PROJECT B

Photovoltaic potential in Millingen aan de Rijn

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ABSTRACT:

The increasing concern about environmental issues, has led to a change in the approach towards the human development. In particular the interest towards more sustainable and renewable energy has increased. Up to now, fossil fuels are the main energetical source and at the same time are presumed to be responsible for the negative effects of human activity on the environment. Moreover, those sources are limited. Finding an alternative renewable source of energy is believed to be the starting point to invert the negative trend. Energy produced exploiting solar radiation is one of the examples of green and renewable sources. Photovoltaic systems are a well-established technology able to convert the irradiation coming from the sun into electric energy. Despite the great technological development occurred in the last years, traditional practical problems remain such as great surfaces requirements for installation and the gap between optimal production sites and consumption sites. Rooftop installed PV system could potentially solve both problems at once, moreover they rely on already existing infrastructures limiting the installation costs. Many studies have been carried out to investigate large scale systems that involve large urban areas (from small villages, to cities, to entire regions). The objective of this paper is to study the potential electricity production that could be achieved by covering all the available rooftops (both households and industrial buildings) in Millingen aan de Rijn, a small town in the Netherlands. The values obtained are compared to the actual electricity consumption. The research is part of a bigger project, that aims to make the village energetically independent, by means of renewable sources. The methodology used is based on open source data found online and statistical analysis. First the buildings were inventoried and divided into classes depending on their shape, orientation and dimension by visual examination of satellite maps. The size was determined from data of the national Dutch cadastre. Using existing literature and visual examination, the actual available rooftop area was computed by means of corrective coefficients. Finally, by means of an online tool provided by PV*Sol the potential energy production was estimated, which resulted to be almost 3 times the domestic consumption (14,569 GWh potential energy produced, 42,89 GWh estimated energy consumption). The results change if a storage system is considered, in this case the produced potential energy is slightly less than the consumed one. This aspect is beyond the scope of this research and it’s included only to have a preliminary reference. The values obtained are results of a qualitative analysis, and further research should be carried out in order to increase the accuracy and include the parameters that have been neglected for simplicity, thus provide more reliable estimations.

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1 Introduction

The alarm about the negative effects of human development on the environment has grown in the last decades. Issues such as air, soil and water pollution, greenhouse effect, paired with the limitation of the resources induced a change in the approach towards the consequences of the technological progress. Consequently, several studies and projects have been focused on finding a solution to those problems, with the objective of reducing the damages done in the past and at the same time convert the overall process in a more sustainable one. Energy is one of the fundamental aspects in technological development. As a matter of fact, the industrial revolution has been determined by the conversion of the main source of energy: from human powered machines to steam powered motors. Hence the importance of the research in this direction. Up to this moment, fossil fuels have been the main energy source. At the same time, they are also accountable for the negative effects that are affecting the Planet. In addition, those resources are limited, given that the human population is rising exponentially, and the resources consumption is augmenting consequently, a renovated interest regarding alternative solutions acquired more and more relevance in the scientific community. The idea is to convert progressively our productive and consuming system in processes that are more sustainable for the environment and will be unlimitedly available: solar, wind, geothermal, water, etc. Are all examples of clean and renewable sources of energy that could, at least partially replace the role of fossil fuels. It is important to point out that at the current state of the art neither of the renewables sources is capable of fully substitute the traditional fossil fuels. The predominant approach is to combine more technologies to overcome this limitation, forming hybrid systems. Many projects and researches have been carried out about this topic.

Photovoltaic (PV) technology is one of the most studied, thus also one of most well established. By means of semiconductors, solar panels allow to convert the energy irradiated by the sun into electrical current, in other terms the electromagnetic energy emitted by the sun is converted into electric energy. PV systems have been widely used in the last years, even among private users. The commercialization of this technology allowed the research to push forward and upgrade remarkably their performance. Being based on clean and unlimited renewable energy source, the efficiency covers a less important role in their analysis. More important are aspects related to their economic and environmental impact that will be briefly discussed in this paper. One of the biggest limitations of this technology is related to the variability of the system. In other terms, PV systems are capable only of instantaneity converting the energy form, but don't have the intrinsic capacity of storing this energy. The energy output strongly depends on many environmental factors (location, weather, positioning, day/night cycle, etc.), unlike other traditional energy sources it lacks the operational continuity. From this descends the worst limitation of photovoltaics: the necessity to have the systems installed in loco where the energy supply is required, and usually the optimal production sites and the most consuming areas don't coincide at all. Rooftop PV could potentially offer a solution to this problem, hence the interest from the scientific community. Having photovoltaics systems mounted on already existing buildings will prevent the soil consumption, that it is an relevant aspect especially in highly populated areas, it could reduce the installation costs and last but not least could provide in loco clean energy reducing or eliminating the logistic problems related to the energy transportation. Therefore, building roofs represent a huge potential for large scale PV applications. [1-9]

European union strategy towards energy reconversion in favour of renewable resources, involves also this strategy as it is testified by the numerous articles referenced. This paper investigates experimentally the particular case, already applied in several real-life experiments, of extensively covering all the buildings present in the municipality with PV panels in order to create a large-scale system capable of producing great amounts of electrical energy, and potentially fulfil all the local energy demand. The objective of this research is to quantify the potential photovoltaic energy production of all the rooftops of Millingen aan de Rijn. This work is part of a bigger project that aim to develop a complex system that will make the town independent from the energetical point of view. The idea is to produce green energy using the afore mentioned large scale PV system, and to use Hydrogen as storage fuel: the surplus of energy will be used to produce Hydrogen, that later could be used as a fuel to produce electricity when the energy provided by PV cells is not sufficient. The first step in this direction involves the roughly qualitative analysis of the potential energy production that can be done using all the available roofs. It is important to point out the main characteristics of the analysed sample. Millingen aan de Rijn is a small municipality, which buildings are mostly made of residential houses and few larger buildings dedicated to commercial, agricultural or industrial purposes. School and churches represent the only exceptions. Thus, the energetical profile of the municipality is mostly determined by domestic consumptions.

As mentioned in the previous section, many studies have been already carried out, even if different approaches and tools have been used, the fundamental structure used remains the same. The most common approach used is determined by a hierarchical approach, organized in levels that virtually follows the energy transduction from the sun radiation to the electric grid. Each level is characterized by a partial loss from the previous higher stage: e.g. the irradiation of the sun outside the atmosphere is much higher than the one on the earth surface. Based on that, the evaluation of the PV follows the investigation of different potentials:

1. Physical or theoretical
2. Geographical
3. Technological
4. Economic

The physical potential is defined as the amount of solar radiation that reaches the earth surface. It strongly depends on the latitude, since the radiation changes with the location on the Earth. Moreover, it is trivial that this value depends on the season, the weather and on the day/night cycle. In most of the studies, included this one, the results are considered on yearly base, thus those aspects are intrinsically considered once the location is selected. The geographical potential is determined by the actual amount of radiation that is possible to exploit, in other terms it is defined as the quote of solar radiation that is possible to collect using the available area that is available to use. In this assignment it is represented by the available rooftop area, obtained from the total rooftop area by subtracting the unusable parts occupied by other features (e.g chimneys, windows, antennas, etc.). Technological potential is related to the efficiency of the solar panels and of the overall system, given the available surface it specifies the percentage of the solar energy that can be actually transformed into electrical current. It is trivial that this aspect it’s related on the PV technology utilized, as well as on the electric components selected for the electric compartment (wiring, inverter, etc.). In this analysis a standard panel and inverter have been chosen as reference, in order to maintain the generality of this assessment. [1-9]

Even though it exiles from the scope of this analysis also a brief economic potential has been evaluated, just to give a comprehensive view of the assessment. Two parameters have been considered the return of invest (ROI) and the energy return of invest (EROI). The first quantifies the years necessary to gain the investment back, the latter provides with a coefficient that is commonly used to estimate the net energetical benefit of a specific source of energy. It is used to compare different energy sources and quantify their quality in terms of how much energy is gained compared to the energy necessary to harvest it (i.e. equivalent energetical cost for panels production, installation, transport, etc.). EROI it’s very important also in terms of sustainability, since it provides a useful index of the net energy analysis that is part of the notorious methodology of Life Cycle Analysis, that analyses the environmental impact of a project from a holistic point of view. This last part of the analysis is purely informative and don’t have any exhaustiveness and accuracy claim. [10-12]

This hierarchical approach was used to carry out this analysis. In this paper all the data were obtained from open sources available online. In particular to evaluate the technological potential, an online tool provided by PV*Sol was used (http://pvsol-online.valentin-software.com/#/). The software also calculates automatically the radiation profile once the location is selected. An additional online tool provided by European Commission, Photovoltaic Geographical Information System (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html) was used as comparison and to determine the irradiation data with high accuracy. The evaluation of the geographical potential, i.e. the inventory of the rooftops, was done using satellite maps openly accessible from Dutch government websites. In detail, cadastre maps (Publieke Dienstverlening Op de Kaart available at https://www.pdok.nl/viewer/) were used to assess the average footprint size, while height map (Actueel Hoogtebestand Nederland available at https://ahn.arcgisonline.nl/ahnviewer/) were used to determine the height profile of the buildings, thus the roof slope, as well as the type of the structure. To further clarify the morphology of ambiguous buildings, the satellite images provided by the online tools were used and occasionally also the images from Google maps (https://www.google.it/maps).

To determine the return of invest another online tool was used (http://pvcalc.org/pvcalc). Although many parameters can be included to perform a detailed economical analysis, just the basic features have been utilized.

In the following sections the methodology will be presented in detail, with particular attention on the assumptions and simplifications that have been made in order to simplify the evaluation. The potential energy production in Millingen aan den Rjin is then presented in detail, including all the intermediate steps with relative tables. The results are then discussed, and the potential energy production is compared with the estimated energy consumption. For the sake of discussion an example of storage system is hypostatized, as well as a brief economical study of the PV system was included to increase the meaning of the overall analysis. In the conclusive part the results of the research are summarized and an outlook for the future work is presented.

2 Methodology

The methodology has been designed following the potentials concept described in the previous paragraph. In order to evaluate the potential energy production from solar irradiation using photovoltaics cells and match it with the village demand the assignment was divided in three main steps:

1. Roofs inventory to determine the possible available surface
2. Potential energy production calculation
3. Energy demand analysis
4. Economic analysis

Furthermore, it was decided to apply a statistical approach, given the relatively large number of houses. The households have been classified into a relevant number of classes depending on several parameters such as size, orientation and typology. In order to simplify the calculation and at the same time provide accurate results, averaged values are used both for the determination of the buildings size, roof slopes and for the energy consumption estimation.

Except the energy demand analysis, all the other part of the research was carried out by means of free online tools. In the following sections the methodology of each step is described in detail.

2.1 Roofs inventory

The inventory of the roofs represents the core part in the analysis of the Geographical potential. To calculate the total available rooftop area for photovoltaics system installation, a statistical approach based on classes was chosen. The idea is to simplify the calculation, by considering large groups of entities that have same characteristics instead of single buildings one by one. Indeed, a calculation based on real data, acquired by direct measures, would have been time demanding and the actual improvement in accuracy wouldn't justify the additional effort. The measurement will be reduced to few relevant houses, that will be used as model to estimate the characteristics of the respective overall class. An exception is represented by special buildings, that are all the big buildings which are not residential units: commercial and industrial buildings, supermarkets, churches and big farm sheds. From now on those buildings will be simply referred as special buildings. Since in those cases the variance is to high and the number of buildings is limited, the actual values have been considered and the results calculated separately, to facilitate an eventual future analysis.

The inventory was done defining 34 building classes, depending on important parameters that influence the performance of PV system, besides the size of the household. Type, shape, orientation and the presence of additional features were the characteristics used to determine the classes. The slope is another important feature of the roof in terms of PV performance, but only two classes were created considering this parameter: flat and inclined roofs. This simplification is justified by the fact that the simulations performed have shown the effect of the inclination is neglectable: in the range of observed inclinations (minimum 20°, maximum 54°) the potential energy output difference is of about 3%. Thus, the average value of 38° was chosen for the inclined roofs of the residential houses, while a steepness of 18° was selected for the special buildings.

Depending on the type, the houses were divided in two classes: single and multiple. In the first category are comprised all the single-family detached houses in which each unit has its own roof; multiple houses are made of multiple living units that are grouped under a common roof, that can be considered as a unique long roof for the purposes of this analysis. Moreover, the two classes have also different average sizes.

Another characteristic used to define the classes was the shape of the roof. In particular in addition to the traditional rectangular based buildings, other two outlines were identified: 'T' and 'L' shaped houses. It is trivial that in those cases the available roof area is smaller with respect to a equivalent rectangular-based building. Similarly, a special class of buildings was created to include the houses that have existing features (chimneys, windows, terraces, ect.) on the roof that reduce the available area for PV panels.

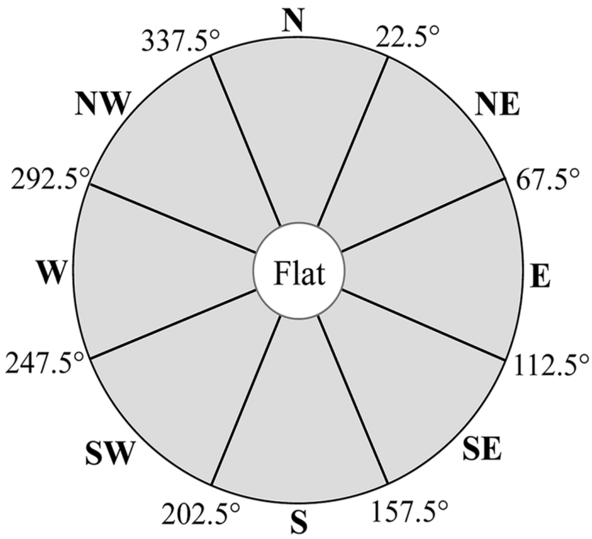

Figure 1: cardinal points and ranges used to determine the orientation classes. Taken without permission from [9]

Last, households were classified depending on the orientation of the roof's facades: this parameter is one of the most important since a north facing panel has been calculated to produce about 50% less energy. From existing literature and for simulations performed, it was decided to have 8 classes in order to have a good approximation but avoiding unnecessary complexity. The classes were selected according to the 4 main cardinal points and 4 intermediate ones; thus, each class comprises a range of 45°. **Figure 1** depict the classes used with respect to the cardinal points. In order to determine the roofs' orientation, graphical inspection of satellite images and height maps were used. In particular to simplify the inventory it was assumed that al the roofs were perfectly symmetrical. Hence the direction of the roofs facades was derived from the orientation of the roof ridge (were the two inclined surfaces meet), since it was easier to determine the alignment using the central pitch. The direction of the two perpendicular roof surfaces was simply determined by summing or subtracting the obtained orientation by 90° respectively.

Each building of the town was inventoried with respect to their orientation, typology and size, by means of visual inspection of satellite images, obtained from Google maps and PDOK viewer. It is important to point out that all the roofs have been considered suitable for PV systems installation: structural integrity of the buildings or inadequate roofs (e.g. made of asbestos panels) were not taken into account. Moreover, the already existing PV panels were not considered since the aim of this research was to estimate the overall potential energy production, rather than the one that could still be achieved.

The average footprint area ($A_{footprint}$) was determined for each building type, considering 100 houses as sample. As mentioned in the previous section it was then used to estimate the size of the buildings for each class. The data were collected from the online tool provided by the Dutch cadastre database (Publieke Dienstverlening Op de Kaart available at https://www.pdok.nl/viewer/). The average slope (θ) of the roofs was determined by means of an online tool provided by the public website (https://ahn.arcgisonline.nl/ahnviewer/) that has an interactive tool that allow to know the height profile of any given line as is depict in **figure 2**.

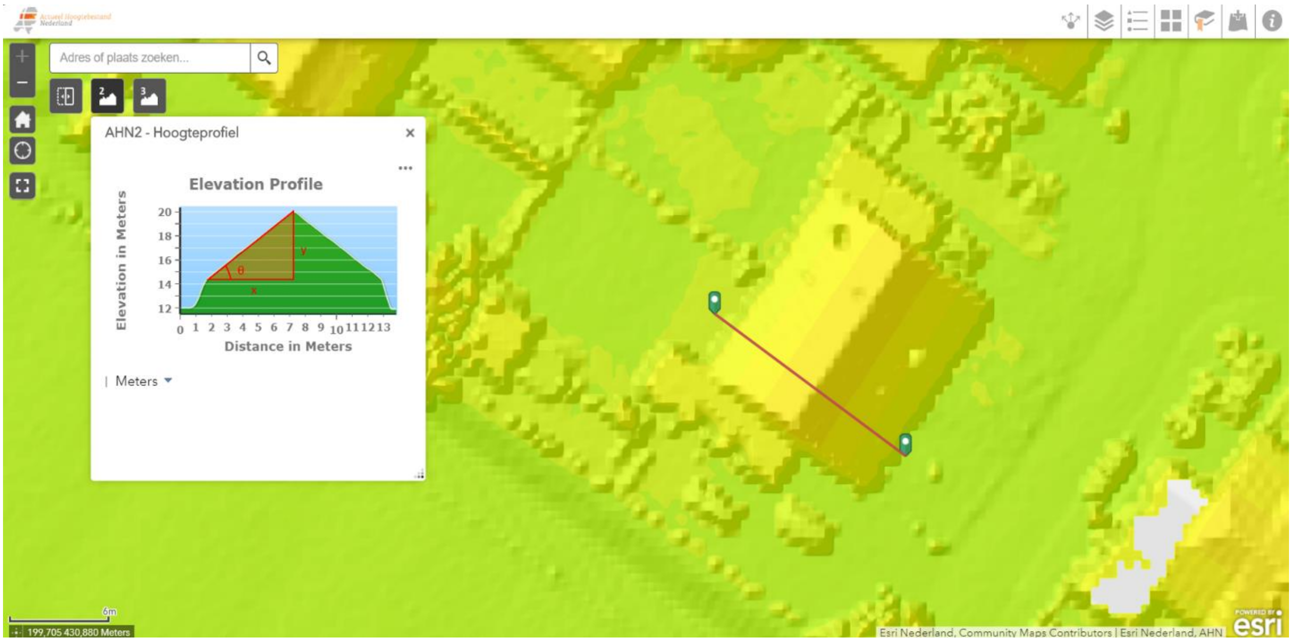

Figure 2: Example of height map; an interactive tool allows to draw a line (right side of the picture, across a house roof) and the software shows the height profile of that segment (on the left side). in red are specified the geometric entities used to calculate the slope (x, y, θ). Adapted without permission from https://ahn.arcgisonline.nl/ahnviewer/.

The slope was easily calculated using the height (y) and the length (x) of the roof by means of the simple trigonometric formula:

$$\theta = \tan^{-1}\frac{y}{x}$$

By projecting the footprint area with the roof inclination angle, it is possible to estimate the roof area (A_{roof}), using the formula

$$A_{roof} = \frac{1}{\cos\theta} \cdot A_{footprint}$$

Conventional households were assumed to have roofs inclined of 38°, while industrial buildings and agricultural shreds a slope of 18°.

In the case of the flat roofs, it was assumed that the panels would be installed at the optimum tilt angle (which results to be 41°). Considering the spacing between the rows, their reciprocal shadowing effect and the installation structures necessary it was selected to have a 0.5 corrective coefficient. Means that only half of the actual rooftop surface it estimated to be useful for the PV energy production. [7]

The presence of chimneys windows and other features reduces the available roof surface. Visual inspection and satellite measurements were used to determine the features of the roofs (shape, presence of windows or chimneys, etc.). To correct the calculated roof area, a series of coefficients were selected, depending on the class. Those corrective coefficients are listed in the table below (**table 1**).

Table 1: corrective parameters used

Feature	Corrective coefficients
Installation space (borders, etc.)	0.9
Windows	0.7
'T' and 'L' shape building	0.8
Flat roofs	0.5

Moreover for every class it was assumed that 10% of the roof was not usable for PV purposes, both to include: estimation errors, the technical space required for installation and maintenance or other characteristics of the roof that could not be identified (e.g. protruding ridges or irregularities). The values of those coefficients descend from existing literature and direct measurement of the satellite images via the integrated tools. [9]

The following formula summarizes the use of the corrective coefficients to obtain the available rooftop surface ($A_{available}$) starting from the calculated roof surface, where C represents the total product of the coefficients. Depending on the class it is made of one or more correction factors.

$$A_{available} = C \cdot A_{roof}$$

After each building was classified in one of the categories, the number of buildings was multiplied for the average footprint area of the specific class. In this way the total footprint area of each class was obtained. Using the symmetry principle discussed previously, the classes were further divided by the actual roof facades orientation and then the available area for each class was obtained using the coefficients described. The final result of this part of the analysis is the total available area for each orientation class, obtained by summing all the classes within the same orientation group. This was necessary since all the individual classes have different corrective coefficients, therefore it is necessary to calculate the total available roof surface at last.

2.2 Potential energy production

Starting from the available rooftop surface calculated in the previous section, the potential energy production was estimated. To do so an online available software was used: PV*SOL. The program requires the user to enter several parameters, that are used to compute the energy production. The software automatically considers the losses, both of the technical part (electrical losses due to the PV system itself) and of the physical part (irradiation losses due to weather conditions, day-night cycle and seasonal variation). Using the hierarchical approach presented in the previous section, PV*SOL allows to estimate both the Physical and the Technical potential at once. In fact, it is possible to select a specific location and the software automatically calculates the irradiation values on a specific inclined plane throughout the year. The irradiance values were checked using also the online tool provided by the European Commission: Photovoltaic Geographical Information System. The software could be used also to analyse the power production, but the data can be visualized only on single households' basis, thus this part was ignored, and the comparison was made with the dataset provided by the supplying company. In **Appendix 1** it is possible to see screenshots of the software used (**figure 4** and **5**). The parameters entered were:

- Location of the system
- Orientation of the roof
- Inclination of the roof
- Characteristics of the PV panels: technology, efficiency, set-up type, number of panels
- Type of inverter

A computation was carried out for each class. Obviously, the location remains constant throughout all the simulations. In order to have accurate values, without losing the generality of the analysis a generic typology of panels and inverter were selected (the software itself allows to use brand-free devices). In particular the type and number of inverters is automatically calculated but it is not necessary for the aim of this assessment except for the evaluation of the losses. The setup of the panels was considered to be done using panels with rear ventilation: temperature can strongly influence the final efficiency of the system, thus the potential energy production. At Netherlands' latitudes the temperature oscillation is not incisive in the PV performances, thus it doesn't have strong effect. In the table below the technical characteristics of the panels used are listed.

Table 2: technical characteristics of the PV panel used to simulate the system

PV panel characteristics	
Power peak	300 W
Efficiency	17.89%
Technology	Monocrystalline
Dimension of the panel	1.677 m^2

Given the available rooftop surface, it is possible to calculate the number of panels that could be installed for each orientation class, dividing by the dimension of a single panel. All the calculations were done using a conservative approach, rounding all he results at the smaller unit. The number of panels is required as parameter for the PV*SOL software. Other parameters could be specified for the analysis, but further analysis is required in order to use them in the simulation: shadowing effects, albedo and soiling were neglected. In particular the shadowing effect regards the analysis of the projected shadow of nearby objects that can reduce the performance of the PV panels. Albedo is a parameter used to estimate the amount of solar irradiation that is adsorbed or reflected by the environment (e.g. snow will reflect most of the radiation, while a black soil will adsorb most of it). Soiling refers to the losses caused by the dust particles that accumulate on the surface of the panel and reduces their efficiency. In general, those parameters depend on the location and on the single household, even though the estimation on a town scale is possible. The analytical effort exceeds the possible increase of accuracy that could be achieved; therefore, those parameters were neglected. Further analysis could consider those parameters to increase the accuracy of the analysis. Once all the data were inserted the power output was calculated, by means of the PV*SOL software.

2.3 Energy demand analysis

The energy demand was evaluated using the village total consumption. The source of this information is the local energy provider (LIANDER). The data obtained refer to the total electrical energy consumption, relative to the last seven years (2013-2019). The average value was used to estimate the energy consumption, in order to at least partially level out the potential variations. For the same period, also the data relative to the electricity consumption at the neighbourhood level were provided, together with the gas consumption data. Those data were not used in this analysis but could be useful in a successive more detailed analysis. (**the complete data can be found here**). In this paper the energy consumption is merely compared with the potential energy production at a yearly scale, to have an idea about the potentialities of such a large-scale PV system. in this analysis the energy consumption related to the industrial or commercial activities was not considered.

2.4 Economical analysis

As aforementioned the aim of this section is to give a complete overview of the assessment in all its aspects, thus the calculations are meant not to be accurate, but just provide a rough idea. Moreover, it would be useful in the future research of the project to have preliminary reference. The return of invest was calculated using an online freely available software (http://pvcalc.org/pvcalc). It should be pointed out that the possibilities of this tool are much grater than the one used to perform the analysis performed in this paper: the basic configuration of the software was used to determine the years within which the investment is regain. In particular the technical parameters used are the nominal power and the annual yield of the system. The first depends on the number of panels installed and on their technical specification, while the latter depends on the geographical location (physical potential). To get a simple result it is necessary to include also two economical parameters: the set-up costs (including purchase and installation) and the nature of the founds used. In order to simplify the calculation, it was assumed that all the financing is done with own founds. It was decided, considering the data found in literature, to set the cost to 1340 €/kW_p where kW_p stands for kilowatt-peak production (maximum power that can nominally be produced by the panels). The useful output is the return of invest in terms of years. In **appendix 1** a screenshot of the tool is shown (**figure 6** and **7**). [10-12]

To estimate the quality of one source or another the EROI is used. It is defined as the ratio of the energy produced by the energy consumed to make the system, expressed in a formula s follows.

$$EROI = \frac{E_{produced}}{E_{invested}}$$

It is quite complex to calculate such value since it depends on many variables and its strongly influenced by how the boundary conditions of the system are defined (i.e. what entities are included as energy invested: production, maintenance, transportation, etc.). EROI takes in consideration all the life cycle of the system, thus from the manufacturing process to the end-of-life of the product. In this paper the energy produced has been considered to be the total potential energy that could be produced by the PV system in 25 years, obtained simply by multiplying the total energy output by the number of years. It is assumed that in such period an overall 5% loss in the PV performance occurs, due to several factors such degradation of the system, maintenance, dirt, etc. The value was then dived by the total available surface area. The denominator has been calculated starting from a so-called Cumulative Energy Demand (CED) cost of 290 kWh/m^2 found in the literature. A cost for the replacement of the faulty equipment have been include, following a conservative approach a middle value of 10kWh/m^2 was selected. Other costs described in the reference paper have been neglected (i.e. energy equivalent of labour and capital). Moreover, the storage system has not been considered at this stage of the analysis. [10-12]

3 Results

In the following section the results are presented. Only the more relevant data are reported in this paragraph, the missing and complete data are provided in the appendix (**Appendix 2**) at the end of the paper. It is important to point out once more that the data illustrated are not completely accurate, since it is a preliminary report hence a qualitative methodology was selected. Nevertheless, the results are statistically accurate. All the final results about the potential energy production are yearly based. All the buildings in Millingen Aan der Rehin have been considered. Approximations were made depending on existing literature and visual inspection on satellite images.

3.1 Physical potential

Using the two software's mentioned in the methodology a yearly irradiance of 1022.1 kWh/m² was estimated in Millingen aan der Rijn. In detail **figure 3** shows the graphical representation of the irradiance in the town through 2016.

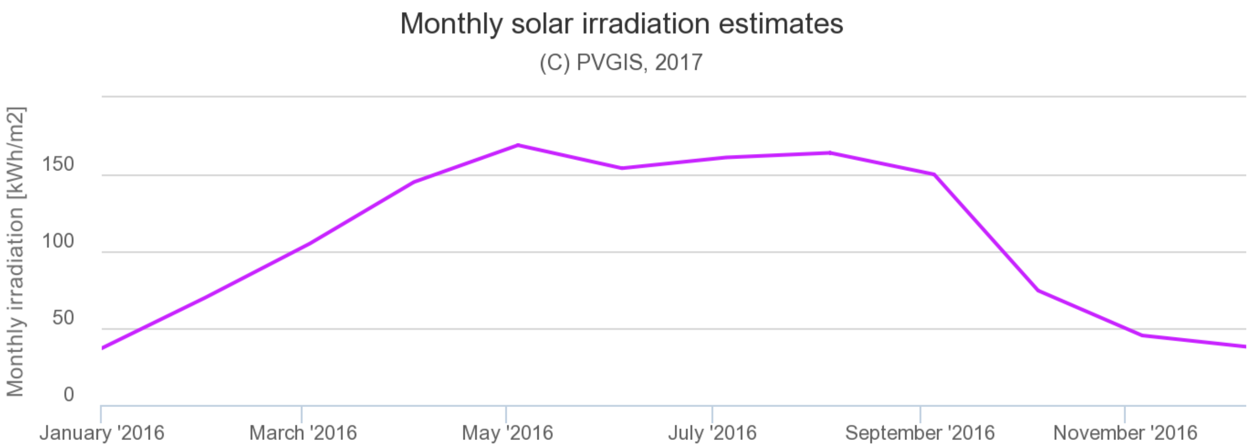

Figure 3: Example of irradiation profile in Millingen through the year in 2016. Taken without permission from (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html).

3.2 Buildings inventory

In the **appendix table A.1** the classification of the buildings depending on their type, and roofs ridge orientation is shown. **Table A.2** shows the same inventory for the special buildings.

3.3 Inclined roofs inventory

In **table A.3** and **A.4** is illustrated the total footprint area for each class, for conventional households and special buildings respectively. In addition is reported the estimated total rooftop area for each orientation class.

Table A.5 and **A.6** show the available rooftop surface for each class, obtained after the application of the relative corrective coefficients. In the last row the total available rooftop surface is reported.

3.4 Potential power production

The following tables (**table 3.1-3.4**) show the total available rooftop area for each class, the respective number of panels that would be installed and finally the potential power production for each orientation range. The values for the North, North-East and North-West directions have been represented in a separate table in order to facilitate the comparison with the other directions (usually north facing roofs are excluded in the planification of PV systems). Below each table the relative total energy output is reported. The first two tables (**3.1 and 3.2**) refer to residential buildings, while the second pair (**3.3 and 3.4**) refer to the special buildings. The last table shows the available rooftop area, number of modules and the potential energy produced for the flat roofs (**table 3.5**).

Table 3.1: geographical and technological potential of conventional households for the "south-facing" orientation classes

Orientation	E	S-E	S	S-W	W
total available roof area [m^2]	41826	31718	38039	23843	41826
n of modules	24945	18917	22687	14220	24945
energy output [kWh]	5479087	5045603	6580409	3951095	5799398
Total energy output [kWh]	2,686E+07				
	26,86 GWh				

Table 3.2: geographical and technological potential of conventional households for the "north-facing" orientation classes

Orientation	N-W	N	N-E
total available roof area [m^2]	31717	37886	23994
n of modules	18917	22596	14311
energy output [kWh]	3298020	3266597	2405764
Total energy output [kWh]	8970381		
	8,97 GWh		

Table 3.3: geographical and technological potential of special buildings for the "south-facing" orientation classes

Orientation	E	S-E	S	S-W	W
total available roof area [m²]	1613	4854	1442	4760	1613
n of modules	962	2895	860	2838	962
energy output [kWh]	227322	766001	371337	770934	235302
Total energy output [kWh]	2,371E+06				
	2,371 GWh				

Table 3.4: geographical and technological potential of special buildings for the "north-facing" orientation classes

Orientation	N-W	N	N-E
total available roof area [m²]	4854	1442	4760
n of modules	2895	860	2838
energy output [kWh]	616728	170028	591523
Total energy output [kWh]	1,378E+06		
	1,378 GWh		

Table 3.5: geographical and technological potential of flat buildings (households and special buildings)

flat roofs	
total available roof area [m²]	19000
n of modules	11332
energy output [kWh]	3317965
Total energy output [kWh]	3,318E+06
	3,318 GWh

3.5 Power consumption

Table 4 shows the overall consumption of Millingen households over the last 7 years. Below the average value is reported.

Table 4: Millingen residential houses total electricity consumption in the past 7 years and relative average value

Year	2013	2014	2015	2016	2017	2018
Total electricity consumption [kWh]	1,479E+07	1,377E+07	1,390E+07	1,528E+07	1,519E+07	1,448E+07
Average electricity consumption [kWh]	1,457E+07					
	14,569 GWh					

3.6 Economic analysis

In the following section the results of the economical analysis are briefly presented. In order to have a meaningful analysis of the data provided a comparison should be done, with both similar renewable technologies and more traditional ones. Since this research exiles from the purposes of this paper, the results are herby compared with the paper used as reference.

Table 5 shows the return of invest (ROI) in terms of years and the parameters used.

Table 5: parameters used for the return of invest calculation, and resulting amortization time

Return of invest calculations (ROI)	
N° of panels	187980
Nominal peak power of one panel (kW_p)	300
Total nominal power installed (kW_p)	56394000
Annual Yield per kW_p (kWh/kW_p)	861
Price (per kWp)	1340
Own founds (%)	100
Amortisation time (years)	8,9

Table 6: estimation of the energetical yield for EROI calculation

Energy produced	
Total energy production per year (kWh/year)	42893113
Total energy production in 25 years (kWh)	1,019E+09
Total availabel area (m^2)	315189
Specific yield (kWh/m^2)	3232

Table 7: estimation of the energetical cost of the system for EROI calculation

energy invested	
CED of the system (kWh/m^2)	290
Equivalent cost for faulty equipment (kWh/m^2)	10
total energy invested (kWh/m^2)	300

In the next two tables (**table 6** and **7**) the parameters considered for the energetic return of invest (EROI) are illustrated. Respectively the top one represents the energy production, thus the numerator of the formula. While the denominator is defined by the energetical costs shown in **table 7**.

Ultimately the EROI resulted to be equal to 10.7.

3.7 Summary

To summarize in the following table (**table 5**) the potential energy production calculated and the estimated energy consumption are reported. By covering all the available rooftops in MIllingen it was estimated that exploiting the solar radiation via PV panels it could be possible to produce 42,89 GWh/year of electrical energy. At the same time the energy consumption was estimated to be 14,56 GWh/year.

Table 8: overview of the results of the potential energy production and estimated energy consumption

Total potential energy production	42,89 GWh
Total estimated energy consumption	14,57 GWh

4 Discussion

A total number of 2452 of buildings were considered in this analysis, mostly households and a small percentile of industrial and agricultural structures. From those buildings a total rooftop area of 379653,2 m^2 was estimated, of which approximately 80% was considered to be available for PV systems installation. The potential energy production done by exploiting this area and by means of generic solar panels with up-to-date technical specifications, resulted to be roughly 30% of the energy needed. In fact, as it is possible to notice in **table 5** there is a surplus of energy production of about 2/3. It is important to point out the limits and boundaries of this assessment before carrying out with the analysis of the results. This study is needed as a first step towards a broader sustainability project and has the sole objective to provide the first rough data that could be used to have an idea and as a starting point for more detailed analysis. All the simplifications and methods considered, the level of accuracy of this research might be not inferior of a 10% error range, which is acceptable approximation in this type of analysis, but of course it wouldn't be tolerable in the case of a planification project. The same approach was adopted when the inventory classes were decided (slope range, orientation range, etc.). Even the data related to the power consumption can not be considered as exact values, since the value utilized is obtained by averaging the values of the last years. For the same reason variations in the parameters have been neglected in order to simplify the calculations. For example, physical potential can vary not only in the night-day cycle, but also in the seasonal scale and even in the long term (i.e. decades). In the same way the accuracy of the visual inspections done to determine the corrective coefficients is prone to errors since is based on subjective analysis. Nevertheless, the overall analysis can be considered useful if the limitations explained are borne in mind, since it can give a preliminary qualitative assessment of the problem.

Looking at the results the amount of potential energy production is much larger that the energy required to fulfil the domestic energetical demands of the town. This result could be easily misread and lead to wrong conclusion: it is important to point out some crucial points. First in this analysis the comparison between energy consumption and production is done on a year scale, secondly it is assumed that the two curves are in the same phase or in other words that the demand and offer are always paired during the time. In reality this is rarely the case. On the contrary, usually the most productive periods never coincide with the most consuming hours. As a matter of fact, during summer the energy harvestable is greater since the daylight last longer and the azimuth of the Sun is higher, hence the potential energy producible will be much larger than in winter. At the same time most of the families use electricity in a more prominent way early in the morning and late in the evening, while they consume less when there is the PV production peak in the central hours of the day. The same concept applies also for variations related to the weather conditions. In order to compensate the difference between the production and the consumption peaks a storage system should be considered. A system that allows to store the surplus of energy and then make it available whenever is needed. Even though the design of a storage system exiles from the goals of this assignment a basic consideration was made.

For what mentioned in the previous section a storage system should be considerate in order to compensate the fluctuations between energy produced and consumed. With the introduction of such apparatus the performance and the results of the analysis change substantially. On the long term this sustainability project aims at using Hydrogen as storage fuel. Thus, just as an example, a hydrogen-based storage system was designed. It is assumed the worst-case scenario, where all the electricity is converted into chemical energy via fuel cells and stored in form of hydrogen gas. Eventually, when needed, the energy stowed into the chemical bonds of the Hydrogen molecules can be converted into electricity, always by means of fuel cells. In terms of efficiency the first conversion process can roughly have a value up to 60%, meanwhile the second up to 50%. If a complete conversion cycle is considered (electricity-Hydrogen-electricity) the total efficiency would be about 30%. Going back to the results of this paper, with a Hydrogen based storage system the effective energy production, due to the conversion losses, would be potentially reduced by a factor of 70%. In the following table (**table 7**) the updated data are reported:

Table 9: final results, considering a storage system

Total potential energy production (considering a Hydrogen storage system)	12.87 GWh
Total estimated energy consumption	14,57 GWh

In this case the difference between energy produced and consumed is much less, but most importantly the potential energy produced became slightly less that the energy consumed. Even if the gap is small and the difference could be accountable to estimation error, it is important to consider it for the future analysis. The quantitative difference is not really accurate, therefore it can not be used to draw any conclusion, but it can provide an interesting qualitative idea of what could be if a storage system is included. In these conditions the energetical independence would be more difficult to achieve, since the potential energy production is slightly not enough to sustain the consumptions based on this analysis.

As expected, the north facing panels (North, North-East and North-West) are much less efficient than the one facing other directions: compared to the optimal south facing panels, they produce up to 50% less of electricity. At this point the choice of considering or less this option, that usually is not taken, regard economic and environmental aspects.

Another important consideration is that the results provided in this paper are relative only to domestic consumption: industrial and commercial activities energy expenditure were not considered. On the other hand, their roofs were included in the determination of the available surface for PV installation. It is trivial that, even if in Millingen there are no large industries, the additional energy demand would be higher. Even more, if the project is to be extended to other services, additional sources of sustainable energy should be taken in account. Public and private transportation done via electric cars or battery powered boats and public illumination are few examples of facilities that could be powered by renewable energy.

Regarding the economic analysis it has been estimated a return of invest (ROI) of 8.9 years, which is much lower than the standard lifetime of such PV systems. As assumed in the calculations, nowadays, a functional lifetime of about 25 years, and more is expected. According to the calculations done using the online tool, the initial investment is completely gained back after less than the half-life of the system. In addition, the results obtained is consistent with the current commercial PV system, which have a ROI between 7 and 10 years. As mentioned in the methodology, it was assumed that all the financing comes from own founds, thus the result could change slightly with different financial pre-conditions. An EROI value of 10.7 was calculated. This result is more difficult to comprehend since it requires a comparison with other sources or systems. Looking at the results calculated in the paper used as reference, the EROI obtained in this paper is very close to such value. Indeed, they calculate an EROI ranging from 9.1 to 9.7, which results to have a 10% difference with regards to the value obtained in this paper. Such error margin can be considered fully satisfying given the qualitative nature of this analysis. Also in this case several additional parameters could be considered in this part of the assessment to increase the level of the accuracy and the meaning of the analysis. [10-12]

5 Future perspectives

The results obtained in this preliminary research gives a first idea about the feasibility of the sustainability project in Millingen but cannot be used as an accurate reference in the later eventual planification stage. The several simplifications and assumption should be corrected and analysed more in detail, in order to increase the level of accuracy. For instance, the households' inventory should be carried out using actual data and not based on statistics. This could be done also using dedicated software that allows to automatically determine the geographical potential via the analysis of the satellite images. The same applies for the determination of the corrective coefficients. The analysis should be carried out considering also the neglected parameters (shading effects, already existing systems, soiling effect, etc.) to get a more accurate estimation. In other words, the quality of the raw data should be improved in order to have more reliable results.

It has been demonstrated the importance of a storage system: a precise dimensioning can strongly influence the performance of the overall large-scale PV system. Therefore, an adequate storage technology should be taken into consideration. In order to do this a more accurate comparison of the consumption/production rate is necessary. In particular to estimate the fluctuations between the two quantities, and thus be able to compensate them with a suitable system, hourly based data (or even with smaller resolution) are required. On the other hand, a more holistic view should be adopted, physical potential should be evaluated also on a longer period of time in order to compensate the natural fluctuations in terms of solar irradiation. In this way the analysis would be more accurate and the results more reliable.

The economic and environmental aspect should be examined more in detail, especially in terms of EROI and about the possibility to install panels also on the north facing roofs.

Last the opportunity to exploit also vertical walls to implement PV installation should be investigated, for example in the large unused industrial buildings located on the banks of the river.

6 Conclusion

In this paper the potential production of electrical energy from solar radiation via photovoltaic technology in a small town in the Netherlands has been investigated. In particular the rooftop PV potential of the totality of the buildings in the Municipality was studied. This preliminary assessment is part of a broader project that aims to make Millingen aan der Rijn energetically independent from the national power grid, only by means of renewable energy sources. A hierarchical methodology was presented: starting from the available irradiation (physical potential), the available rooftop surface was estimated (geographical potential) and finally the potential energy production was calculated (technical potential). The analysis was carried out by means of online freely available tools. The available roof surface was deduced from online maps (satellite, height and cadastre) and using statistical approaches. All the buildings roofs of the town were inventoried and classified into relevant groups, defined by several characteristics such as orientation, shape and size. The available surface obtained was used to calculate the potential energy production via an online software. The final results were compared with the electricity consumption, whose data were obtained from the local energy provider (LIANDER). Despite the qualitative analysis, done using a conservative approach the potential power production (42,89 GWh) resulted to be much higher than the energy consumed (14,57 GWh). Nevertheless, it has been shown that a storage system should be taken into consideration to compensate the variations between energy demand and offer (energy is produced when not needed and vice versa). If such system is considered, in particular one based on Hydrogen as storage fuel, the potential electricity production is slightly not sufficient to cover the consumption. Being an initial analysis, the qualitative nature of the results obtained provides a good statistical first look of the assignment, but further research is necessary to increase the accuracy of the results. Parameters such shadowing effects and seasonal variations should be investigated in detail, industrial consumptions should be included in the analysis and the quality of the raw data should be increased (footprint area, slope, corrective coefficients). In addition, an adequate storage system should be considered, and the analysis of the data should be focused accordingly: energy consumption and consumption should be compared at least on an hourly scale. In conclusion, this research provides a useful starting point in terms of PV potentials for the sustainability project in Millingen aan der Rijn.

7 References

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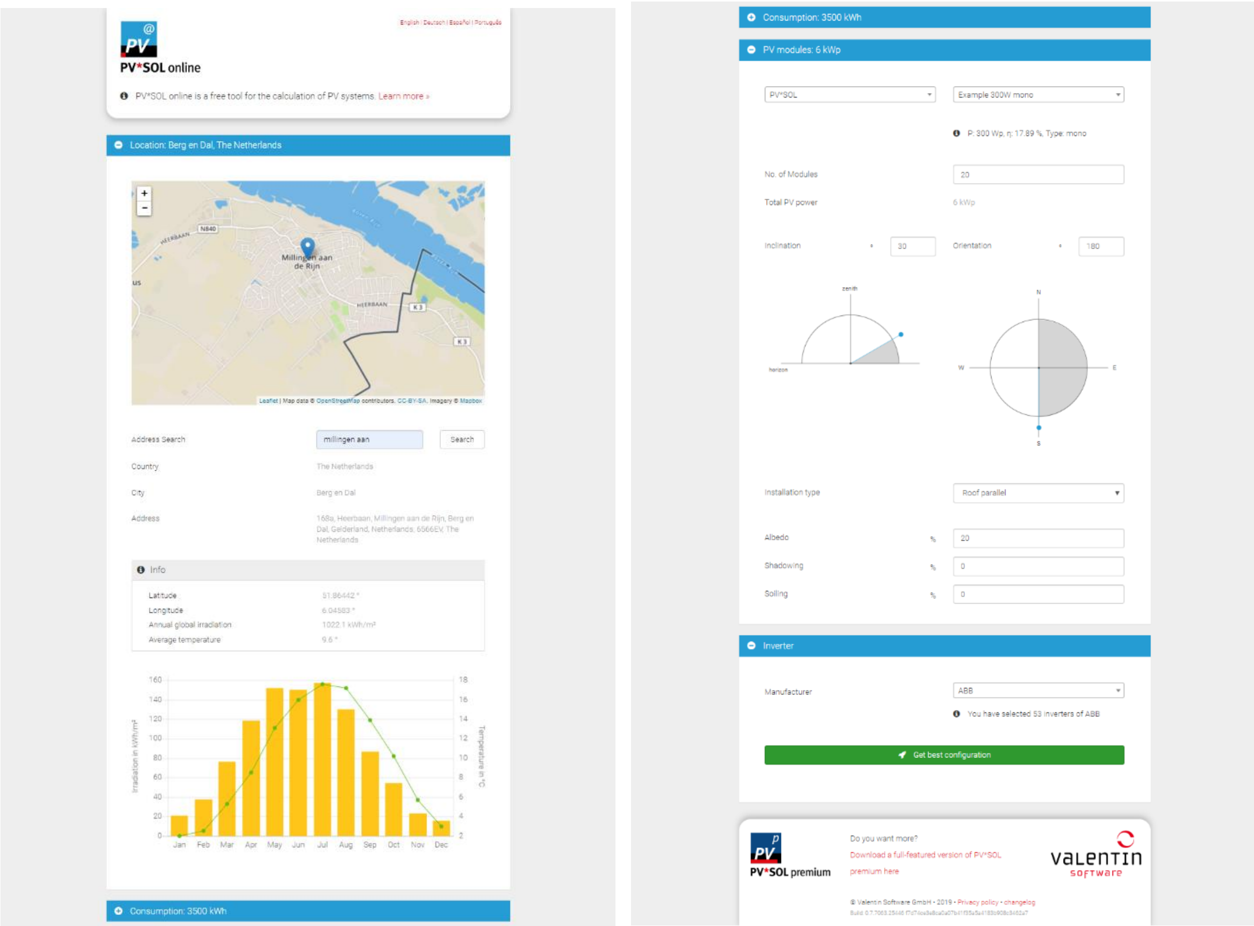
8 Appendix 1



a) *b)*

Figure 4: a) and b) schreenshots of the online tool used to estimate the potential power production (http://pvsol-online.valentin-software.com/#/)

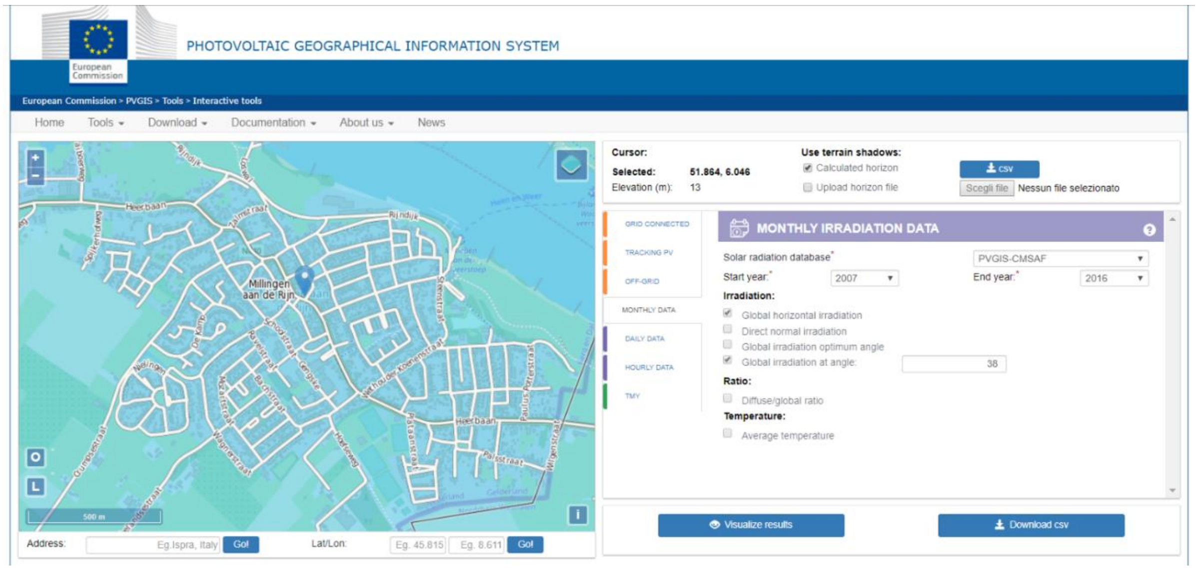


Figure 5: screenshot of the Photovoltaic Geographical Information System tool provided by the European Commission (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html)

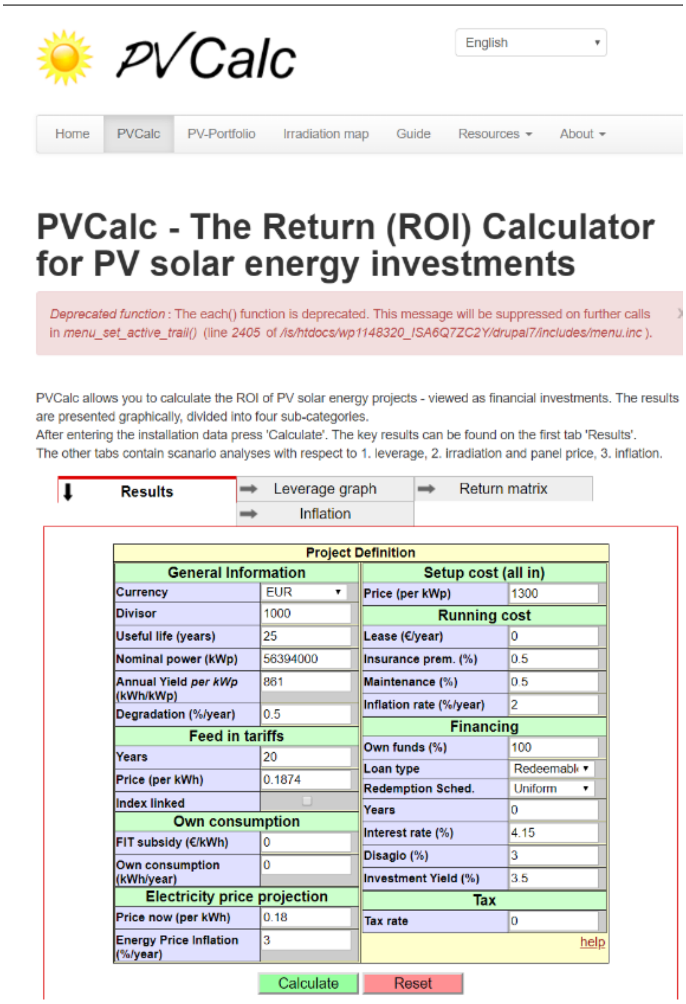


Figure 6: screenshot of the online tool used to calculate the return of invest (http://pvcalc.org/pvcalc)

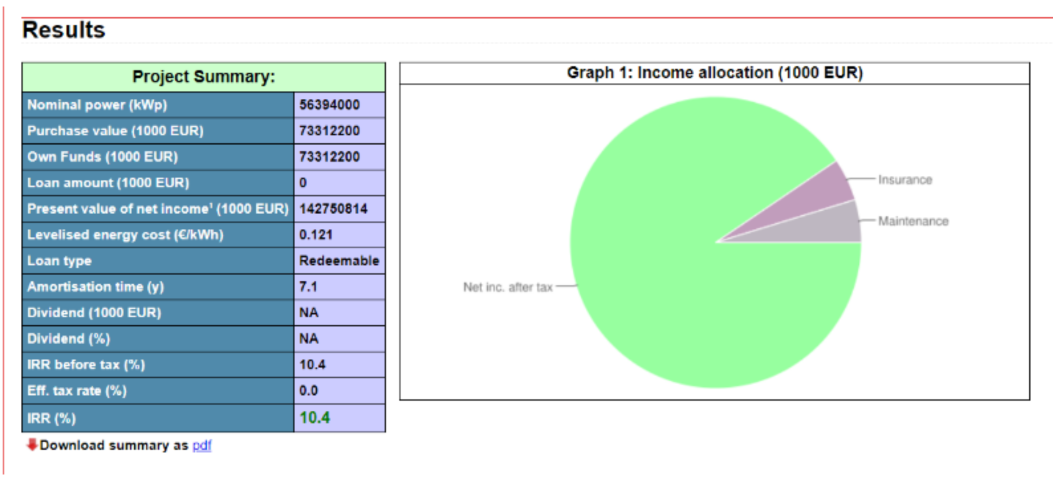


Figure 7: screenshot that shows the results of the economical analysis (http://pvcalc.org/pvcalc)

9 Appendix 2

In the following appendix all the relevant tables are reported. Further information are contained in the attached excel worksheet, in addition more detailed data about energy consumption can be found in this file.

Table A. 1: residential buildings inventory, depending on size, shape and orientation of the roof edge

	Roof Edge Orientation	N-S	W-E	SW	SE	No orientation
single units	**double pitched**	177	169	142	153	-
	double pitched with windows	26	17	2	6	-
	flat	-	-	-	-	42
	4 pitched	6	3	-	27	-
	angled double pitched	-	6	-	-	-
	"T" dounble pitched	56	19	19	13	-
multiple units	**single pitched**	-	1	-	1	-
	double pitched	406	390	334	201	-
	flat	-	-	-	-	99
	double pitched with windows	9	14	29	9	-

Table A. 2: special buildings inventory, depending on size, shape and orientation of the roof edge

Roof Edge Orientation	N-S	W-E	SW	SE	No orientation
industrial, agriculture shreds	9	4	14	22	-
large flat buildings (school, supermarket,etc.)	-	-	-	-	25
church	-	1	1	-	-

Table A. 3 residential buildings footprint area depending on orientation and relative estimated rooftop area

	Orientation	E	S-E	S	S-W	W	N-W	N	N-E	No orientation
single units footprint area [m²]	double pitched	10620	8520	10140	9180	10620	8520	10140	9180	
	double pitched with windows	1560	120	1020	360	1560	120	1020	360	
	flat	-								5040
	4 pitched	810	270	810	270	810	270	810	270	
	angled double pitched	0	0	420	0	0	0	420	0	
	"T" double pitched	3920	1330	1330	910	3920	1330	1330	910	
multiple units footprint area [m²]	single pitched	0	0	120	0	0	0	0	120	
	double pitched	20300	16700	19500	10050	20300	16700	19500	10050	
	flat	-								9900
	double pitched with windows	450	1450	700	450	450	1450	700	450	
	Total footprint area [m²]	37660	28390	34040	21220	37660	28390	33920	21340	14940
	Total rooftop area [m²]	47791,2	36027,4	43197,4	26928,6	47791,2	36027,4	43045,1	27080,8	14940

Table A. 4: special buildings footprint area depending on orientation and relative estimated rooftop area

	Orientation	E	S-E	S	S-W	W	N-W	N	N-E	No orientation
special buildings footprint area [m²]	industrial/agriculture sheds	1706	5032,5	1104,5	5032,5	1706	5032,5	1104,5	5032,5	-
	large flat buildings (school, supermarket,etc)	-	-	-	-	-	-	-	-	27283
	church	-	100	420	-	-	100	420	-	-
	Total footprint area [m²]	1706	5132	1524	5032	1706	5132	1524	5032	27283
	Total rooftop area [m²]	1793	5393	1601	5288	1793	5393	1601	5288	28674

Table A. 5: residential buildings available rooftop area depending on orientation

	Orientation	E	S-E	S	S-W	W	N-W	N	N-E	No orientation
single units rooftop area [m^2]	double pitched	12129	9730	11581	10484	12129	9730	11581	10484	
	double pitched with windows	1247	95	815	287	1247	95	815	287	
	flat									4536
	4 pitched	925	308	925	308	925	308	925	308	
	angled double pitched	0	0	383	0	0	0	383	0	
	"T" double pitched	3979	1350	1350	923	3979	1350	1350	923	
multiple units rooftop area [m^2]	single pitched	0	0	152	0	0	0	0	152	
	double pitched	23184	19073	22271	11478	23184	19073	22271	11478	
	flat									8910
	double pitched with windows	359	1159	559	359	359	1159	559	359	
	Total available rooftop area [m^2]	41825	31717	38038	23842	41825	31717	37886	23994	6723

Table A. 6: special buildings available rooftop area depending on orientation

	Orientation	E	S-E	S	S-W	W	N-W	N	N-E	No orientation
special buildings rooftop area [m^2]	industrial/agriculture sheds	1793	5289	1160	5289	1793	5289	1160	5289	-
	large flat buildings (school, supermarket,etc)	-	-	-	-	-	-	-	-	27283
	church		105	441	-	-	105	441	-	-
	Total available rooftop area [m^2]	1613	4854	1440	4760	1613	4854	1440	4760	12277