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Typical values for active solar energy in urban planning

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Abstract

There is an urgent need to start generating energy within cities in order to pave the way for a more sustainable and resilient society. Renewable energy by means of active solar energy systems (solar thermal, ST and/or photovoltaics, PV) can be generated using roofs and facades of buildings. In this study, the annual solar energy potential of typical Swedish city blocks was analysed in order to develop guidelines for urban planners and architects. The results show that the design of the city blocks has a significant effect (up to 50%) on the total annual solar energy production. The study also shows that the contribution from active solar energy can be significant even in the urban environment, but shading by adjacent buildings may greatly limit the total amount of energy produced.

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1. Introduction

Cities are home to more than half of the world population [1] and consume the majority of global energy [2] and resources. Future cities will be faced with the necessity to reduce their energy demand significantly while shifting to local urban energy production systems. Political instruments, such as the energy performance of buildings directive (EPBD) [3], are already in place to prepare for net zero-energy buildings, and eventually, net zero-energy communities and cities in the European Union. An increased use of active solar energy as well as an awareness of the passive use of solar energy -by solar gains and daylight- is needed to reach sustainable solutions. Smart planning of new urban districts will help cities to reach their goals of energy reduction and energy production; in such a way that urban districts could become more self-reliant [4].

The urban design process is a complex one with a range of stakeholders taking various decisions at each stage of the process. Solar energy is just one of the many parameters affecting this process [5], but paradoxically, the energy

yield of solar systems is very dependent on design decisions made in the early stages of the design process. Besides the design of the cityscape, other key issues to accelerate the implementation of solar energy in the urban environment are: legal framework, processes, methods and tools, good examples, and further education [6].

Architects and urban planners are amongst the actors shaping new urban districts and by making right and informed decisions, future buildings can be both energy efficient and energy self-reliant. Building Performance Simulation (BPS) tools can support the decision-making process regarding solar energy [7-11] as will be demonstrated in this study.

1.1. Density

The layout and density of urban districts are two of the most important parameters to consider in the early design phase. The density of the urban fabric is expressed by the Floor Space Index (FSI), Plot Ratio or Floor Area Ratio (called FSI in the rest of this article). Formerly defined, the FSI is the ratio of a building's total floor area in relation to the size of the plot on which it is built, see Figure 1. A plot with no buildings on it has a FSI of 0. Building the same amount of floor area as the plot area results in a FSI of 1; two floor slabs covering the entire plot results in FSI=2 etc. The same FSI can thus be reached by adjusting the ground floor area and the amount of floors in a building, as shown in Figure 1. Also, a site with a large unoccupied space and a high FSI will result in tall buildings. Table 1 shows the FSI of different cities. Note that in some cases, the maximum allowed FSI is per plot, and that the FSI is only per building plot, not including streets, which explains why some cities are known to be very spread (like e.g. San Francisco compared to Amsterdam or Paris). Note that it is difficult to provide an overview of FSI of cities in the world due to differences in calculation methods.

Table 1. Overview of FSI in different cities [12]

City	Floor Space Index	City	Floor Space Index
New York	10-15 (centre)	San Francisco	9 (maximum)
Central Amsterdam	2	Hong Kong	12
Paris	3	Los Angeles	13 (centre)
Bangkok	8 (maximum in centre)	Singapore	2.8 (maximum)

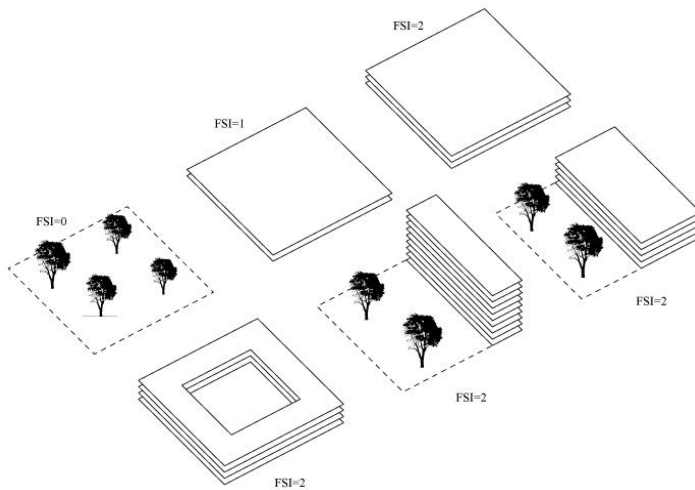


Figure 1. Principle of Floor Space Index (FSI).

1.2. Solar energy potential

Every building has a solar energy potential, which is the amount of energy that can be produced using building surfaces covered with photovoltaics (PV) or solar thermal (ST) systems. In this research, a parametric study was carried out, based on typical layouts and densities of Swedish urban city blocks in order to investigate the effect of the urban layout and density on the solar energy potential. The results of this analysis will provide guidelines for urban planners when designing new urban districts.

2. Method

Four typical Swedish city blocks designs were modelled based on city blocks in the Southern cities of Malmö and Lund (Figure 2); two of them based on existing city blocks (Rörsjöstaden and Norra Fäladen), and two of them based on planned city blocks (Hyllie and Brunnsbög). As can be seen in Figure 2, the three designs Rörsjöstaden, Hyllie and Brunnsbög are relatively similar and generally present a rectangular “donut” shape. Note however that Hyllie is more square than Rörsjöstaden and Brunnsbög. In Rörsjöstaden, the buildings have a pitched roof while all other designs have a flat roof. In Norra Fäladen, the buildings are scattered differently on the plot.

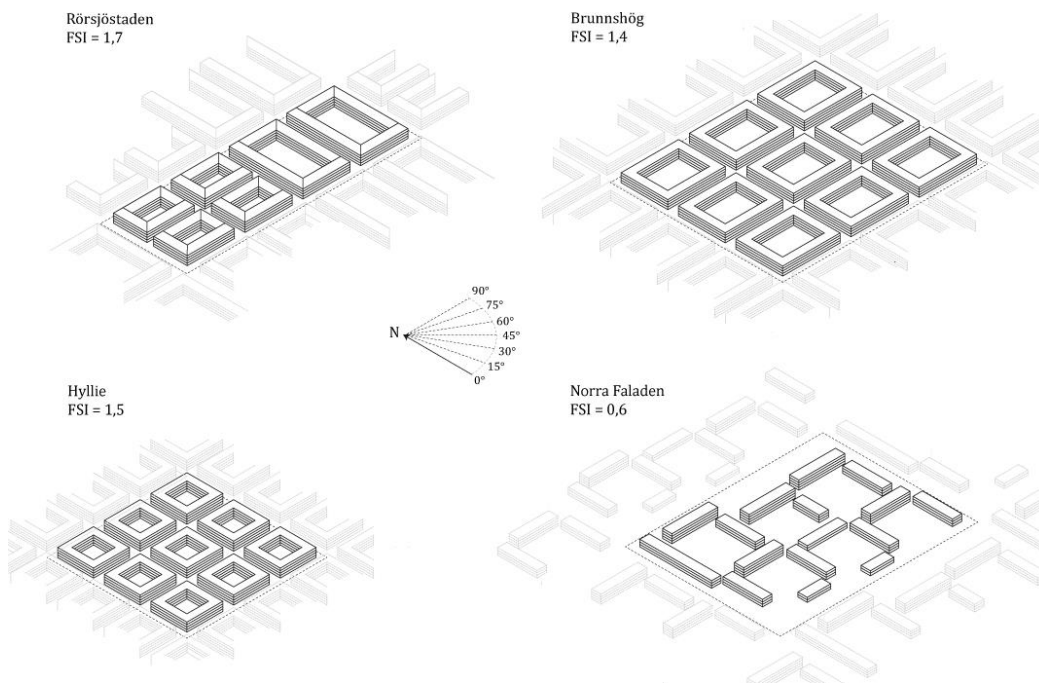


Figure 2. The four simulated city blocks and their actual FSI.

In addition to studying the impact of urban design layout on solar energy production, this study analysed the effect of ‘rotation’ and ‘density’ of the city block on annual solar energy production. The rotation of the city blocks varied from 0° to 90° counter clockwise (with 15° increments) with respect to South (Figure 2). The density ranged from 0.5 to 2.5 FSI. The four modelled city blocks had an existing density (as displayed in Figure 2), but for the present study, the FSI was virtually altered by adding or deleting floors in the 3D models (Figure 3). Important to notice is that the city blocks are modelled with equally dense adjacent city blocks, streets and courtyards similar to the real world situation.

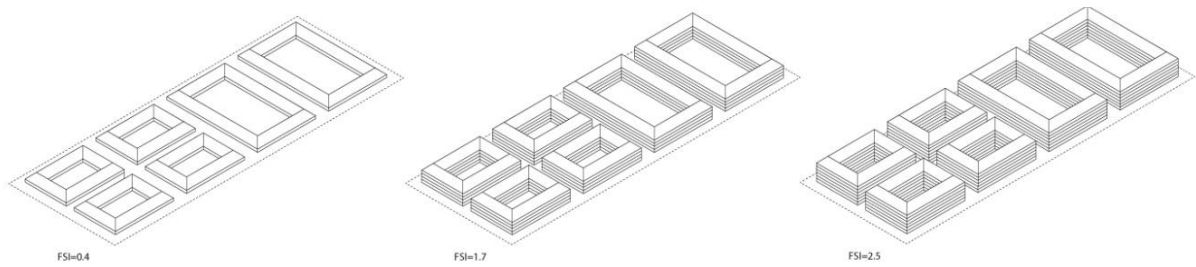


Figure 3. Alternation of density (FSI) of Rör sjö staden

The four city blocks were modelled in Rhinoceros [13] with the help of information from the urban planning departments of Lund and Malmö. The annual solar irradiation analysis was performed in DIVA-for-Rhino (D4R), a Radiance based program [14] embedded in the CAAD program Rhinoceros using the GenCumulativeSky [15] model for solar radiation. Settings for these simulations were as presented in Table 2. Many of these parameters are default values in the DIVA-for-Rhino program and will be used in the Radiance engine for performing the simulation. The ambient bounces setting – the maximum number of different bounces computed by the indirect calculation- was however altered to increase the accuracy. The reflectance value was set to resemble the reflectance of surfaces, roofs, and ground.

Table 2. Settings of DIVA-for-Rhino

Parameter	Setting	Parameter	Setting
Ambient bounces	5	Start date	01 01
Ambient divisions	1000	End date	12 31
Ambient super-samples	20	Hour range	00 24
Ambient resolution	300	Geometric density	100
Ambient accuracy	0.1	Reflectance of facades and roof	35%
Weather data	Lund (Meteonorm)	Reflectance of ground plane	20%

The next step consisted of comparing the total annual solar irradiation with the energy demand of the buildings. The surfaces on the roof and façade which received an annual solar irradiation superior to 650 kWh/m²a were considered suitable, which is justified in an earlier study [16]. This threshold is dependent on many parameters; a study by Compagnon [10] suggested a value of 800 kWh/m²a for PV, but in this case 650 kWh/m²a was selected to achieve a shorter payback time than the life time of the system in the Swedish context.

Furthermore, the suitable area was considered to be split into photovoltaic (PV) systems (80% of the surface, 20% efficiency) and solar thermal (ST) systems (20% of the surface, 40% efficiency). Solar thermal and PV systems behave differently if they get shaded: if ST systems get shaded partly, in most cases, the output will decrease accordingly. For PV systems however, the output drops more than proportionally. In this case, the difference in behaviour between the two different technologies was omitted. Windows, lift shafts, and other installations were considered to cover 25% of the suitable area. The electricity need of the buildings was considered to be 50 kWh/m²a, consisting of 20 kWh/m²a for common electricity use [17] and 30 kWh/m²a for household electricity [18]. The space heating demand was set at 20 kWh/m²a, which can be reached in Sweden with a very low energy design [19]. Taking these assumptions into consideration, the heating coverage (amount of heat produced / heat demand) and the electricity coverage (amount of electricity produced / electricity demand) was calculated.

Two hypotheses were tested: 1) the Norra Fälåden design will perform poorly compared to the other designs due to self shading and 2) the Rör sjö staden will perform better than the Brunns hög design due to its pitched roofs.

3. Results

The computer tool D4R can provide both graphic and numerical results. In section 3.1., graphical results are presented while section 3.2. provides numerical results.

3.1. Graphical results

The direct embedding of D4R into the CAAD program Rhinoceros is advantageous since it does not require extra translations or additional programs to show results and it is possible to analyse the results interactively, i.e. the user is able to use the results in various ways. One way is simply to show the annual solar radiation on the analysed geometry (Figure 4, top).

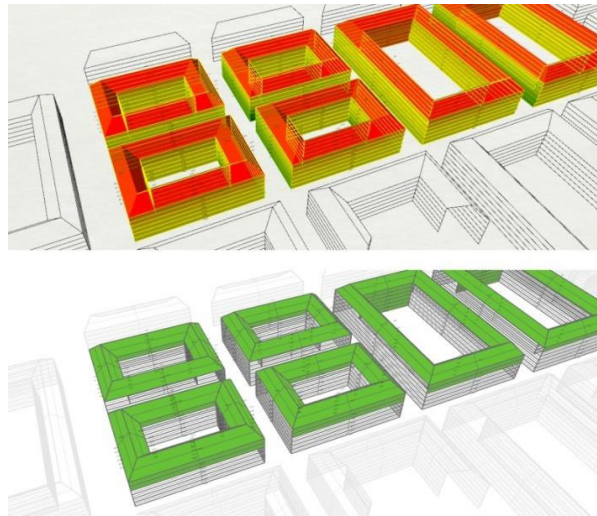


Figure 4. Interactive use of results

Another way to display the results is by using a filter. An example of such a filter is shown in Figure 4 (bottom), where the green surfaces represent surfaces that receive an annual solar irradiation superior to $650 \text{ kWh/m}^2\text{a}$. By applying such a filter, architects and urban planners get direct feedback about the most valuable surfaces for the design.

3.2. Numerical results

In this section, the focus is on the annual electricity coverage, followed by the annual heating coverage, and the annual energy coverage. Figure 5 shows the annual electricity coverage of the four building blocks. A 100% coverage means that the annual electricity produced by PV equals the annual electricity use.

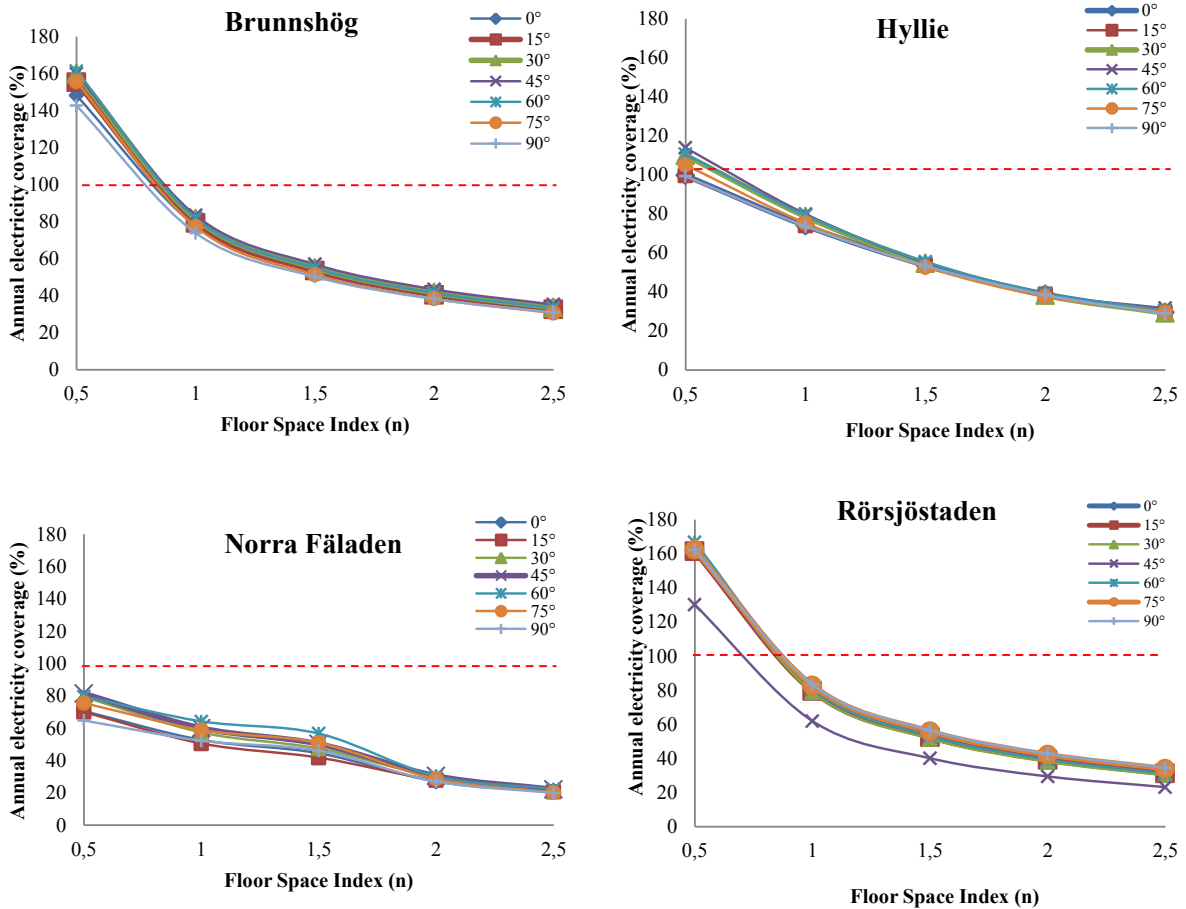


Figure 5: Annual electricity coverage at different densities

The four graphs in Figure 5 show that there is a significant difference in annual electricity coverage due to the layout of the city blocks, especially for the lowest densities. In general, it can be seen that for the higher densities (>1.5), the absolute differences between the different layouts are less significant. The reason for this can be explained by the decreasing suitable area (roof area plus suitable facade) per floor area. At lower densities, the amount of suitable area is relatively high compared to the floor area, while at higher densities, this ratio decreases. The patterns of Brunnskö and Rörjsjöåden are almost identical, also at lower densities. Hyllie does not follow the same pattern as Brunnskö, although their geometry is quite identical (Brunnskö is a bit more rectangular). The irregular pattern in the results obtained for Norra Fälåden is most likely caused by its special “scattered” geometry increasing the impact of self shading.

Furthermore, the rotation of the building blocks did not have as much impact in the Brunnskö, Hyllie and Rörjsjöåden layouts as expected, except for the Rörjsjöåden 45° rotation, which provided less energy covering for all densities. This is due to the fact that, at exactly 45° , a big part of the roof received slightly less than the threshold due to shading at the place where the two sloped roof surfaces meet.

The results also show that rotation has a larger impact in the Norra Fälåden layout compared to the other layouts. Note, in addition, that differences between orientations also became less significant at higher densities.

Figure 6 shows the heating coverage of the building blocks. This figure shows similar patterns as in Figure 5, which was expected since the only difference lies in another efficiency of the solar technology and energy demand. The only difference is thus found in the absolute values.

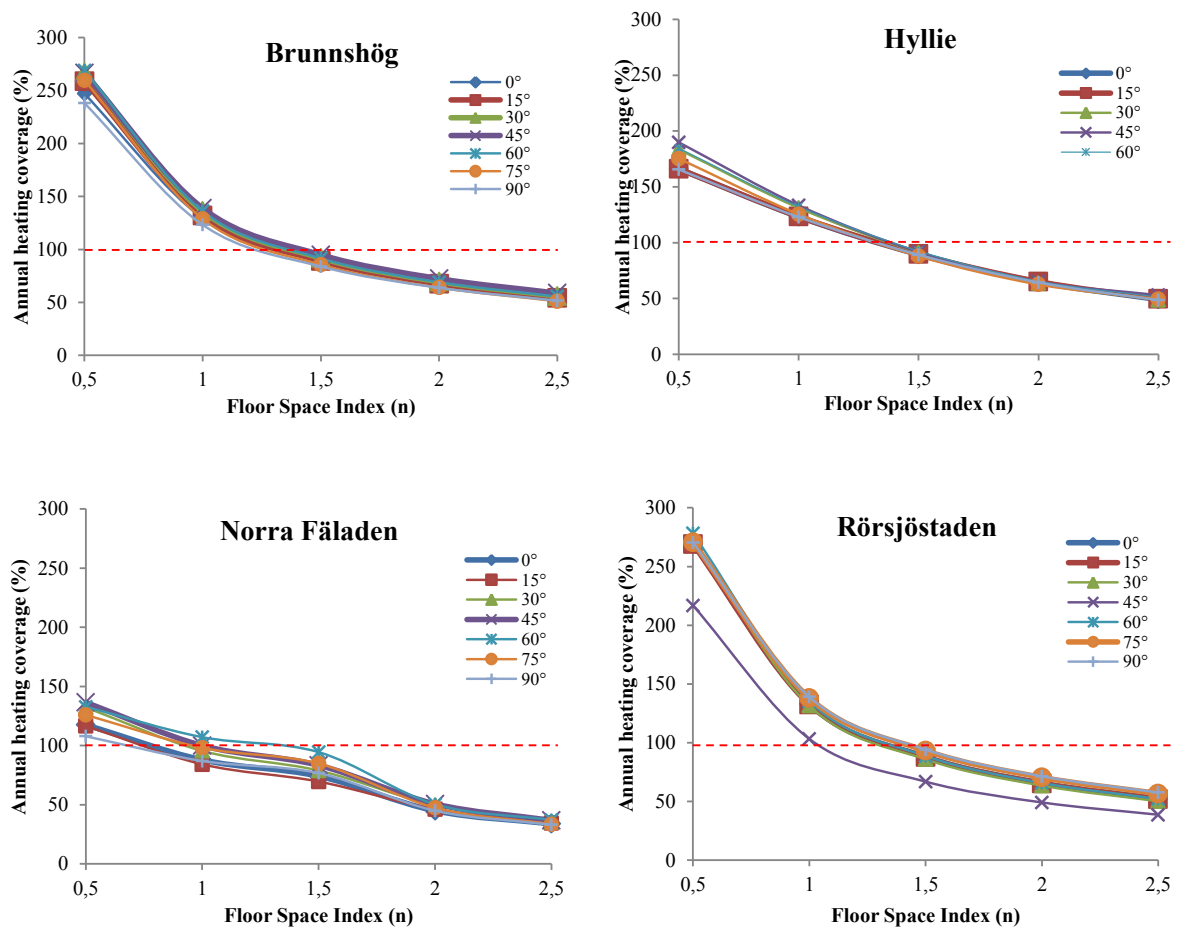


Figure 6: Annual heating coverage at different densities

The annual energy coverage can be calculated for the different building blocks by summarising the produced electricity and heat, divided by the total energy need of the building blocks. Summarising heat and electricity is often done by taking conversion factors into account, but for the sake of simplification, this is not done in this study. Figure 7 shows the annual energy coverage, in which the average of all rotations is calculated per layout.

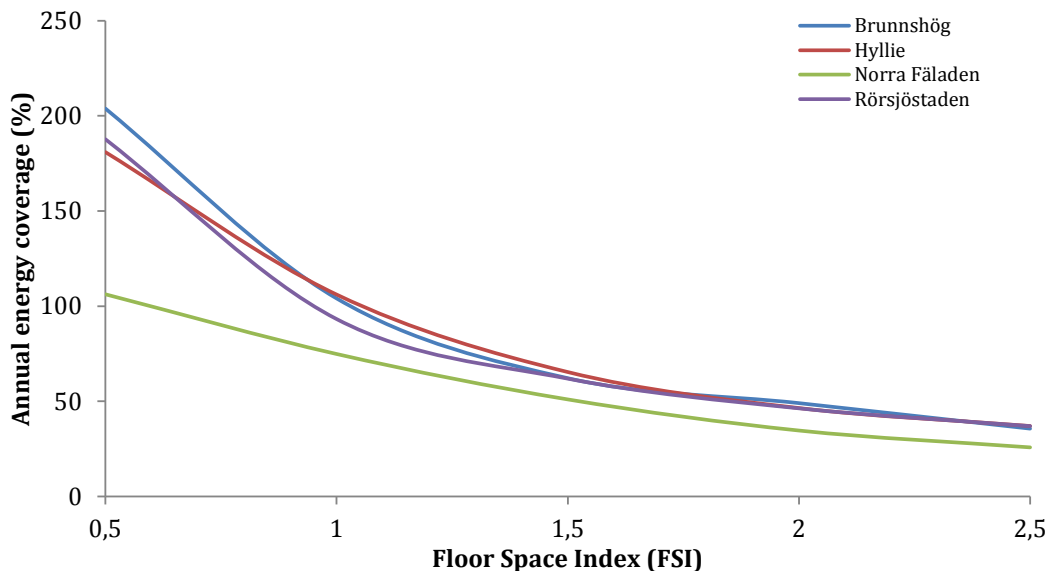


Figure 7. Annual energy coverage

It becomes clear that Brunnshög, Rörsgästaden, and Fäladen have almost identical values and patterns. The pattern which clearly stands out is the one of Norra Fäladen. Table 3 shows the normalised energy coverage of all building blocks per FSI (0.5; 1; 1.5; 2; 2.5) (the maximum energy coverage per FSI is underlined) and emphasises the differences between the different layouts, orientations and densities.

Table 3. Annual energy coverage per city block (%)

FSI	Brunnshög	Hyllie	Norra Fäladen	Rörsgästaden
0.5	<u>1.00</u>	0.89	0.52	0.92
1	0.98	<u>1.00</u>	0.71	0.88
1.5	0.95	<u>1.00</u>	0.78	0.95
2	<u>1.00</u>	0.95	0.71	0.94
2.5	0.96	<u>1.00</u>	0.70	0.99

Table 3 shows that the maximum energy coverage for FSI=0.5 is for the Brunnshög design. For FSI=1 and 1.5, it is the Hyllie design, for FSI=2, it is the Brunnshög design, and for FSI=2.5, it is the Rörsgästaden design. The differences between the Brunnshög, Rörsgästaden, and Norra Fäladen design were minimal especially for the higher densities, often within a range of 10%. The biggest differences were seen at the Norra Fäladen design, differing at a maximum of 48% for FSI=0.5, similar to the heating coverage and electricity coverage as shown in Figure 5 and 6.

4. Discussion and conclusions

A parametric study was carried out to evaluate the solar energy potential of four common designs of city blocks in Sweden. In addition to design layout, the evaluated parameters were density and rotation. Surfaces on the building envelope -roof and facade- were considered to be suitable when they received more than 650 kWh/m²a. The solar energy potential of the city blocks was simulated with DIVA-for-Rhino and was expressed as the energy coverage, i.e. the energy produced by solar energy divided by the amount of energy used in the building blocks. Two hypotheses were stated at the beginning of the study: 1) the Norra Fäladen design will perform poorly compared with the other designs and 2) the Rörstaden will perform better than the Brunnsög design due to its pitched roofs.

The first hypothesis was confirmed. In none of the cases did the Norra Fäladen design return the highest energy coverage. This configuration also proved to be more unpredictable than the others, i.e. the energy coverage varied in a “chaotic” way for different densities and rotations. The design of the Norra Fäladen design consisted of various scattered building blocks, resulting in strong mutual shading effects.

The second hypothesis was infirmed. The building blocks with a pitched roof did in most cases not return much higher energy coverage, as expected. The Rörstaden design was comparable to the Brunnsög and Hyllie design, which basically had the same design but with flat roofs. The design of a roof solar system should obviously be kept in mind; a flat roof can have a high potential, but the setup of the system –number of rows, row distance, and inclination- also plays a crucial role in converting these flat roofs into energy producing surfaces. In the present study, the collectors were assumed to lay flat on the roof (no inclination resulting in no mutual shading, no row distance).

Furthermore, results show that 100% coverage or higher with solar energy can be achieved only for low densities (FSI<1.25) for the studied conditions in Sweden. This study thus confirms the fact that a significant contribution could come from active solar energy but that solar energy systems need to be supplemented by rigorous energy conservation measures and other renewable energy sources like wind, geothermal energy, waste heat, etc.

One great limitation of this study concerns the issue of annual versus monthly or hourly production and coverage by means of solar energy. A further study into the monthly and even hourly coverage would be very useful, since the amount of solar energy fluctuates significantly during the year and day in Sweden.

Another limitation is to ignore the difference in behaviour between solar thermal and PV systems. Also, the assumption to have 80% PV and 20% ST has a big impact on all the absolute values in this study, however, the patterns and relative differences between the designs would be the same.

Overall, this study shows that quantifying the solar energy potential of city blocks in an early design stage and providing a visualisation and quantification of the solar energy potential facilitates the comparison of design alternatives leading to a successful design. In the urban design process, it would be beneficial if this information is passed on to the architects of these buildings. Also, these solar potential studies can provide an underlying document for real estate owners who want to perform a cost and benefit analysis.

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