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# Assessment of the BIPV potential at the city of Prague and their effect on the built environment

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## ABSTRACT
This work highlights the BIPV potential in two urban areas with different characteristics at the city of Prague. Representative building blocks were selected and CitySim software tool was used for the assessment of the hourly irradiation profiles on each surface over 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 built environment. Results indicated that only 5.5% of the total area can be used in Vinohrady and 13.7% in Jizni Mesto contributing on average by 32% and 31% on the hourly electricity demand respectively.

## KEYWORDS
Building-integrated photovoltaics, solar potential, architecture, load matching

## INTRODUCTION
The building sector is the major consumer of energy, accounting for around 40% of the worldwide consumption (UNEP, 2012). On the road towards Low or Zero Energy Buildings, renewable energy harvesting becomes compulsory and thus photovoltaic systems are expected to be the main technology to generate on-site electricity. PV systems have great potential to be used in the city context through various BIPV products (Shukla et al., 2017). Rooftop PVs are so far considered to be the most common application since it provides the best annual energy harvesting. However, due to significant decrease in prices and technological improvements in PV industry, building facades now represent good potential especially for high-rise buildings. Successful integration of PVs into a building requires both technical and architectural knowledge.

In this context, a suitable procedure is needed to assess the solar potential and propose PV concepts based on the characteristics and cultural aspects of the location. This paper aims to analyse the PV potential of two locations within the city of Prague. Considering the solar availability and shadings for the surrounding buildings, the available area for installation is determined and suitable PV applications are proposed considering all the constraints imposed form the locations and building morphologies. Finally, suitable index is used to investigate the interaction between on-site generation and building's electricity demand on hourly basis.

## METHODS
### Location characteristics
Two urban areas in the city of Prague with different characteristics were selected and used for analysis and comparison. A representative building block, constitute of residential buildings,

was selected for each location as presented in Fig.1. Case one, Vinohrady, is within a high dense area of the city centre with considerable architectural and cultural value. Houses built around 1900 are characterized by sloped roofs in different shapes and heights. Case two, Jizni Mesto, is a suburban area built in 1970es. Prefabricated high rise buildings are characterized by simple shape, flat roofs and big vertical facades with balconies on South and West orientation.

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

**Solar PV potential**

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

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

Once the radiation values on each surface are available, they can be analyzed to assess the PV potential. For this purpose, an irradiation threshold was used indicating the minimum amount of annual radiation required for PV system to be beneficial. Such thresholds are somewhat arbitrary; conservative value of 800 kWh/m$^2$annually is proposed by many authors (Li et al., 2015), while others define it as a percentage of the horizontal insolation (Vulkan et al., 2018). Considering the technological progress and enormous decline of PV costs within last decade, approximately 58% according to (Maturi et al., 2017), lower values such as 650 kWh/m$^2$ (Kanters et al., 2014) are still reasonable. To this end, 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:

$$E_{PV} = \eta * PR * \sum_{i=1}^{n_{threshold}} (I_i * A_i) \quad (2)$$

,where $\eta$ is the PV conversion efficiency, $PR$ is the performance ratio representing all system losses (mismatch, inverter..), $n_{threshold}$ is the number of surfaces exceeding irradiation threshold, $I_i$ is the cumulative insolation (kWh/m$^2$.year) and $A_i$ the relative area (m$^2$) of surface $i$.

Afterwards, data for the annual electricity consumption of representative buildings in each location, were collected and analyzed in hourly basis according to the occupants (REMODECE, 2008) and typical user profiles (Staněk, 2012). Based on the peak loads and the selection criteria that apply in each location, PV systems were sized properly, while load match index (Voss et al., 2010) was used as indicator of the hourly self-consumption of the PV generated energy.

**BIPV integration criteria**

It is evident that excessive use of PV systems can often have an adverse effect on the build environment and thus criteria and recommendations about dimensioning and positioning are needed. In order to select an appropriate BIPV application, both technical, architectural and economical aspects should be included. In case of Jizni Mesto, there is no limitations arising from the near environment and thus several scenarios and PV technologies can be considered (Fig.2). High performance modules can be installed on flat roof of the buildings horizontally to camouflage the installation or tilted to optimize performance. On vertical facades, 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 (Jolissaint et al., 2017) could be a solution, providing good durability and aesthetic quality. Finally, complementary building elements such as windows and existing balconies are well suited to support PV integration representing good compromise in terms of energy performance and aesthetics. In addition, optimized semi-transparent PV elements could be used as shading devices to increase indoor thermal comfort by mitigation of overheating during summer, but still to provide daylighting and to make use of passive heating during winter (Skandalos et al., 2018).


Figure 2. Examples of architecturally integrated PV systems in the two building blocks: (1) PV balconies. Source: Etsprojects; (2) Coloured PV-façade. 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. Source: (López and Frontini, 2014).

On the other hand, BIPV integration in the sensitive built environment such as Vinohrady district, is a more challenging task. 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 the historical context (Munari Probst and Roecker, 2015), small scale highly innovative PV products are needed. Suitable surfaces are limited to the sloped roof, flat terraces and vertical facades facing to the courtyard. Based on the geometry of each surface, BIPV applications such as solar glazing or PV tiles, balustrades and PV shutters (Fig.2) constitute effective practices of integration in the building envelope providing a balanced solution between technical and architectural standards as defined in (Frontini et al., 2012).

**RESULTS & DISCUSSION**

**Solar PV potential**

Results from solar analysis in both locations are presented in form of annual irradiation colour map (Fig.3). As expected, best solar resources were observed for sloped roofs facing south (Vinohrady), exceeding the 1200kWh/m$^2$ annually. However, different roof typologies were recognised and thus solar potential varies according to its slope and orientation. Relative results for the flat roofs of Jizni Mesto were slightly lower (around 10%), but still exceed the irradiation thresholds. Conversely, facades in both locations found to receive significantly lower level of irradiation, especially the ones on East and West façade. This is also explained from the increased shading factors. Average solar obstruction can reach up to 57% for a building in Vinohrady (high density) and 22% in Jizni Mesto respectively. Consequently, only a small portion of the total building area can be considered as suitable for PV integration. Percentages for buildings in each location vary between 5-18% in Vinohrady and 15-27% in Jizni Mesto respectively.

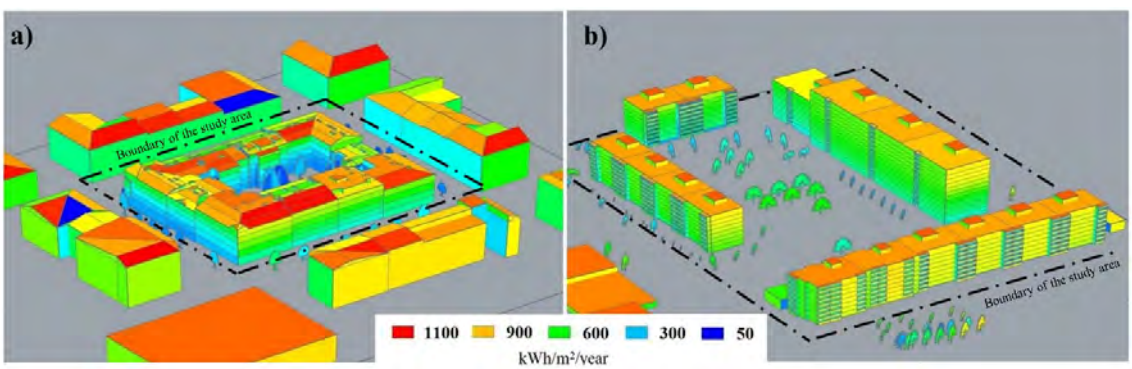


Figure 3. Annual solar irradiation map for each building block in a) Vinohrady and b) Jizni Mesto.

With respect to the hourly irradiation profiles, maximum PV potential in each location was calculated and presented in Fig.4. PV modules were assumed to be installed at the same plane with the building surface considering typical values for the conversion efficiency ($\eta$) according to the BIPV application ($\eta$=15% for roofs and $\eta$=8% for facades/balconies/glazing). For Vinohrady, annual PV generation could be up to 440MWh with peak generation in July (62 MWh). However, 58% of that energy is related to the building surfaces facing streets and thus could not be considered according to the criteria discussed in previous section (Fig.4a). Similar results for the Jizni Mesto revealed 2.7 times higher PV potential (1100 MWh/annually) with relative contribution from roof, façades and balconies by 49%, 45% and 6% respectively (Fig. 4b).

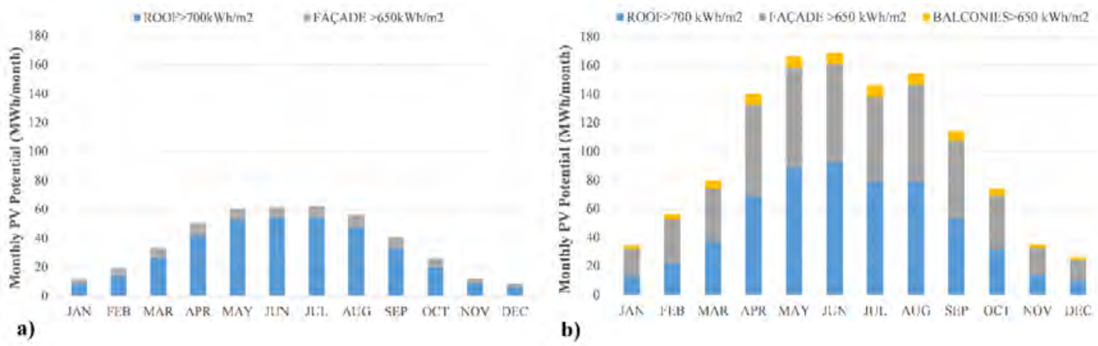


Figure 4: Monthly PV potential for the building block in a) Vinohrady and b) Jizni Mesto based on the selected irradiation thresholds.

**System evaluation**

Hourly peak loads were calculated and used as indicator, together with the criteria discussed in previous section, to size properly the PV systems in each building. Consequently, suitable PV systems were considered and results regarding the interaction between electricity consumption and generation are presented in Fig.5 for both locations. Despite the PV potential in Vinohrady, available space is limited to only 5.5% of the total building area due to the integration criteria applied. It is obvious that the generated energy is not enough to cover the loads of the building block (Fig.5a). However, almost all the generated PV energy can locally be used within the building block and it is enough to compensate on average by 38% (max value of 49% per building) the hourly electricity demand. In case of Jizni Mesto, there is no such limitations and thus 19% of the area can be used according to the irradiation thresholds. In that case, PV generation is enough to cover the electricity demand during the summer period, but also leads to excess of energy for 35% of the PV operation time (hourly). Therefore, better interaction between generated and consumed electricity is needed to increase the self-consumption of the buildings providing more efficient performance. If 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.5b). Alternatively, excess of energy can be used for cooling purposes since peak production coincides with peak cooling demand. Analytical results, regarding maximum load match index (hourly intervals) between the buildings in Jizni Mesto found to be 43%.

## CONCLUSIONS

Two representative building blocks, with different characteristics and level of preservation in the urban context of Prague, were selected and analysed for their hourly solar radiation per unit area according to the local weather data. As expected, most of the potential is intrinsically related to roofs, while façades suffer more the shadowing effect caused by the surroundings. According to the integration criteria and energy consumption applied in each location, suitable PV systems were proposed. Only small part of the building area can be used, varying from 5.5% for Vinohrady and 13.7% for Jizni Mesto. Interaction between electricity demand and consumption revealed that proposed PV systems could compensate on average by 32% the hourly energy demand in Vinohrady and by 31% in Jizni Mesto. It is evident that even in areas with sensitive built environment adoption of solar energy is still possible for balancing local electricity needs. Further work is needed to assess the indirect effect (thermal, daylighting) of the proposed solutions. Also economic assessment based on the actual market conditions (BIPV prices, installation costs and electricity tariffs) will also reveal the profitability of the proposed solutions.

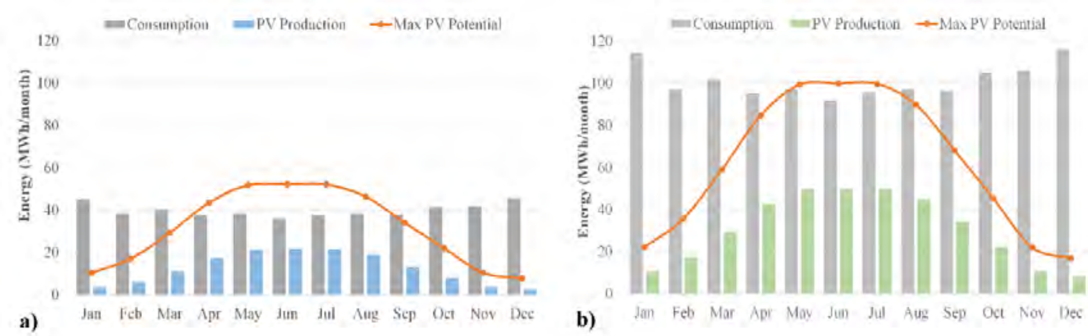


Figure 5: Annual electricity consumption and generation of the proposed PV system together with maximum potential according to irradiation threshold (800kWh/$m^2$ year) based on monthly data for a) Vinohrady and b) Jizni Mesto.


## ACKNOWLEDGEMENT

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