EVALUATION OF SOLAR ENERGY INTEGRATION POTENTIAL IN A NEIGHBORHOOD

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ABSTRACT
Decision support tools for the integration of solar energy can help cities and communities accelerate the adoption of photovoltaic energy on unutilised buildings’ roof space. The objective of this paper is to provide a complete framework for the optimal integration of photovoltaics for urban neighbourhoods and apply it for the creation of a lighthouse solar neighbourhood project in a Swiss village. Initially, the solar potential of the buildings is determined, in terms of both incoming solar radiation and roof area availability, utilizing a Digital Elevation Model (DEM). However, apart from solely determining the potential, energy management techniques are subsequently employed to examine the temporal dimension of energy demand and generation. Using optimisation techniques, the optimal roof structures to be fitted with photovoltaics are determined, as well as the needs for electric storage capacity. Multiple criteria are used for the decision process and the interplay between cost optimal solutions and solutions that maximise the renewable energy used locally is investigated.

INTRODUCTION
In the quest to tackle climate change and promote renewable energy, buildings are expected to play an important role by adopting locally installed distributed generation technologies. Among different options, solar photovoltaics are expected to be prevalent due to the unutilised roof spaces, but also due to the flexibility of electricity that can be used for different needs (e.g. lighting, appliances, heating, etc.) but also exchanged between buildings and the electrical grid. Creation of solar cadastres in the form of a solar potential inventory and map, with information about the roof area availability and solar radiation for each building in a specific area is seen as a very informative tool to promote the installation of photovoltaics. Solar cadastres have already been adopted by several cities in the world (e.g. City of Vienna, 2010). These maps are usually the outcome of modelling activities, since the use of data from nearby meteorological stations together with interpolation algorithms are prone to errors due to the complicated geometry of the urban environment. Thus, modelling of solar potentials is seen as a favourable approach.

A solar cadastre containing information for roof areas and solar radiation for each building allows the identification of the most suitable buildings for solar installations. However, questions like how much of this potential should be utilised, how the generated electricity should be managed and whether storage should be integrated need to be considered as well. Thus, to move from the solar potential towards realisation, support tools to assist decision-making must be in place. An important success factor is also the consideration of the operation of the system, including the temporal element of energy generation and demand, in order to calculate how much energy can be used locally, how much should be exchanged with the grid (imported or exported) or stored for later use. Moreover, the design should incorporate multiple criteria to reflect different viewpoints of renewable energy. That could help communities determine which roofs out of the total potential should be selected, in order, for instance, to minimise the total cost of energy supply or maximise the amount of renewable electricity that is used locally.

Literature review
Different techniques are available in the literature to model the urban solar potential. Specifically for this topic, extensive review papers have been published (Jonsson et al., 2012; Freitas et al., 2015). There are two main techniques based on the way that buildings are represented (Jonsson et al., 2012). The first represents the buildings using vector data e.g. in a CAD environment, whereas the second employs Digital Elevation Models (DEM). A DEM is a raster grid in which each cell contains the elevation value of the location it represents; hence, they are also labelled as 2.5D. The advantages of the first approach is that surfaces are represented smoothly, while solar radiation on building facades can also be calculated. On the other hand, they are difficult to create for a large number of buildings and the incorporation of surrounding topography (e.g. mountains) is an onerous task. The use of a DEM allows the easy incorporation of topography, as such data are usually available from national topographical services due to their multiple applications in fields like hydrology or flight planning. Moreover, they are usually integrated with GIS environments allowing the easy manipulation of geospatial data. The main
disadvantage is that the representation is pixelated; hence, the resolution of the DEM should be carefully selected to allow for high accuracy, but without the excess computational burden.

Both approaches have been used to calculate solar potentials at different scales. Brito et al. (2012) and Redweik et al. (2013) used DEMs to calculate the photovoltaic potential for regions in Lisbon. Kodysh et al. (2013), performed similar calculations for Tennessee, USA, while a similar DEM-based approach was used to create the web tool PVGIS that contains data for the PV potential for the whole of Europe (Šúri et al., 2005). Using vector-based models, Jakubiec and Reinhart (2013) used the DAYSIM engine to calculate the photovoltaic generation potential in Cambridge, MA, USA. Finally, Compagnon (2004), with a focus wider than photovoltaics, calculated the solar and daylight potential for an urban area in Fribourg, Switzerland.

Apart from quantifying the solar radiation, an additional step is required: the quantification of the available roof area for solar installations. The models that were used for the solar calculations can also be used for the calculation of the total area. Additionally, statistical techniques have also been reported, e.g. by developing and using correlations between the available roof area and the population of an area (Wiginton et al., 2010). However, building roofs cannot be used in their entirety due to skylights, satellite dishes and other obstructions, which are mostly not included in the model creation process. The main approach that studies have been using to tackle this issue is the reduction of the total area to the usable area by using a reduction factor (e.g. in Bergamasco and Asinari (2011); Izquierdo et al. (2008)).

In the aforementioned studies, a common element is that the scope was limited to the solar potential. The management of the renewable energy flows, the need for storage, and the optimal structures that can be integrated with PV are not investigated. In this work, apart from determining the potential of a case study neighbourhood, the optimal integration of this potential with the existing energy system is investigated, considering temporal elements of energy generation and demand, using hourly time steps.

CASE STUDY

A neighbourhood in the village of Zernez, Switzerland, is selected for the application of the developed framework and the illustration of the results. The motivation lies in creating a solar-powered neighbourhood in the village that could function as a lighthouse project to promote renewable energy generation for the complete village, and for neighbouring communities. Zernez is located at an altitude of 1,474 m and the total building stock consists of 308 buildings, whereas the selected neighbourhood contains 45, mostly residential buildings.

MODELLING FRAMEWORK

Solar cadastre creation framework

In this section, all the steps required for the optimal integration of PV in the village’s neighbourhood are presented. The first step of the modelling framework and the objective of this section is to create a solar cadastre for each building in terms of both solar radiation and roof area availability. Out of the methodologies outlined in the previous section, the use of a DEM is selected due to the possibility to incorporate the surrounding topography, which for the specific case study selected is important.

Digital Elevation Model (DEM) creation

Initially, the DEM to be used for the analysis must be created. For Switzerland, a readily available model for the whole country by Swisstopo (Swisstopo, 2014) is selected, titled swissALTI3D, depicting only the ground morphology, without development, at a cell size of 2m by 2m. Since building information is not incorporated in the DEM, a vector model is created and turned into a raster map of the desired resolution (1m x 1m). A higher resolution is selected for better representation of the buildings’ roofs. Finally, after resampling the ground DEM to match the building raster’s resolution, the two raster grids are overlaid to obtain a single DEM that includes information for both the ground and the buildings.

Roof area availability

The initial calculation that can be performed with the combined DEM is the determination of the available roof area. For that reason, for each cell that corresponds to a building’s roof, the slope and the orientation are determined and non-suitable cells are excluded from the analysis. These are cells that have an orientation higher than 292.5° or lower than 67.5°, with 0°/360° being the north orientation. Additionally, cells with a slope higher than 70° are also eliminated. The area of each cell in the raster map that corresponds to a building’s roof is equal to the cell size i.e. 1 m². However, since in reality it corresponds to a 3D surface, the area is corrected by dividing the 2D area with the cosine of the slope.

Having identified the suitable cells for each roof, the total roof area \( A_{3D}^{tot} \) is quantified for each building by summing up the areas of the individual cells. However, only a subarea of the complete roof can be utilised for PV due to roof obstructions. For this study, it is assumed that 60% of the total roof can be utilised (IEA-PVPS, 2002), hence, the usable roof area \( A_{3D}^{tot,final} \) is reduced to 60% of \( A_{3D}^{tot} \) for each building.

Solar radiation calculation

Subsequently, using the combined raster map, the quantification of the incoming solar radiation to each building’s roof is performed. For this task, the Solar Analyst model, by Fu and Rich (1999), incorporated in ArcGIS, is used. The model utilises a DEM as a basis that incorporates the locations of interest as well as the
surrounding topography. The model can calculate the solar radiation for each cell of the DEM or for a subset of points. Since we are only interested in the radiation incident on the buildings’ roofs, we opted for the second option.

A brief description of the model is given here; more information can be obtained from the original publication by Fu & Rich (1999). Within the model, the DEM is initially used to calculate the slope and orientation of each cell of interest and to perform shading calculations. For each cell, an upward-looking viewshed is calculated, similar to a fisheye photograph, which incorporates the horizon angles for all directions. Additionally, a sunmap is created showing the position of the sun in the sky for the whole year, as well as a skymap dividing the sky into patches from which diffuse radiation can originate. By overlaying the viewshed with the sunmap, the hours of the year that direct radiation is available for each cell of the DEM are determined. Similarly, by overlaying the viewshed on the skymap, the sky sectors from which diffuse radiation can originate are defined.

In order to model the atmospheric conditions, the model requires values of atmospheric transmissivity and diffuse ratio. The first is defined as the ratio between the direct radiation reaching the earth’s surface and the extra-terrestrial radiation, while the latter is the ratio between diffuse and global radiation. Previous publications that have used the same model have used single values for the atmospheric parameters for the whole year. However, this cannot capture the variation of atmospheric conditions within the year. In this study, a brute-force calibration approach was initiated, instead. Monthly global solar radiation data was obtained for a location in Zernez using Meteonorm (Meteotest, 2015); subsequently, the monthly solar radiation for the same point in Zernez was calculated using the ArcGIS model for all combinations of transmissivity and diffuse ratio, with both values ranging from 0.1 to 1. The pair of values ranging from 0.1 to 1. The pair of values was selected and the model was executed for each month separately, with hourly time steps.

Finally, knowing the eligible roof cells, we can calculate an average hourly solar radiation value for each building, as shown in Eq. (1). This way the hourly solar radiation for the whole year and for each building separately is calculated, as shown below:

$$p_{sol}^{h} = \frac{\sum_{i=1}^{N} (A_{D}^{3D} \cdot p_{sol}^{i})}{A_{tot}^{3D}}$$

(1)

Note that in order to obtain the average solar radiation the total available area $A_{tot}^{3D}$ is used, as it cannot be known in advance which cells would belong to the usable roof area.

**Electricity demand profiles**

The next step that is required is the determination of the electricity demand of the buildings in the examined neighbourhood. Electricity usage for non-heating purposes is only considered in this work i.e. lighting, appliances and similar usage, as this is applicable to all buildings of the neighbourhood. The objective is to create hourly profiles for a year’s horizon to study interday and seasonal variations of demand. However, due to the lack of measurements from all the buildings, the Swiss norm SIA 2024 (SIA, 2006) was taken into account, which allows the creation of typical hourly profiles for a day’s lighting and electrical appliances usage, depending on the building type. Profiles are also differentiated for weekdays and weekends. Extrapolating these profiles for the whole year, assuming that every day is the same would be an option to achieve the desired objective; a non-realistic nonetheless. For that reason, a degree of variability is introduced for each building individually. Taking a daily profile, several blocks of hourly periods are created, for instance [00:00 – 06:00], [07:00 – 09:00], etc. Then within these periods the demand data are randomly resampled with replacement. This allows the sequence of actions within the day to remain the same (e.g. morning activities vs evening activities), however, they could be shifted within their respective blocks. Using the aforementioned technique, the total demand of the buildings in the neighbourhood is equal to 847,450 kWh.

**Energy hub model for optimal PV integration**

The energy management tool of choice in this paper is the energy hub; a versatile modelling concept that was introduced by the Power Systems Lab of ETH Zurich (Geidl & Andersson, 2007) and allows for modelling different scales of energy systems. It can be used for optimal dispatch problems, as well as for energy design problems taking into account the operational characteristics of the energy conversion and storage devices, such as the case in this paper. A schematic of the energy hub model considered in this paper to represent the examined energy system is shown in Fig. 1.

![Energy hub schematic](image)

*Figure 1. Energy hub representation of the examined energy system*

On the left side of the schematic, the inputs to the energy hub are depicted. These are grid electricity $P_{grid}$, and solar radiation flows $P_{sol}$. Additionally, to enable a more flexible operation of the energy system, a battery storage module is also considered, and the corresponding charging and discharging flows $Q_{ch}$ and $Q_{dis}$ are depicted. The buildings’ demand for electricity, $L_{elec}$, is illustrated on the right side of the energy hub schematic. Finally, electricity flows out of
the system are allowed too, for PV electricity exports back to the grid $P_{cap}$. It must be noted that the electric storage module does not represent a single physical entity, but it is an aggregation of the total battery capacity installed in all buildings with PV.

Multiple objectives are considered for this optimisation problem to allow for the consideration of different perspectives. Firstly, the minimisation of the total cost of energy supply is considered, which is defined as follows:

$$f_1 = \sum_{b=1}^{M} \left( P_{cap} (b) \cdot IC_{PV} + Stor_{cap} \cdot IC_{stor} \right) + \sum_{t=1}^{\text{8760}} \left( P_{grid} (t) \cdot C_{grid} + P_{PV} (t) \cdot C_{maint} - P_{exp} (t) \cdot \text{FIT} \right) \cdot PVAF$$

(2)

where $P_{cap} (b)$ is the installed capacity on building $b$, $Stor_{cap}$ is the storage capacity, $IC_{PV}$ and $IC_{stor}$ are the investment costs for the photovoltaics and the storage module, $C_{grid}$, $C_{maint}$ are the costs of 1 kWh of grid imported electricity and the maintenance cost of PV per kWh generated, respectively. Finally, $P_{PV}$ is the aggregate electricity generation from the installed panels. The cost data used in this study are shown in Table 1.

The amount of generated PV electricity $P_{PV}$ is defined as follows:

$$P_{PV} (t) = \sum_{b=1}^{M} P_{cap} (b) \cdot P_{sol}^{tot} (b, t) \cdot n_{pv}, \ \forall t$$

(3)

where $n_{pv}$ is the conversion efficiency of PV panels, selected as 15%.

### Table 1

<table>
<thead>
<tr>
<th>Economic data used in the cost objective function</th>
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<tr>
<td>PV investment cost – $IC_{PV}$</td>
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<tr>
<td>Storage investment cost – $IC_{stor}$</td>
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<tr>
<td>Grid electricity cost – $C_{grid}$</td>
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<tr>
<td>Feed-in tariff – FiT</td>
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<tr>
<td>PV maintenance cost – $C_{maint}$</td>
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<tr>
<td>Planning horizon – $T$</td>
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<td>Discount rate – $r$</td>
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The Present Value of Annuity Factor (PVAF) is used to calculate the present value of future cash flows. It is defined as follows, with $T$ being the number of periods considered and $r$ the discount rate.

$$PVAF = \frac{1 + r} {r (1 + r)^T} - 1$$

(4)

The second, competing objective considered is the maximisation of the renewable share. The renewable share is defined as the ratio between the PV electricity that is generated and used locally, and the total electricity demand. Thus, essentially, it is equal to the ratio of the total load that is not met by grid electricity.

$$f_2 = 1 - \frac{\sum_{t=1}^{8760} P_{grid} (t)} {\sum_{t=1}^{8760} P_{elec} (t)}$$

(5)

The multi-objective problem, as presented previously, is solved using the $\varepsilon$-constraint method (Haines et al., 1971). It can be expressed as follows:

$$\min f_1$$

s.t. $f_2 \geq \varepsilon, \varepsilon \in \{\varepsilon^1, \varepsilon^2, \ldots, \varepsilon^u\}$

(6)

The method consists of breaking the multi-objective problem into a series of single objective problems. This is achieved by solving the single-objective $f_1$ problem, while imposing a constraint to the second objective for a lower limit equal to $\varepsilon$. The problem is solved in an iterative manner for different, equally distributed values of $\varepsilon$, from $\varepsilon^i$ which is the value for $f_2$ when $f_1$ is minimized in a single-objective manner to $\varepsilon^j$ which is the value for $f_2$ obtained in the single objective $max f_2$ problem.

The first constraint of the optimization problem is the energy balance of the system.

$$L_{elec} (t) = P_{grid} (t) + \theta \left[ P_{sol}^{tot} (1, t) + Q_{dis} (t) - Q_{ch} (t) - P_{exp} (t), \ \forall t \right]$$

$$\theta = [n_{pv} \cdot PV_{cap} (1) \ldots n_{pv} \cdot PV_{cap} (M)]$$

(7)

$\theta$ is the coupling matrix of the system that contains the conversion efficiency of the panels and the variable for the installed PV capacity for each building.

To prevent the installation of PV capacity higher than the potential calculated for each building, an additional constraint is required:

$$PV_{cap} (b) \leq A_{tot, final}^{3D} (b), \ \forall b$$

(9)

For the operation of the storage module, the following constraints are introduced:

$$E (t + 1) = n_{self, dis} \cdot E (t) + n_{ch} \cdot Q_{ch} (t) - (1/n_{dis}) \cdot Q_{dis} (t), \ \forall t$$

(10)

$$E (t) \leq Stor_{cap}, \ \forall t$$

(11)

$$Q_{ch} (t) \leq Q_{max}^{ch} (t), \ \forall t$$

(12)

$$Q_{dis} (t) \leq Q_{max}^{dis} (t), \ \forall t$$

(13)

Equation (10) refers to the energy balance of the storage module for each time step. The term $E$ is the total stored energy, $n_{self,dis}$ refers to self-discharge losses of the battery, $n_{ch}$ and $n_{dis}$ are the charging and discharging efficiencies. Eq. (11) imposes an upper limit to the stored energy that is equal to the storage’s capacity. Finally, Eq. (12-13) limit the maximum charging and discharging rates to $Q_{max}^{ch}$ and $Q_{max}^{dis}$, which are selected to be equal to 40% of the storage’s capacity. In this work, a simple model has been adapted to describe the battery. An overview of battery models for various studies and applications is given by Mousavi & Nikdel (2014).

Overall, from the outlined multi-objective energy hub model, the variables $PV_{cap}$ and $Stor_{cap}$ pertain to design
elements of the energy system, while the variables \( P_{\text{grid}}, P_{\text{exp}}, Q_{\text{ch}}, Q_{\text{dis}} \) refer to its operational aspects.

RESULTS AND DISCUSSION

Solar potential

In this section, the results regarding the solar cadastre are presented. The spatial distribution of both the area and the annual solar radiation for the considered buildings is shown in Fig. 2. It is evident that the buildings with the highest area availability are not necessarily also the buildings with the highest solar radiation. Therefore, selecting buildings using just the cadastre results could be misleading; thus the need for the decision support tools is further amplified. The raster map of annual radiation as the output of the solar radiation tool is also included in Fig. 2c, showing the distribution of solar radiation on the roofs of the buildings considered. Regarding the available roof area, the total among all buildings is equal to 3,310 m\(^2\). The average annual solar radiation that is incident on the buildings’ roofs is equal to 1,360 kWh/m\(^2\).

Optimal integration of PV

As was also mentioned earlier, the following step after the solar potential determination is the use of the energy hub model to determine the optimal integration of photovoltaics.

Starting from the single objective problems, the results are presented in Table 2. For the cost optimal case, the total cost of 2.775 million CHF corresponds to the total cost of the system with 1,030 m\(^2\) of PV installed, corresponding to 31% of the total roof area. The analogous total cost in the case when no PV is installed is equal to 2.87 million CHF. The resulting renewable share for this configuration is equal to 25%. However, due to cost considerations, no storage capacity is added in the system. The building roofs selected and the installed PV capacity in m\(^2\) is shown in Fig. 3. On the other hand, as expected, when the renewable share maximisation is the objective, all the available roof space is occupied, leading to a renewable share of 67%. Additionally, to reduce the grid imports and use PV generated electricity locally, 1,300 kWh of storage capacity is added. Operational characteristics of the system, concerning PV energy flows, grid imports and exports are also reported in Table 2.

\[
\begin{array}{l|l|l}
\text{Table 2} & \text{Energy hub – Single objective results} \\
\hline
\text{min } f_1 & \text{max } f_2 \\
\hline
\text{Total cost (kCHF)} & 2,775 & 6,180 \\
\text{Renewable share (%)} & 25 & 67 \\
\text{PV capacity (m}^2) & 1,030 & 3,310 \\
\text{Storage capacity} & - & 1300 \\
\text{Grid imports (kWh)} & 634,850 & 283,050 \\
\text{PV energy generated (kWh)} & 225,630 & 688,000 \\
\text{Grid exports (kWh)} & 13,030 & 53,900 \\
\end{array}
\]
However, apart from the two conflicting objectives, the Pareto front of optimal solutions, illustrating the trade-off between the two “edge” points is shown in Fig. 4. The installed PV capacity for each point is presented using the colourbar. Additionally, the total cost breakdown for each system configuration and the installed battery capacity are also presented. It is seen that in order to move from the cost optimal system towards configurations with higher renewable share, initially, PV capacity is added, and after the majority of the roofs are covered, at around 40% renewable share, storage capacity is included. Examining the cost breakdown, as expected, the photovoltaic investment cost is increased until the maximum capacity is reached and then remains constant. A similar profile is followed by the PV maintenance cost. Grid electricity cost is reduced, due to reduced imports in order to accommodate increased local utilisation of PV electricity. The storage cost is increased in accordance to the installed capacity. An interesting profile is noted for the exported electricity benefit. Initially, as PV capacity is increased and hence, the PV electricity generation as well, the exports are also increased due to the lack of storage capacity to store the excess electricity. However, after the battery capacity becomes non-zero and is gradually increased, PV electricity exports are reduced in order to allow local use of the electricity and hence an increased renewable share. Thus, the benefit from exported electricity is also reduced.

For each point of the Pareto front of Fig. 4, the corresponding PV generation and grid imports/exports are presented in Fig. 5. Similarly, to the cost structures, grid imports are decreased with increasing renewable share, while PV generation is steadily increasing until the maximum capacity point. Finally, grid exports follow the same profile as the grid export costs in Fig. 4.

Finally, Fig. 6 illustrates the potential of the energy hub to prescribe the hourly operation of the system regarding the energy flows in and out of the system. Two different system configurations are selected corresponding to a “low” and a “high” renewable energy system.
share, equal to 30% and 60%, respectively. In the former case, no storage capacity is included and as it can be seen from Fig 6, during the night hours, demand is met completely by grid electricity, while during the day PV electricity is enough to cover the needs of the buildings with any excess exported back to the grid. In the second case, a similar pattern is observed for the night hours; however, during the day, initially any excess electricity is exported, while later it is stored, to be used during the first evening hours that the PV energy is not enough to cover the demand.

Figure 6. Hourly operation of the energy system for a sample day and two different renewable shares

CONCLUSIONS
Integration of solar photovoltaic energy with the built environment could significantly contribute towards the increased capacity of renewable energy. For that reason, a complete workflow is presented that deals with the determination of the potential for solar energy in urban configurations. However, it also takes the next step required, which is to study the operation of the system considering the temporally varying demands and generation profiles. Thus, using the energy hub concept, the optimisation of energy flows within the system is performed and the optimal structures to be fitted with PV are determined considering economic and environmental criteria. The workflow has been applied in order to design a solar powered neighbourhood for a Swiss village in order to act as a lighthouse project to promote renewable energy. For the specific case study, with today’s cost structures, 25% of the electricity demand can be covered with PV, yielding also a cost benefit compared to the case when no PV is installed. Moreover, it is seen that increased PV capacity can only increase the renewable share to a certain extent, before storage capacity is necessary to increase the local utilisation of renewable energy. However, due to the high cost of batteries, the total cost in these cases is significantly increased; hence, another conclusion could be the need for the development of more affordable electric storage technologies.

In terms of future work, incorporation of the heating sector of the buildings and the interplay between solar photovoltaic and solar thermal technologies will be investigated. Additionally, the use of photovoltaics in combination with heat pump systems to cover the heating demand of the buildings, especially during hours of excess electricity availability, will be studied in future research efforts.

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REFERENCES


