Assessment of the photovoltaic potential at urban level based on 3D city models: A case study and new methodological approach

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ABSTRACT

The use of 3D city models combined with simulation functionalities allows to quantify energy demand and renewable generation for a very large set of buildings. The scope of this paper is to determine the solar photovoltaic potential at an urban and regional scale using CityGML geometry descriptions of every building. An innovative urban simulation platform is used to calculate the PV potential of the Ludwigsburg County in south-west Germany, in which every building was simulated by using 3D city models.

Both technical and economic potential (considering roof area and insolation thresholds) are investigated, as well as two different PV efficiency scenarios. In this way, it was possible to determine the fraction of the electricity demand that can be covered in each municipality and the whole region, deciding the best strategy, the profitability of the investments and determining optimal locations. Additionally, another important contribution is a literature review regarding the different methods of PV potential estimation and the available roof area reduction coefficients. An economic analysis and emission assessment has also been developed.

The results of the study show that it is possible to achieve high annual rates of covered electricity demand in several municipalities for some of the considered scenarios, reaching even more than 100% in some cases. The use of all available roof space (technical potential) could cover 77 % of the region's electricity consumption and 56% as an economic potential with only high irradiance roofs considered. The proposed methodological approach should contribute valuably in helping policy-making processes and communicating the advantages of distributed generation and PV systems in buildings to regulators, researchers and the general public.

Keywords

Urban energy consumption; PV potential; Urban solar potential; Roof-top photovoltaic systems; Distributed Generation; 3D city models.

1. Introduction

It is an undeniable fact that our present living standard strongly depends on electricity and other forms of energy. Urbanization has led to a high increase in energy use, with buildings being one of its largest contributors and playing a significant role on climate change. As part of the sustainability strategy in Europe, the Energy Performance of Buildings Directive (EU, 2010) and others such as the Renewable Energy Directive (EU, 2009) have defined a package of measures that sets the path for notable and long term improvements in the energy performance of Europe's building stock. Some examples are the introduction of Nearly Zero Energy Buildings (NZEB) or the obligation to utilize on-site renewable energy. In addition, the tendency of new regulations is to extend the system boundaries from a single building to the urban area, allowing the interaction between different energy flows.

The new concept of distributed energy generation is becoming increasingly important, with the effect that the distribution network is evolving from a once passive power-consuming to an active power-generating part of the electric power system (Srećković et al., 2016). Among the different widespread distributed energy applications, there is a growing consensus that the deployment of photovoltaic (PV) systems in buildings is an attractive option. Analyses have shown that about 60% of the roof area in Europe is suitable for solar technologies (IEA, 2002; Weiss et al., 2010), which could be solar thermal (S_{TH}) or photovoltaics. In this work the focus is on solar photovoltaics. However, in spite of the fact that the advantages for individual buildings have been studied, there is little understanding of the potential benefits of an urban scale implementation of such systems (Jo and Otanicar, 2011).

Electricity production by PV is growing world-wide and grid-parity is a reality in many places, even in low irradiance countries such as Sweden (Molin et al., 2016). Solar radiation is a clean and abundant source of energy and PV is expected to contribute even more significantly in the future, since rooftops provide large areas suitable for solar energy exploitation. However, unlike the non-urban environment with little constraints to energy production, buildings have limitations on the available area, and many factors have to be considered such as construction restrictions or obstructions due to the surroundings.

The better the knowledge about the PV potential and investment cost of a region, the easier it is to help policy-making processes, prevent future disparities between supply and demand, and communicate the advantages of building integrated systems to the general public (Freitas et al., 2015). Therefore, the first step for this approach is an analysis to determine the solar potential of regions, which might be a challenging task due to the complexity of the urban environment.

Although a lot of research has been presented to measure the PV potential of buildings and plenty of studies have focused on the improvement of solar assessment by developing software and algorithms, 3D city models have not been made available in public domain on a full-scale yet. In order to estimate the PV potential, different approaches are applied, from simple estimations to airborne LiDAR (Light Detection and Ranging) technologies (Horváth et al., 2016). Depending on the scale and the level of detail required, some methodologies will be more appropriate than others.

In the last decade Germany has experienced a massive increase in constructed PV plants. However, only a small fraction of the installed capacity is integrated within buildings (Strzalka et al., 2012). There is a large disparity between regions, which motivates investigations of regional potentials that according to Mainzer et al. (2014) have not been done in earlier reports.

1.1. Aims and objectives

The scope of this paper is to determine the PV potential at an urban scale, which might be highly beneficial for urban energy management considering different CO_2 saving and investment approaches. Both the technical and economic potential are investigated and identified for each single building of the region according to its specific roof shape receiving solar radiation.

The present study introduces an innovative tool for the determination of the PV potential at an urban and regional scale by using 3D city models: the Java-based SimStadt platform (SimStadt, 2016), which contains simulation models from the INtegrated Simulation Environment Language (INSEL, 2014), both developed at the Stuttgart University of Applied Sciences. In addition, a literature review regarding the different methods of PV potential estimation and available roof area reduction coefficients has been carried out.

With the view of showing its full capabilities when dealing with PV potential analysis for whole regions, SimStadt has been used in this study to estimate the PV potential of the Ludwigsburg County in south-west Germany (state of Baden-Württemberg), in which every individual building was simulated (157724 buildings in total). The main purpose of this study is to determine what fraction of the electricity demand can be covered in both each municipality and the whole region, deciding the best strategy so as to reach that aim, the profitability of such investments and determining the optimal locations. An economic analysis and emission assessment has also been developed, as well as some insights into the uncertainty of the PV potential estimations.

2. Literature review

2.1. Review of methods for estimating the solar potential

The literature review which has been carried out shows that there are many different methodologies which aim to determine the PV potential of a region, but as yet few methods for assessing urban scale impacts of solar energy system applications have been developed (Jo and Otanicar, 2011). One of the most important aspects which should be borne in mind is the scale, since the same techniques cannot be applied at local, regional or continental level. Additionally, it is necessary to know which data is available. Unlike Building Information Model (BIM) standards which serve as exchange support between different building tools allowing high interoperability, no comprehensively applicable model standard exists until now for Urban Energy Modelling (Nouvel et al., 2015a). That is the reason why developers had to start from the beginning and create their own data models.

As it has been mentioned before, there are many different approaches when dealing with solar potential estimations. The study performed by Schallenberg-Rodríguez (2013) does a very complete methodology review and intercomparison. According to it, the main difference among the different procedures is the method used to determine the roof area: based on the ratio roof surface per capita, establishing a correlation between the population density and the roof area, or computing the total roof area of the target region. In (Li et al., 2015) the solar potential in urban residential buildings is investigated at different levels of site densities, comparing the solar potential under different urban forms whose total available roof area was calculated with sample urban settings and weather data as the inputs. Other possible options are based on building typology through on-site data collection and visual inspection of a certain area (Horváth et al., 2016) or statistical calculation models which compute the total roof area through aerial object-specific image recognition (Karteris et al., 2013). Nevertheless, although the mentioned studies include very efficient and robust estimation models, they might not be replicable for the scope of the present study.

On the other hand, the three most important roof-area estimation methods according to Melius et al. (2013) are the following:

-*Constant-value methods:* they are a useful starting point for their speed, but they make very simplified rule-of-thumb assumptions such as the ratio of tilted versus flat roofs, the number of buildings with desirable rooftop orientations, or the amount of space obstructed by building components. The constants are then applied to the total building stock, determined from the Census for example.

-*Manual selection methods:* rooftops with characteristics that appear suitable for PV are manually selected from sources such as aerial photographs and visually inspected for shading and building obstructions. They are more accurate, but very time-intensive and not easily replicable.

-*Geographic Information Systems (GIS)-based methods:* used by the majority of analyses, they mainly use 3D models in order to determine the available rooftop area of a region, identify obstructions or assess shadow effects on buildings. They are much more accurate and replicable but computer-resource intensive.

Our focus will be on GIS-based methods, since they can play a very important part in supporting decision making by tackling the urgently required energy transition (Ramirez Camargo et al., 2015). For very precise calculations the most appropriate option is 3D modeling and building simulation (Horváth et al., 2016). Nevertheless, this methodology might only be applied to small-scale regions such as a city or a county due to the fact that it is a time-consuming and resource-intensive process (Kurdgelashvili et al., 2016).

3D city models have shown huge potentials in the field of city planning, and the number of cities represented is increasing exponentially, at the same time that the investment costs and time required to build these models is decreasing thanks to new data collection technologies such as LiDAR. Drones have also become a very efficient and low-cost solution. An example of study which makes use of 3D city models is the one presented by Singh and Banerjee (2015), which uses high-granularity land use data available in the public domain and GIS-based image analysis of satellite images. Conversely, Lukač et al. (2014) present a novel PV potential estimation over LiDAR data, taking into account the nonlinear efficiency characteristics of the PV modules and inverter.

Other publications consider the time series analysis of supply and demand (Ramirez Camargo et al., 2015), assess the time-dependent annual electrical energy losses (Srećković et al., 2016), build a Digital Surface Model (DSM) from LiDAR data (Redweik et al., 2013), use ortho-imagery through cadastral data (Bergamasco and Asinari, 2011a) or do object oriented image analysis and GIS combined with remote sensing image data to quantify the available roof area (Jo and Otanicar, 2011). It should also be mentioned that the use of PV can help mitigate blackout problems and assess the feasibility of rooftop PV in remote urban areas (Gautam et al., 2015). A very thorough and valuable GIS-based study was developed by Mainzer et al. (2014) for all municipalities in Germany. However, the statistical data was assumed to be homogeneous (no variation in typical building sizes between different municipalities for example), apart from the fact that the PV potential of non-residential buildings could not be assessed.

In other studies such as (Srećković et al., 2016) or (Khan and Arsalan, 2016), even if GIS were used it was mainly to calculate roof areas, but not to compute solar production, which will be done in the present study. Therefore, the outcomes of this research should contribute valuably to the body of knowledge, since very few studies have used both detailed building and solar irradiance data to compute the PV production on specific sites (Schallenberg-Rodríguez, 2013).

2.2. Process of determination of the available roof area

Once the 3D model of the region has been obtained, it is possible to know the total built area and the geometry of the buildings that shape it. However, many circumstances may lead to the reduction of the initial roof area. An extensive literature review has shown the great variety of different reduction coefficients used for calculating the available roof area of a region. Most studies focus on the determination of roof and facade areas, distinguishing between flat and tilted roofs (Kurdgelashvili et al., 2016; Mainzer et al., 2014; Melius et al., 2013; Schallenberg-Rodríguez, 2013) or between building types (Bergamasco and Asinari, 2011b; Schallenberg-Rodríguez, 2013).

There seems to be an agreement so as to differentiate between architectural suitability and solar suitability (Byrne et al., 2015; Schallenberg-Rodríguez, 2013). However, these studies differ since their level of detail varies, and there is no common classification for their coefficients. Some of them give disaggregated factors (Bergamasco and Asinari, 2011b; Byrne et al., 2015; Izquierdo et al., 2008; Schallenberg-Rodríguez, 2013), while others show more global ones (IEA, 2002; Mainzer et al., 2014; Melius et al., 2013). In addition, unlike the publications made by Byrne et al. (2015) and Luque and Hegedus (2011) most of these studies do not consider the coefficients for the separation of the PV panels (GCR) or the Service Area (SA), necessary for maintenance operations.

After gathering all the information from related studies, it was decided to use for this study the approach shown in the flowchart in Figure 1, which illustrates the way to calculate the utilization factor (UF). It should be noted that no previous study has used all of these factors at the same time, but only partially. This approach includes all the reduction coefficients which we consider as essential for our study and shows the calculation process for estimating the available roof area for PV purposes, after which calculations of the PV potential can be performed.

Unlike previous publications in which these coefficients are applied to the aggregated results of a whole region, our study considers their application for each building individually, which increases the accuracy of the procedure. This is due to the fact that the 3D model allows us to know their characteristics, enabling us to apply different factors depending on the building that is being analyzed.

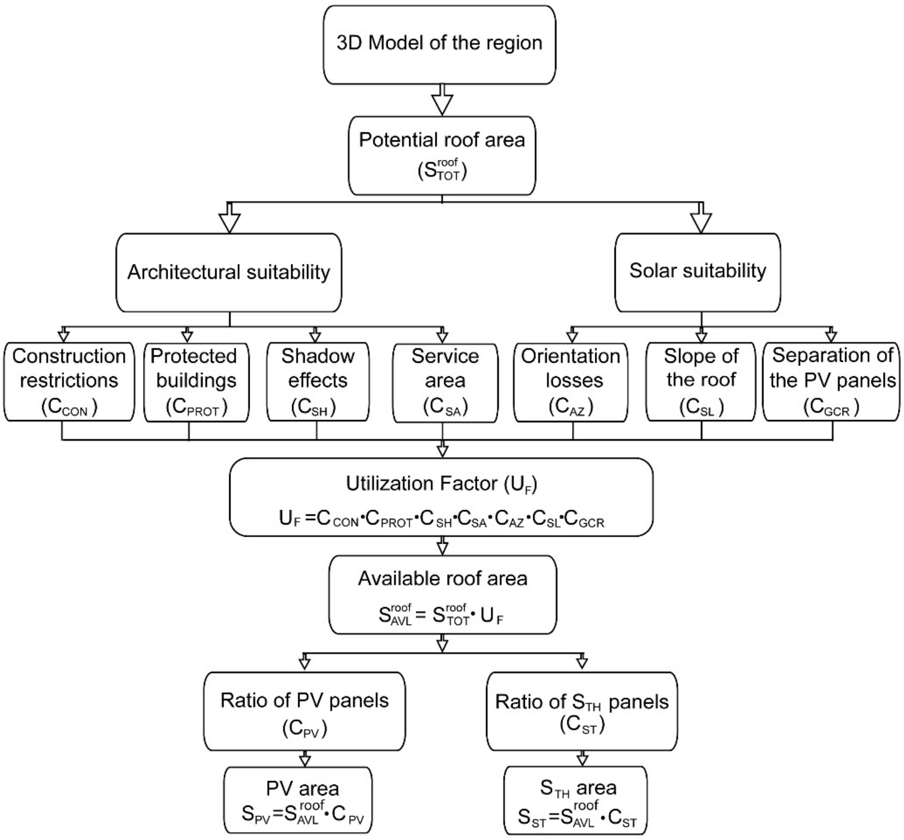

Figure 1: Flowchart of the available roof area calculation process.

With a view to understanding the scope of each reduction coefficient, they are going to be briefly explained:

-*Construction restrictions* (C_{CON})*:* it refers to space already occupied by elements located on the roof, such as elevators, air extractors, chimneys, stairwells, water tanks, HVAC installations or windows.

-*Protected buildings* (C_{PROT})*:* this coefficient may be applied to buildings where for some reason no facility can be built on, due to historical considerations for example.

-*Shading effects* (C_{SH})*:* it considers the shadowing produced by the roof itself or by other buildings.

-*Service Area* (C_{SA})*:* necessary space for maintenance and access. At higher tilt angles the space freed up due to the spacing between the PV panels (C_{GCR}) can be used (Byrne et al., 2015).

-*Orientation losses* (C_{AZ})*:* it takes into account the relative amount of solar radiation which reaches the surface due to its azimuth.

-*Slope of the roof* (C_{SL})*:* it takes into account the relative amount of solar radiation which reaches the surface due to the slope of the roof.

-*Separation of the PV panels* (C_{GCR})*:* it considers the distance between the panels so as to avoid reciprocal shadowing. According to Luque and Hegedus (2011), shade on as little as 5-10% of an array can reduce its output by over 80%.

-*Ratio of PV panels* (C_{PV})*:* Ratio of the available roof area used to install PV panels.

-*Ratio of S_{TH} panels (C_{ST}):* Ratio of the available roof area used to install S_{TH} panels.

2.3. Process of determination of the technical PV potential

The PV potential is calculated in the way shown in Figure 2.

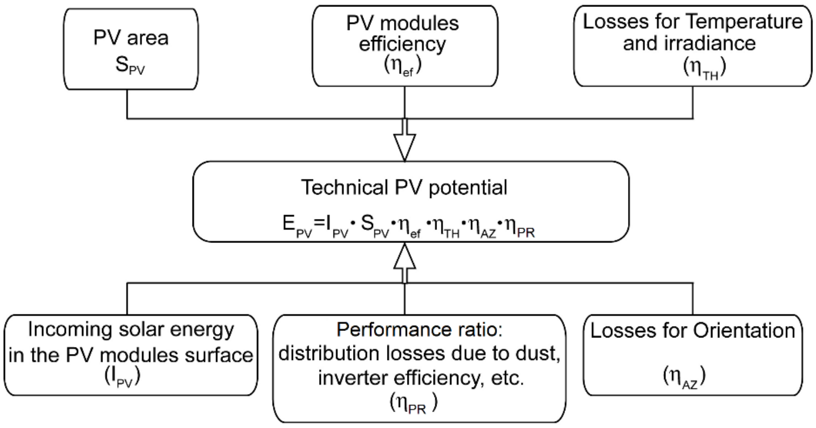

Figure 2: Flowchart of the technical PV potential calculation process.

-*PV area (S_{PV}):* total available roof area used to install the PV panels [m^2], determined by the SimStadt software (SimStadt, 2016).

-*Incoming solar energy (I_{PV}):* annual insolation in the PV modules surface [kWh/m^2·year] also calculated by SimStadt.

-*PV modules efficiency (η_{ef}):* efficiency of the PV modules depending on the technology used.

-*Temperature and irradiance losses (η_{TH}):* efficiency loss due to climate characteristics. This parameter is currently object of great interest in the technical community (Bergamasco and Asinari, 2011b).

-*Losses for orientation (η_{AZ}):* it takes into account the reflection losses due to non-normal incidence angle of the Sun's rays (Li et al., 2015).

-*Performance ratio (η_{PR}):* losses due to conversion efficiency of the inverter, cabling losses, dust on the panels and others. Electricity storage will not be considered in the present study.

3. Input data and simulation tools

3.1. Data model and weather processor

For the modelling of the 3D building data, the Open Geospatial Consortium (OGC) Standard CityGML (CityGML, 2012) has been chosen. CityGML is an open, multifunctional XML-based data model, a flexible spatio-semantic data format which offers powerful methods for the evaluation of various analyses for city districts, whole cities or regions.

A considerable advantage of CityGML in comparison with other 3D city model formats is that it specifies object modelling in four increasing Levels of Detail (LOD1, LOD2, LOD3 and LOD4), enabling the city model to adapt to local building parameter availability. The most simple building representation is LOD1, consisting in a rectangular block. LOD2 includes the full building geometry with varying heights of building parts and the roof shape, LOD3 a detailed façade geometry including doors and windows, and LOD4 the inclusion of indoor spaces. In

2014, the complete building stock of Germany was modelled with CityGML – LOD1, and some regions like Baden Württemberg or Saxony have already completed their 3D city model with LOD2 (Nouvel et al., 2015b). In order to generate the 3D city models, LiDAR, stereo air photo or digital cadaster enhanced with building information can be used. In particular, laser scanning methods which are often used nowadays allow an automatic generation of CityGML models of whole cities in a short time.

On the other hand, analyzing the solar potential of a region requires local weather data, either hourly or monthly, in order to know the horizontal and diffuse radiations, ambient temperatures, etc. The quality of the solar radiation data depends on the source, including ground station measurements, satellite images or combinations of both types (Assouline et al., 2017).These data are imported into the SimStadt platform through a weather processor from different databases such as PVGIS (PVGIS, 2012), INSEL (INSEL, 2014), or by using Meteonorm weather files chosen by the user.

3.2. Urban modeling platform SimStadt

Recently, urban simulation and 3D GIS have progressed considerably, but without notable interaction between them. With the purpose of taking both domains into account and supporting public authorities and engineering companies in the planning of the energy transition at urban scale, the urban energy simulation platform SimStadt (SimStadt, 2016) was developed by the Stuttgart University of Applied Sciences in the framework of a project funded by the German federal Ministry of Economic Affairs and Energy.

Based on the open 3D CityGML models, its workflow-driven structure is highly modular and extensible, allowing for a potentially unlimited variety of urban analysis provided that the required data is available in the 3D model. Each workflow step has hypotheses, parameters and intermediate results which can be modified and assessed through the Graphical User Interface (GUI), enabling the user to create scenarios accordingly. In addition, if some information is not deducible or available at building level, such as building age necessary for heat demand calculations, default data are used from the building library. In the case of PV potential calculations all the required information is contained in the CityGML model, as only geometry data are used for the modeling.

The start of the workflow in SimStadt is the virtual 3D CityGML model. It should be noted that SimStadt handles all LODs. Given the diversity of the quality of the 3D models, the next step would be the use of the healing module “CityDoctor”, required to check and correct the geometry of the model. Then, the data-processing allows for the completion of the model. After that, the energy simulations can be carried out. SimStadt has the capacity of obtaining hourly or monthly data in every simulation, although the results of the present study are annual given that the main goal is to estimate the annual PV potential of a region. The latest version of SimStadt can perform a variety of multi-scale energy analyses such as heating/cooling demand diagnosis, building refurbishment scenarios or photovoltaic potential. Other workflows are under way. Last of all, the results can be visualized in different ways with performance indices, graphs or maps, as well as being exported to a file.

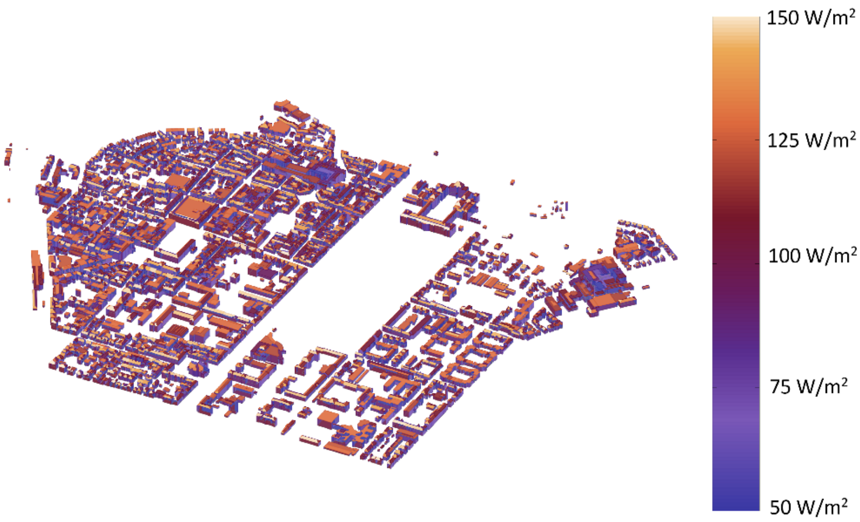

Figure 3: Example of radiation map simulated using SimStadt to determine optimal PV locations in a municipality.

Once the weather data are available, the radiation processor can compute the incoming irradiance on every building boundary surface, based on their geometry and the direct, diffuse and horizontal irradiances delivered by the weather processor.

In the current version of the SimStadt platform, the user can select two different radiation distribution models:

-*INSEL model:* based on the Hay sky model for diffuse irradiance calculation, requires INSEL and simulates solar irradiance on arbitrary surface orientations. Its execution time is fast and does not depend on the 3D model size. Shading and inter-reflections are not considered.

-*Simplified Radiosity Algorithm (SRA):* it is coupled with the Perez sky model, and considers both shadowing and the reflection effects of the surrounding buildings. Its execution time depends on the 3D model size and the amount of simulated buildings.

The current study will be based on the INSEL model without shading due to the large amount of buildings that will be analyzed. Shadowing effects will be approximated through a reduction coefficient (see section 5.1).

3.3. PV Potential analysis tool

Regarding the PV potential tool included within SimStadt, the sequential workflow steps are shown in Figure 4. The input is the CityGML file of the region. Although it can also work with LOD1, LOD2 is preferable. LOD3 and LOD4 include more information and they could be interesting to analyze facades for example, but other data would be irrelevant for our purpose (such as internal partitions).

The outputs of this tool are: irradiance, suitable roof area, nominal power and annual energy yield for every individual building. It is also able to perform the overall calculations, as well as show valuable graphs and 3D maps with data such as PV suitability in order to assess optimal locations.

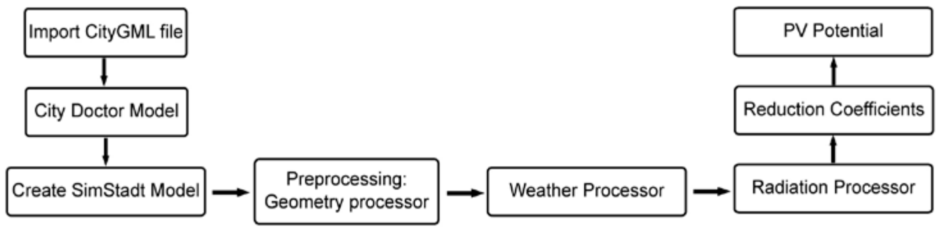

Figure 4: Process of determination of the PV potential.

3.4. Electricity demand of each municipality

The calculation of the electricity demand is based on the available concession bills of each municipality, with data of 2013 or 2012 depending on the case. If the data from the concession bills was not available for any municipality, the electricity demand was calculated by using area-related parameters, which were taken from German industry standards. More specifically, the net floor space was required to calculate electricity consumption using typical values from the standards. This floor area was determined from the building geometry in the workflow of heat demand calculations.

4. Description of the case study

The methodology was applied to the German County district Ludwigsburg. This county is located in the south-west of Germany, covers a ground area of approximately 700 km^2 and has a population of 354551 inhabitants. There is a total of 39 municipalities, of which 34 participated in a climate protection concept and could be analyzed. In total, 157724 buildings were considered.

The 3D CityGML models were created by the state surveying office *Landesamt für Geoinformation und Landesentwicklung Baden-Württemberg (LGL)*, based on the official real estate cadaster information system and stereo aerial photographs, with about 80% of the buildings defined in LOD2 and 20% in LOD1.

Based on the 3D models, the photovoltaic potential was calculated and compared with the electricity demand for each municipality. The purpose is to determine the fraction of the electricity demand which can be produced with PV and which strategies have to be adopted to reach that aim.

5. Calculation methodology and assumptions

The reduction coefficients presented in sections 2.2 and 2.3 vary greatly from one study to another. Therefore, the values for the present study have been chosen after reviewing the proposals made by many authors, with the purpose of adapting them to the scope and characteristics of our study.

5.1. Reduction factors of the roof area

-*Construction restrictions* (C_{CON}): many studies (Bergamasco and Asinari, 2011b; Byrne et al., 2015; Eicker et al., 2014; IEA, 2002; Karteris et al., 2013; Kurdgelashvili et al., 2016; Mainzer et al., 2014; Melius et al., 2013; Schallenberg-Rodríguez, 2013) show different values depending on the building type, the slope of the roof and other considerations. In addition, a representation of a sample rooftop can be seen in (Khan and Arsalan, 2016). Taking all the proposals into account, our study will use a value of C_{CON}=0.8 for flat roofs and C_{CON}=0.9 for tilted roofs. These values correspond to the ones suggested by (Schallenberg-Rodríguez, 2013), whose distribution of building types in the considered region and distinction of reduction factors was the most suitable one for the present study.

-*Protected buildings (C_{PROT}):* we will assume for this study that no historical buildings are in the city quarter, so C_{PROT}=1.

-*Shadow effects (C_{SH}):* Our study is based on the 3D model of different municipalities, calculating the PV potential with a radiation processor based on the Hay model, and not taking the interaction among buildings into account, which strongly depends on urban density. After reviewing many references (Bergamasco and Asinari, 2011b; Byrne et al., 2015; IEA, 2002; Izquierdo et al., 2008; Kurdgelashvili et al., 2016; Schallenberg-Rodríguez, 2013; Wiginton et al., 2010), it can clearly be seen that the variability when consulting this factor is very high and strongly depends on the type of buildings. Taking into account these publications and that the area under study has low building densities, values of C_{SH}=0.7 for flat roofs and C_{SH}=0.8 for tilted roofs have been chosen.

-*Orientation losses (C_{AZ}) and slope of the roof (C_{SL}):* Unlike previous publications, our study uses the SimStadt platform, which already takes these factors into account for calculating the PV potential, since it calculates the radiation for each surface orientation. So in our case, C_{AZ}=1 and C_{SL}=1.

-*Separation of the PV panels (C_{GCR}):* to minimize row to row shading, Kurdgelashvili et al. (2016) and Luque and Hegedus (2011) suggest that the setback ratio (SBR), defined as the gap between rows divided by the vertical distance between the high and low sides of adjoining rows, should be at least 3:1 for cloudy mid-latitude regions. In this way, the ground cover ratio (GCR) is defined as follows:

$$C_{GCR} = \frac{1}{\cos\beta + SBR \bullet \sin\beta} \quad ,$$

where β is the array tilt with respect to the horizontal.

If the roof is flat, we will show in Section 5.3 that the PV panels will have a tilt angle of 25°. Considering a SBR=3, this means that C_{GCR}=0.46. The study presented by Byrne et al. (2015) also uses this approach.

If the roof is tilted, we will consider that C_{GCR}=1, since the panels will be installed parallel to the roof and no separation is necessary to avoid row to row losses.

-*Service Area (C_{SA}):* this factor depends on the separation of the PV panels. A table is presented by Byrne et al. (2015) considering different tilt angles and the corresponding GCR and SA coefficients. If the roof is flat, our study will consider a tilt angle of 25° and the same coefficient as that study, which in this case would be C_{SA}=0.97 (C_{GCR}=0.46 already accounts for available space). If the roof is tilted, C_{SA}=1 will be considered.

-*Ratio of PV panels (C_{PV}):* We will only consider the installation of PV panels in our study. C_{PV}=1.

-*Ratio of S_{TH} panels (C_{ST}):* We will not consider the installation of solar thermal panels (S_{TH}). C_{ST}=0.

Although the variability of these reduction coefficients in the reviewed studies is very high, the application of these disaggregated coefficients in our study leads to global values of the

Utilization Factor similar to others (Byrne et al., 2015; IEA, 2002; Mainzer et al., 2014; Melius et al., 2013).

5.2. Reduction factors of the PV potential

-PV modules efficiency scenarios (η_{ef}): The current status of the photovoltaic technology is displayed in (Green et al., 2016), which shows listings of the highest confirmed efficiencies for a range of photovoltaic cell and module technologies. However, the present study will consider two different scenarios, in which PV panels of two different commercial technologies are implemented for the PV potential calculations. These scenarios are shown in Table 1:

Scenario	Technology	Efficiency [%]
A	Wafer-based silicon modules	16.0
B	Thin film modules	11.0

Table 1: PV efficiency scenarios.

-Temperature and irradiance losses (η_{TH}): we will use a value of η_{TH}=0.9, according to Bergamasco and Asinari (2011b) and the references therein.

-Losses for orientation (η_{AZ}): the study presented by Li et al. (2015) concludes that this coefficient for PV is kept nearly constant (equal to 1). However, Bergamasco and Asinari (2011b) use a factor of 0.9. Therefore, our study will consider an average, a value of η_{AZ}=0.95 when the panels are not facing the south. If they are, then η_{AZ}=1.

-Performance ratio (η_{PR}): this factor for inverter, cabling and other system losses varies depending on the study, so we have decided to follow the proposal made by Bergamasco and Asinari (2011b) which we regard as the most appropriate, using a factor of η_{SYS}=0.84.

The summary of all the selected reduction factors is presented in Table 2:

Reduction factor	Value
C_{CON}	Flat roofs: 0.8 Tilted roofs: 0.9
C_{PROT}	1
C_{SH}	Flat roofs: 0.7 Tilted roofs: 0.8
C_{SA}	Flat roofs: 0.97 Tilted roofs: 1
C_{AZ}	1 (considered in SimStadt)
C_{SL}	1 (considered in SimStadt)
C_{GCR}	Flat roofs: 0.46 Tilted roofs: 1
C_{PV}	1
C_{ST}	0
η_{ef}	Scenario A: 0.16 Scenario B: 0.11
η_{TH}	0.9
η_{AZ}	Az=0: 1 Az≠0: 0.95
η_{SYS}	0.84

Table 2: Summary of reduction coefficients.

5.3. PV optimal inclination

The tilt angle of the PV array is one of the keys to an optimum energy yield. However, several aspects have to be taken into account when choosing it, since it influences other parameters. Using the climatic data of the region and doing simulations within SimStadt considering different tilt angles, the highest PV yield is obtained for a tilt angle of 35° with a rather flat maximum, value which was validated by using PVGIS (PVGIS, 2012) in the region.

This means that the reduction of the PV production is very low when the tilt angle is close to the optimal. However, there is an aspect that most studies fail to bear in mind when calculating the PV potential: the separation of the PV panels in flat roofs. The higher the tilt angle, the lower the available roof area, since the gap between rows has to be increased to minimize reciprocal shadows. This can be seen through the C_{GCR} coefficient (Luque and Hegedus, 2011). This indicates that installing the panels horizontally (C_{GCR}=1) would increase the PV potential of a region dramatically, due to the fact that the influence of increasing the C_{GCR} coefficient and thus the available area is much higher than that of the tilt angle. Nevertheless, other issues have to be considered. For instance, the panels have to be tilted so as to diminish the losses due to dust, and the C_{SA} coefficient should be also kept in mind. In addition, increasing the available roof area by decreasing the tilt angle would result in a higher investment, which would probably be unaffordable.

As a consequence, we have chosen a tilt angle of 25° facing south for the PV panels when the roof is flat, since the difference of the PV production compared to the optimal angle is very low and it allows a smaller distance between rows, therefore increasing the available roof area. If the roof is tilted, the tilt angle of the PV panels will be that of the roof, installing the panels in parallel, and the orientation will also be the same.

5.4. Definition of the technical and economic potential

As previously mentioned, the technical potential is defined by implementing PV panels on all available surface. This means that the whole available roof area after applying the reduction coefficients in the previous section will be used. On the other hand, the economic potential is the result of considering only buildings with solar yields on their roof above a threshold value, which indicates a minimum amount of radiation that is required for the installation to be economically worth considering (IEA, 2002) , or could be a percentage of the maximum PV yield in the region (Compagnon, 2004). In addition, a minimum roof area will be considered, so buildings whose roof areas are below that minimum will not be taken into account. These two thresholds reduce the number of PV installations as a function of the economic profitability of their implementation.

In order to select the optimal minimum roof area a graph is presented in Figure 5, which shows its influence for one of the municipalities analyzed in this study.

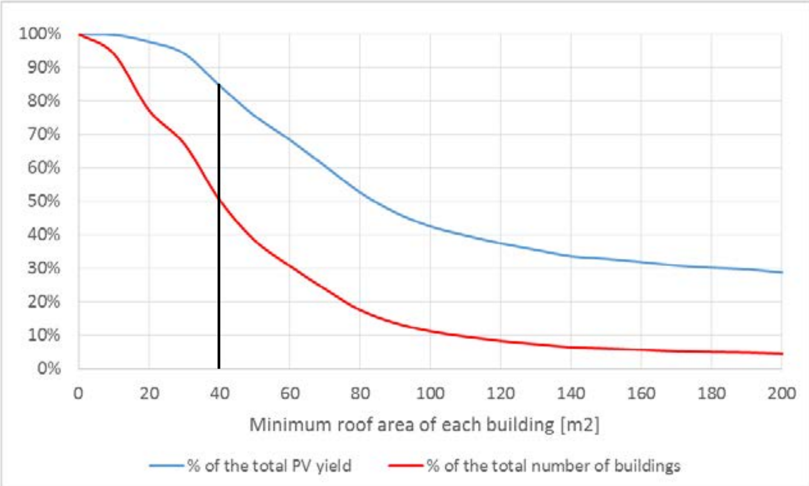

Figure 5: Influence of the minimum roof area on the PV yield and number of buildings.

As we can see, it is possible to reduce noticeably the number of buildings interventions while avoiding a high decrease of the total PV yield, since those buildings with small roof areas which only produce a small fraction of the PV yield would not be considered. In our case we decided to set a minimum of 40 m^2, which allows us to do the interventions in only 50% of the buildings, while maintaining 85 % of the total PV yield.

On the other hand, an insolation threshold has to be chosen, which is closely related to the energy production per square meter PV installed and thus the economics. A similar study was performed by Mohajeri et al. (2016). The relationship of this insolation threshold with respect to the number of buildings is very different from that of the minimum roof area, which is why the payback period has also been taken into account in this case. It is commonly acknowledged that a standard PV system in Germany can reach about 30 % of self-consumption (IEA-PVPS, 2016), so this is the percentage assumed for the economic calculation. The details of the economic analysis will be described in Section 6.3.

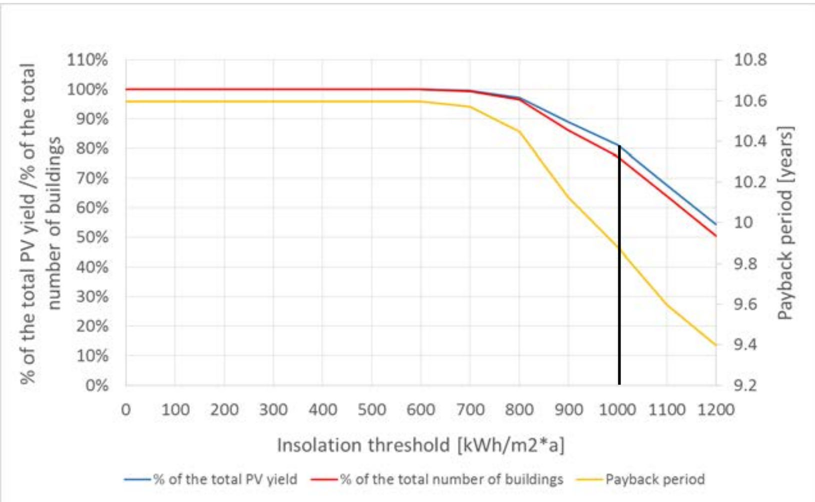

Figure 6: Influence of the insolation threshold on the PV yield.

Figure 6 shows the payback period (right axis) and percentages of the total PV yield and number of buildings (left axis) as a function of the insolation threshold. The correlation of the number of buildings and PV yield is very similar, but the higher the insolation threshold, the lower the payback period. Assuming that the decision maker intends to have a payback period of approximately 10 years, a value of 1000 kWh/(m^2·year) can be chosen, allowing to reduce the number of building interventions while maintaining an appropriate payback period and PV yield.

To sum up, in the present study the economic potential will consider an annual insolation threshold of 1000 kWh/(m^2·year) and a minimum roof area of 40 m^2 for each building.

6. Results and discussion

6.1. PV potential of all the municipalities and the whole region

After gathering all the 3D CityGML models of the municipalities which constitute the County of Ludwigsburg, each of them was simulated within the SimStadt platform. Once the software calculated the area and solar radiation for each roof surface of the buildings by using the weather and radiation processors, the reduction coefficients proposed in Table 2 were applied, depending on the characteristics of each individual building. Then the aggregated values of PV potential nominal power [kW_p] and PV potential yield [MWh/year] for the whole municipality were calculated. This was done for the technical and economic potential, as well as for the two PV efficiency devised scenarios.

As can be seen in Figure 7, the technical PV potential (installing PV modules on as much surface as is available) differs in each of the 34 municipalities. Scenario A (wafer-based modules with a higher efficiency) is always better than Scenario B (thin-film modules), due to the fact that the PV yield depends linearly on the efficiency of the modules. While Scenario A suggests that many municipalities could achieve more than a 100% coverage of the electricity demand, which means an electricity surplus in the region, only two of them would achieve it when Scenario B is considered.

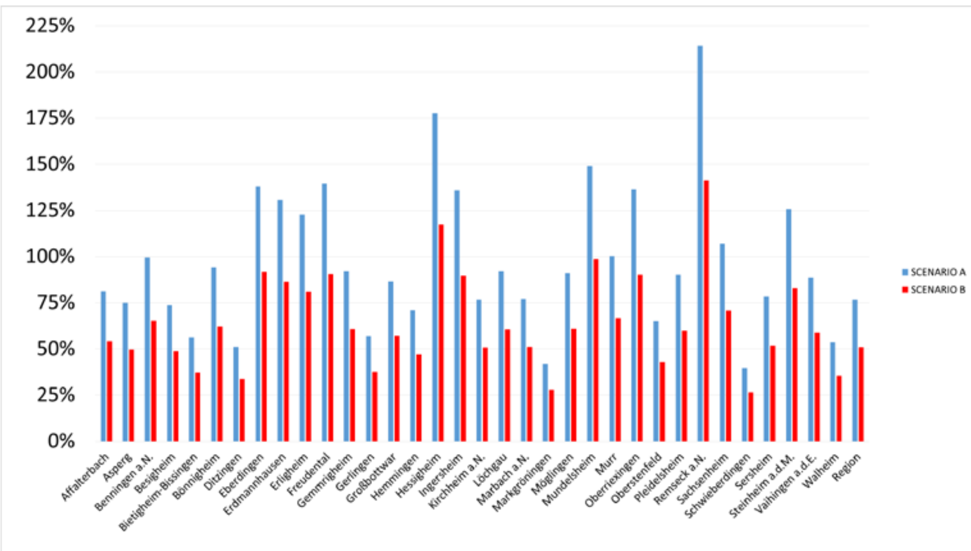

Figure 7: Percentage of the electricity demand covered in each municipality by PV for the technical potential strategy.

Figure 8 shows the results for the economic potential in each municipality, discarding every building with a roof area lower than 40 m^2 or an insolation lower than 1000 kWh/(m^2·year). As it is apparent, the results are much lower than those of the technical potential in every municipality. In this case only a few municipalities could achieve more than a 100% electricity demand coverage.

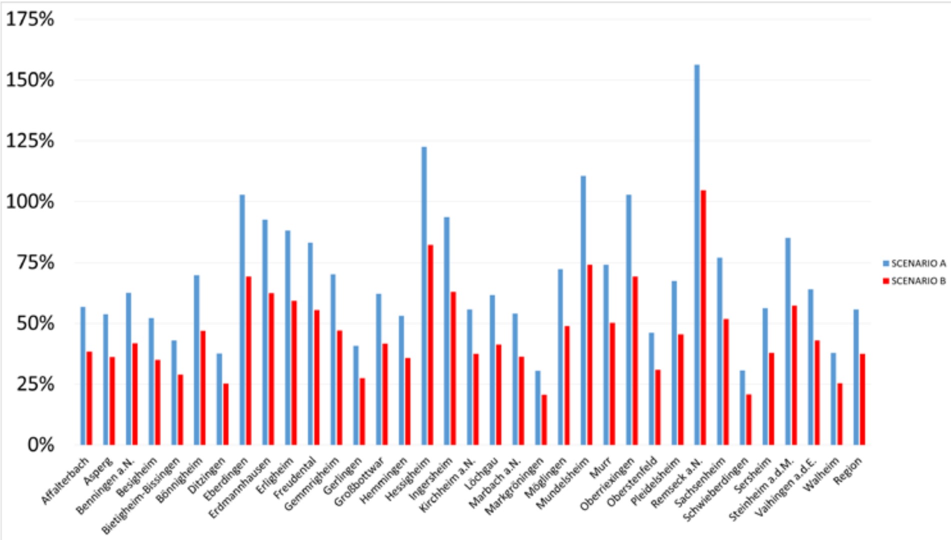

Figure 8: Percentage of the electricity demand covered in each municipality by PV for the economic potential strategy.

Regarding the aggregated values for the whole county, the results can be seen in Figure 9. The main characteristics of the region are summarized in Table 3.

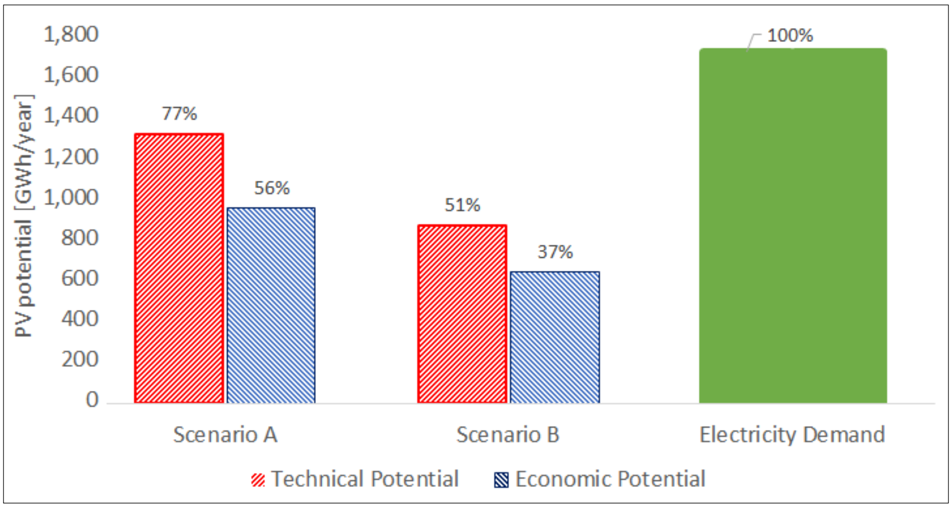

Figure 9: Percentage of the electricity demand covered by PV in the whole region for the two scenarios: technical and economic potential.

Variable	Result
Total electricity demand of the region	1717 [GWh/year]
Total population of the region	354551 inhabitants
Total number of buildings simulated in SimStadt	157724 buildings
Total roof area of the region	22.26 [km^2]
Total available roof area of the region	11.14 [km^2]
Average % of flat roofs:	16 %
Average % of tilted roofs:	84 %
Average surface to volume ratio of the buildings:	0.84 [m^{-1}]

Table 3: Summary of the characteristics of the Ludwigsburg County.

If PV modules could be installed on all the available surface (technical potential), using wafer-based silicon modules (scenario A) could cover 77 % of the electricity demand of the region.

On the other hand, if thin-film modules were used (scenario B with less efficiency), then only 51% could be achieved. It should be noted that the efficiency of the PV modules improves every year, so these percentages would increase accordingly.

Conversely, taking the economic potential into account would result in lower payback periods, but the met electricity demand would be lower than that of the technical potential. Wafer-based silicon modules would cover 56% of the electricity demand, while thin-film based modules would cover only 37 %. The summary of the obtained results for the region is shown in Table 4.

Scenario	Variable	Result	Description of the variable calculated by SimStadt
SCENARIO A	$E_{PV}^{Technical}$	1318 [GWh/year]	Technical PV potential
	$P_{PV}^{Technical}$	1642 [MW_p]	Total technical PV nominal power
	$E_{PV}^{Economic}$	957 [GWh/year]	Economic PV potential
	$P_{PV}^{Economic}$	1107 [MW_p]	Total economic PV nominal power
SCENARIO B	$E_{PV}^{Technical}$	872 [GWh/year]	Technical PV potential
	$P_{PV}^{Technical}$	1087 [MW_p]	Total technical PV nominal power
	$E_{PV}^{Economic}$	644 [GWh/year]	Economic PV potential
	$P_{PV}^{Economic}$	744 [MW_p]	Total economic PV nominal power

Table 4: Summary of the results obtained by SimStadt for the two different scenarios and strategies.

6.2. Emission calculations

Quantifying the potential CO_2 emission savings due to the implementation of PV modules is another important outcome that may be inferred from this study. This way, we are able to evaluate for each strategy and scenario considered the amount of CO_2 emissions avoided and the percentage of reduction compared to the initial situation, in which all the electricity is obtained from the grid.

Table 5 shows the value of the CO_2 emissions for the whole region not regarding any PV systems.

Variable	Result	Description
$CO_{2,tot}$	918814 [tCO_2/year]	Annual CO_2 emissions.
$CO_{2,coef}$	535 [gCO_2/kWh]	Coefficient of CO_2 emissions in Germany (Umweltbundesamt, 2016).

Table 5: CO_2 emissions of the region in the initial case.

To better understand the emission savings, a full Life-Cycle Assessment (LCA) would be necessary to evaluate the environmental impact of the PV modules. For simplicity, after reviewing related publications (Nugent and Sovacool, 2014; Peng et al., 2013) the present study will consider a CO_2 emission coefficient of 50 gCO_2/kWh for the PV electricity generation.

The CO_2 emissions avoided and the CO_2 emissions produced after PV implementation are calculated in the following way:

$$CO_{2,avoided} = E_{PV} \cdot (CO_{2,coef} - CO_{2,coef,PV})$$

$$CO_{2,produced} = E_{PV} \cdot CO_{2,coef,PV} + (E_{Demand} - E_{PV}) \cdot CO_{2,coef}$$

Table 6 presents the results for the technical and economic potential of the two considered scenarios.

SCENARIO	Strategy	CO_2 emissions avoided [tCO_2/year]	CO_2 emissions produced [tCO_2/year]	CO_2 savings achieved [%]
SCENARIO A	Technical potential	639141	279674	70%
	Economic potential	464262	454552	51%
SCENARIO B	Technical potential	422907	495907	46%
	Economic potential	312288	606527	34%

Table 6: CO_2 emissions of the region for each approach of the study.

The results show the huge potential contribution of rooftop PV to the reduction of the CO_2 emissions (and therefore other pollutants).

6.3. Economic feasibility

Another purpose of the present study was to develop an economic analysis of the implementation of PV modules in the region regarding the proposed strategies, so as to assess their feasibility.

For the calculations, it is assumed that 30% of the PV production of the region will be used for self-consumption (IEA-PVPS, 2016), while the remaining 70 % will benefit from the feed-in-tariffs devised by the government. In addition, it will be considered that maintenance of the systems would annually incur additional costs of 4% of the corresponding investment.

The total investment costs C_t [€] were estimated through the total nominal installed power P_{PV} [kW_p], and the annual savings A_s [€/year] (by avoiding the electricity costs) were identified and calculated in the following way:

$$C_t = P_{PV} \bullet C_{System}$$

$$A_s = E_{PV} \bullet \left(F_{Self} \bullet C_{elec} + \left(1 - F_{Self}\right) \bullet C_{ft}\right) - C_t \bullet F_m$$

The chosen factors which were applied for the calculations are shown in Table 7.

Variable	Result	Description
C_{elec}	0.22 [€/kWh]	Electricity price per kWh (Experience value).
C_{ft}	0.1231 [€/kWh]	Feed-in tariff for small PV facilities in Germany (Bundesnetzagentur, 2015).
C_{System}	1280 [€/kW_p]	Average price for the installation of 1 kW_p PV (ISE Fraunhofer Institute for Solar Energy, 2016).
F_{Self}	30 [%]	Percentage of the electricity used for self-consumption.
F_m	4 [%]	Annual percentage of maintenance costs.

Table 7: Listing of economic indicators and their parameters for the PV potential of the region.

After extracting the required variables from SimStadt and applying the chosen economic indicators, the results were obtained for each proposed strategy and scenario (see Table 8).

SCENARIO	Strategy	Energy yield [GWh/year]	Nominal power [MW_p]	Total Investment Costs [M€]	Total Annual Savings [M€/year]
		E_{PV}	P_{PV}	C_t	A_s
SCENARIO A	Technical potential	1318	1642	2101	116
	Economic potential	957	1107	1416	89
SCENARIO B	Technical potential	872	1087	1391	77
	Economic potential	644	744	953	60

Table 8: Economic results for each proposed strategy and scenario.

Several findings can be deduced from the presented results. As can be seen, the economic potential of both scenarios would translate into much lower necessary investment costs for the implementation of the PV modules compared to the technical potential strategies. Nevertheless, it would also mean less PV yield, annual electricity savings and emissions reduction.

The PV economic expectations could be enhanced through technological innovations allowed by economies of scale. This would make the projects more profitable, and attract new investors. The removal of administrative barriers by the governments themselves and incentives to persuade the population about the usefulness of PV systems on buildings should be emphasized in some countries, in order to allow for a widespread implementation of these promising solutions as far as sustainable development and energy conservation are concerned.

6.4. Uncertainty of the method

Acknowledging the uncertainty of PV potential estimation methods is a major point for further research, since it is not frequently present in many studies. Limited input data and the use of default values are important sources of uncertainty, as well as simplifications and hypotheses. The variations of solar radiation also have to be taken into account. Depending on the question, either long term average weather files or weather data for a specific year under consideration should be used.

In the case of PV potential estimations all the required information is geometry data, contained in the 3D model. The higher the Level of Detail, the more accurate the PV estimations. As an example, in order to evaluate the variations of using different LOD's the aggregated results of each municipality regarding the technical PV potential have been compared to what the results would have been if modeled in LOD1, which considers all roofs to be flat. The results are shown in Figure 10.

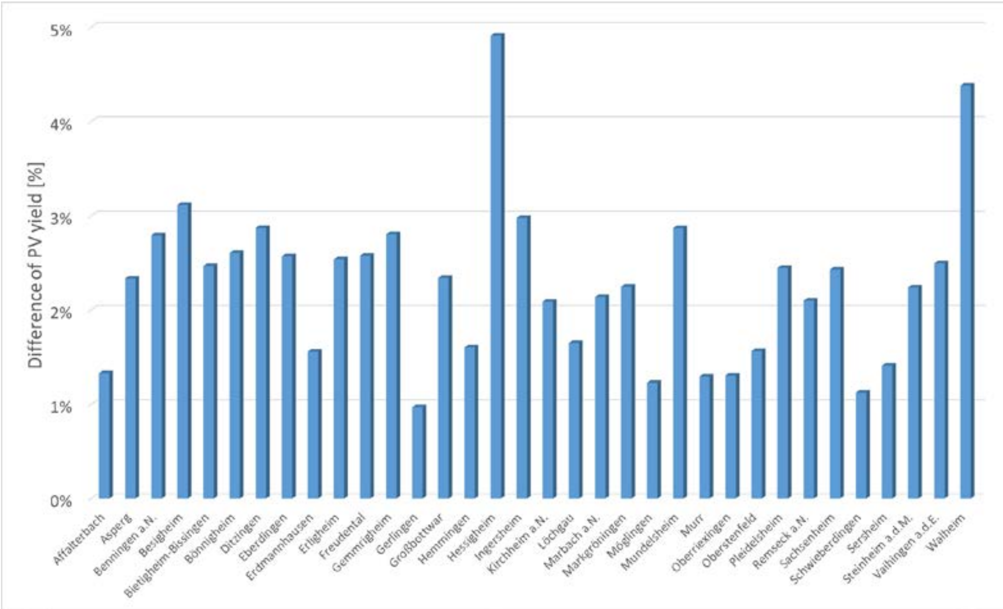

Figure 10: Percentage of difference between the PV potential yield considering LOD2 and LOD1 models.

As is apparent, in every case a LOD1 model would underestimate the PV potential of the region. The explanation lies in the fact that although considering only flat roofs with a south facing tilted PV generator would mean higher specific radiation, the module separation to avoid shading would reduce the useful roof area by a factor of 0.46, as well as other reduction coefficients which are more restrictive in flat roofs. The potential roof area is always underestimated in the LOD1 model. The installed module area in the region under the assumption of only flat roofs is between 6.67 % and 13.34 % lower than for the LOD2 roof structure with predominantly tilted roofs. In fact, the two municipalities in Figure 10 with a higher percentage of difference are the ones with a higher average tilt angle of their roofs. Nonetheless, the differences are rather small, so in case of having a LOD1 model the results can be expected to be accurate enough.

It should also be noted that using reduction coefficients in order to assess construction restrictions in roofs or the influence of trees and buildings is another important source of uncertainty. An increase in the level of detail of the 3D models which includes this information could replace in the future these reduction coefficients with more accurate values for each individual building.

With regards to the validation of the results, researchers have frequently little information about the accuracy of their estimates (Melius et al., 2013). In order to validate our results, the outcomes obtained by Mainzer et al. ,2014 (whose study considers the PV potential of all the regions in Germany) have been consulted. In the Ludwigsburg County area, they obtained a value of technical potential greater than 1000 MWh/km^2 and 1000-4000 kWp/km^2 for the region. The results of the technical potential in our study for Scenario A are 1443.5 MWh/km^2 and 1799.4 kWp/km^2, and for Scenario B 955.8 MWh/km^2 and 1191.0 kWp/km^2. Therefore, the results are quite consistent with the ones obtained by them. As stated in (Freitas et al., 2015), it is expected that as further and more sophisticated solar maps and further and more diverse installation case studies are published, an interactive dialogue between these two research areas will lead to model validation and improvement.

7. Conclusions

This paper proposes to use 3D urban data models based on the CityGML standard to analyze the photovoltaic potential on an urban and even regional scale. The simulation methodology is based on a building by building roof surface analysis and irradiance simulation and carefully revises reduction factors for the energy yield determination, applying them for each building separately. Realistic strategies and scenarios for PV implementation were developed in a case study region in Germany. Economic calculations have also been performed so as to analyze the feasibility of the required investments.

According to the results obtained, it is possible to achieve high rates of electricity demand covered by PV in many municipalities (even more than 100% for low density municipalities, which means an electricity surplus). Within the entire region with 34 municipalities investigated, PV systems could generate 77 % of the electricity consumption by using all available roof space, producing a total of 1318 GWh/year through the installation of 1642 MWp, thus reducing the CO_2 emissions noticeably. Conversely, 56% of the electricity demand could be produced if only roofs with enough insolation and a minimum surface area for an economically feasible PV installation are used. To realize the economically viable PV installations and reduce the electricity related CO_2 emissions by 51%, the estimated investment per capita is around 4000 Euros or a total of 1416 million Euros in the County. In conclusion, if properly designed these PV systems could significantly decrease primary energy consumption and emissions, reaffirming their usefulness and the important role they can play in the near future.

8. Future work

During the development of this research work, some future directions have been identified which could result in more precise PV potential calculations. First of all, due to the large amount of buildings and the required computational time of more sophisticated radiation processors, the Hay model was used in this study to analyze all the involved municipalities. Since the interaction between buildings was not taken into account, a shadowing reduction factor was considered, taken from the literature review. However, this reduces the accuracy of the procedure which makes use of precise geometry building models. In the future, the use of tiling strategies that are currently under development will reduce the required computational time, consequently making the calculations feasible for the SRA radiation model, which considers the influence between buildings and is already implemented within SimStadt. This improvement will also help to make the large scale more valuable.

Additionally, the present study has only considered roof surfaces, but it could be extended to facades. The importance of further research regarding the uncertainty of the PV potential estimations should also be highlighted. Last of all, the progress in the field of 3D modelling will ensure in the future that models with higher LODs are available, thus increasing the accuracy of the PV potential analyses.

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