CHALLENGES FOR BUILDING INTEGRATED PV IN HIGH-RISE URBAN ENVIRONMENTS - THE EXAMPLE OF PV ON UTRECHT CENTRAL STATION

E.A. Alsema[1], J. M.Goud[1], J.W. Kuil[2], M.K. Unger[3]
[1]W/E Consultants Sustainable Building, Utrecht, The Netherlands; Email: alsema@w-e.nl
[2]AT Osborne, Utrecht, The Netherlands;
[3]ProRail B.V., Utrecht, The Netherlands

ABSTRACT:

A number of challenges and design issues for building-integrated PV in urban areas is investigated in general and for a specific case study: a large railway station in Utrecht, The Netherlands. Because of the surrounding high-rise buildings that are already present around the station or that may be erected in the near future, shading loss could become an important limiting factor for the installable PV potential. Detailed shading loss analyses were performed for the area of the platform canopies and for the terminal roof. Yield reductions of more that 20% were observed for some sections of the roof area and these section were further excluded from the potential estimate. Based on these analyses a total installable PV potential of 647 kWp was found. In the end it has been proposed that the platform canopies will be equipped with 149 kWp of semitransparent PV panels within the next six years.

Keywords: Building Integrated PV, Energy Performance, Shading losses

1 INTRODUCTION

A large potential for installation of PV system will have to be found in the build environment, especially when we consider the more densely populated countries in Western Europe. Studies have shown that a very large potential does indeed exist if we consider all kinds of roof area[1]. Installation of PV on buildings has the advantages that: no coverage of land area is necessary, that energy can be generated close to the demand centres, thus lowering the burden on distribution networks, and that cost savings may be possible if roof-integrated PV arrays partially replace conventional roofing materials. Also the savings on BOS materials (balance of system materials, all system components except PV panels) can have a beneficial effect on the energy pay-back time and CO_2 footprint of the PV systems [2].

However the design of building integrated PV poses several extra challenges, especially if we consider urban environments with high-rise buildings. In this case special consideration will have to be given to potential shading of the PV array and the resulting system losses which may be quite significant. Moreover, the deployment of PV on buildings with a special function, like a railway station, can pose additional restrictions on the overall design of the BIPV system.

In this paper we will discuss a number of challenges that PV designers and architects can encounter when designing a building that should have integrated PV, based on a case study for a large railway station.

First we will consider design challenges in more general terms and the specific lessons when considering BIPV for a large railway station (section 2) before we turn to the issue of shading losses (section 3) and the estimation of installable PV capacity for the considered railway station buildings (Section 4).

2 DESIGN CONSIDERATIONS

2.1 General

A first set of design considerations stems from the programmatic requirements for the new building itself, for example:

- roof carrying capacity, this may restrict installation of conventional PV panels;
- light entrance into building in case (semi)transparent PV panels are used;
- safety considerations; impact resistance of overhead panels, electrical safety.

Secondly the design will need to take into account the technical aspects of PV system and its performance. Typical issues in this context are:

- performance losses from shading by higher parts of the considered building or by surrounding buildings;
- effects from varying tilt and orientation angles of specific array sections on the total system performance;
- lay-out of module strings and placement of placing of inverters (relation to points above)
- performance losses from dust collection on PV panels and necessity to clean panels;

Other technical issues relate to installation and maintenance of the PV panels:

- accessibility of roof areas for PV panel installation work;
- accessibility of roof areas, inverters and electrical connection boxes for maintenance and repairs;
- feed-in point where PV power is connected to existing electrical network;

And of course the aesthetic considerations for good building integration are not to be neglected:

- visibility of panels and other components from various viewpoints (also from surrounding buildings);
- overall aesthetic quality of PV array area (colours, reflection of sunlight, visibility of frames or supports, reflected or transmitted light, contrast between PV- and non-PV surfaces).

Finally economic considerations involve among others:

- structure of energy tariffs and feed-in subsidies;
- ratio of generated energy used in-house and supplied to external grid;

* *Presented at the 24th European Photovoltaic Solar Energy Conference, Hamburg, 20-25 September 2009*

- capability of PV system to reduce capability of PV system demands;

The evaluation of all these issues will of course be different for each particular building and each location. In an urban area issues like shading losses but also aesthetic quality will need more attention than for buildings in an industrial or commercial zone. Especially in urban areas the above issues will have to be evaluated carefully in a feasibility or design study.

In the remainder of this paper we discuss one specific case study, namely the integration of PV on a new building for a large railway station in Utrecht, The Netherlands. We will focus our discussion on the issue of shading losses which was expected to be a critical factor for the feasibility of PV integration in this building.

2.2. Case of Utrecht railway station

The railway station in Utrecht, The Netherlands is located at a site with many high-rise buildings, both existing buildings and buildings in the planning phase. This station which now receives yearly 55 million travellers will be largely reconstructed in the next 6 years to accommodate an expected growth to 100 million travellers.

ProRail, the owner of the station, is working to improve its building stock towards a higher degree of sustainability and to invest in renewable energy production around its buildings and railway infrastructure. Therefore ProRail wanted to investigate the feasibility of PV panels on the roofs of the new station building. Two roof areas were considered:

- the platform canopies,
- the terminal roof.

In spring 2008 W/E Consultants Sustainable Building was commissioned by ProRail to assess the PV installation potential for the new station, along with the required investments, expected economic benefits and technical barriers for PV integration.

Already in the first stage of the study it became clear that for the terminal roof the carrying capacity of the roof construction would pose a limitation on the allowable weight of the PV panels. The use of conventional glass-laminated PV panels with a typical weight of 12-15 kg/m^2 is therefore impossible. In effect only installation of light-weight flexible PV-laminates (typical weight < $4kg/m^2$) would be possible on the terminal roof.

Secondly, from an aesthetical point of view the architect would only allow laminates which stayed within the 60 cm width of the welted metal roofing sheets which form the roof cover.

Finally, the curved form of the roof implies that several sections of the roof will have a slightly different tilt angle with respect to the horizontal plane. Shading from surrounding buildings further increases irradiation differences between roof sections. For this reason a careful evaluation of the expected energy yield per roof section was necessary for the terminal.

For the platform canopies other considerations were relevant. In the first place these canopies had to be partly transparent in order to ensure sufficient light admission to the rail platform below. Also the canopies were already designed to employ cold-curved glass panels. From another project there was already experience with inclusion of solar cells within these cold-curved glass panels. The spacing between cells should be adapted in such a way that the desired transparency is obtained. The production cost of such panels will of course depend on the cell coverage factor, as shown in figure 1 below.

Safety requirements in relation to the high-tension overhead wires above the rail track prohibited access to the outer sides of the canopy for installation and maintenance work, therefore only the central sections of the canopies could be utilized. Deposition of copper dust from the overhead wires (caused by wear) may necessitate regular cleaning of panels in the platform area.

Extensive shading loss analyses were performed for both the platform canopies and the terminal roof. We will discuss the approach and results for the canopies in the next section.

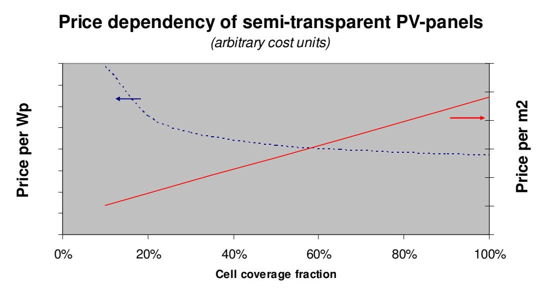

Figure 1: Price dependency on cell coverage fraction for semitransparent modules (crystalline silicon).

Figure 2: Artist impression of new train station. PV may be installed on the terminal roof and platform canopies.

3 SHADING CALCULATIONS

3.1 Introduction

PV applications in urban environments will always have to deal with effects from surrounding buildings, next to the design requirements for the building itself.

In the case of Utrecht central Station this issue was highly relevant because of the distinguished architecture and changing high-rise environment.

Based on two building scenarios the expected performance of building integrated PV elements has been determined for different sections of the roof area. These performance calculations have been performed with a simulation model which considers hourly solar positions and resulting shading losses and irradiation levels. The aim of the calculations was to identify those areas on the station roof where no excessive shading losses occur. Shading loss here is the reduction of the yearly yield of a horizontally positioned PV system due to shading. As an maximally acceptable shading loss we more or less arbitrarily selected a value of 20%.

In this section the modelling approach, calculations and results of shading calculations for the PV system on platform canopies is described. Next, the results of shading calculations for the terminal roof are presented shortly.

3.2 Characteristics of platform canopies

The main design characteristics of the new platform canopies (See Figure 3), with respect to application of PV are:

- slightly curved glass central section of roofs;
- due to safety reasons side sections of roof are not accessible for maintenance or cleaning purposes;
- transparency requirements (min. 35% transparency of glass);
- nearly horizontal surface;

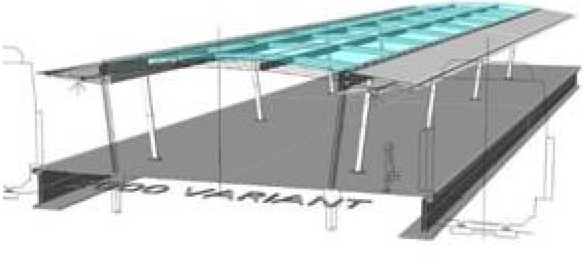

Figure 3: Artist impression of new platform canopy with central section made of curved glass elements. (source: Benthem Crouwel Architects)

Given these characteristics, glass-glass c-Si wafer based PV panels are the favoured type of panels. Moreover, specially prepared glass-glass PV panels can be bent to a slight curve. ('cold bending') Using this approach, the PV panels perfectly fit the platform canopies.

Three platforms will get new canopies to begin with. The length of these canopies will be up to 285 meters, the width varies from 11 tot 15 meters. Over 3.900 m² of these canopies will exist of curved glass panels. On the longer term more canopies will be replaced.

3.3 Surroundings: Utrecht Central Station area

Not only Utrecht Central Station, but also its surroundings are being restructured. The main consequence with respect to the application of PV in the area is the construction of a number of new high-rise buildings around the railway station. During the day, these buildings will cause shading on the platform and terminal roofs and thus a reduction in PV panel yields.

In order to assess the potential effects of shading from surrounding buildings on the PV yield the building programme for the next 30 years was considered. It turned out that for a significant part of the building programme the realisation is not yet certain. In order to deal with this uncertainty two scenarios were developed:

- Best-case scenario: Only the existing and high-rise buildings and those which with considerable/great certainty of construction are included;
- Worst-case scenario: Both existing high-rise buildings and all buildings which possibly could be constructed are included.

A 3D sketch of the two scenarios is shown in Figure 4.

3.4 Model: PVSYST

Now that the design of the platform canopies and two building scenarios have been defined the next step is to investigate the effects of shading, tilt and orientation on the yield of the PV panels. After a review of available software tools we selected the PVSYST simulation model (v.4.21) because it is one of the few models that allows an easy evaluation of shading by surrounding buildings. Other software tools are either simplistic or require high-end CAD software for defining the buildings.

PVSYST [3] is a software tool that enables to study system performance using hourly simulations based on local climate data (we used the Standard Reference Year for De Bilt, near Utrecht). Surroundings like buildings and trees can be taken into account, with the aid of a 3D sketch tool (see Figure 4). A large number of different system components can be chosen and important loss factors are quantified, e.g. reflection, orientation, shading and mismatch losses.

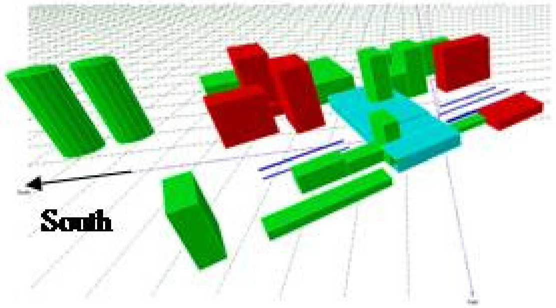

Figure 4: 3D representation of Utrecht Central Station and surroundings. Blue blocks and lines represent the terminal and the platform canopies. Green blocks represent buildings in the best-case building scenario. Red blocks represent additional buildings in the worst-case building scenario.

3.5 Simulation approach

Every model is a simplified representation of reality. In this case the main simplifications were:

- horizontal positioning of PV panels;
- simplified building shapes (e.g. Figure 4);
- string lay-out not optimised;
- shading loss calculated for relatively large areas;

The model (PVSYST) allows the user to evaluate the performance of only one single array area per run. This also means calculation of shading losses are only evaluated for the system as a whole. In order to be able to find roof sections where the shading losses are higher respectively lower than our cut-off level of 20%, we had to divide the total available roof area into several smaller subsystems which were then simulated individually. These subsystems was defined following an iterative approach:

- starting from the side of the canopy nearest to the terminal;
- starting with subsystems with a length of 5 meters;
- when the shading loss dropped below 20%, the grid size was increased;
- separate calculations per platform canopy and for both sides of the terminal;

The final choice of subsystems in the best-case scenario is shown in Figure 5.

3.6 Simulation results

All subsystems were positioned in the same way: horizontal. The losses due to this non-optimal slope (and orientation) compared to an optimum system are, on a yearly basis, 14%. Somewhat surprisingly, we observed that the losses due to non-optimal slope and orientation were roughly equal for each subsystem. The shading loss, however, is different for each subsystem dependent on its location with respect to the surrounding buildings.

The shading losses per subsystem in the best-case scenario are shown in a schematic plan of the railway station in Figure 5.

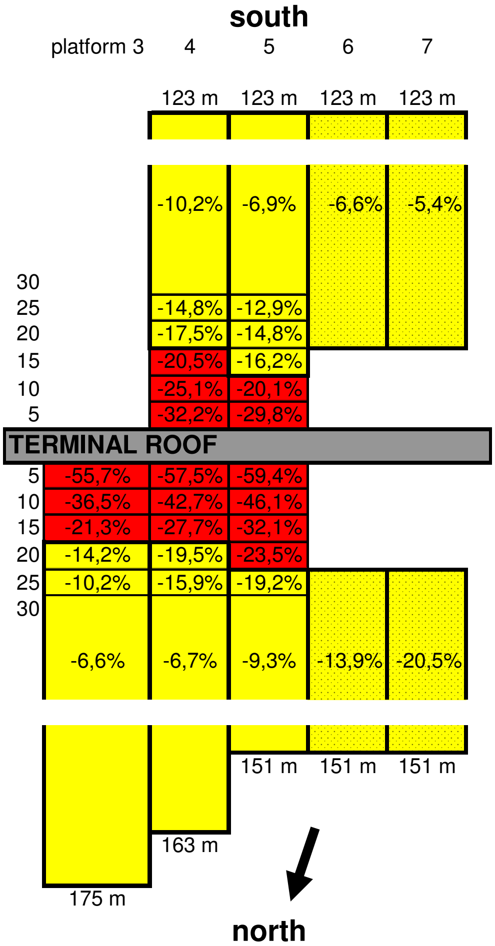

Figure 5. Schematic representation of platform canopies to 7. Each separate coloured block represents a PV subsystem for which shading loss was calculated. Within each block the calculated shading loss in the best-case building scenario is shown. Yellow blocks represent subsystems with shading loss < 20%; red blocks represent subsystems with shading loss > 20%. Platforms 6 and 7 were not included in further calculations.

Detailed shading loss calculations were performed for platform canopies 3, 4 and 5. These are the canopies that will be built within a short term. For platforms 6 and 7 only a rough calculation was made (see Figure 5), because their realisation lies further in the future. For the same reason these platforms are not included in the calculation of the total area that is suitable for PV systems.

Mainly PV subsystems in the area near the terminal turn out to have high shading losses, both at the north and south sides of the terminal.

After calculation of the shading losses, the area of the subsystems with shading loss less than 20% was added up to determine the total area suitable for PV installation. For both shading scenarios, the total suitable area for PV systems is:

- best-case scenario: 3,200 m²;
- worst-case scenario: 2,550 m²

The equation for the normalized yearly energy production is:

$$Q_{syst} = Q_{syst,opt} * \eta_{orient} * \eta_{shading}$$

where $Q_{syst,syst}$ is the yearly energy production per kWp of a PV system on the same location with an ideal orientation and slope. This variable $Q_{syst,nom}$ includes all other system losses, e.g. mismatch and ohmic losses. η_{orient} is the orientation factor, which is 100% for ideal orientation and slope; $\eta_{shading}$ is the shading factor, equal to (1 – shading loss). The orientation factor was in our case equal to 0.86, since the reduction of the yearly electricity yield due to non-optimum orientation and slope is 14%. The shading factor, the product of shading and orientation factor and the normalised yield are all shown in Table I.

Table I: Shading factors, product of shading factor and orientation factor and normalised yearly system yield for the platform canopies. A suitable area for PV panels we selected only those sections of the platform canopies with shading loss < 20%. Orientation factor η_{orient} is 0.86.

	$\eta_{shading}$	η_{orient}* $\eta_{shading}$	**Yearly yield (kWh /kWp/ year)**
Optimum system	1,00	1,00	800
Best-case system (3.200 m²)	0,92	0,80	640
Worst-case system (2.550 m²)	0,85	0,73	580

3.7 Results for terminal roof

The same approach as described for the platform canopies were applied to assess shading loss and to find appropriate surfaces for PV systems on the terminal roofs.

The same two shading scenarios that were used for the platform canopies were used to determine the shading losses for PV systems on the terminal roof. Again the terminal roof was divided into a number of sub systems. The division in sub systems follows the shape of the terminal and the building parts that protrude from the main roof area. As with the platform canopies, the subsystems were placed horizontally, but on different heights, following the undulations of the roof.

The net roof surface is ca. 19.000 m². From the shading calculations it turned out that in both scenarios the gross area available for PV systems is:

- best-case shading scenario: 9.000 m²;
- worst-case shading scenario: 6.900 m²

For these gross areas, the presence of skylights in the roof and intervals between the flexible laminates are taken into account.

The shading factors and estimate of normalised yearly yield per scenario are shown in Table II:

Table II. Shading factors, product of shading factor and orientation factor and normalised yearly system yield for the terminal roof. Suitable area for PV panels we selected only parts of the terminal roof with shading loss < 20%.

	$\eta_{shading}$	$\eta_{orient} * \eta_{shading}$	**Yearly yield (kWh /kWp/ year)**
Best-case system (9.000 m²)	0,89	0,77	620
Worst-case system (6.900 m²)	0,87	0,75	600

4 INSTALLABLE PV CAPACITY

The total available area for PV panels and yearly yield per m² for two shading scenarios are described in the previous section. As explained, areas with shading loss higher than 20% were excluded. With these data the total installable PV capacity and yearly energy yield was calculated.

The installable capacity, P_{syst} [kWp] is:

$$P_{syst} = A_{tot} * P_{STC}$$

with A_{tot} [m²] the roof area with shading loss < 20% and P_{STC} [kWp/m²] the nominal power of the PV module.
NB. In the panels for the platform canopies only 30% of the panel area will be covered with solar cells, to meet the desired transparency of the roof.

P_{STC} is 140 Wp/m² for the c-Si solar cells for the canopies (on individual solar cell level) and 60 Wp/m² for the flexible solar laminates for the terminal roof.

Next the yearly electricity yield Y_f [kWh] can be calculated according to:

$$Y_f = Q_{syst,} * P_{syst},$$

The results are presented in Table 3.

Table 3. Installable PV capacity and yearly yield for PV systems on platform canopies and terminal roof of Utrecht Central Station in two building scenarios.

	Installable capacity P_{syst} (kWp)	**Yearly yield Y_f (MWh / year)**
Platform canopies		
best-case	134	86
worst-case	107	62
Terminal roof		
best-case	540	335
worst-case	414	248

It was found that up to 647 kWp of PV could be integrated into the roof areas of the station, without compromising too much on system performance (best-case scenario). The yearly electricity production in that case was estimated to be 421 MWh.

5 LATEST DEVELOPMENTS IN THE UTRECHT STATION PROJECT

It has recently been decided that PV will be integrated in the platform canopies of platforms number 3 to 5 in the new station building. As described above these roofs will equipped with semitransparent PV panels. In those parts of the canopy that were identified in shading study as less suitable, dummy cells will used.

The semitransparent PV panels will be provided with 15x15 cm_2 multicrystalline solar cells which are laminated between two glass sheets. The spacing between the cells will be such that 30% of the panel area is covered with solar cells. For the lamination a PVB-based safety foil will be employed, in order to meet the safety requirements for overhead glass panels (i.e. danger of falling glass pieces). A market survey has shown that there are two suppliers that produce modules with this technique.

The 70% transparency of the panels will ensure that sufficient light from outside can reach the platform floor. When installed the PV panels will well visible from the platforms as well as from the terminal building. The picture below shows how these panels will look standing on the platform.

Also an information display will be installed to show the renewable energy production to the public.

Figure 6: Impression of the station platform with transparent PV panels in the canopy above the platform (darker areas are solar cells).

The peak power rating of the PV system will be 149 kWp, and yearly energy production – taking into account remaining shading losses – is estimated at 97 MWh. The total avoided CO_2 emission is then about 54 ton year. The generated electricity will employed directly to drive the station's escalators. This has the additional advantage that one does not need to feed the generated PV energy into the public grid at the low feed-in tariff of 0.07 ct/kWh that will be paid out by the energy company. The saving on purchased electricity on the other hand will be 0.12 ct per kWh. (N.B. Installations of this size were not eligible for feed-in subsidies in 2008).

A European subsidy on the project has been granted. The final decision about the investment in the PV system will made by ProRail in October 2009.

6 CONCLUSIONS

Based on the lessons from the Utrecht station feasibility study the following conclusions can be drawn:

- PV installation potential in urban environments may be limited by shading losses;
- Careful consideration of shading loss and other technical limitations is very important to avoid disappointment in later stages;
- Suitable tools for shading loss analysis are not readily available; ideally such tools should be integrated in building design CAD software;
- Even in high–rise urban environments considerable roof area remains which is attractive for PV installations.

REFERENCES

[1] International Energy Agency, Potential for Building Integrated Photovoltaics, Report IEA-PVPS T7-4, 2002, http://www.netenergy.ch/pdf/BiPVPotentialSummary.pdf

[2] Wild-Scholten, M.J. de, E.A. Alsema, E.W. ter Horst, M Bächler, and V Fthenakis. *A Cost and Environmental Impact Comparison of Grid-Connected Rooftop and Ground-Based PV Systems*, in *21st European Photovoltaic Solar Energy Conference*, Dresden, 2006, p. 3167-3173.

[3] PVSYST, Software for photovoltaic systems, University of Geneva, Switzerland, http://www.PVsyst.com