     for i in range(8760):
189         date = "A" +str(i+2)
190         cel = "B" +str(i+2)
191         p["A1"]="Time of the year [kWh]"
192         p[date]=str(i)
193         p[cel] = h_prod[i]*1000/gp
194     workbook4.save(filename="Production.xlsx")

```

A.14 Python code to obtain the hourly electrical hourly production of the facades

```

1 from openpyxl import load_workbook
2 from openpyxl import Workbook
3 import numpy as np
4
5 wbNE = load_workbook(filename="NE.xlsx")
6 wbE = load_workbook(filename="E.xlsx")
7 wbSE = load_workbook(filename="SE.xlsx")
8 wbS = load_workbook(filename="S.xlsx")
9 wbSW = load_workbook(filename="SW.xlsx")
10 wbW = load_workbook(filename="W.xlsx")
11 wbNW = load_workbook(filename="NW.xlsx")
12 NE = wbNE.active
13 E = wbE.active
14 SE = wbSE.active
15 S = wbS.active
16 SW = wbSW.active
17 W = wbW.active
18 NW = wbNW.active
19
20 PE = np.zeros(8760)
21 PS = np.zeros(8760)
22 PW = np.zeros(8760)
23 IE = 0
24 IS = 0
25 IW = 0
26 AE = 3630900
27 AS = 5580110
28 AW = 3510490
29
30 for i in range(10,8770):
31     IE += 0.25*(float(NE.cell(row=i, column=6).value) + 2*float(E.cell(row=i, column=6).
value) + float(SE.cell(row=i, column=6).value))
32     IS += 0.25*(float(SE.cell(row=i, column=6).value) + 2*float(S.cell(row=i, column=6).
value) + float(SW.cell(row=i, column=6).value))

```

```

33     IW += 0.25*(float(SW.cell(row=i, column=6).value) + 2*float(W.cell(row=i, column=6).
34         value) + float(NW.cell(row=i, column=6).value))
35 print(IE)
36 print(IS)
37 print(IW)
38 for i in range(10,8770):
39     PE[i-10] += 0.25*(float(NE.cell(row=i, column=6).value) + 2*float(E.cell(row=i, column=
40         =6).value) + float(SE.cell(row=i, column=6).value))/IE
41     PS[i-10] += 0.25*(float(SE.cell(row=i, column=6).value) + 2*float(S.cell(row=i, column=
42         =6).value) + float(SW.cell(row=i, column=6).value))/IS
43     PW[i-10] += 0.25*(float(SW.cell(row=i, column=6).value) + 2*float(W.cell(row=i, column=
44         =6).value) + float(NW.cell(row=i, column=6).value))/IW
45
46 wb = Workbook()
47 p = wb.active
48 for i in range(8760):
49     cel = "A" + str(i+2)
50     p[cel] = PE[i]*AE + PS[i]*AS + PW[i]*AW
51 wb.save(filename="ProdFacade.xlsx")

```

A.15 Load curves for the three installations, UCLouvain, and the households

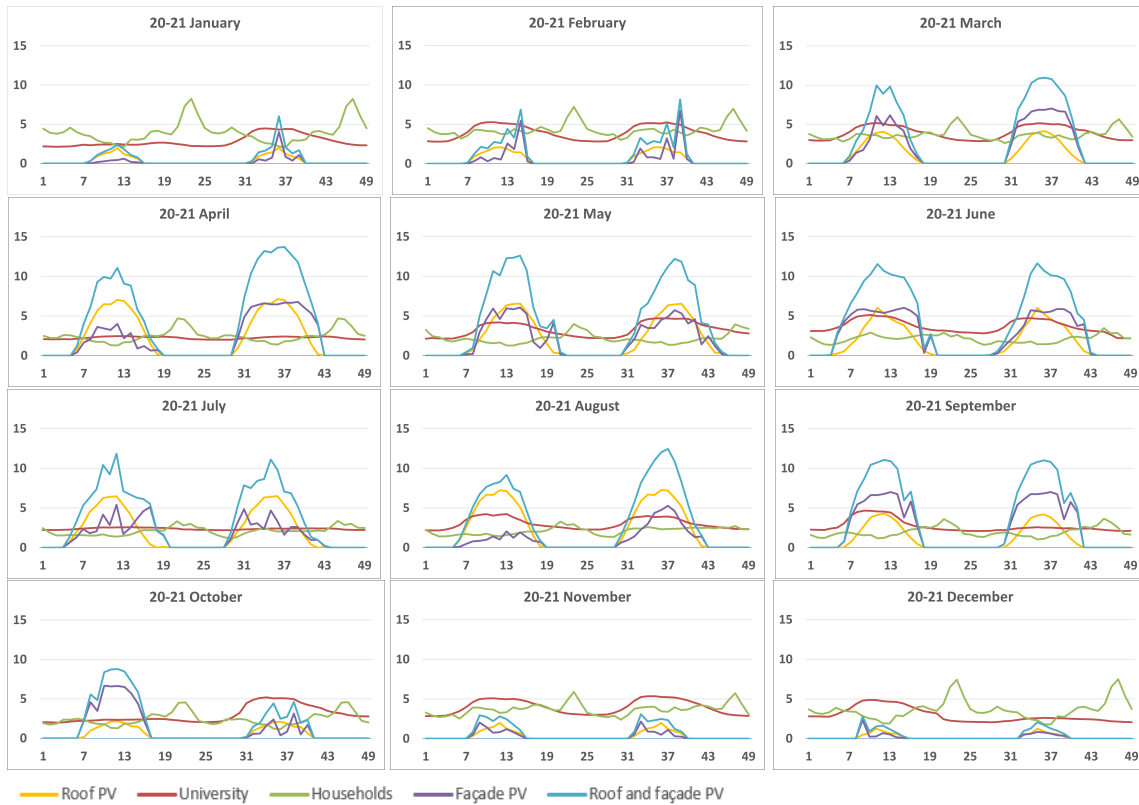


Figure A.5: Load curves of the roof and facade productions compared to the consumption of UCLouvain and Louvain's households in [MWh]

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