Nikolaos SKANDALOS [1)],
Jan TYWONIAK [1,2)],
Kamil STANEK [1,2)],
Lenka MAIEROVA [1,2)]

[1)] CTU in Prague, University Centre for Energy Efficient Buildings
[2)] CTU in Prague, Faculty of Civil Engineering

Reviewer
Vasilis C. KAPSALIS, Ph.D.

The PV Potential in the City of Prague: Methodology and Assessment for Residential Buildings

Fotovoltaický potenciál v Praze – Metodika a hodnocení pro obytné budovy

This work highlights the Building-Integrated Photovoltaics (BIPV) potential in two urban areas with different characteristics in the city of Prague. The representative building blocks were selected and the CitySim software tool was used for the assessment of the hourly irradiation profiles on each surface over a one-year period. Considering appropriate irradiation thresholds, suitable surfaces were then quantified. Integration criteria are discussed and suitable BIPV applications are proposed considering, not only energy performance, but also their impact on the quality of the built environment. The Photovoltaic (PV) potential is compared with the estimated local electricity demand derived from the population distribution within the building block. Analysis indicated that only 5.5% of the total area can be used in Vinohrady and 13.7% in Jizni Mesto contributing by 32% and 31% on average on the hourly electricity demand, respectively. The PV generation exceeds the local non-baseload demand during the summer period, but is less significant during winter. A preliminary financial analysis reveals a payback time of 17.5 and 20 years for Vinohrady and Jizni Mesto areas, respectively. It is evident that, even in the areas with a sensitive built environment, adoption of solar energy is still possible for balancing local electricity needs.
Keywords: *Building-integrated photovoltaics, solar PV potential, architecture, load matching*

Příspěvek se zabývá potenciálem využití stavebně integrované fotovoltaiky v odlišné zástavbě Prahy. Pro dva reprezentativní obytné bloky byly pomocí software CitySim stanoveny hodinové profily ozáření všech povrchů v průběhu roku. Z toho pak byly určeny vhodné plochy pro fotovoltaické instalace. Uvažovány byly nejen energetické vlastnosti ale i vliv na kvalitu zastavěného prostoru. Potenciál fotovoltaické produkce je porovnáván s místní potřebou elektrické energie pro obyvatele. Analýzy ukazují, že celkově jen 5,5% ploch může být využito na obytném bloku na Vinohradech a až 13,7% ploch na obytném bloku na Jižním Městě, což přispívá k pokrytí potřeby elektrické energie domácností v průměru z 32% a ve druhém případu z 31%. Fotovoltaická produkce v takovém případě v letním období přesahuje místní spotřebu. Předběžná finanční analýza ukazuje návratnost 17,5 roku pro Vinohrady a 20 let pro Jižní Město. Potvrzuje se, že i v architektonicky náročném prostředí je využití solární energie pro významné pokrytí místní spotřeby možné.
Keywords: *stavebně-integrovaná fotovoltaika, fotovoltaický potenciál, architektura, soulad produkce a spotřeby*

INTRODUCTION

The building sector is classified among the major energy consumers, contributing by 40% of the primary energy consumption in Europe [1]. Currently, there is a major transformation taking place through national building codes, roadmaps and building rating systems. In addition, emphasis has been put on the adoption of renewable energy systems on the building envelope [2]. Among other options, solar photovoltaics are expected to be the main technology to generate on-site electricity to match the building's consumption [3]. This is enhanced by the fact that the location of the energy source is commonly the same as the location of the energy use. Consequently, the generated electricity cannot be used instantly to cover the building needs only (e.g., lighting, appliances, heating, etc.), but also exchanged between the buildings and the electrical grid.

Building-Integrated Photovoltaics (BIPV) – defined as photovoltaic cells integrated into the building envelope as part of the building structure – have great potential to be used in a city context. It can replace conventional building materials, and also be used as external separation elements, like balconies, shading devices and other applications [4]. Rooftop PVs are, so far, considered to be the most common application since it provides the best annual energy harvesting. However, due to the significant decrease in prices and increase in technological improvements in the PV industry, building facades now represent a good potential, especially for high-rise buildings. Even if they receive less irradiation compared to rooftops, they could make a major contribution because of the larger surface areas involved. In addition, vertical-integrated PV modules will produce relatively more power in winter, as well as in the early and late hours of the day.

Consequently, it is important to adjust the slope and azimuth of the PV installations, in order to spread the electricity generation over a larger period of time increasing the PV self-consumption of residential buildings [5]. However, the successful integration of PVs in a city context requires not only technical optimisation to maximize production, but also to preserve the quality of the urban, landscape and cultural environments. A match between the building's energy needs, the solar energy potential and the site's identity has to be targeted [6].

Several case studies have already been performed for incident solar radiation on individual buildings, small neighbourhoods or on a city scale, indicating the nice PV potential in existing locations. Depending on the availability of the data, regional characteristics, as well as scale of study, several methodologies have been suggested to determine the PV potential. Brito et al. [5] investigated the PV potential for two areas in the city of Lisbon using LIDAR data. It was found that the roof and facade PV potential can contribute to 50–75% of the total electricity demand.

Assouline et al. [7] using a combination of support vector machines (SVMs) and geographic information systems (GIS) found that the potential PV production for the urban areas in Switzerland corresponded to 28% of Switzerland's electricity consumption in 2015.

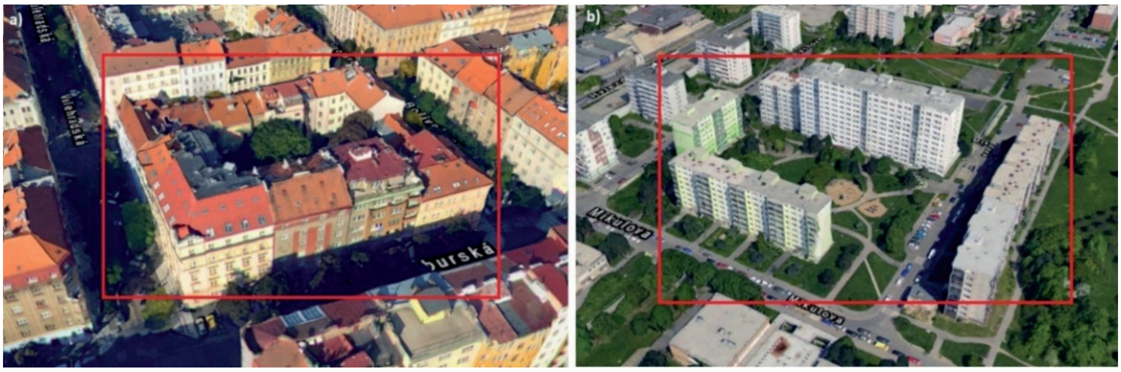


Fig. 1 Aerial view of the selected locations in a) Vinohrady and b) Jizni Mesto.

There are also studies on the effects of the urban form on the solar PV potential. According to Compagnon [8], a building's layout for constant density can lead to variations of the solar potential. Besides, increasing the building aspect ratio or site coverage has a positive effect on the PV potential, although the effect of mutual shading becomes more significant according to Li *et al.* [9]. In this context, a new algorithm for the spatio-temporal calculation of a shadow in the urban environment was proposed by Vulkan *et al.* [10]. The methodology implemented for a neighbourhood in Rishon LeZion, Israel, with diverse building typologies indicated that some facades can make a substantial contribution to the overall solar potential of urban buildings.

Solar energy harvesting for individual buildings in the city of Prague has been studied in the past, but the PV potential in urban areas has not yet been investigated. This study aims to fill this gap indicating how the detailed mapping of the existing architecture can quantify the PV potential of urban residential buildings in the historical and modern city areas. Using data from IPR Praha (the Institute of Planning and Development of the city of Prague), we describe the topography, for two case study areas. Considering the solar availability and shadings for the surrounding buildings, the available area for installation is determined and suitable PV applications are proposed based on the characteristics and cultural aspects of the location. Then, the hourly PV generation of the roofs and facades is compared with the estimated local electricity demand on an hourly basis discussing strategies for better load matching.

METHODOLOGY

Location characteristics

Prague is the capital and largest city in Czech Republic located in the north-west (at 50°05'N and 14°25'E) of the country. The climate is considered to be semi-continental, characterised by large seasonal temperature differences, with cold winters and warm (and often humid) summers. In order to investigate the PV potential, solar radiation and other meteorological data (temperature, wind speed, etc.) were provided from a local weather station. An annual global horizontal radiation is approaching 1065 kWh/m^2 with a peak value of 161 kWh/m^2 in June, while lower values of solar irradiation are observed during winter months (a min value in December).

In this work, two urban areas in the city of Prague with different characteristics were selected as the application sites for the assessment of the PV potential. A representative building block, constituted of residential buildings, was identified for each location as presented in Fig.1. Case one, Vinohrady, is within a highly dense area of the city centre with considerable architectural and cultural value. Houses built around 1900 are characterised by sloped roofs in different shapes and heights. Case two, Jizni Mesto, is a suburban area built in the 1970s. Prefabricated high rise buildings are characterised by their simple shape, flat roofs and big vertical facades with balconies with a South and West orientation. They are lighter, with a higher fenestration ratio and better thermal insulation compared to the ones in Vinohrady.

Solar PV potential

Appropriate 3D models for each building block were prepared based on the geometry of the buildings, including the dimensions and shape of the roof superstructures (dormer, chimney, etc.). The building surfaces were divided according to the floor level, excluding areas that for some reason cannot be considered for PV integration (e.g., north facade). Radiation on the building surfaces is commonly influenced by the nearby environment and, thus, the heights of the surrounding buildings, trees and elements in each direction were considered in the model for evaluating the shading. Afterwards, the 3D model was imported to CitySim Pro [11], an urban energy modelling tool developed at LESO-PB/EPFL, for further analysis. The incoming solar radiation was calculated in hourly values, according to the type of the building surface and the climate data collected by a nearby weather-station. Each building surface was defined by its area, orientation and tilt angle. Finally, the percentage of solar obstruction was calculated as the ratio of the solar radiation within the surrounding context to the one without the surrounding obstacles. The hourly values were solar weighted, the annual shading index (*SI*) was derived according to Eq. 1.

$$SI = \frac{\sum_{i=1}^{N=8760} F_{sh} G_i}{G_t} \quad (1)$$

where

$F_{sh,i}$ is the hourly shading factor of each building surface,
G_i is the hourly solar radiation [W/m^2]
G_t is the annual solar radiation [W/m^2]

Once the radiation values on each surface are available, they can be analysed to assess the PV potential. For this purpose, an irradiation threshold was used, indicating the minimum amount of annual radiation required for the PV system to be beneficial. Such thresholds are somewhat arbitrary; a conservative value of 800 kWh/m^{2}annually is proposed by many authors [9], while others define it as a percentage of the horizontal insolation [10]. Considering the technological progress and enormous decline in PV costs over the last decade, approximately a 58 %, according to [12], lower value such as 650 kWh/m^2 [13] is still reasonable. To this end, the PV potential calculated as the relative fraction (percentage) of the roofs and facades of the buildings that can be used for PV integration. Based on the area of the suitable surfaces, a simple model was applied to quantify the annual energy output (E_{PV}) of each building block according to Eq. 2:

$$E_{PV} = \eta \cdot PR \cdot \sum_{i=1}^{n_{threshold}} \left(I_i A_i\right) \qquad (2)$$

where

η is the PV conversion efficiency,

PR is the performance ratio

$n_{threshold}$ is the number of surfaces exceeding irradiation threshold,

I_i is the cumulative insolation (kWh/m^2.year) and

A_i is the relative area (m^2) of surface i.

Electricity demand and system performance

Afterwards, the following procedure was used to derive the annual electricity load curves of the representative buildings on an hourly basis. Only the non-thermal use of electricity is considered in this study, i.e., the derived load curves include all means of the households' electricity consumption except the use for space heating and hot water preparation.

In the first step, a normalised hourly electricity consumption profile of a typical Czech household was constructed based on data published by the Czech electricity and gas market operator (OTE a. s.) for consumer class 4 – households with non-thermal use of electricity (TDD4) [14]. This normalised hourly consumption profile consists of 8760 values between 0 and 1, with a typical differentiation between working days and weekends, and with higher consumption in winter compared to summer. In the second step, the number and area of the households, and the number of the occupants in the representative buildings were estimated. These basic statistics describing the representative buildings were then matched to the data on the annual non-thermal electricity consumption in Czech households, reported by the Czech Statistical Office (ČSÚ) [15] and the REMODECE Project [16], to estimate the total annual electricity consumption (MWh/year) in the representative buildings. Finally, in the third step, the normalised hourly consumption profile and the total annual electricity consumption were combined into the hourly load curves of the representative buildings, in kW (see Figure 2). A more detailed description of the whole procedure can be found in [17].

Based on the peak loads and the selection criteria that apply in each location, the PV systems were sized properly, in order to enhance the PV self-consumption and reduce excess power during the summer period. In addition, a comparison between the electrical loads and the PV generation for the selected locations was made through the calculation of the load match index as described in [18]. According to eq. 3, it was calculated for hourly time intervals indicating the average hourly contribution of the PV systems on the building loads.

$$f_{load,i} = \frac{1}{n}\sum_{i=1}^{n} \min\left[1, \frac{g_i}{l_i}\right] \cdot 100 \quad [\%] \qquad (3)$$

where

i is the time interval (hour, day, month)

g_i is the instantaneous on-site electricity generation

l_i is the instantaneous electricity demand

n is the sum of time steps over a year period

Financial analysis

Finally, a financial analysis was undertaken to investigate the profitability of the proposed systems. In this context, the Net Present Value (NPV) – defined as the sum of present incoming (benefits) and outgoing cash flows over the lifetime of the project – was calculated according to eq. 4 [19].

$$NPV = -C + \sum_{t=1}^{N} \frac{F(t)}{(1+i)^t} \qquad (4)$$

where

C is the initial investment costs (€)

$F(t)$ is the annual income generated by the PVs (€/year)

N is the lifetime of the investment (years)

i is the real rate of interest (%)

The initial investment includes the cost of the PV modules, electrical components (inverters, cables, etc.) and claddings (frames, aluminium substructures, etc.). It is worth mentioning that the size of the PV plant has an effect on the cost of the installation. Considering the actual size of the installation, in this work, typical values of 1350 €/kWp, and 1290 €/kWp were used for crystalline silicon and thin-film PV technologies, respectively [20]. In the case of Vinohrady, more advanced PV products are used and, therefore, the cost of the BIPV increases. The end user prices are converted to €/m^2, with an average value of 300 €/m^2 [21]. Finally, a fixed maintenance cost of 0.5 % per the initial cost was assumed in both cases.

For the calculation of the annual income, the following inputs were used: annual energy output (kWh), coefficient of performance considering representative degradation rates (%/year) for each PV technology, energy price (€/kWh) and possible Feed-in-tariff or fiscal incentives. Then, the cash flow over the life time of the PV system (25 years-expected) was prepared and the payback time (PBT) [19] was estimated as an indicator for the number of years needed to compensate for the initial investment.

BIPV integration criteria

It is evident that excessive use of PV systems can often have an adverse effect on the built environment and, thus, the criteria and recommendations about dimensioning and positioning are needed. In order to select an appropriate BIPV application, both technical, architectural and economic aspects should be included. In the case of Jizni Mesto, there are no limitations arising from the near environment and, thus, several scenarios and PV technologies can be considered (Fig. 3). High performance modules can be installed horizontally on the flat roof of the buildings to camouflage the installation or tilted to optimise the performance. On the vertical facades, the PV modules should be grouped together in an ordered way creating unique textures (e.g., horizontal stripes). In this context, ceramic panels or solar glazing in various colours [22] could be a solution, providing good durability and an aesthetic quality. Finally, complementary building elements such as windows and existing balconies are well suited to support the PV integration representing a good compromise in terms of the energy performance and aesthetics. In addition, optimised semi-transparent PV elements could be used as shading devices to increase the indoor thermal comfort by mitigating overheating during the summer, but to still provide daylight and to make use of passive heating during winter [23].

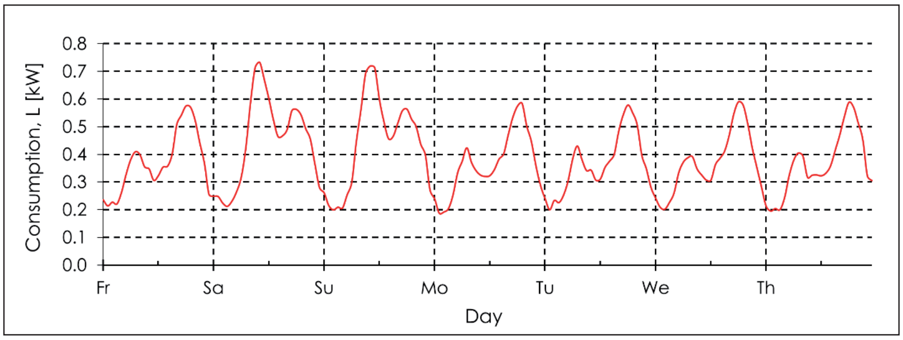


Fig. 2. A typical load profile for the electricity consumption of a household in Prague [17].

Fig. 3. Examples of architecturally integrated PV systems in the two building blocks: (1) PV balconies. Source: Etsprojects; (2) Coloured PV- facade. Source: Swissinso; (3) Roof-added PVs. Source: Cromwellsolar; (4) PV tiles. Source: Tradeford; (5) PV shutter and PV blinds. Source: COLT international, Solargaps; (6) PV terrace [26].

On the other hand, the BIPV integration in a sensitive built environment, such as the Vinohrady district, is a more challenging task. The applicability of conventional PV modules in buildings with strong architectural or cultural value is limited. Since the full integration and imperceptibility of the technical elements from the public domain is the most important criteria for the acceptance of the BIPV within a historical context [24], small scale highly innovative PV products are needed. Suitable surfaces are limited to the sloped roof, flat terraces and vertical facades facing the courtyard. Based on the geometry of each surface, BIPV applications such as solar glazing or PV tiles, balustrades and PV shutters (Fig. 3) constitute effective practices of integration in the building envelope providing a balanced solution between the technical and architectural standards as defined in [25].

RESULTS & DISCUSSION

Solar PV potential

The results from the solar analysis in both locations are presented in the form of annual irradiation colour maps. As expected in Vinohrady, the best solar resources were observed for the sloped roofs (35° slope) facing south, exceeding 1200 kWh/m^2 annually (Fig.4). However, the different roof typologies were recognised and, thus, the solar potential varies according to its slope and orientation. The facades were found to receive a significantly lower level of irradiation, which is explained from the mutual shading effects (high density), especially for the lower part of the buildings. The calculated annual shading indexes can reach up to 57 %. Only 19.7 % of the total surface area exceeds the irradiation

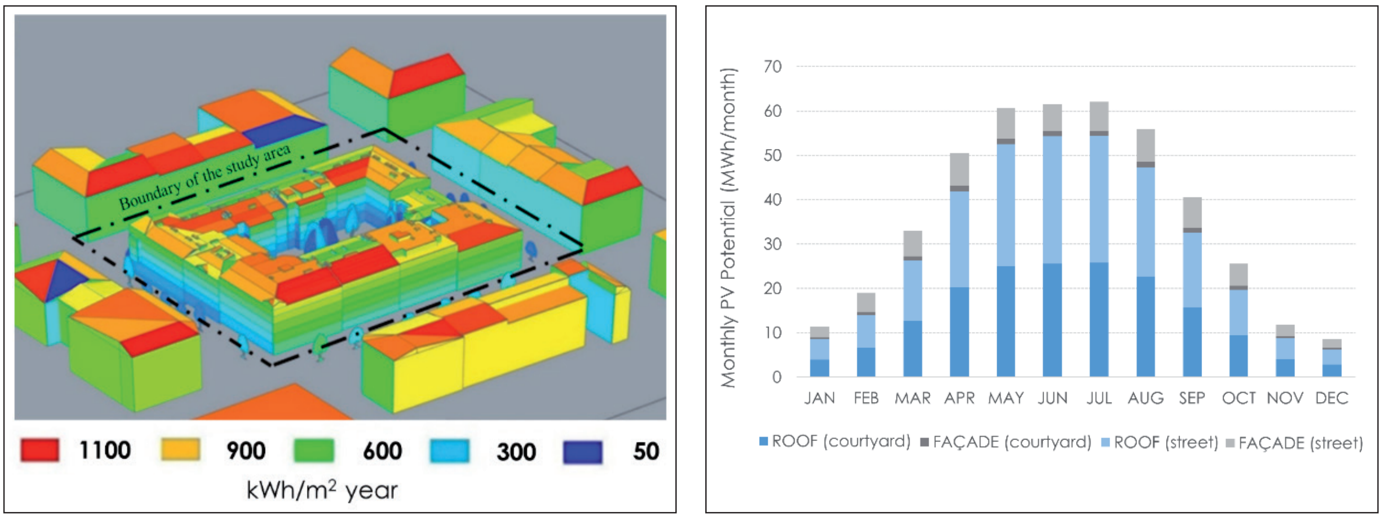


Fig. 4. The annual solar irradiation map and relative PV potential of the building block based on the selected irradiation thresholds in the Vinohrady area.

threshold of 650 kWh/m^2 and is mainly related to the roof areas. With respect to the hourly irradiation profiles, the maximum PV potential in the area was calculated and presented in Fig. 4. The PV modules were assumed to be installed on the same plane with the building surface considering the typical values for the conversion efficiency (η) according to the BIPV application (η = 15 % for the roofs and η = 8 % for the facades/balconies/glazing). Additionally, an appropriate performance ratio (PR) was used to take all system losses (inverter, mismatch, etc.) into account. For Vinohrady, the annual PV generation is estimated to be 440 MWh approximately, with a peak value in July (62 MWh) and the least generation in December (8.5 MWh). It is worth mentioning that only 42 % of this generation corresponds to the building surfaces facing the courtyard and, thus, could be considered according to the criteria discussed in the previous section.

The relative results for the building block in Jizni Mesto are presented in Fig. 5. The max potential was slightly reduced (around 10 %) compared to Vinohrady, but still exceeds 1000 kWh/m^2 annually. This corresponds to flat roof on top of the buildings, followed by the south-facing facades. Furthermore, solar obstruction was found to be significantly lower due to the less dense urban environment of the location. The highest shading indexes calculated in the range of 23 %, indicating acceptable resources even for the East/West facades (to some extent). According to the selected irradiation threshold (650 kWh/m^2), 35 % of the total building area can be considered as suitable for the PV integration. Based on the irradiation profiles, the simulated PV potential is equal to 1195 MWh/annually, 2.7 times higher when compared to the Vinohrady case. The highest contribution refers to the roof area, followed by the vertical facades and balconies with the relative percentages of 49 %, 45 % and 6 %, respectively (Fig. 5). Extensive PV integration on the vertical facades in Jizni Mesto has an impact on the monthly values (compared to the Vinohrady case) shifting the peak generation to June (Fig. 5).

Electricity demand

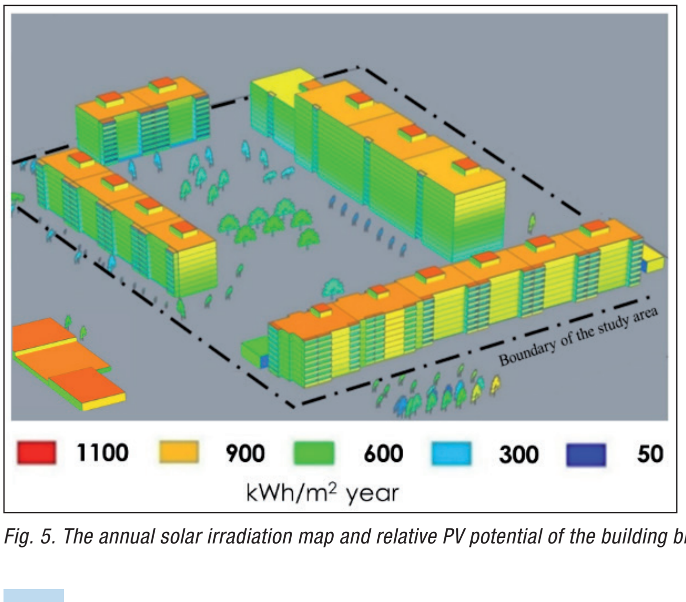
The statistical data regarding the population distribution and annual consumption per household [16] were used to determine the electricity demand in both areas. For the given number of apartments, the estimated number of occupants was then multiplied by the per capita electricity demand. The limited available data, regarding the consumption of the selected building blocks, was also used for the validation. For the building block in Vinohrady, the overall electricity demand was estimated at 478 MWh/year. As for building block in Jizni Mesto, the increased number of residents due to the high-rise buildings, results in a higher annual electricity demand of 1214 MWh/year. The analytical results for the annual demand and production per building are presented in Table 1. One can observe that the PV production is significantly reduced compared to the PV potential of the area in Vinohrady. The available space is limited to only 5.5 % of the total building area due to the integration criteria applied (discussed in previous sections).

System evaluation

Having a look at the comparison between the demand and the production in monthly intervals, it is clear that the generated electricity is not enough to cover the loads of the building block in Vinohrady. On the contrary, there are no such barriers limiting the PV integration in Jizni Mesto and, thus, even for higher irradiation thresholds, the PV generation is enough to compensate the electricity demand during the summer period. From that point of view, it is important to investigate the load match over a shorter time step to ensure a minimum excess of PV energy. For that purpose, typical load profiles (Fig. 2) for residential buildings were used to analyse the electricity demand in hourly time-steps.

During this process, the hourly peak loads were calculated and used as an indicator, to properly size the PV systems in each building. In the case of Vinohrady, the maximum loads observed for building 6 is equal to 17.2 kW, while ranging between 27-120 kW for the whole block. An excess of energy was observed for small periods during the summer only, but still the PV self-consumption accounts for 92 %. Almost all the generated PV energy can be used locally within the building block and it is enough to compensate by 32 % (the max value of 49 % for the building case) the hourly electricity demand on average.

In the case of Jizni Mesto, the PV generation is enough to cover the electricity demand during the summer period, but also leads to an excess of energy for 35 % of the PV operation time (hourly). Therefore, better interaction between the generated and consumed electricity is needed to increase the self-consumption of the buildings providing more efficient performance. If the maximum load matching is taken into account, integration will be limited to only 13.7 % of the total building area leading to lower PV generation. Fig. 6 depicts the interaction between the electricity demand and the production for the new system over a typical winter and summer day. A wider peak power production and, thus, a better match to the load diagram is observed. A small excess of energy is observed at noon and can be used for cooling purposes to eliminate overheating risks. Alternatively, this can be delivered to the surrounding buildings and facilities across the street. Finally, the average and max values for the load match index (hourly intervals) among the buildings in Jizni Mesto were found to be 31 % and 43 %, respectively. The larger PV system size hardly improves the load match index if no measures for electricity storage are taken.



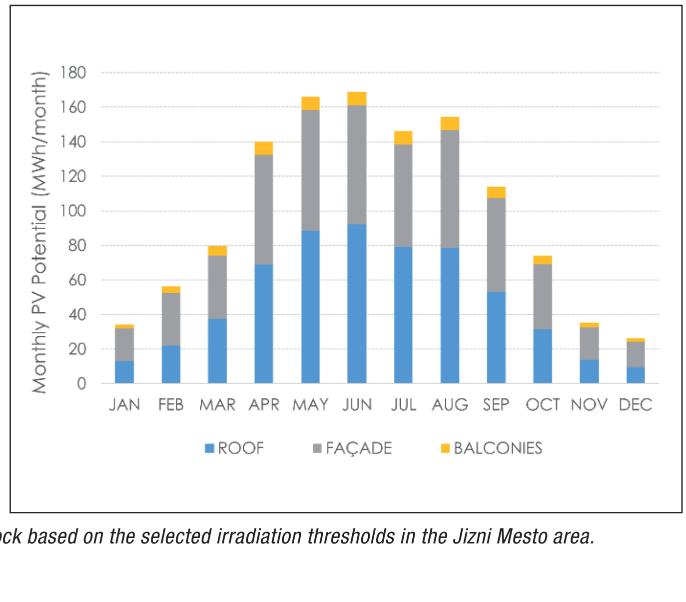


Fig. 5. The annual solar irradiation map and relative PV potential of the building block based on the selected irradiation thresholds in the Jizni Mesto area.

Tab. 1 The annual electricity demand and production per building in Vinohrady and Jizni Mesto area.

	Electricity demand (MWh/year)		PV production (MWh/year)	
Building No.	**Vinohrady**	**Jizni Mesto**	**Vinohrady**	**Jizni Mesto**
1	40.8	112.2	13	54.1
2	62.7	576.6	20	300.7
3	56.1	196.8	10.4	121.3
4	63.6	328.5	17.4	266
5	39.2	-	14.3	-
6	68.4	-	19.9	-
7	35.9	-	15.2	-
8	31.3	-	15	-
9	63.6	-	17.9	-
10	16.9	-	6.7	-

It can be observed that even with a higher percentage of surface area used in Jizni Mesto, the average hourly load match is similar to the case of Vinohrady. The higher population density of the high-rise buildings leads to different consumption patterns compared to the family households in Vinohrady. This is also explained from the PV production per unit area in Vinohrady (163 kWh/m^2), which was found to be up to 32 % higher compared than the one in Jizni Mesto (111 kWh/m^2). This is a direct consequence of the limited vertical integration on the facades (lower solar resources), when the contribution approaches 50 % of the area used for Jizni Mesto.

Fig. 7 depicts the accumulated PV generation for the proposed systems in both locations. Apart from the total electricity demand discussed earlier, the PV generation is also compared to the non-baseload load demand - determined by subtracting the minimum load of the previous 24 h from the hourly demand load [5]. Assuming that the baseload demand can be covered from alternative sources, the results clearly indicate that the PV generation exceeds the non-baseload demand in both areas during the summer period. More specifically, the demand is satisfied for five consecutive months from April to August. Surprisingly, even for a lower extent of PV integration, the Vinohrady area achieves better results. In contrast, during the winter months, the PV generation decreases drastically and is not enough to meet (the increased) the total nor the non-baseload demand.

Financial analysis

Based on the methodology presented in Section II, a preliminary financial analysis was performed for a period of 25 years (expected lifetime of the investment). The NPV was calculated by subtracting the initial cost from the discounted annual income from the PV generation. For the calculations, a real rate of interest of i = 2.26 % and an initial energy price of 0.142 €/kWh with a growth rate of 1.8 % (according to Eurostat) were assumed, based on the current situation in the Czech Republic.

The annual electricity generation for the next 25 years was estimated, considering the degradation rates from a recent study with similar conditions [27]. The results, already discussed, indicated 92 % self-consumption in Vinohrady and 10% lower in Jizni Mesto. This means that most of the PV electricity is consumed directly form the buildings in both areas. In 2013, the Czech Parliament amended Act No. 165/2012, which *de facto* abolished the feed-in tariff scheme for PVs by the end of 2013. Since there is no financial support right now, the excess part of the PV generation, exported to the grid, was not taken into account in the results presented in Fig. 8.

In the graph, the value of year 0 is associated with the initial investment cost of the system. Based on the PV costs discussed in Section II, this is equal to 360000 € for Vinohrady and 873000 € for Jizni Mesto. The payback time, i.e., the number of years needed to make the NPV positive, was found to be 17.5 and 20 years for Vinohrady and Jizni Mesto, respectively. The payback time can be reduced further considering the sav-

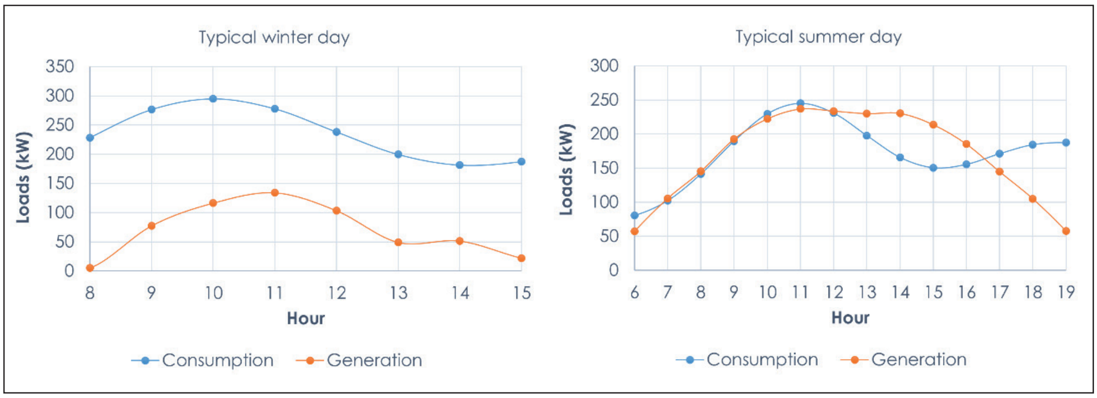


Fig. 6. The hourly electricity demand (blue line) and generation (red line) over a typical a) winter and b) summer day for the building block in Jizni Mesto.

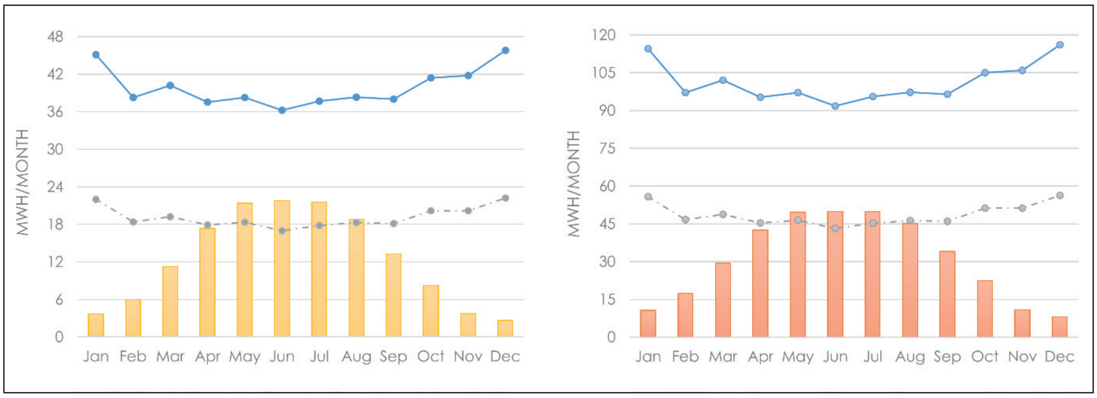


Fig. 7. The monthly PV generation and electricity demand (blue line: total electricity demand; grey line: non-baseload demand) of the proposed system for a) the Vinohrady (left) and b) Jizni Mesto (right) areas.

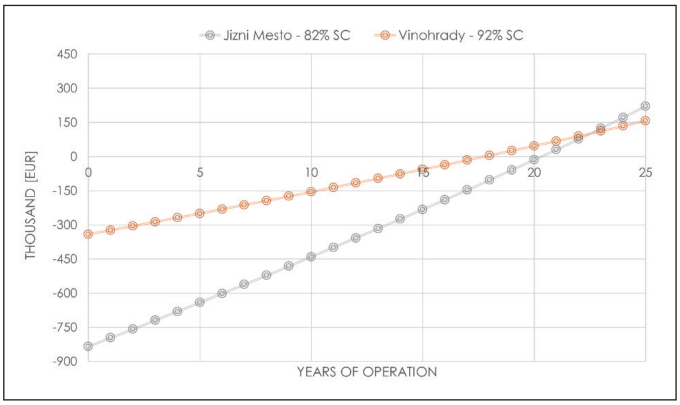


Fig. 8. The Net Present Value (NPV) associated with the investment of the PV installation in the Vinohrady (92% self-consumption) and Jizni Mesto (82% self-consumption) areas.

Tab. 2 An overview of the PV potential for the two case studies.

Case study area	Vinohrady	Jizni Mesto
Total Area (m^2)	21775	34200
Percentage of Area (≥ 650 kWh/m^2.y)	19.7	36.5
PV potential (MWh/year)	440	1195
Percentage area used for PVs (%)	5.5	13.7
Electricity demand (MWh/year)	478	1214
PV generation (MWh/year)	150	370
Avg. Load match index (%)	32	31
PV self-consumption	92	82
Payback Time (years)	17.5	20

ings from the conventional building materials, and the energy saving provided by the applied solutions and more efficient strategies to increase self-consumption. Given that facilities like schools, supermarkets, etc. exist across the street (at the boundaries of the study area), the excess PV energy can be delivered and decrease the payback time in Vinohrady by 1.5 years and up to 4 years in Jizni Mesto. Consequently, a more detailed study should be considered to thoroughly investigate these scenarios.

CONCLUSIONS

Two representative building blocks, with different characteristics and levels of preservation, were selected and analysed to quantify the PV potential of urban residential buildings in historical and modern city areas. According to the selected irradiation thresholds, the analysis revealed almost a 3 times higher potential in Jizni Mesto compared to the Vinohrady area. As expected, most of the potential is intrinsically related to the roofs, while the facades suffer more of a shadowing effect caused by the surroundings. The phenomenon is more intense in the Vinohrady area, where only 13 % of the PV potential is related to the facades, when the additional contribution in Jizni Mesto is approaching 50 %.

The integration criteria was discussed and suitable PV applications are proposed, considering not only energy performance, but also their impact on the quality of built environment. Afterwards, a methodology was used to estimate and compare, in an hourly time-step, the electricity generation and demand. It was found that only small part of the building area can be used accounting for 5.5 % in Vinohrady and 13.7 % in Jizni Mesto. Interaction between the electricity demand and consumption revealed that the proposed PV systems could compensate, on average, 32 % of the hourly energy demand in Vinohrady and 31% in Jizni Mesto. Considering the actual self-consumption rate and actual market conditions (BIPV prices, installation costs and electricity tariffs), the economic assessment indicated that the payback time of the investment is equal to 17.5 years for Vinohrady and 20 years for the Jizni Mesto area. A summary of the results obtained for the two case studies is presented in Table 2.

It is evident that even in areas with a sensitive built environment, adoption of solar energy is still possible for balancing the local electricity needs. Further work is needed to assess the indirect effect of the BIPV systems on the built environment by means of thermal and daylighting performance. This paper can be used as reference for future case studies in the process of building a sustainable city.

Contact: Nikolaos.Skandalos@cvut.cz

ACKNOWLEDGEMENT. This work has been supported by the Ministry of Education, Youth and Sports within National Sustainability Programme I (NPU I), project No. LO1605 – University Centre for Energy Efficient Buildings – Sustainability Phase and by the Operational Programme Research, Development and Education of the European Structural and Investment Funds, project CZ.02.1.01/0.0/0.0/15_003/ /0000464 Centre for Advanced Photovoltaics.

The authors would also like to acknowledge Solar Energy and Building Physics Laboratory (LESO-PB) of EPFL in providing the CitySim software.

REFERENCES

[1] UNEP. Building Design and Construction: Forging Resource Efficiency and Sustainable Development. 2012.
[2] IEA-PVPS. Trends 2015 in photovoltaic applications: Survey report of Selected IEA countries between 1992 and 2014. Paris, FR. 2015.
[3] TRIPATHY, M., SADHU, P. K. and PANDA, S. K. A critical review on building integrated photovoltaic products and their applications. *Renewable and Sustainable Energy Reviews.* 2016, 61, 451-65.
[4] SHUKLA, A. K., SUDHAKAR, K., BAREDAR, P. Recent advancement in BIPV product technologies: A review. *Energy and Buildings.* 2017, 140, 188-95.
[5] BRITO, M. C., FREITAS, S., GUIMARÃES, S., CATITA, C., REDWEIK, P. The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data. *Renewable Energy.* 2017, 111, 85-94.
[6] FLORIO, P., PROBST, M. C. M., SCHÜLER, A., SCARTEZZINI, J-L. Visual prominence vs architectural sensitivity of solar applications in existing urban areas: an experience with web-shared photos. *Energy Procedia.* 2017, 122, 955-60.
[7] ASSOULINE, D., MOHAJERI, N., SCARTEZZINI, J-L. Quantifying rooftop photovoltaic solar energy potential: A machine learning approach. *Solar Energy.* 2017, 141, 278-96.
[8] COMPAGNON, R. Solar and daylight availability in the urban fabric. *Energy and Buildings.* 2004, 36, 321-8.
[9] LI, D., LIU, G., LIAO, S. Solar potential in urban residential buildings. *Solar Energy.* 2015, 111, 225-35.
[10] VULKAN, A., KLOOG, I., DORMAN, M., ERELL, E. Modeling the potential for PV installation in residential buildings in dense urban areas. *Energy and Buildings.* 2018, 169, 97-109.
[11] ROBINSON, D., HALDI, F., KÄMPF, J., LEROUX, P., PEREZ, D., RASHEED, A., WILKE, U. CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning. In: *Eleventh International IBPSA Conference: Building Simulation.* Glasgow, UK. 2009.
[12] MATURI, L., ADAMI, J., LOVATI, M., TILLI, F., MOSER, D. BIPV Affordability. In: *33rd European Photovoltaic Solar Energy Conference and Exhibition.* Amsterdam, the Netherlands, pp. 2621 - 5. 2017.

[13] KANTERS, J., WALL, M., DUBOIS, M-C. Typical Values for Active Solar Energy in Urban Planning. *Energy Procedia.* 2014, 48, 1607-16.

[14] Czech electricity and gas market operator (OTE a. s.) [online]. 2011. Available from: http://www.ote-cr.cz/

[15] Czech Statistical Office (ČSÚ). Energy consumption in households in the Czech Republic in 2003. (Energo 2004), Report 8109-05. Prague, 2005.

[16] REMODECE. Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe. In: *Annual electricity use in the Czech Republic* [online]. 2008. Available at: http://remodece.isr.uc.pt

[17] STANĚK, K. *Photovoltaics for buildings*: Grada for the Department of Building Structures at the Faculty of Civil Engineering of the Czech Technical University in Prague. 2012.

[18] VOSS, K., MUSALL, E., LICHTMESS, M. From Low-Energy to Net Zero-Energy Buildings: Status and Perspectives. *Journal of Green Building.* 2011, 6, 46-57.

[19] EVOLA, G., MARGANI, G. Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate. *Energy and Buildings.* 2016, 130, 794-810.

[20] HONRUBIA-ESCRIBANO, A., RAMIREZ, F. J., GÓMEZ-LÁZARO, E., GARCIA-VILLAVERDE, P. M., RUIZ-ORTEGA, M. J., PARRA-REQUENA, G. Influence of solar technology in the economic performance of PV power plants in Europe. A comprehensive analysis. *Renewable and Sustainable Energy Reviews.* 2018, 82, 488-501.

[21] VERBERNE, G., BONOMO, P., FRONTINI, F., VAN DEN DONKER, M. N., CHATZIPANAGI, A., SINAPIS, K., FOLKERTS, W. BIPV Products for Façades and Roofs: a Market Analysis. In: *29th European Photovoltaic Solar Energy Conference and Exhibition.*(Amsterdam, the Netherlands, pp. 3630 - 6. 2014.

[22] JOLISSAINT, N., HANBALI, R., HADORN, J-C., SCHÜLER, A. Colored solar façades for buildings. *Energy Procedia.* 2017, 122, 175-80.

[23] SKANDALOS, N., KARAMANIS, D., PENG, J., YANG, H. Overall energy assessment and integration optimization process of semitransparent PV glazing technologies. *Progress in Photovoltaics: Research and Applications.* 2018, 26, 473-90.

[24] MUNARI PROBST, M. C., ROECKER, C. Solar Energy Promotion & Urban Context Protection: Leso-qsv (quality- Site-visibility) Method. In: *31th PLEA Conference.* Bologna, Italy. 2015.

[25] FRONTINI, F., MANFREN, M., TAGLIABUE, L. C. A Case Study of Solar Technologies Adoption: Criteria for BIPV Integration in Sensitive Built Environment. *Energy Procedia.* 2012, 30, 1006-15.

[26] LÓPEZ, C. S. P., FRONTINI, F. Energy Efficiency and Renewable Solar Energy Integration in Heritage Historic Buildings. *Energy Procedia.* 2014, 48, 1493-502.

[27] KICHOU, S., WOLF, P., SILVESTRE, S., CHOUDER, A. Analysis of the behaviour of cadmium telluride and crystalline silicon photovoltaic modules deployed outdoor under humid continental climate conditions. *Solar Energy.* 2018, 171, 681-91.