EuroSun 2002 - Bologna, Italy

Computer Evaluation of the Solar Energy Potential in an Urban Environment

Jean-Louis Scartezzini*, Marylène Montavon*, Raphaël Compagnon**

*) Solar Energy and Building Physics Laboratory (LESO-PB)
Swiss Federal Institute of Technolgy in Lausanne (EPFL)
CH - 1015 Lausanne
Phone: +44 21 693 4545 Fax +44 21 693 2722
E-mail: jean-louis.scartezzini@epfl.ch, marylene.montavon@epfl.ch

**) Engineering and Architecture School Fribourg (EIAF)
University of Applied Sciences of Western Switzerland (HES-SO)
CH - 1705 Fribourg
Phone: +41 26 429 66 11 Fax: 026 429 66 00
E-mail: raphael.compagnon@eif.ch

Abstract

Besides a more efficient energy use, large scale application of solar energy technologies in the urban context will be necessary in the upcoming decades to achieve a drastic reduction of greenhouse gas emissions in the biosphere. The preliminary assessment of the overall utilisation potential of solar energy was undertaken for that purpose in three different urban sites, representative of the largest Swiss cities. The first one examined was the district of "Kleinbasel-Matthäus", a dense housing area erected before the 2nd World War in Basel (Switzerland).

Spatial distributions of solar irradiation and daylight fluxes over the overall building facades and roofs were calculated using ray tracing simulation techniques, to point out the more appropriate locations for different solar technologies (passive and active solar energy, photovoltaics and daylighting). Several performance indicators were used moreover to determine the optimal solar strategies for this urban context.

It was shown that about half of the building envelope area (facades and roofs) remains appropriate for the use of solar technologies despite the urban character of the site (building obstructions, effect of urban canyon). These preliminary results indicate that the perspective of curbing greenhouse gas emissions through use of renewable energies in large cities can reasonably be envisaged for the future.

1. Introduction

According to the investigations of the Intergovernmental Panel for Climate Changes (IPCC), a drastic reduction of greenhouse gas emissions (GHG emissions) is required on a global scale, within a 50 year perspective to preserve the dynamic equilibrium of the biosphere [Leg 90]. As a consequence, CO2 emissions, which reach today about 6.5 tons per capita in Switzerland on a yearly basis, will have to be reduced to one ton per person per year around the middle of the 21st century.

Recent national studies [SAT 99] came to the conclusion that this could be achieved by the year 2050 throughout the country, with no unacceptable socio-economic impacts, by halving the fossil fuel energy consumption of different national activity sectors (housing, industry, transport). Besides through a more efficient use of conventional energy sources, such a large reduction of energy consumption can only be achieved by promoting, in a massive way, the utilisation of renewable energies in the built environment through different available solar technologies (passive and active solar use, photovoltaics and daylighting).

The assessment of the solar energy utilisation potential in an urban context is undertaken for that purpose in three different urban sites, representative of the largest Swiss cities and contributing to a significant fraction of the national energy consumption:

- a dense residential area, close to the city centre, made of buildings erected before the 2nd World War,
- a large multi-storey housing area, constituted of 12 - 36 apartment buildings built between 1945 and 1975,
- a non-residential and commercial area located in the town's suburbs and surrounded by parking lots and green fields.

Computer simulation techniques, developed for that purpose and based on detailed 3D models of these large urban districts, are used to determine the distributions of solar irradiation and daylight fluxes on the different building facades and roofs [Com 01]. Several performance indicators assessed with these computer techniques are used moreover to determine the most appropriate solar energy utilisation strategies in a specific urban context.

An urban site that corresponds to the first defined category was spotted in the city of Basel, located in the north-eastern part of Switzerland. An overview of the assessment of the solar energy potential of the urban site, together with an overview of the computer simulation methodology used for that purpose, are presented in this paper.

2. Description of the urban site

The first considered urban site, named "Klein Basel - Matthäus", is situated near the city centre of Basel alongside the Rhine river (cf. Figure 1).

Figure 1: General view of "Klein Basel - Matthäus" district

The site is mainly made of 4 - 5 storey housing blocks, built during the first half of the 20th century (66% of buildings erected before 1945) in the course of the industrialisation of Basel.

The overall town site was originally planned and constructed as a whole, which led to a coherent urban typology made of courtyard building blocks surrounded by access streets (see Figure 2). Many restaurants, as well as workmen spaces, enriched the human quality of this part of the town. Covering more than 550'000 m2 for an overall population of 15'300 inhabitants, this town site is characterised by one of the highest population densities of Swiss cities.

This city area was considered for another specific reason: it will be used as a pilot site within the framework of a drastic energy savings incentive programme (the "2000 Watts Society" project). The programme was launched in 2001 by the authorities of the Kanton Basel in the framework of the "Strategy for Sustainable Development" of the Council of the Swiss Federal Institutes [Nov 01]: it aims at drastically reducing the energy consumption of different town sites, as required to avoid the perspective of massive climate changes, by cutting down the average yearly power consumption per inhabitant from the present value of 6'500 Watts down to 2'000 Watts (current average power consumption per capita for the whole planet). On a purely technical basis, such a "Factor 4" reduction in energy consumption can be achieved in the building sector, whose average power consumption (1'600 watts for housing heating and electrical appliances in Switzerland) can be reduced down to 450 Watts with the current energy saving and solar technologies.

3. Computer simulation methodology

The computer methodology used to assess the solar energy utilisation potential of "Kleinbasel - Matthäus", is based on the approach developed by Compagnon within the framework of the PRECis project ("Assessing the potential for renewable energies in cities"): reference [Com 01] gives a detailed presentation of the project.

The overall procedure, based on the Radiance ray tracing programme [War 92], was modified, however, to take into account the larger area of the considered urban site (59 hectares instead of 10-30), as well as the higher complexity of the 3D digital model of the district (detailed building shapes and typology, higher urban density). Figure 3 illustrates this model, which required about 35'273 segments to define the different building surface elements (facades and slanted roofs).

Figure 2: Typical view of "Klein Basel - Matthäus" district

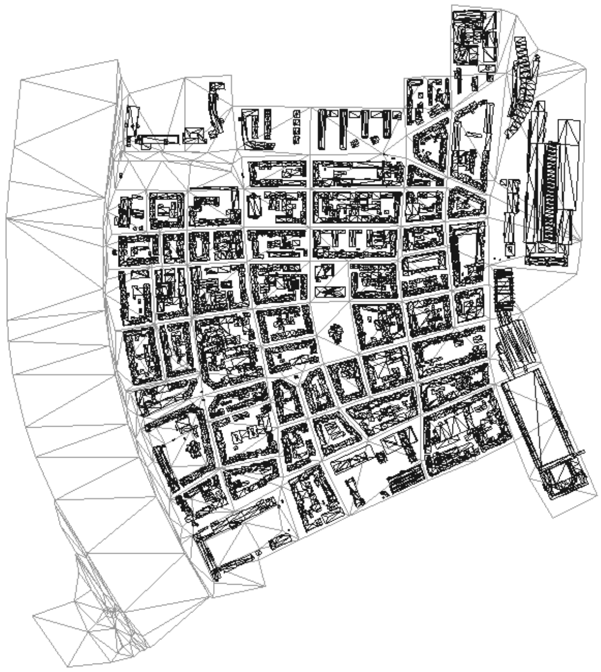

Figure 3: 3D digital model of the "Kleinbasel - Matthäus" district ("3D face" format).

According to this procedure, the final energy which can potentially be produced by the different solar technologies in this urban site (passive and active solar use, photovoltaics and daylighting) was assessed in several steps:

- Climate data of the site of Basel were processed statistically in order to build up representative average radiometric and photometric sky models [Kun 95];
- A site ground relief, as well as additional building features (surface reflectances), were incorporated in the 3D digital model of the urban site;
- Both data sets were processed by computer simulation (ray tracing techniques) to determine the solar energy and daylight flux distributions on the building envelopes (facades and slanted roofs);
- Finally, several performance indicators were calculated according to these distributions in order to determine the optimal solar energy utilisation strategy for this urban site (relative fraction of appropriate building surfaces, appropriate surface locations, etc.).

The principal solar performance indicators used in this context were:

- Irradiance and illuminance statistical distributions, determined for the building facades and roofs over winter (solar passive energy) and annual periods (active solar energy, photovoltaics, daylighting);
- The relative fraction of building surfaces appropriate for the different specific solar technologies, determined on the basis of corresponding minimal irradiance and illuminance thresholds [Com 01] (e.g. 1000 [kWh/m^2] on a yearly basis on a roof for PV solar technology);
- Polar diagrams showing the main orientation of the building facades, weighted by sky view factors to take into account the daylighting (diffuse component) and the passive cooling potential (thermal radiation) of the urban site.

Visualisation techniques offered by the Radiance simulation programme were used moreover to identify the appropriate locations for implementing the different considered solar technologies (e.g. locations characterised by an annual irradiance larger than 1'000 [kWh/m^2 year] for PV applications). A detailed mathematical definition of these indicators is given in reference [Com 01].

4. Solar performance indicators of the urban site

The solar performance indicators of "Kleinbasel - Matthäus" were thus assessed using computer simulations carried out under the Linux environment on a Pentium IV PC: 20 hours CPU processing time were required for that purpose.

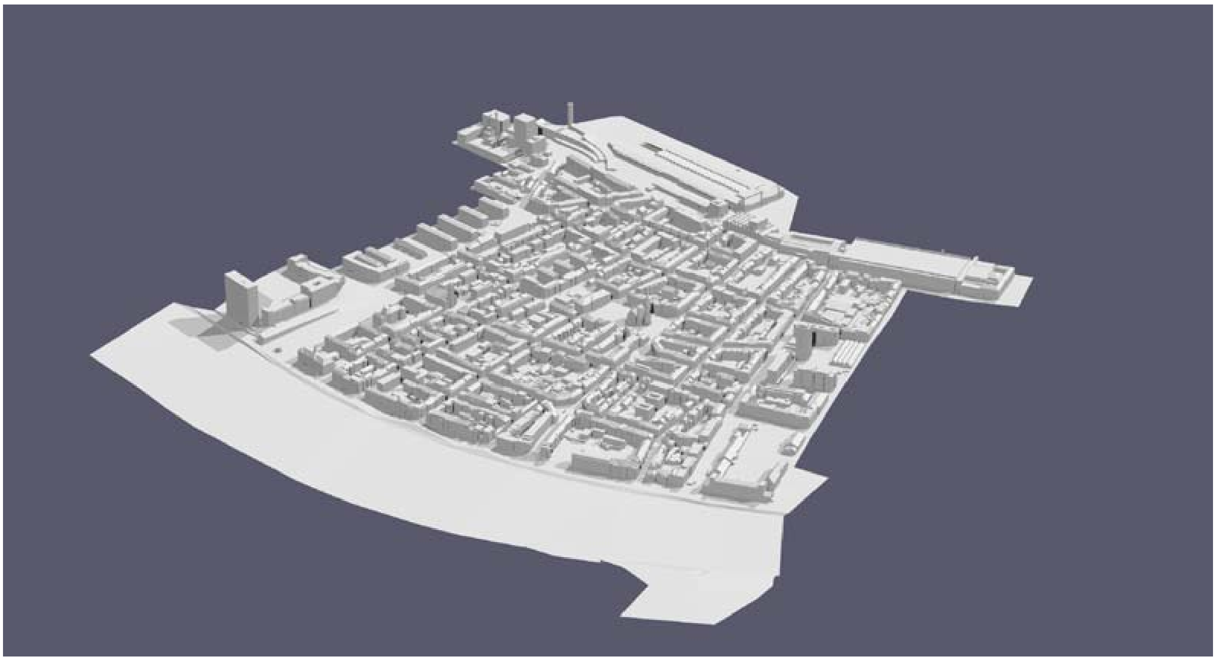

Figure 4: View of "Kleinbasel - Matthäus" rendered by ray tracing techniques

Figure 4 shows a rendered view of the urban site obtained through ray tracing (Radiance programme view).

Figure 5 illustrates the "orientation rose" of the overall building facades of the urban site (polar diagram) determined on the basis of the facade area, as well as through weighting of these areas by their respective "Sky View Factor" (i.e. the fraction of the sky vault viewed by the facade divided by 0.5, the value corresponding to an unobstructed facade).

The predominant orientation of the building facades of the urban site matches the principal geographic orientations (cardinal directions), as shown by this diagram. The latter indicates moreover that:

- most of the building facades are oriented due south (and due north) corresponding to a favourable situation for solar technologies
- the urban character of the site is however responsible for a significant reduction of the sky fraction viewed by the building facades.

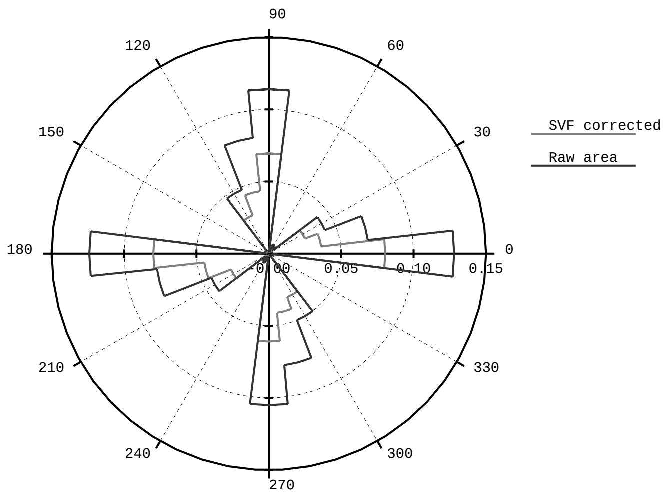

Figure 5: Polar diagram of the overall building facades of the urban site (raw area and Sky View Factor corrected)

In spite of this, most of the building facades (and roofs) benefit from rather favourable sky view conditions, as shown by Figure 6: Sky View Factor values lie between 0.2 - 0.5 for the facades and 0.85 - 1 for the roofs.

This is confirmed by the statistical distributions of the solar irradiation (cf. Figure 7 (a)) and illuminance (cf. Figure 7(b)) of the building facades and roofs.

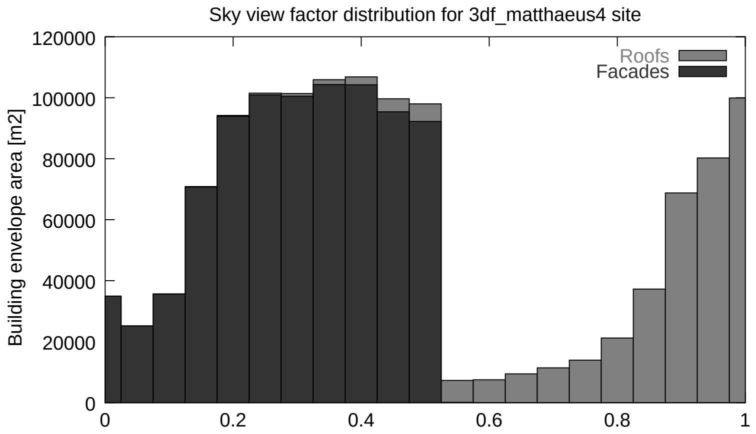

Figure 6:

Statistical distributions of the facade and roof Sky View Factors (SVF values)

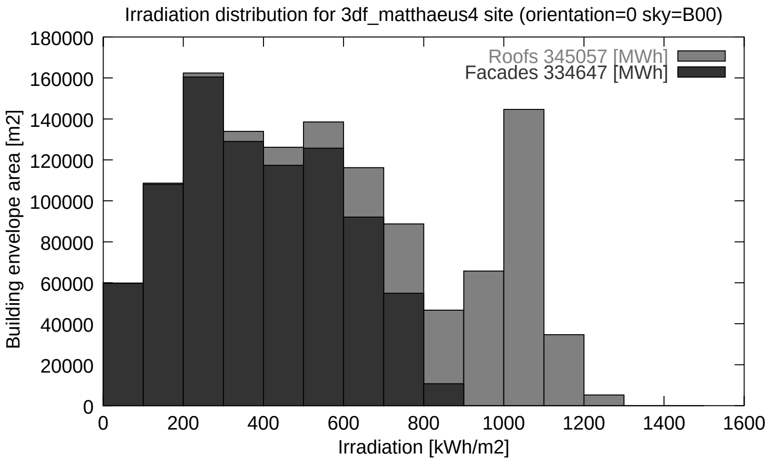

Figure 7a:

Statistical distribution of yearly irradiation on the building facades and roofs.

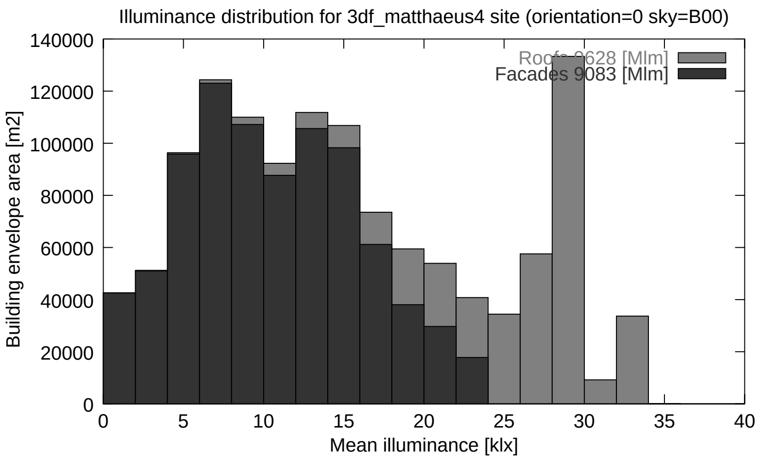

Figure 7b:

Statistical distribution of yearly average illuminance on the building facades and roofs.

These statistics show that very significant fractions of building facades and roofs benefit from yearly irradiation and illuminance values that are perfectly adequate for operating different solar technologies.

By assuming minimal required irradiation or illuminance thresholds for each specific technology, the corresponding fractions of building facades and roofs were determined (cf. Table 8). The thresholds themselves were determined according to procedures presented in detail in [Com 01], based on the following assumptions:

- The minimal vertical irradiation required for passive solar energy use leads to a positive energy balance for state-of-the art glazings in the Basel climate (117 [kWh/m^2] for a heating period).
- The values required for active solar energy use and photovoltaics, which differ for facades and roofs, correspond to the edge of normal operating conditions (e.g. 800 [kWh/m^2 year] for PV in vertical facades and 400 [kWh/m^2 year] for active solar energy use).
- The mean illuminance required for daylighting techniques used on vertical openings (utilisation coefficient of 0.05) leads to a 500 Lux illuminance on a workplane (10 [kLux] mean illuminance required over the whole year).

Table 8 gives the corresponding facade and roof fractions, which show that a very significant part of them remains appropriate for solar technology operation, despite the urban character of the site. It shows, moreover, that half of these areas can reasonably be used on the building facades (passive solar energy use and daylighting) and roofs (active solar use and photovoltaics), depending on the considered technology.

Considering the very large facade and roof area of the site (858'000 and 373'000 m^2 respectively), a considerable solar utilisation potential can be foreseen for "Kleinbasel - Matthäus", which opens encouraging perspectives for the "2000 Watts Society" project.

5. Conclusion

The preliminary assessment of the overall utilisation potential of solar energy in the urban context is necessary to achieve a sound and reasonable implementation of these technologies in large cities. Such an evaluation is currently undertaken in Switzerland at three different urban sites that are representative of the Swiss urban environment (dense residential building blocks erected before 2nd WW, large multi-storey dwellings of the 1945-1975 period, non-residential and commercial area in town suburbs).

Solar technology	Passive (*)	Active	PV	Daylighting (**)
Relative fraction of appropriate				
- facade area	48.7%	46.7%	1.3%	51.1%
- roof area	-	92.2%	49.4%	-
Required minimal threshold for				
- facades	117 [kWh/m^2]	400 [kWh/m^2]	800 [kWh/m^2]	10 [kLux]
- roofs	-	600 [kWh/m^2]	1000 [kWh/m^2]	-

Table 8: Relative fraction of building facade/roof areas appropriate for a given solar technology
(*) Calculation over the heating season
(**) Yearly calculation for a 8h00 to 18h00 daylight period

The assessment was carried out using computer simulation techniques (3D digital model, ray tracing) for the large urban site of "Kleinbasel - Matthäus" in the city of Basel (Switzerland).

Solar irradiation and daylight flux distributions over the building facades and roofs were evaluated to find the most appropriate solar energy utilisation strategies in these specific contexts. Several performance indicators were used, moreover, to determine the relative fraction of building area that is appropriate for a given solar technology (passive and active solar energy use, photovoltaics and daylighting).

It was shown that a very significant part of the building facades and roofs (about half of their area) remains appropriate for the different considered solar technologies, despite the urban character of the site. A drastic reduction of the energy consumption of this urban site, as targeted within the framework of the "2000 Watts Society" project, can reasonably be envisaged for the future thanks to the contribution of these technologies.

References

[Leg 90] "Global Warming", edited by Jeremy Leggett, Oxford University Press, Oxford - New York (1990).

[SAT 99] Swiss Academy of Engineering Sciences (SATW), "CH 50% - Dividing fossil fuel energy consumption of Switzerland by a factor 2", ASST/SATW, Zurich, (1999).

[Nov 01] Novatlantis Programme, "2000 Watts Society - Pilot region Basel", Kanton Basel and Council for Swiss Federal Institutes, (2001).

[Kun 95] S. Kunz, "METEONORM: Meteorologische Grundlagen für die Sonnenenergienutzung", CISBAT'95 Proceedings, EPF Lausanne, 12-13 October 1995

[Com 01] R. Compagnon, "PRECIS: Assessing the potential for Renewable Energies in Cities", Technical Report, EIAF, Fribourg (2001).

[War 92] G. J. Ward, "The Radiance Synthetic imaging system", Lawrence Berkeley National Laboratory, (1992)