Optimization of solar energy potential for buildings in urban areas – a Norwegian case study

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Abstract

The paper presents a case study of an office building with a façade integrated PV system in Norway. Due to the urban surrounding the PV system is subject to significant overshadowing. The aim is to optimize the solar energy potential of the building in order to propose improved alternatives to the current system applying a multi-level simulation approach. The first level is performed to calculate the maximum solar potential on the building envelope in an unobstructed scenario. The second level examines the shading effect on the building in its urban context. The analyses allow localizing the areas of the building with the highest solar potential. In the third level, the energy output of different solar technologies (solar thermal and PV) is evaluated. The results demonstrate that the solar potential analysis in the early stage is important for choosing the most performing system.

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1. Introduction

The future requirements for buildings in the EU will include both a high level of energy efficiency and a large degree of local renewable energy generation, solar energy systems on buildings can be expected to become more common [1]. In Norway the number of solar energy installations is increasing, although the market is still small

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compared to neighbouring countries. Most of the solar energy installations are connected to buildings, either fully integrated into the building or added to it. Historically, the largest part of the installations in the country have been small systems (below 1 kW) installed on vacation homes [2]. Due to increased attention to energy efficiency in buildings, and increasingly strict energy regulations, more and more solar energy installations are now being added to buildings. A number of larger-scale solar energy projects were realized in Norway in the last couple of years. Large PV systems include Oseana Culture Center, Campus Evenstad, and Powerhouse Kjørbo. Large solar thermal installations include the 13 000 m² system that was installed in 2013 by Akershus energi, and is now delivering energy to the district heating grid. The largest fraction of the energy demand for an average Norwegian residential building is heating. Active and passive utilization of solar energy is therefore important. Solar heated passive houses have been built as far North as Tromsø, at latitude 69° N. However, for office buildings the heating fraction is lower, and there may even be a cooling demand in summer. The available solar radiation in Norway is not much lower than in Central Europe. The specific challenges are instead related to the distribution of the solar radiation over the year, since most irradiation is available during the summer months and only a limited amount during the winter. The sun path also changes significantly during the course of one year. The sun height at noon in Oslo in the summer is around 55°, while in the wintertime it is below 10°. The low sun angle means that façade installations can be a good option, especially for energy used for heating. It also means that shading from surrounding buildings can be a problem. Modern cities are complex urban environments, characterized by high urban densification due to the progressive increase of population that live and work in the cities. In this scenario the complex and dynamic overshadowing effect on building surfaces has become a relevant issue to address. In order to guarantee solar access and prevent the reduction of solar availability of buildings it is necessary to conduct preliminary analyses [3].

2. Background

The aim of the work is twofold: to study the optimal solution for active use of solar energy in a case study building, and to gain experience with the presented method of analysis for solar energy utilization in urban environments. The paper is intended to show how the solar potential analyses in the early design stages of a building project can be used to design high-performing solar energy systems. The case study building (x in Fig. 1) is a seven-floor office building (2012) located in Trondheim (latitude 63° N). The surrounding area is dominated by large non-residential buildings, such as a sports arena (y) and a high-rise hotel (z). A year later, seven-floor apartment blocks (v) were built to the South and are now shading the case study building during a significant part of the year.

The total heated floor area is 11 000 m² of which 7 300 m² satisfies the Norwegian energy class A (maximum 84 kWh/m² per year) [4]. The area of the South façade is 1 470 m² and the area of the flat roof is around 1 000 m². The building is connected to the district heating grid, which supplies energy for heating, cooling and hot water. Once the HVAC system has been fine-tuned, the energy demand is estimated to be around 600 000 kWh per year, of which 65 % is covered by electricity and 35 % by district heating. A 200 m² photovoltaic (PV) system is installed on the mid parts of the South and West façades (dark blue in Fig. 1 (right)). The energy output during the first year of operation was 14 400 kWh. It means the solar cell system covers 3 % of the electricity demand, or around 2 % of the total energy demand of the building. The system is described in section 4 and [5].
3. Solar mapping

3.1. Method

The solar energy analysis of the building was conducted in three levels: 1) solar potential analysis of the building envelope, 2) solar potential analysis of the building in its urban context and 3) analysis of solar energy systems. In the first level of the analysis, the building was considered in an unobstructed scenario, i.e. without any urban environment. The aim is to estimate the maximum solar potential of the building envelope. In the second level analysis, the building was analyzed in its existing urban context, i.e. with the surrounding buildings and topography. A 3D model was constructed using information from the Trondheim Municipality public map [6].

The comparison between the two analyses reveals the impact of the complex surrounding in terms of a reduction in solar radiation on the building envelope. The solar potential analysis makes it possible to localize the areas of the building with the highest levels of irradiation when the surrounding urban environment is taken into consideration. Both sets of analyses were performed using the dynamic simulation tool DiVA for Rhino [7], a Radiance-based program validated for complex daylight calculations and solar energy distribution over complex 3D surfaces. Different solar radiation components are calculated by adjusting the number of ambient bounces (ab), or indirect reflections from the surroundings (ground and buildings) [8]. Setting ab=0 gives a value of the direct radiation, while the number of bounces sets equal to 3 allow calculating the mutual solar contributions and reflections.

3.2. Results

The results of the solar potential analysis of the building in the unobstructed scenario and in the urban context are shown in Fig. 2 (a) and (b), respectively. When shading from the surrounding urban environment is taken into account, the total amount of radiation incident on the entire building envelope is reduced by 12%. The result for the south façade, which is the one most affected by the shading, are summarized in Table 1. The reduction in global radiation is not reduced to the same degree as the direct radiation (33.5 % compared to 28.4%), since the global radiation also includes reflections from the surrounding surfaces.

![Fig. 2. The solar radiation on the building alone (a), and with the influence of the urban environment (b), on the south façade in the unobstructed scenario (c) and the visualization of the current PV area (in dashed white line), area A (in dashed blue line) and area B (in dashed green line) (d).](image-url)
Table 1. Solar analysis of the South façade.

| Area               | Radiation analysis | Unobstructed scenario | In urban context | Reduction due to shading |
|--------------------|--------------------|-----------------------|------------------|--------------------------|
| South façade, 665.6 m² | Direct (ab=0)      | 525                   | 349              | - 33.5 %                |
|                    | Global (ab=3)       | 904                   | 647              | - 28.4 %                |

The amount of reflections depends on the specific material properties and structure of any urban environment. The two areas (A and B) on the building envelope were located using the results from the solar potential analysis. The selection of areas was based on two criteria: high level of solar radiation and low influence of shading. Area A, like the present PV system, located on the southern façade, but in the top area. As Fig. 2 shows, the available irradiation on this part of the façade is not so much influenced by shading. Area B is the top flat area on the roof.

4. Solar energy analysis

4.1. Method

The third level in the analysis is to investigate the output from different solar technologies. A PV system and a solar thermal system were simulated for each alternative system locations, and their energy outputs were compared. The simulation tool PVsyst [9] was used to simulate the PV systems and Polysun [10] was used in the analysis of the solar thermal systems. The urban environment was represented by a 3D shading model in PVsyst, and a compound horizon line in Polysun. To enable easy comparison of the energy output, and to show realistic alternatives to the present system, the four alternatives were designed to cover the same area as the real PV system (200 m²). The systems on area A are installed vertically while the systems of area B are installed with a tilt angle of 37° a row-to-row spacing of 5 m to avoid self-shading, which was found to be optimal with regards to achieving the highest energy output per installed module. The required row-to-row distance could have been reduced by lowering the tilt angle, thereby increasing the number of modules that could be installed. However, since the module area was constant and set to 200 m², this was not studied here.

A model of the existing PV system was also constructed and serves here as the base case to which the other systems are compared. The PV system consists of 121 modules, arranged in nine strings, with a total rated power of 27.2 kWp (kilowatt peak). The simulated annual yield of the base case system was 12 280 kWh. This is 15 % lower than the actual yield (14 400 kWh) that was measured during the first year of operation of the real system. Data on the modules and inverters from the real system are used in the simulation. The deviation between the simulation results and the actual production is influence by a number of factors, including shading from the high-rise hotel (which was not completed during the first year of electricity production but was included in the model). In addition, statistical meteorological data and not the actual irradiation, is used in this simulation. The use of measured data will be included in future studies.

The two alternative PV systems were kept as similar as possible to the base case, except that they are instead located in area A and B. The same types of modules were used, but the inverters from base case were updated to a newer edition from the same producer, so that maximum power point tracking could be performed on string level.

The two solar thermal systems include of 200 m² of flat plate collectors, connected to the hot water supply circuit. The collectors are connected to a 16 000 l buffer storage via an external heat exchanger. The potable water is heated outside of the tank via another heat exchanger. The building is connected to the district heating grid. There are several examples from Denmark and Sweden showing how solar collector systems can be connected to the district heating network in different ways [11].

4.2. Results

The results of the PV and solar thermal simulations are shown in Table 2 and a comparison of the monthly yield profiles of systems A and B is shown in Fig. 3. The base case is included for comparison. In all the cases, the solar
energy systems contribute with a quite small fraction of the building energy demand. The solar thermal systems have a significantly higher output than the PV systems, and the roof mounted solar thermal system contributed with the highest fraction of the building energy demand (9.1 %). The roof mounted systems (B) have higher energy outputs during the summer months while the façade-mounted systems (A) instead have peaks in spring and autumn.

Table 2. The results of the solar energy systems simulations.

| System                  | Annual yield (kWh) | Increase from base case (%) | Percentage of building energy demand (%) |
|-------------------------|--------------------|-----------------------------|------------------------------------------|
|                         |                    |                             | Electricity     | Thermal     | Total     |
| Base case (current system) | 12 280             | -                           | 3.1            | -           | 2.0       |
| PV system A             | 18 340             | 49                          | 4.7            | -           | 3.1       |
| PV system B             | 24 340             | 98                          | 6.2            | -           | 4.1       |
| Solar thermal system A  | 43 580             | 255                         | -              | 20.8        | 7.3       |
| Solar thermal system B  | 54 390             | 343                         | -              | 25.9        | 9.1       |

Fig. 3. The monthly energy output from the solar energy systems (PV and solar thermal) on façade area A and roof area B, and the base case.

5. Discussion

The results from the solar energy analysis show a difference in both the amount of energy and output profiles of façade and roof mounted systems. The energy yield from the roof mounted systems are higher, but peaks in the summer, which may not be beneficial for a system that is used for heating. The façade mounted systems have peaks in spring and autumn, when the need for heating is larger. For both the A and B systems, the solar thermal output is significantly larger than the electricity output, and covers a higher fraction of the building’s energy demand. However, it should be noted that the energy output from a solar thermal system cannot be directly compared to that of a PV system even though they are both measured in kWh. Energy from solar thermal systems is generally connected to a short term thermal storage, such as a water tank. When the storage tank is heated to its set value, additional thermal energy is not useful to the system. This is not the case for the electricity, which can be exchanged with the grid at all times and used flexibly. There is a possibility of connecting solar thermal collectors to the primary circuit in the district heating grid, in a similar way to electricity grid connection, as have been done, for example, in some cases in Sweden [11].

These output values for the solar thermal systems are quite low, between 220 and 280 kWh per m² collector, but in line with the findings of most of the solar collector systems connected to district heating in Sweden [11]. A better designed system on the roof should have an output of at least 300 kWh/m² collector area, while the output from the façade system is expected to be lower. The influence on the results presented here would be to make them even more pronounced, since the difference between electricity and solar thermal output would be even larger.

The shading analysis in Polysun is based on a 2D model of the horizon. It is not as advanced as in PV syst, where a 3D scene can be constructed, and the influence of shading on the solar thermal system is therefore not as reliable
as for the PV system. On the other hand, the influence of shading is more complex for PV modules than for solar thermal modules, where the reduction in output is more or less proportional to the shaded area. This is not the case for PV modules, where the energy reduction can be significant even for small shadings. For a PV system that is at times partially shaded, the energy yield can be increased by using module level converters, instead of string level conversion. The shaded modules would then not influence the output of the unshaded modules. Calculation of the base case show that using module level conversion could have increased the output by 9.3 % [5].

In this work, the simulations are made separately; the solar potential analysis was useful to find the most suitable areas. In the future works the authors’ intention is to directly link the output from the first level of the analysis with the input of the second and third levels. The story of the case study building, where subsequently constructed buildings are shading an already installed PV system, raises questions of the right to solar radiation. With an increasing number of solar energy installations in urban areas, regulations on solar rights and solar access will become more important.

6. Conclusions

An office building in Trondheim with a 200 m² PV system has been studied. A solar potential analysis of the building by itself and in its urban context has been presented. It was found that the irradiation on the PV system is reduced by up to 28 % due to shading from the urban environment.

Two alternative areas with higher levels of radiation were proposed based on the solar potential analysis. A PV system and a solar thermal system were simulated for each of the areas. The results from the simulations show that a solar thermal system installed on the roof would have given the largest contribution to the energy demand of the building.

As solar energy installations in urban areas will become more common, solar potential analysis can be used to localize the most suited areas on a building in its urban context, and solar energy simulations can evaluate the benefits of different solar technologies.

This study has demonstrated how a multi-level solar analysis can be used in the early design stages of a project in order to support technical decisions and mitigate the reduction of solar potential due to the urban shading effect.

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