

Impact of passive solar design parameters on an office building energy use in Serbia

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Abstract:

It is widely accepted among architects, civil, mechanical and electrical engineers today that due attention has to be paid during building design process to energy saving, daylight use, advancing heating and cooling by exploiting solar energy, improving natural ventilation and minimizing environmental impact. Although reduction in building energy use can be achieved by using relatively simple individual measures, high performance requires coherent use of distinct measures that jointly optimize complete building performance. We study here relationships of passive solar design parameters – glazing type, windows-to-wall ratio of façades, presence of shading on the southern façade, and U-value of opaque envelope components – with total energy demand in an office building in prevalent climatic conditions in Serbia, through EnergyPlus simulations of all combinations of selected parameter values for a case study of an office building. Current building regulations in Serbia prescribe the use of highly efficient glazing in building design, together with low U-value of opaque envelope components and high building airtightness. As a consequence, cooling energy needs become more important than heating energy needs, contrary to customary design practice in Serbia. Simulation results suggest that the optimal windows-to-wall ratio for the southern façade stems toward the minimum feasible value, while the optimal windows-to-wall ratio for the northern façade has a nontrivial value, due to the positive impact of larger northern windows-to-wall ratios on the cooling demand. Results further show that the shading of southern windows is not necessary for small windows-to-wall ratios of the southern façade. However, with shading present, the architect obtains greater freedom in selecting larger southern windows-to-wall ratio, while maintaining proximity to optimal solution.

Keywords:

Passive solar design, Office building, Building energy simulation.

1. Introduction

Building energy use essentially depends on the way we plan, design, and build, and represents an important factor of climate change. Buildings are durable with at least 50-100 years of expected lifetime, so that building decisions have long-lasting consequences. One of such consequences is that buildings are one of the largest energy consumers today, with a significant amount of energy used for heating and cooling. It is generally agreed among architects, civil, mechanical, and electrical engineers today that in the design process due consideration has to be given to reducing energy use, natural daylight, increasing solar energy use for heating and for cooling, improving natural ventilation and reducing environmental impact, all without reductions in comfort or the living standard. This agreement is evident through various concepts of low energy buildings, and mostly implemented through improvements in building envelope, the use of highly efficient technical systems, and the use of renewable energy sources. The concept of nearly-zero energy buildings, set as the goal for all new buildings in EU by 2020, requires building's energy efficiency to be raised to the next level through a coherent use of passive and active measures that reduce energy use and exploit renewable energy sources. Since the passive measures are both more cost effective and more influential than the active measures (see, e.g., [1,2]), the determination of an optimal combination of passive measures, and in particular passive solar design measures, is a necessary first step in any such effort.

Our goal here is to study design parameters that significantly influence the ratio of solar energy utilization for reducing energy use in office buildings in Serbia:

- structure and thermal characteristics of building envelope;
- windows-to-wall ratio (*WWR*) of façades;
- window types and their thermal characteristics;
- sunshading elements.

The influence of these parameters is estimated through a case study in which we determine and study optimal combinations with respect to total energy use, among all combinations of selected values of these parameters in the design of an office building.

The paper is organized as follows. In Section 2 we give a short review of similar studies in the literature, in Section 3 we describe the case study and its energy simulation, while in Section 4 we analyse and discuss simulation results. Lastly, Section 5 contains simulation results for PV plant added to the roof of the building, showing that optimal combinations are positive energy buildings.

2. Literature review

We first give a short review of earlier studies with goals similar to ours. A more comprehensive review of passive solar design optimization studies may be found in our survey paper [3].

Poirazis et al. [4] study the influence of façade construction and plan type on the energy use for heating, cooling, lighting and mechanical ventilation through a parametric study of a single skin, six storey, late 1990s office building located in Gothenburg, Sweden. The design variables include *WWR*, seven window types, two plan types and three heating/cooling setpoint combinations. The results suggest that a proper combination of glazing, shading and control setpoints may lead to only 15% increase in the energy consumption of fully glazed buildings, compared to the reference building having 30% *WWR*.

Tsikaloudaki et al. [5] study the cooling performance of windows in office buildings in the Mediterranean region through parametric studies of a typical office module with moderate level of wall insulation, located in Athens, Larnaca, Lisbon, Malaga and Rome. The design variables are *WWR*, frame-to-glazing ratio, glazing thermal and solar transmittances, window orientation and level of external shading. They notice that advanced fenestration products may increase cooling load, as their extremely low thermal transmittance prohibits the dissipation of the heat from internal gains to the outdoor environment.

Leskovar and Premrov [6] study optimal *WWR* values that minimize total annual heating and cooling energy use for a case study of a two-storey house with prefabricated timber-frame structural system, located in Ljubljana, Slovenia. The house is well-insulated, using triple low-e glazing, overhangs on the south and external vertical shading devices on the west and the east facades. The design variables are *WWR* values of each façade, three timber-frame macro-panel systems and the building orientation. The results indicate that the optimal *WWR* for walls with very low U-values is smaller than in walls with higher U-values.

Persson et al. [7] evaluate the influence of the size and orientation of triple glazed, low-e windows on heating and cooling energy loads on a case study of terraced passive houses in Gothenburg, Sweden. The results show that the size of triple glazed, low-e windows does not have a major influence on the heating load, due to the extremely well-insulated walls and the efficient ventilation system, but it is relevant for the cooling load. The optimal solution has smaller window area facing south and larger window area facing north when compared to the already built houses.

Gratia and Herde [8] study energy-efficient design of office buildings in the Belgian climate with respect to the building insulation level, airtightness, internal gains control, *WWR* values for different external wall orientations, ventilation strategy and thermal mass use, through several parametric

studies on the case studies of two office buildings located in Uccle, Belgium. Their findings indicate great importance of windows area and glazing type on the building energy use.

Yıldız and Arsan [9] identify the most significant parameters of energy performance among 35 parameters related to building design, HVAC and lighting for buildings in hot-humid climates by considering an existing 10-storey apartment building in Izmir, Turkey. The study indicates that the total window area, glazing U-value, its solar heat gain coefficient and the building aspect ratio have the largest influence on the energy performance.

The above mentioned studies suggest that the wall insulation, *WWR*, glazing type and the presence of shading belong to the most relevant passive solar design parameters. They also observe that in highly insulated buildings the optimal *WWR* for the southern façade tends to be smaller than the optimal *WWR* for the northern façade, as the advanced glazing with high solar fraction and low thermal transmittance has a negative impact on the cooling load. In the next section, we will confirm these observations, as well as obtain some further clarifications, through a case study of an office building in a sunny and continental climate of Belgrade, Serbia.

3. The case study

3.1 The building shape

The case study is a four-story office building located in Belgrade, Serbia, whose floor plan (see Fig. 1a) represents an open plan, team office. References [1,10-12] suggest that the optimal shape of a rectangular building tends to be either a square, which minimizes ratio of the building volume and the envelope surface area, or a rectangle with the ratio of sides between 1.3 and 1.5, with the longer side oriented toward south, which better exploits solar gain during the heating season. Due to the light propagation depth of 7m, the building model for the case study is chosen to have a rectangular floor shape of dimensions 20m x 14m, with the sides ratio of 1.43. The floor height is 4m, so that the building model has a simple cubical form (see Fig. 1b).

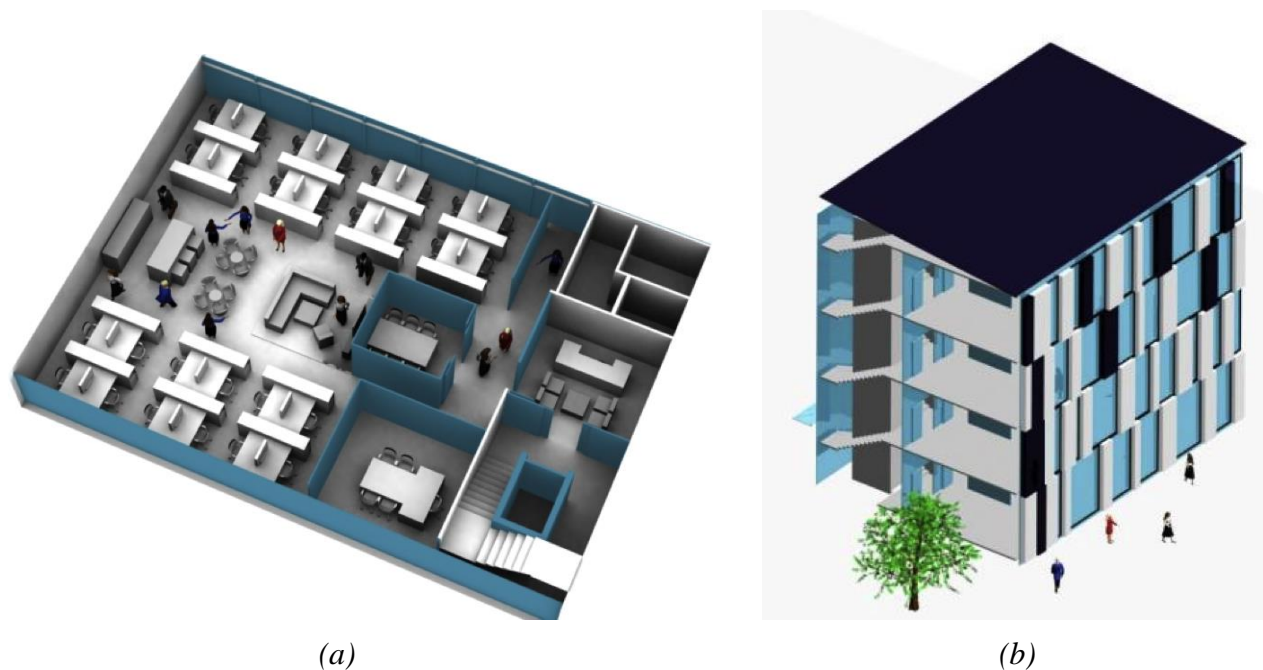


Fig. 1. The case study office building: a) elevated floor plan, b) section showcasing architectural perception of the southern façade with *WWR* of 62.5%.

3.2 Opaque envelope components

The basic task of opaque envelope components is to provide the best possible thermal insulation of the inner space. The building model is chosen to have a contact façade, with its outer walls consisting of:

- plastic stucco 0.5cm,
- graphite-enhanced expanded polystyrene (EPS) with one of three predefined thickness,
- clay brick 25cm, and
- cement-lime plaster 2cm.

Three different EPS thicknesses were selected for the study:

- 10cm, yielding thermal transmittance of walls of 0.283 W/(m² K),
- 15cm, yielding thermal transmittance of walls of 0.201 W/(m² K), and
- 30cm, yielding thermal transmittance of walls of 0.107 W/(m² K).

The remaining opaque envelope components have constant U-values: floor on the ground has the U-value of 0.264 W/(m² K), floors between stories have the U-value of 0.416 W/(m² K), while the roof has the U-value of 0.147 W/(m² K).

3.3 Glazing

Glazing has important influence on several functions within a building:

- its thermal transmittance U_g is essential for preservation of heat energy,
- its solar heat gain coefficient g determines the proportion of utilization of available sun energy during the heating season, while
- its visible light transmittance LT is important for provision of natural daylight during the working hours and reduces the need for artificial lighting.

Six types of Pilkington glazing [13], whose characteristics are outlined in Table 1, have been chosen as alternatives for this case study. Data have been based on 90% argon filling.

Table 1. Glazing types considered as alternatives in the case study [13].

Type	Panes	Glazing properties		U_g , W/(m ² K)	g , %	LT , %
		Thickness	Glass configuration			
G1	2	4+16+4	Optifloat Clear + K Glass (#3)	1.5	72	74
G2	2	4+16+4	Optifloat Clear + Optitherm S3 (#3)	1.1	61	80
G3	3	4+12+4+12+4	Optitherm S3 (#2) + Optifloat Clear + Optitherm S3 (#5)	0.7	50	71
G4	2	6+16+6	Optifloat Grey + K Glass (#3)	1.5	42	36
G5	3	4+16+4	Optitherm S1 (#2) + Optitherm S1 (#3)	1.0	38	61
G6	2	6+16+6	Eclipse Advantage Arctic Blue + Optitherm S1 (#3)	1.0	21	31

Labels #2, #3 and #5 in Table 1 denote the ordinal number of the glazing surface to which the low-emissivity coating was applied, counting from the exterior surface. K Glass, Optitherm S1 and Optitherm S3 have low-emissivity coatings to improving their thermal performance. Optifloat Grey and Eclipse Advantage Arctic Blue are solar control glazings with low solar heat gain coefficients.

Frames used in the case study have the properties of Rehau Geneo PHZ profile systems [14] with thermal transmittance $U_f = 0.79$ W/(m² K) and linear thermal transmittance $\psi_g = 0.030$ W/(m K).

3.4 Windows-to-wall ratio

The *WWR* values for the southern and the northern façades are independent of each other in the case study, in order to determine the optimal *WWR* separately for each façade. The minimum *WWR* for both façades amounts to 25%, since the minimum window area equals 1/7 of the floor surface in Serbian building regulations [15, Art. 13] and the daylight propagates up to 7m within the interior. The maximum *WWR* for both façades is 100%, while the remaining feasible *WWR* values are obtained in steps of 12.5%.

3.5 Shading

The case study building uses horizontal brise-soleils as exterior shading for the southern façade. As the maximal daily temperature exceeds 27°C from the third decade of May until the second decade of September, brise-soleils need to completely shade the window surface at the zenith at least during this period. The sun angle at the zenith increases from 66° on May 20 to 69° on June 22, and then decreases down to 46° on September 20. The width and the vertical distance between the slats are thus set equal to 10cm each, with slats having horizontal inclination. The brise-soleils are folded during the heating season to ensure full exploitation of passive solar heating, and unfolded during the cooling season.

3.6 Other case study settings

The working hours are set from 8am to 4pm, five days per week. It is assumed that 50% of the employees are present in the building from 7.30am to 8am and from 4pm to 4.30pm. Internal heat gains have been taken in accordance with the guidelines published in Energy Consumption Guide 19 [16] and recently updated CIBSE Guide F [17].

The case study has LED artificial lighting with consumption of 3 W/m² per 100 lux. According to Serbian regulations [18], necessary light intensity on desk surface in office spaces is 250 lux, so that, in the absence of daylight, artificial lighting consumes 7.5 W/m². Lighting has linear control with a photo sensor placed in the center of each floor at desk height (80cm). Its consumption is well correlated with façades' *WWR* and glazing *LT*.

Fresh air is provided by a combination of natural ventilation and mechanical ventilation with heat recovery. It has been observed in [19] that natural ventilation is an effective cooling measure in climates where the daily difference between the maximal and the minimal temperature is at least 10-12°C during the cooling period. This is satisfied in Belgrade, where the daily temperature oscillations are 10,4°-10,5° from May to July and 11,7°-11,9°C in August and September. Natural ventilation is provided both during the working hours and at night from 10pm to 6am, out of the heating season, and applied when the zone's internal operating temperature is higher than both 22°C and the outside temperature.

Heating and cooling is provided by a heat pump. A relatively small hot water consumption of 0.2 l/m² in the office building is covered by the heat pump, which uses 688 kWh of electricity annually for this purpose.

The remaining case study settings, important for building energy simulations, are shown in Table 2. Monthly climate parameters for Belgrade, taken from [20, 21], are given in Table 3.

3.7 Simulation process

Building energy use was simulated with EnergyPlus. The time step was set to 10 minutes, natural ventilation calculation method to "Calculated", and HVAC design to "Simple" with autosizing. Since each floor represents an open office with the minimal presence of partition walls, each floor was treated as a single zone in simulations.

As seen above, the case study has several variable parameters—3 possible EPS thicknesses, 6 northern window types, 7 northern *WWR* values, 6 southern window types, 7 southern *WWR* values and 2 possibilities for the presence or absence of the shading of southern windows. In total, there are 10 584 parameters combinations, whose simulation was managed by jEPlus [22]. Each simulation took about three minutes on Fujitsu Lifebook E782 with Intel Core i7-3612QM on 2.1 GHz. Since this processor is able to run eight EnergyPlus simulations in parallel, simulation of all 10 584 parameter combinations took about 67 hours of computer time.

Table 2. Fixed case study settings.

Setting	Unit	Value
Heating setpoint during the working hours	°	20
Setback heating setpoint	°	12
Cooling setpoint during the working hours	°	26
Setback cooling setpoint	°	30
Floor area per employee	m ²	9
Metabolism rate (a mix of 50% male and 50% female employees)	W/person	114.39
Internal heat gain from computers, printers, and appliances	W/person	100
Building air tightness	ach	0.5
Minimum fresh air inflow during the working hours	l/(s·person)	10
Maximum mechanical ventilation rate	ach	3.0
Maximum natural ventilation rate	ach	5.0
Heat pump heating COP	/	3.5
Heat pump cooling COP	/	4.5
Heat pump auxiliary annual electricity consumption	kWh/m ²	6.52

Table 3. Monthly climate parameters in Belgrade, Serbia [20, 21].

Month	Average global solar irradiation on horizontal surface, kWh/m ²	Maximum temperature, °C	Average temperature, °C	Minimum temperature, °C	Average wind speed, m/s
Jan	46	18.4	0.0	-10.0	3.6
Feb	63	17.8	1.7	-7.7	3.6
Mar	108	21.0	5.9	-3.0	4.6
Apr	142	26.6	12.0	0.0	3.5
May	180	32.0	17.5	4.0	2.6
Jun	186	34.0	20.3	8.0	2.5
Jul	194	33.2	21.7	10.0	2.6
Aug	173	33.4	21.6	10.0	2.2
Sep	128	32.2	17.7	8.0	3.0
Oct	91	30.0	12.3	-2.3	3.0
Nov	52	18.0	5.4	-3.0	2.9
Dec	33	17.0	1.3	-19.0	3.0

4. Simulation results and discussion

Simulation results of all 10 584 parameter combinations are freely available online at the address <https://sanjastevanovic.files.wordpress.com/2015/01/simresults-stevanovic-ecos.xlsx>. The results consist of the amounts of electricity necessary for heating, for cooling and for artificial lighting. Besides these parameter-dependent amounts, the case study building has further fixed electricity needs: 25 040 kWh for computer systems and appliances, 6 780 kWh for the heat pump systems, and 688 kWh for water heating.

The heating and the cooling electricity demand are, expectedly, concurrent objective functions. For example, heating electricity demand is minimized when the southern façade has 75-100% WWR with the glazing G3 and no external shading and the northern façade has 25% WWR with the glazing G3. On the other hand, cooling electricity demand is minimized when the southern façade has 25% WWR with the glazing G6 with external shading and the northern façade has 25-37.5% WWR with the glazing G6. Therefore, we use total electricity demand as the objective function for comparing different parameter combinations.

The minimum total electricity use is 34 936 kWh, obtained when EPS has thickness of 30cm, both southern and northern windows use the glazing G3, the southern façade has 25% WWR with shading present, and the northern façade has 50% WWR. The maximum total electricity use is 49 971 kWh, obtained when EPS has thickness of 30cm, both southern and northern windows use the glazing G1, the southern windows have no shading and both the southern and the northern façade have 100% WWR.

All six glazing types considered in simulations have U-value at most 1.5 W/(m²K), in accordance with Serbian regulations on energy efficiency of buildings [23]. The case study building, in addition, has good airtightness, heat recovery and natural ventilation, so that all parameter combinations yield energy efficient buildings that fall into energy classes A+ and A. Nevertheless, 30% reduction in total electricity demand between the maximum and the minimum total electricity demand, that corresponds to avoided emission of 7.95t CO₂ in the current Serbian electricity mix, signifies the importance of introducing building energy simulation and design optimization in everyday design practice.

4.1 Southern façade and shading

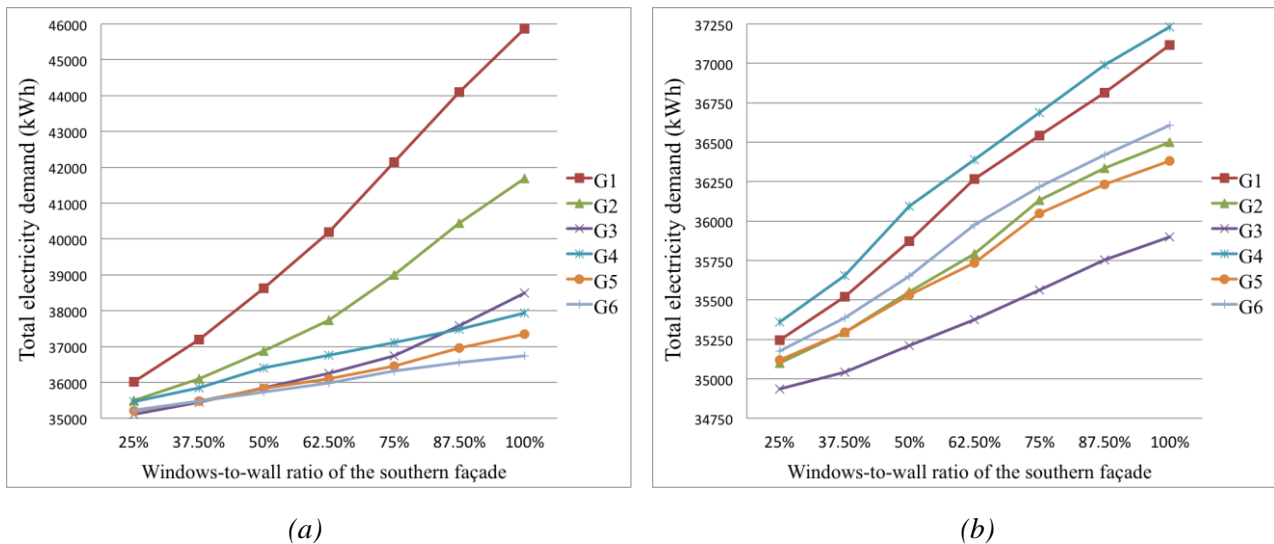


Fig. 2. Minimum total electricity demand with respect to the southern façade's glazing type and WWR: (a) without shading, (b) with shading. Note that we have used substantially smaller range for total electricity demand in (b) in order to enhance its clarity.

Diagrams in Fig. 2 show the minimum total electricity demand for parameter combinations with fixed southern façade's glazing type and WWR, without shading (Fig. 2a) or with shading (Fig. 2b). Analysis of the parameter combinations that yield these minimal demands shows that the optimal glazing type for the southern façade depends on both WWR and the presence of shading. The optimal glazing type without shading is either G3 or G5 or G6 for WWR of 25-50%, while it is only G6 for WWR of 62.5-100%. The optimal glazing type with shading is G3, regardless of WWR. On the other hand, it is clearly visible that the optimal WWR for the southern façade is 25%, which reduces negative impacts of the solar gain on the cooling demand.

Comparing the diagrams in Fig. 2a and 2b, it is clear that the presence of shading decreases total electricity demand for each glazing type and each *WWR* of the southern façade. Yet, the influence of shading on the difference of electricity demands depends on both the solar heat gain coefficient of glazing and *WWR*. As a consequence, presence of shading does not have substantial impact when glazing has small *g* and the southern façade has small *WWR*.

The total electricity demand of all 10 458 parameter combinations is distributed within the range from 34 936 kWh to 49 971 kWh. Hence there exist a large number of parameter combinations whose total electricity demand is relatively close to the minimum one. To discuss the influence of shading, we focus here on the parameter combinations whose total electricity demand is within the smallest 10% of all parameter combinations. Among these, 600 combinations have shading, while 360 do not have shading, confirming that low electricity demand may be achieved without shading, although the architect then has to pay much more attention to the choice of glazing and *WWR* for the southern façade.

On the other hand, the above conclusion that the optimal *WWR* for the southern façade is 25% should not be taken as a limiting factor, as the smallest 10% of all parameter combinations contain parameter combinations with each feasible value for *WWR* of the southern façade. Namely, when the shading of southern windows is present, the minimum total electricity demand grows much more slowly with the increase in *WWR* of the southern façade, so that the architect obtains greater freedom in choosing the southern façade's *WWR*.

However, diagram in Fig. 3 shows that the glazing type and *WWR* for the southern façade cannot be combined arbitrarily. The increase in *WWR* leads to the decrease in the share of glazing types different from G3, so that the glazing types G1 and G4 do not appear in the smallest 10% when *WWR* is at least 75%, while there are only a handful of parameter combinations with the glazing types G2, G5 and G6 in the smallest 10% when *WWR* is 87.5% or 100% on the southern façade.

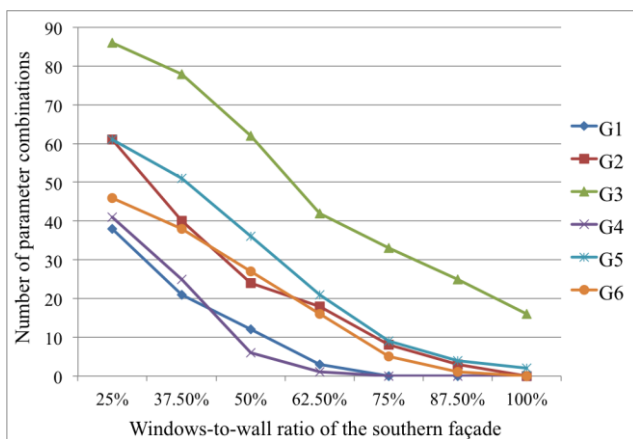


Fig. 3. Numbers of parameter combinations with total electricity demand in the smallest 10% with respect to the southern façade's glazing type and *WWR*.

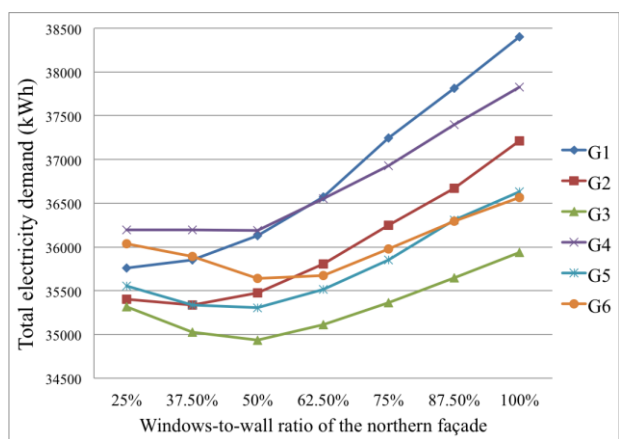


Fig. 4. Minimum total electricity demand with respect to the northern façade's glazing type and *WWR*.

4.2 Northern façade

Diagram in Fig. 4 shows the minimum total electricity demand for parameter combinations with the fixed northern façade's glazing type and *WWR*. Analysis of the parameter combinations that yield these minimal demands shows that the optimal glazing type for northern windows is G3, regardless of *WWR*. Diagram in Fig. 4 indicates that the optimal *WWR* for the northern façade lies between 37.5% and 50%. Larger *WWR* on the northern façade has positive effect on cooling during summer, but it also increases heating demand during winter. The positive summer cooling effect is more

pronounced for smaller *WWR* values, while the negative heating effect becomes dominant for larger *WWR* values, leading to saddle shaped curves in Fig. 4 for glazing types G3, G5 and G6.

4.3 Fully glazed façades

Fully glazed façades are architecturally attractive due to their increased transparency and structure dematerialisation. For parameter combinations with either one or both façades fully glazed, the most appropriate glazing types for the southern façades are G3 with shading, as the best insulated glazing, and G6, as the glazing with the smallest solar heat gain coefficient. The optimal glazing type for the northern façade is G3, which reduces heating needs, and also G6 in the case of both façades fully glazed.

If the southern façade is fully glazed only, then the optimal *WWR* of the northern façade is between 25% and 50%. If the northern façade is fully glazed only, then the optimal *WWR* of the southern façade is between 25% and 37.5%. The optimal parameter combinations with only one fully glazed façade have very similar total electricity demand—between 35 900 kWh and 36 033 kWh. When restricted to the heating, cooling, lighting and mechanical ventilation electricity demands only, this represents 10.5–11.9% increase over the parameter combination with the smallest total electricity demand, much in line with earlier findings of Poirazis et al. [4].

If the southern and the northern façade are both fully glazed, the optimal parameter combination has total electricity demand of 37 058 kWh, which represents an increase of 23% in heating, cooling, lighting and mechanical ventilation demands, when compared to the best parameter combination with total electricity demand of 34 936 kWh.

4.4 Thickness of EPS in the outer walls

It is generally agreed that the smaller U-value of walls leads to more energy efficient building, and this is also evident from the distribution of EPS thicknesses among 960 parameter combinations whose total electricity demand belongs to the smallest 10% of all parameter combinations:

- 12 parameter combinations with EPS thickness of 10 cm,
- 196 parameter combinations with EPS thickness of 15 cm,
- 752 parameter combinations with EPS thickness of 30 cm.

Higher U-value of walls with EPS thickness of 10 cm is somewhat compensated by the proper choice of glazing parameters: all 12 parameter combinations have glazing G3 on both southern and northern windows, with the southern façade's *WWR* from 25-75% and the northern façade's *WWR* from 37.5-62.5%. Nevertheless, their total electricity demand falls between 36 293 kWh and 36 428 kWh, which is close to the limit for the smallest 10% of all parameter combinations. Similarly, total electricity demand of those parameter combinations with EPS thickness of 15 cm falls between 35 640 kWh and 36 439 kWh, which is situated between 4.7% and 10% in the range of all parameter combinations.

5. Photovoltaic plant

In order for the case study office building to become a nearly zero energy building, it is necessary to significantly meet its electricity demand from renewable sources on site or in its vicinity. The most architecturally suitable way is to install a grid-connected PV plant on roof of the building. There are two options for installing a PV plant: integration of modules into the roof or classical installation of modules on the flat roof, shown in Fig. 5a and 5b. To compare the outputs of these installation options, we have simulated them with PVSYST 5.21 [24]. PVSYST has generated synthetic hour data based on the average global solar irradiation and temperature data from Table 2. Simulations were performed with the option "Project design", with Si-mono Sharp NU-180R1H chosen as the

PV modules. These modules have dimensions 1 318 mm x 994 mm and the nominal power of 180 Wp. The roof area available for plant installation is 280 m².

For a PV plant integrated into the roof (Fig. 5a), the installation must have a gentle slope (a suitable choice being 6°) for storm water drainage and back air duct for ventilation. Since in this case all modules belong to the same plane, there is no shading between adjacent rows of modules, and the whole surface can be effectively used for installation. PV plant can therefore have 12 rows with 15 PV modules each, with the nominal power of 32.4 kWp.

For a classically installed PV plant (Fig. 5b), modules are placed on the flat roof under the slope of 35°, which maximizes the annual amount of generated electricity. To prevent shading between adjacent rows of modules, PV plant can, at most, have 10 rows with 14 PV modules each, with the nominal power at most 25.2 kWp.

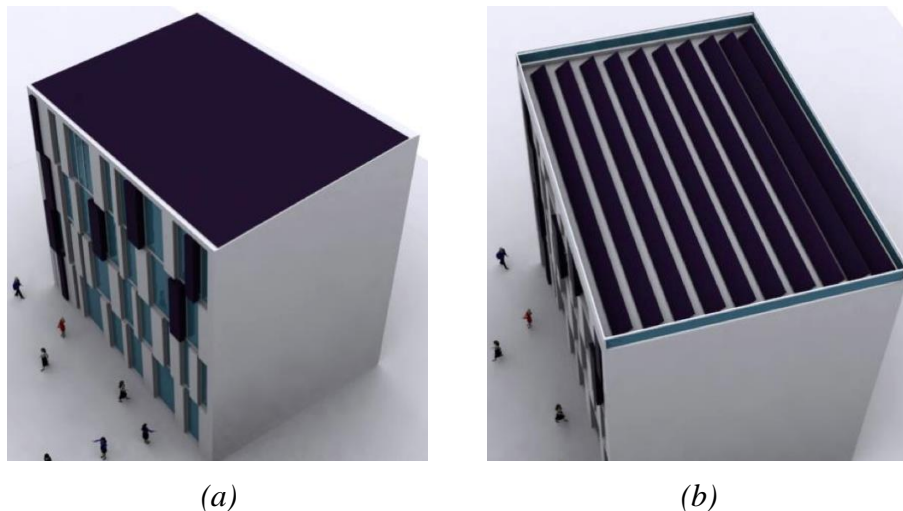


Fig. 5. Axonometric views of the case study building with a photovoltaic plant: (a) integrated into the roof, (b) classically installed on the roof.

PVSYST simulation results show that during the first year:

- the roof integrated PV plant generates 37 698 kWh of electricity, while
- the classically installed PV plant generates 32 658 kWh of electricity.

It is, thus, clear that the classically installed PV plant is unable to cover the total electricity demand for any of the 10 458 parameter combinations of the case study building. On the other hand, the roof integrated PV plant generates more electricity due to better utilization of the available roof area. A total of 4 937 parameter combinations of the case study building become positive energy buildings with the roof integrated PV plant. Finally, it should be noted that currently available PV modules have an annual degradation efficiency of about 0.88%, guaranteeing at least 80% of the nominal power after 25 years. This means that, although the amount of generated PV electricity will decline over time, those parameter combinations with total electricity demand close to minimum will continue to yield nearly zero energy buildings for a number of years to come.

6 Conclusions

Analysis of total electricity demand of all combinations of selected passive solar design parameters for the case study of an office building in Serbia and, in particular, of those parameter combinations with total electricity demand close to minimum, led us to some interesting and useful observations.

First, it is apparent that in modern airtight, energy efficient buildings with high performance glazing, the cooling demand becomes more important than the heating demand. As a consequence,

the optimal *WWR* for the southern façade stems toward the minimum feasible value. However, the optimal *WWR* for the northern façade has a nontrivial value, due to the saddle shape of curves in Fig. 2 and the positive impact that larger *WWR* of the northern façade has on the cooling demand.

Secondly, shading of southern windows is not necessary when the southern façade's *WWR* is small enough. However, with shading, architect has greater freedom to select a larger *WWR* value, while retaining proximity to the optimal solution. This freedom extends to a fully glazed façade as well, provided that the other façade has small *WWR*.

The optimal glazing type for climate conditions of Serbia turns out to be G3, due to the combination of its low U-value and relatively large solar heat gain coefficient, followed by the solar control glazing type G6 in cases without shading.

Finally, the roof integrated PV plant generates more electricity annually when compared to the classical, sloped installation, due to better utilization of the available roof area. It also enables the case study to become a positive energy building for much larger number of combinations of passive solar design parameters.

Acknowledgments

The author was supported by the research grant TR36035 "Spatial, environmental, energy and social aspects of developing settlements and climate change—mutual impacts" of the Serbian Ministry of Education, Science and Technological Development.

Nomenclature

g solar heat gain coefficient of glazing, %

LT_{visible} light transmittance of glazing, %

U_f thermal transmittance of framing, W/(m² K)

U_g thermal transmittance of glazing, W/(m² K)

WWR windows-to-wall ratio, %

Greek symbols

ψ_g linear thermal transmittance of the joint between framing and glazing, W/(m K)

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