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Article

Development of a Façade Assessment and Design Tool for Solar Energy (FASSADES)

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Abstract: Planning energy-efficient buildings which produce on-site renewable energy in an urban context is a challenge for all involved actors in the planning process. The primary objective of this study was to develop a façade assessment and design tool for solar energy (FASSADES) providing the necessary information for all stakeholders in the design process. The secondary objective was to demonstrate the tool by performing an assessment analysis of a building block. The FASSADES tool is a DIVA4Rhino script, combining Radiance/Daysim and EnergyPlus for simulating the annual production of solar thermal and photovoltaic systems on facades, the cost-effectiveness of the solar energy system, and the payback time. Different output methods are available; graphically within the 3D drawing environment and numerically within post-processing software. The tool was tested to analyse a building block within a city under Swedish conditions. Output of the developed tool showed that shading from nearby buildings greatly affects the feasibility of photovoltaic and solar thermal systems on facades.

Keywords: solar energy; solar thermal; photovoltaics; density; facade; assessment; feasibility; urban planning

1. Introduction

Planning future resilient cities is a challenging task for urban planners, architects and other involved stakeholders. Political directives, such as the EPBD in Europe [1], commands the design of buildings with a reduced energy demand that can be (partly) met by an on-site generation of renewable energy [2]. Planning such nearly Zero Energy Buildings (nZEB) is especially challenging in the context of cities, where the access to sunlight is scarce due to shading by adjacent buildings, which limits solar gains for passive heating, daylight, and for producing energy by means of photovoltaics (PV) or solar thermal (ST). Even if buildings can greatly reduce their energy demand, it is difficult to produce all of the needed energy on-site by means of solar energy alone [3,4], especially due to the high demand for electricity in modern buildings.

Involved stakeholders need to obtain all necessary information to assess *if* and *how* the implementation of solar energy would be a feasible alternative for generating renewable energy. Providing decision-makers information in the design process by means of tools is a valid strategy to make informed design decisions. This task is addressed by IEA SHC Task 51, which will provide "support to urban planners, authorities and architects to achieve urban areas and eventually whole cities with architecturally integrated solar energy solutions (active and passive), highly contributing to cities with a large fraction of renewable energy supply" [5].

Several tools currently exist for the assessment of solar energy in the built environment. The existing assessment tools can be roughly divided into three categories: (1) tools for the urban scale; (2) for the building scale; and (3) for the system scale.

The most common tool for assessing solar energy at the urban scale is the solar map, which consists of a GIS system providing the annual solar irradiation on building surfaces (mostly roofs), often accompanied by the output of a possible solar thermal or photovoltaic system, and connected to a website [6]. A study performed by Kanters *et al*. [6] showed that there is a large distribution in quality of such solar maps: some of them only provide irradiation values, while others provide additional information concerning the production of a possible solar system; some tools divide roof areas into categories while other tools provide financial feasibility studies. One of the most advanced solar maps is the one from Cambridge, USA, described by Jakubiec and Reinhart [7]. This map provides data about the position and system size of PV systems on roofs, the produced amount of electricity, the installation size, and the financial payback time. In this case, the output of the PV system is, besides the efficiency and additional losses, also calculated by taking into account the air temperatures near urban rooftops. The spatial resolution of this solar map is 1.25×1.25 m^2 and the time resolution is hourly. In parallel to this, other authors [8] described a method of calculating the solar energy potential of roofs and facades in an urban landscape, with a spatial resolution of 1 m and a time resolution of 1 h. However, this method shows only the irradiation on facades and roofs, not the production of a possible solar energy system, although a threshold value is mentioned for PV systems.

A wider variety of tools exists to analyse solar energy at the building scale of which an extensive list of Building Performance (BPS) tools was set up within the framework of IEA SHC Task 41 [9–11]. Architects were asked—in surveys and interviews—which tools they used for solar design and to rate their satisfaction of the listed tools. The conclusion was that a further development of such tools was needed towards an integrated tool that is user-friendly and also could provide graphical results. In the USA, Crawley [12] compared 20 well-used BPS tools with each other, concluding that product developers use different ways to describe the capabilities of BPS tools. More recently, Ibara and Reinhart [13] compared six different well-used irradiation distribution methods, concluding that some of the analysed programs showed large relative errors compared to measured data. Later, Jakubiec and Reinhart [14] developed the tool DIVA4RHINO which combines several of the most-used programs for daylight, thermal analysis, and solar analysis.

At the detailed system scale, many programs focus either on PV or ST and include many detailed parameters like system components—tanks, storage, inverters, batteries, *etc.* An example used for PV systems is PVSYST, used by e.g., Fartaria [15] to calculate mutual shading of direct normal and diffuse radiation and by Sharma [16] to simulate the output of a grid-connected system. For ST systems, an example of a detailed system simulation software is TRNSYS, used e.g., by Wills [17] to study solar heating with a single-house scale seasonal storage, by Terziotti [18] to study the seasonal solar thermal energy storage in a large urban residential building, and by Bernardo [19] to study the retrofitting of domestic hot water heaters for solar water heating systems.

The abovementioned tools consider many aspects of solar energy, but focus on a specific scale. In addition, the knowledge level needed to operate these tools is relatively high. Actors in the urban planning and building design process need extensive data to assess solar energy potential. Real estate developers are an example of important actors of the design process. In many countries, real estate developers will develop buildings within an urban plan and take a series of decisions really affecting the potential for solar harvesting on building facades and roofs. Real estate developers are mostly interested in investment costs and payback times of the solar energy technology.

The primary objective of this study was to develop a façade assessment and design tool for solar energy (FASSADES), providing the necessary information for all stakeholders involved in the design process. The secondary objective was to validate the tool by performing an analysis of a building block.

2. Method

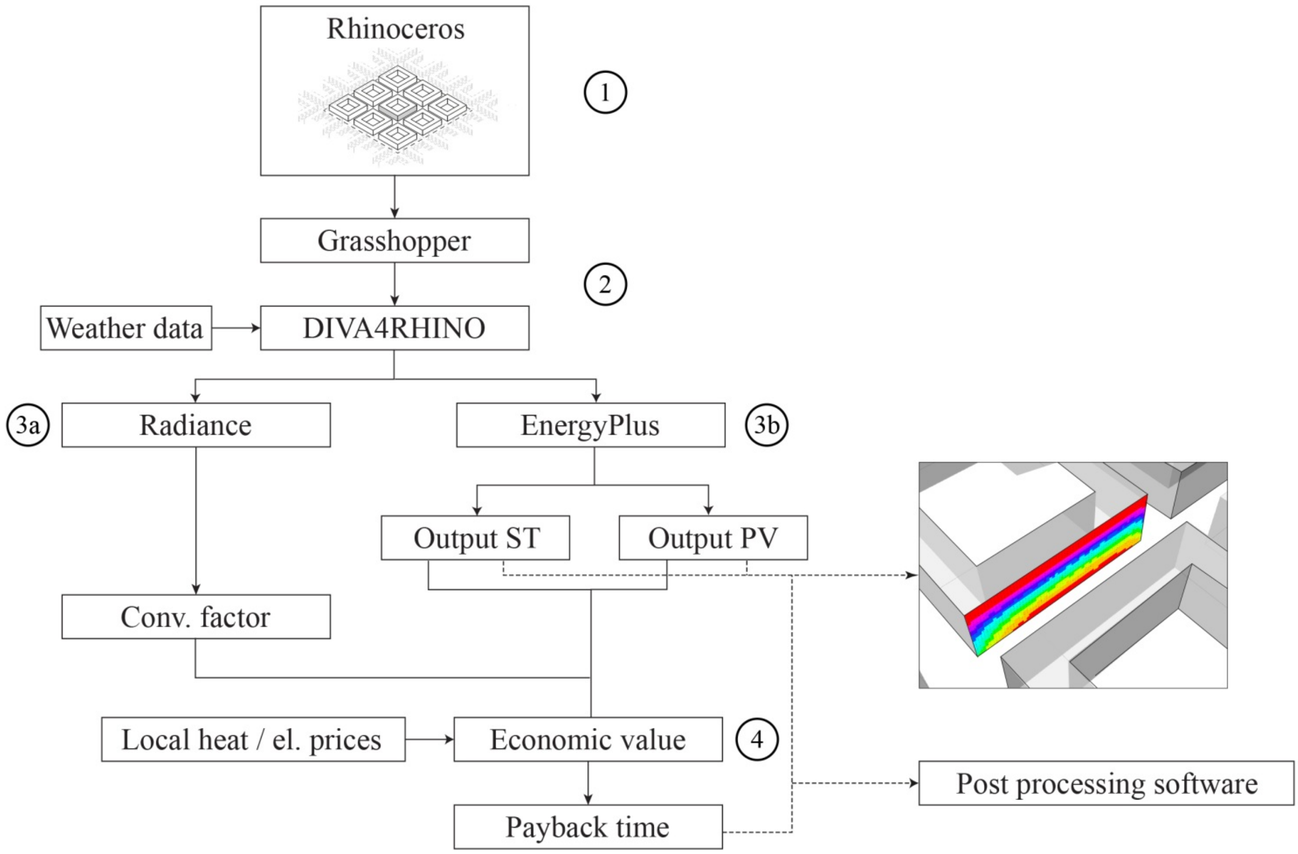
The working method started with the development of a workflow to enable assessment analyses of the solar energy access. The FASSADES tool enables users to fully assess the solar potential of facades. This full assessment can only be done by the simulation of the solar irradiation on the whole façade (taking shading due to surroundings into account), the calculation of the (hourly) output of a possible ST or PV system, the economic value of this production, and the payback time of the solar energy system. The workflow of the tool is shown in Figure 1.

The workflow as displayed in Figure 1 is explained step-by-step in the next sections.

2.1. Steps 1 and 2

All elements affecting the solar access of facades need to be included in the 3D model which is imported in the simulations. In the FASSADES tool, users either construct their model in the CAD program Rhinoceros [20], import files from other CAD applications or users write a script in Grasshopper. Once the 3D model of the building is constructed in Rhino, it is loaded into the plugin Grasshopper; a visual programming language connected to Rhinoceros [21]. In Grasshopper, the facade to analyse is divided into surfaces of 1 m × 1 m.

Figure 1. Workflow of the FASSADES tool.



2.2. Step 3

In Step 3, simulations are performed with DIVA4Rhino—a daylighting and energy modelling plug—for Rhinoceros [14]. DIVA4Rhino runs in this case two validated simulation programs to predict solar energy access: Radiance/Daysim and EnergyPlus [22]. It is beneficial to run these two programs parallel to each other; Radiance calculates the annual solar irradiation on the façade relatively quickly, but is not (yet) able to output hourly values of diffuse and direct irradiation. EnergyPlus is able to provide the hourly direct and diffuse irradiation on a surface, but is not able to run many analyses in an acceptable period of time.

2.2.1. Step 3a

In Step 3a, an annual Radiance/Daysim simulation of the façade is performed. The Radiance/Daysim component in DIVA4Rhino uses the cumulative sky model developed by Robinson and Stone [23].

For the analysis of the building block discussed later in this study, the settings of the Radiance/Daysim simulations are displayed in Table 1. A ground plane and the surrounding buildings need to be included in the scene.

Table 1. DIVA4Rhino settings for Radiance/Daysim and EnergyPlus simulations.

Weather data		**Copenhagen EPW**
Reflectances	Ground	20%
	Buildings	35%
Energy + simulations:	Time steps per hour:	6
	Time period	Annual
	Reflections	Full exterior with reflections
	Output	Zone Beam Solar from Exterior Windows Energy and Zone Diffuse Solar from Exterior Windows Energy
Radiance simulations:	Nodes offset	10 mm
	Ambient bounces	10
	Ambient divisions	1000
	Ambient super-samples	20
	Ambient resolution	300
	Ambient accuracy	0.1

The Radiance/Daysim simulation is used to generate the dimensionless weighting factor σ. In this study, a weighting factor is the ratio of the annual solar irradiation on a surface with respect to the average solar irradiation on the facade (see Equation (1)). These weighting factors are then used to adjust the results of the EnergyPlus simulation, which is Step 3b.

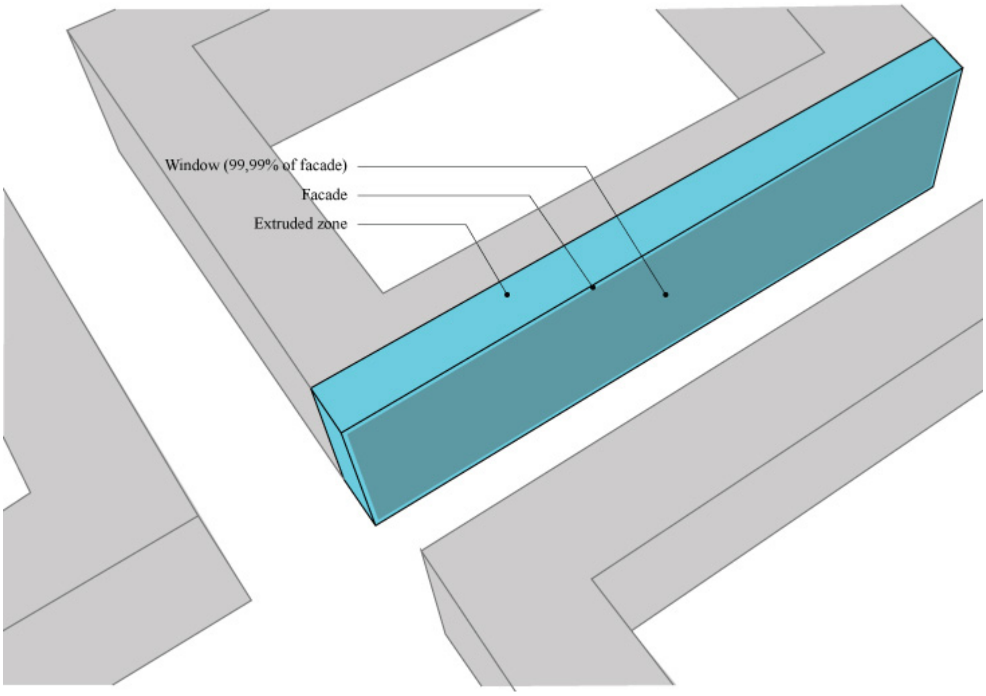
$$\sigma = \frac{H_{\mathrm{n}}/A_{\mathrm{n}}}{H_{\mathrm{f}}/A_{\mathrm{f}}} \tag{1}$$

where, σ, weighting factor (−); H_{n}, annual solar irradiation on surface *n* (kWh); A_{n}, area of surface *n* (m^2); H_{f}, annual solar irradiation on whole façade (kWh); A_{f}, area of whole façade(m^2).

2.2.2. Step 3b

It was expected that the best comparison between the two technologies (PV or ST) was by comparing the hourly output. In order to calculate the hourly output of the solar energy systems, it was necessary to simulate the diffuse and direct irradiation on the façade. Most parts of the façade are shaded by surrounding buildings which makes it complicated to compute the direct and diffuse solar irradiation manually. Therefore, an EnergyPlus simulation was run to simulate the hourly diffuse and direct solar irradiation on the façade, a tool which is used in earlier studies [24–26]. For EnergyPlus to run, the analysed façade is extruded 1 m backwards, constructing a zone (Figure 2). A window is inserted in the analysed façade, with a size of 99.99% of the façade. This window was given the material *window low-iron 2.5 mm* (with a solar transmittance at normal incidence of 0.904). The values for the direct and diffuse solar gain through the windows were then later corrected with a factor of 1/0.904. This will cause a small source of error since the solar angle is normally not at normal incidence. However, the construction of a fictitious zone in EnergyPlus was necessary to include the full effect of shading due to surrounding buildings.

Figure 2. Construction of EnergyPlus simulation.



2.2.3. Step 3c

The output of a solar thermal system is dependent on the connected system. To avoid the simulation of complex system components connected to the solar panels, the hourly output of the ST system is calculated with Equation (2), which is based on previous literature [27], and provides the possibility to calculate the output of a system for absorber temperatures of 25 °C, 50 °C, 75 °C, and 90 °C.

$$Q_{ST} = F'(\tau\alpha)_n(K_b(\theta)I_b + K_dI_d) - F'U_1(T_m - T_a) - F'U_2(T_m - T_a)^2 \quad (2)$$

$$K_b(\theta) = 1 - b_0(\frac{1}{\cos\theta} - 1) \text{ for } \theta \leq 60°$$

$$K_b(\theta) = (1 - b_0)\cdot(\frac{90°-\theta}{30°}) \text{ for } 60° \leq \theta \leq 90°$$

where, Q_{ST}, useful output power of the ST system (W/m^2); $K_b(\theta)$, incident angle modifier (–); $F'(\tau\alpha)_n$, zero loss efficiency for beam radiation at a normal incidence angle (–); I_b, beam irradiance (W/m^2); K_d, diffuse angle modifier (–); I_d, diffuse solar irradiance (W/m^2); U, Heat loss coefficient [W/(m^{2}K)]; T_m, Average temperature in absorber (°C); T_a, surrounding air temperature (°C).

The following input parameters are required for solving Equation (2):

- Direct irradiation (W/m^2);
- Diffuse irradiation (W/m^2);
- Incidence angle (°);
- Ambient temperature (°C);
- Features of a solar panel. The following parameters were obtained by comparing several ST product specifications [28]:
- $F'(\tau\alpha)_n$: 0.851 (–);
- K_d: 0.9 (–);

- $F'U_1$: 4.036 (W/m^{2}K);
- $F'U_2$: 0.0108 (W/m^{2}K^2);
- B_0: 0.09 (–).

The EnergyPlus simulation performed in Step 3b provides the direct and diffuse irradiation per hour. The incidence angle is the difference between the normal of the analysed surface and the solar angle. The normal of the surface is extracted from Grasshopper and the solar angle is calculated using the solar vector component in DIVA4Rhino. The hourly ambient temperature is extracted from the weather data. In the FASSADES tool, Grasshopper is connected to Excel to export the hourly results and perform the calculation of Equation (2). For PV systems, the output E_{PV} is calculated with Equation (3).

$$E_{PV} = (I_b + I_d)\cdot\eta_{rel}\cdot\eta_{sys} \tag{3}$$

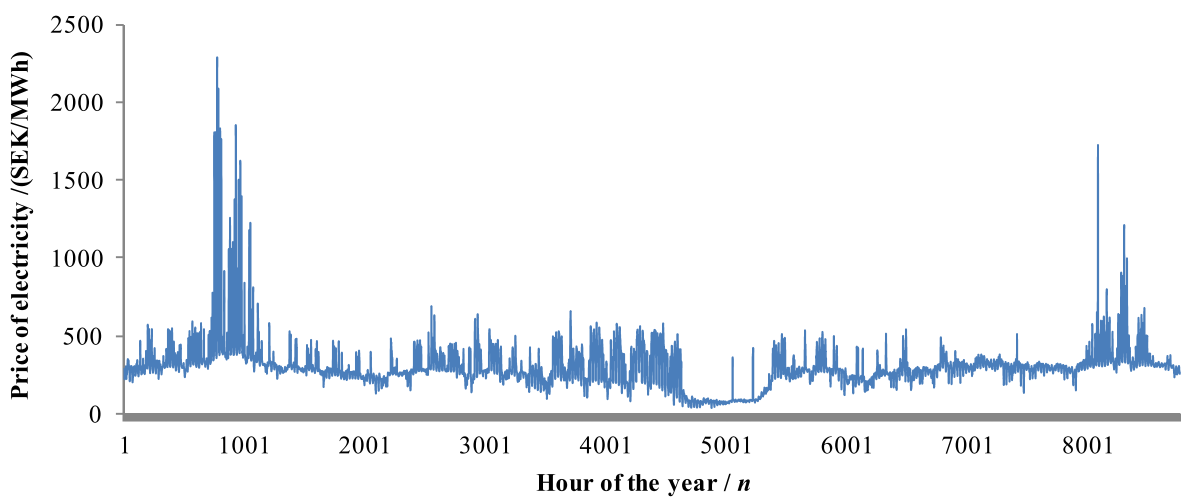
where, E_{PV}, output of the PV system (W); η_{rel}, relative module efficiency (–); η_{sys}, system efficiency (–).

This equation is not taking the temperature dependency of PV systems into account. In the analysis of the building block, an efficiency of 15% and 10% additional losses are taken into account in order to calculate the output of the PV system.

2.2.4. Step 4

In Step 4, a financial value is attributed to the output of a unit surface area, as calculated in Step 3. In Sweden, heat and electricity prices vary greatly over the year. Since Sweden does not have a feed-in Tariff legislation, the value of the produced electricity is calculated in this study as being the saved electricity. The hourly electricity market price is taken from NordPoolSpot, the market organisation in the Nordic countries [29]. In the validation study presented here, the hourly electricity price was from 2012 and from region SE4 (the South of Sweden). The variation of electricity prices over the year is presented in Figure 3.

Figure 3. Hourly market electricity price from NordPoolSpot (in 2012, region SE4) [29]. Reproduced with permission from [29]. Copyright 2013 NordPoolSpot.



In Sweden, it is possible to apply for a subsidy when installing a PV system, with a maximum subsidy of 1.2 million Swedish Crowns (SEK) [30].

Putting value on the output of heat from ST systems is more difficult than for the production of PV systems. Urban district heating networks is the most common heat supply method in the larger Swedish cities. Heat from the ST system with a system temperature of 25 °C and 50 °C directly replaces bought heat from the urban heating district network (representing 100% of the heat price), while heat produced from systems with higher temperatures (75 °C and 90 °C) feed into the urban heating district system, for 90% of the heat price. Table 2 provides an overview of the costs of heat from the urban district heating companies in the largest cities in Sweden. Note that in most cases, the value presented in Table 2 is only one part of the total heat price since consumers also pay for how much heating power they need, although this is not considered in this study.

Table 2. Price of heat from urban district heating networks in Sweden (SEK/MWh).

Provider	**Fortum** [a]	**Mälar Energi** [b]	**Vattenfall** [c]	**Göteborgs Energi** [d]	**Öresunds-kraft** [e]	**EON** [f]	**Average**
Jan	714	440	748	503	866	559	638
Feb	714	440	748	503	866	559	638
Mar	714	388	748	503	866	559	630
Apr	469	388	748	346	485	161	433
May	285	292	309	99	485	161	272
Jun	285	292,00	309	99	123	161	211
Jul	285	292,00	309	99	123	161	211
Aug	285	292,00	309	99	123	161	211
Sep	285	292,00	309	99	123	161	211
Oct	469	292,00	748	346	123	370	391
Nov	469	388,00	748	346	485	370	468
Dec	714	440,00	748	503	866	559	638

Notes: [a] Trygg (subscription form); [b] in Västerås, 2014; [c] in Uppsala, for houses 2014; [d] 2012; [e] in Helsingborg, 2014; [f] for companies, 2013.

2.3. Step 5

The output of the FASSADES tool can be both visual and numerical. For visualisation, two different approaches can be chosen: the mask and a colour range.

The first visual output option is a mask, which can display the surfaces with a production above a certain threshold value for one of the technologies (ST 25 °C, ST 50 °C, ST 75 °C, ST 90 °C or PV) This threshold value can be chosen per technology. Applying a mask has been used in previous research [31,32], but this was always based on irradiation, not on production.

The second option is to show a colour range over the façade, representing the annual production of this surface, per technology (ST 25 °C, ST 50 °C, ST 75 °C, ST 90 °C or PV).

From the FASSADES tool, it is also possible to numerically process the results. If users are interested in the energy production of a specific surface, they can export the hourly production of that surface. This production Ψ is calculated by Equation (4).

$$\Psi_{PV} = \sigma \cdot E_{PV} \quad (4)$$

$$\Psi_{ST} = \sigma \cdot Q$$

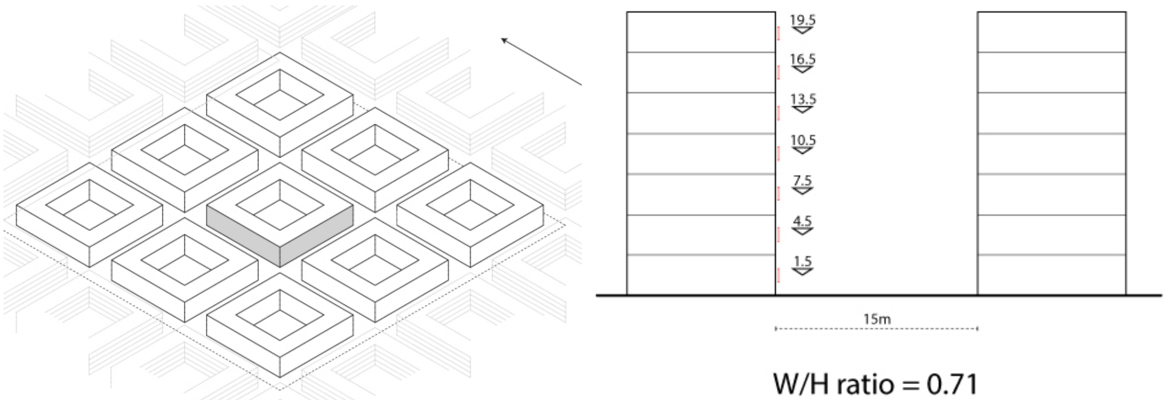
where, Ψ_{PV}, PV output of a surface (W); Ψ_{ST}, ST output of a surface (W); σ, weighting factor (−); E_{PV}, output of the PV system (W); Q_{ST}, output of the ST system (W).

3. Results

The FASSADES tool was used to validate the methodology. The tool was used to assess the energy production and the financial return of ST systems integrated in façades of a typical building block representing a typical urban planning situation in Sweden.

Besides analysing the whole façade, the centre (middle) between two floors (heights of these centres are displayed in Figure 4 were analysed to obtain more detail concerning the shading patterns by surrounding buildings and their effect on the potential for solar energy over the height of the façade. Weather data from Copenhagen was used since it is the closest IWEC data available for the south of Sweden.

Figure 4. The analysed façades and section of the analysed urban canyon.



3.1. Annual and Hourly Production of the Whole Façade

The façades were analysed one-by-one in the FASSADES tool, with a running time of around 3 min per façade. The annual production of the different technologies per façade was visualised, of which some examples are shown in Figure 5.

The production of ST and PV as a function of height on façade is displayed in Figure 6.

The following aspects can be noticed in Figure 6:

- The production of 90 °C heat is very limited and is even 0 kWh on the North façade, due to the relative low irradiation in Sweden;
- The difference between the solar thermal production at 25 °C and ST with the other system temperatures and PV is significant. For example, at z = 19.5 m, the ST production at 25 °C is 314 kWh/m^{2}a, the production of ST at 50 °C is 45% of this value, at 75 °C, it is 21% of this value, at ST 90 °C, 13%, and for PV, the production corresponds to only 29% of the ST 25 °C production. Note also that the ST production (25 °C) on East and West facades is higher than the PV production on the South façade;
- Shading due to surrounding buildings has a significant impact on the solar energy production. The production of almost all technologies decreases by 50%–70% for lower positions

(e.g., 1.5 m) compared to the higher ones (e.g., 19.5 m). This shading effect was also observed in an earlier study [3].

Figure 5. Annual production of ST 25 °C, ST 50 °C and PV at the East façade.

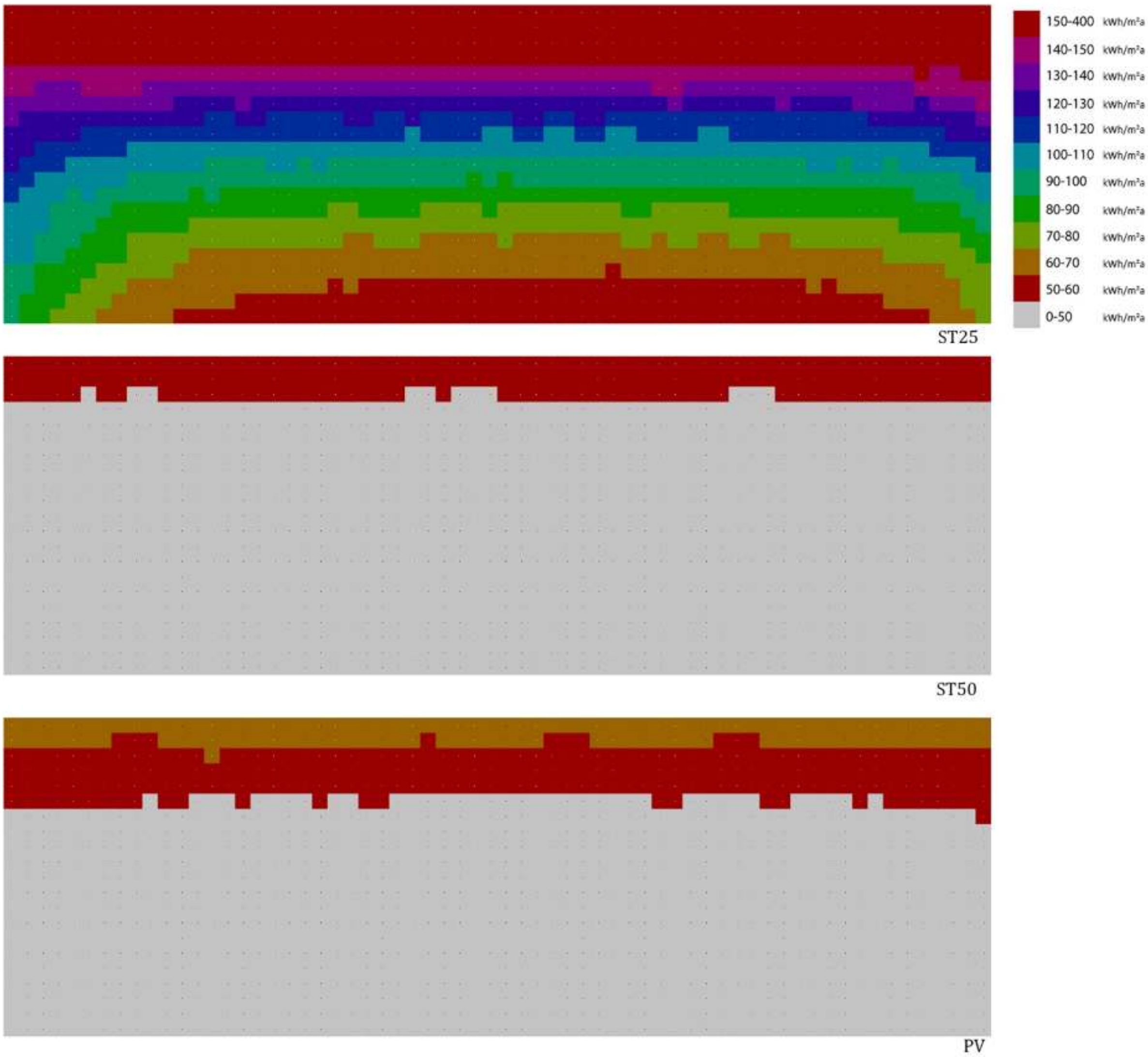
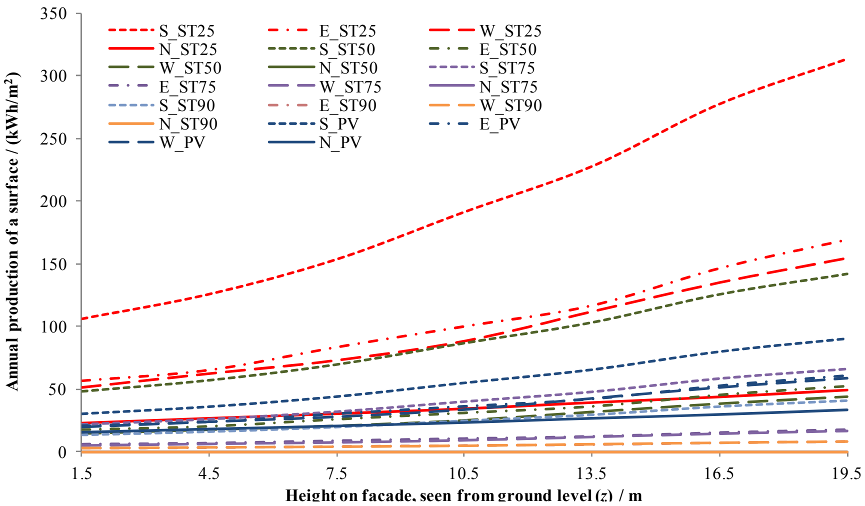
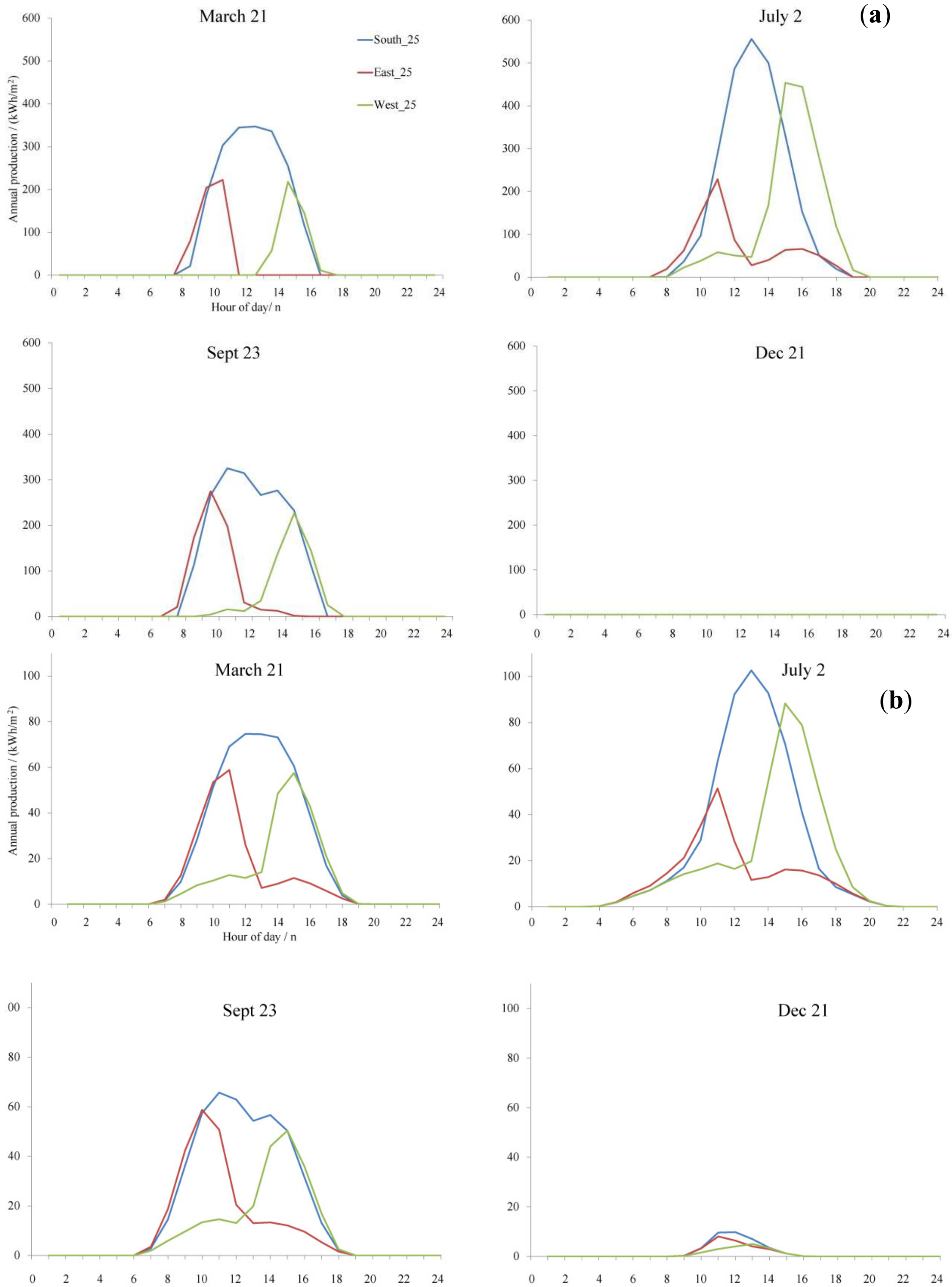


Figure 6. The annual energy production as a function of height from ground.



Since the FASSADES tool is able to export values per surface on an hourly basis, users can also study specific days of the year. As an example, an analysis was performed on four different days of the year in each season: 21 March, 2 July, 23 September, and 21 December. The highest sensor point (z = 19.5 m) was taken to compare the South, East, and West façades. The results are shown in Figure 7a (ST 25 °C) and Figure 7b (PV).

Figure 7. (**a**) Solar Thermal production (25 °C) during the four selected days; (**b**) PV production during the four selected days.



Analysing Figure 7a,b, the following aspects can be noted:

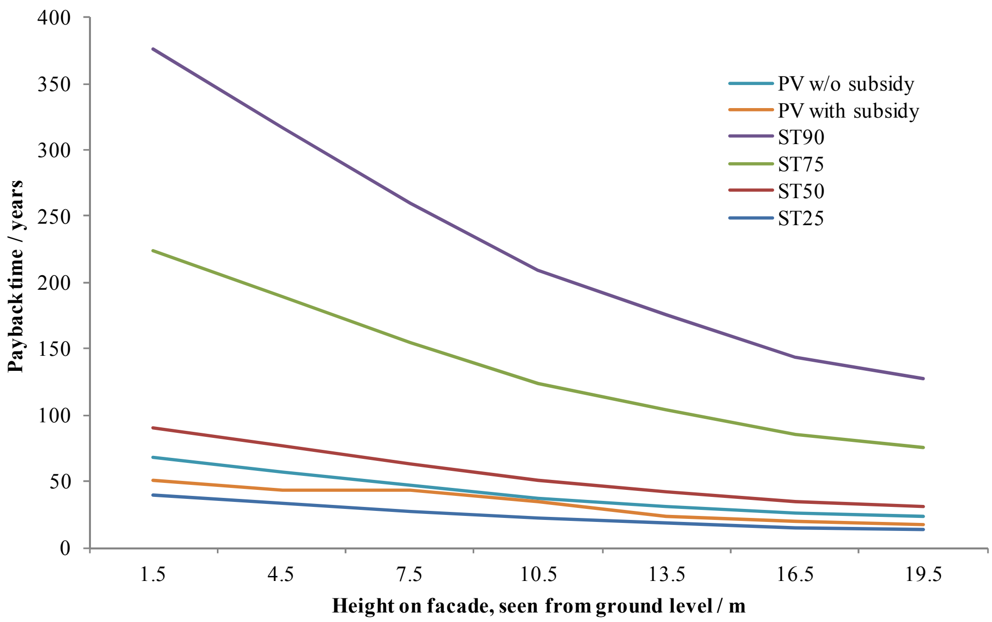
- In the morning, production from the East façade is slightly higher than from the South façade (until 09.00), although differences are very small. In the afternoon, the production from the West façade is higher than the production from the two other facades, especially on 2 July, when the production is notably higher. During the majority of the day, the production from the South façade is higher than from the East and West façades;
- On 21 December, there is no production of solar heat (25 °C) and hardly any production of PV.

Also, the heat production is about 500% higher than the electricity production on the selected days. It is however hard to compare these two different energy sources.

3.2. Assessment of the Whole Façade

The FASSADES tool calculates the production of ST/PV and the economic value of the produced energy; both for heat and electricity, based on current heat and electricity prices. Real estate owners, as well as other people in the position to install solar energy systems in buildings, need to assess the economic benefits of installing solar energy technologies. The payback time is one important metric to calculate the feasibility of investment decisions. Another metric could be the profit after 25 years of use. In this study, a price for Solar Thermal system of 1500 SEK/m^2 was used, and 1666 SEK/m^2 for PV systems. Figure 8 shows the payback time as a function of the height from the ground on the South facade, based on the production as shown in Figure 6 and the economic value of this produced energy.

Figure 8. Payback time as a function of height.



Instead of showing the height from ground level, the production from the South façade *versus* the payback time is shown in Figure 9.

Considering that 25 years is a reasonable payback time, Figure 9 shows the following aspects:

- Installing a ST system providing a system temperature 50 °C, 75 °C, and 90 °C is not financially interesting, since it is unlikely to produce sufficiently on facades;
- Installing a ST system delivering 25 °C heat is economically interesting, especially at higher levels on the façade;
- Installing PV on the façade can be economically interesting, especially with subsidy and on the higher levels of the façade. The differences between subsidised and non-subsidised PV cells are relatively small in the graph, probably because the subsidy is proportional to the investment (Figure 9).

Figure 9 shows that eventually all technologies become economically interesting if the production (and thus irradiation) is high enough; a situation which is hard to reach in dense cities and on facades. Table 3 shows the different production values needed to achieve a certain payback time (5–25 years).

Figure 9. Payback time *vs.* production.

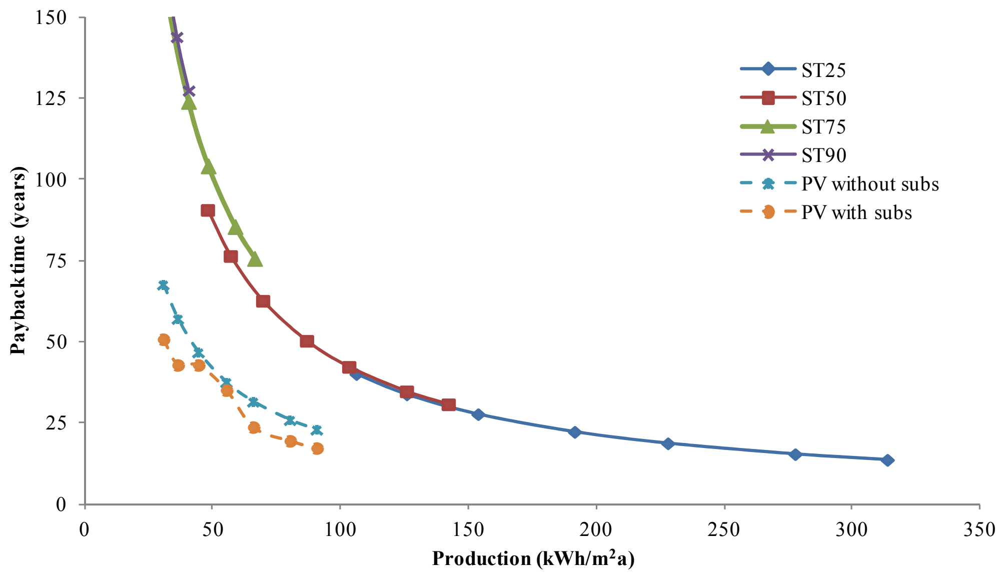


Table 3. Minimum production (kWh/m^{2}a) per technology (for *x* years of payback time).

Years	25	20	15	10	5
ST25	170	213	284	425	851
ST50	175	218	291	437	873
ST75	201	252	335	503	1006
ST90	208	260	347	520	1040
PV w/o	83	104	139	208	416
PV with	76	95	126	189	378

Obviously, production values increase when the surface is unobstructed, on a roof and/or optimally inclined, resulting also in shorter payback times, since higher irradiation values result in a shorter payback time.

The tool also showed that there is a necessity to simulate the output on an hourly basis, since generalising the output by performing only annual analyses—*i.e.*, having one amount of production per year—is not providing the level of detail needed to assess the true value of production, since heat and electricity prices vary greatly over the year (in Sweden). This is especially true for the value of heat; the average annual price of heat is 0.41 SEK/kWh (average of the far right column of Table 2). In reality, the results of the simulation of the building block in this study show that the effective revenue of heat per façade varies per façade (Table 4).

Table 4. Effective revenue (SEK/kWh).

Orientation of façade/system temperature	ST 25 °C	ST 50 °C	ST 75 °C	ST 90 °C	PV (SE4)
South (averaged)	0.35	0.34	0.30	0.29	0.80
East (averaged)	0.32	0.32	0.27	0.26	0.80
West (averaged)	0.31	0.31	0.27	0.27	0.79
North (averaged)	0.28	N/A	N/A	N/A	0.80

If, on average, every produced kWh would save energy, then the values should equal the average price of heat. Table 4 shows that this is not the case, due to the differences in production over the day and year and the corresponding prices at the moment of production. Finding a way to store heat would benefit the economics of ST systems.

4. Conclusions

An assessment and design tool for solar energy on façades was developed by combining Radiance/Daysim and EnergyPlus with DIVA4RHINO. The Radiance/Daysim module performs an annual solar irradiation analysis on unit surface area, while the EnergyPlus program performs an annual solar analysis with an hourly output. Combining the output of the two programs provides the hourly irradiation on the unit surface area.

The next step is the calculation of the production of a unit surface area as a solar panel (ST) or solar cell (PV). The output of the ST is calculated for system temperatures of 25 °C, 50 °C, 75 °C, and 90 °C. Then, the economic value of the produced energy is predicted by taking into account the current local heat and electricity prices. The payback time is then calculated based on the investment costs and the annual revenues.

The tool was validated by applying it to an analysis of a typical Swedish building block. The results showed, amongst others, that PV and ST (25 °C) for unshaded façade surfaces are the only technologies providing a payback period shorter than 25 years. Shading due to surrounding buildings significantly affects both the irradiation and production, leading to long payback times.

The results also highlighted that a detailed simulation on an hourly basis is needed to fully assess solar energy potential production and cost benefits.

The FASSADES tool can be improved further: at the moment, only one part of the building envelope at a time can be analysed. Another improvement would be to make the tool easier by using user-defined objects, limiting the knowledge level needed to use the tool.

Calculations performed in the FASSADES tool depend on many parameters, which could cause errors: many assumptions are being made, especially regarding the financial costs and benefits.

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Author Contributions

The co-authors contributed actively to the discussion of this research and in reviewing the article.

Conflicts of Interest

The authors declare no conflict of interest.

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