BIPV planning process towards nearly zero energy districts

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Abstract

Buildings can be classified among the leading energy consumers and CO_2 emitters contributing by 40% of the primary energy in EU. Consequently, the development and implementation of energy efficiency strategies in building sector becomes top priority. In this context, Building Integrated Photovoltaics (BIPV) is being considered as promising contributors for both on-site electricity generation and energy savings in buildings.

This paper presents a framework for the development and early-design guidance of a nearly-zero neighborhood in Prague using open-source simulations tools suitable for educational purposes. The approach starts with methods for urban solar analysis to identify the most radiated parts of buildings' surfaces, propose suitable PV systems and estimate the annual energy yield. Then, simulation model is presented for the assessment of the operational Energy Use Intensity (kWh/m^2) that feed the input for BIPV sizing. Calculated metrics, based on the design parameters selected by the user, will provide information on energy balance and potential for energy self-sufficiency leading to Zero-Energy Building target.

Keywords: photovoltaics, building energy simulation, early design, architecture

INTRODUCTION

The building sector is classified among the key energy consumers and CO_2 emitters in Europe [1]. Currently, there is a major transformation taking place through national building codes, roadmaps and building rating systems. The energy needs has to be reduced and supply the remaining low demand from renewables (EPBD recast) [2].

From this perspective, Building-Integrated Photovoltaics (BIPV) could be the main technology to generate on-site electricity, satisfying part of buildings' demand. Generated electricity cannot only be used instantly to cover building needs (e.g. lighting, appliances, cooling, etc.), but also exchanged between a cluster of buildings. Buildings with a positive energy balance can compensate those with negative balances increasing the PV self-consumption and achieve the zero energy target.

In the current study, BIPV technology is presented as an effective option for buildings to optimize the use of the solar energy source. The paper prsesents a design methodology aiming to provide effective guidance to building engineers, architects or students during the early-design phase. The method employs specific "integrated" software tools, able to address all issues related to the project (e.g. energy balance, life-cycle costs, economic issues, architectural appearance, etc.) into a single platform.

SOLAR CITY CONCEPT

In project CAP, we are focusing on the development of the "Solar City" – a self-sufficient zero energy neighbourhood. A residential district in Zizkov (Fig.1) with a total gross floor area of approx. 100 000 sqm, was selected as demo case for the implementation of the proposed methodology. Design and analysis are integrated within a single simulation environment, where a model is constructed and evaluated according to several targets, in order to allow the designer/student to provide quick and reliable predictions.

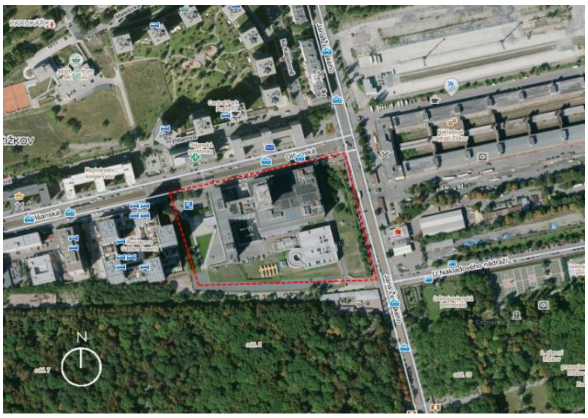

Fig.1: The selected site for the development of Solar City neighborhood (total site area of 39471 m^2).

DESIGN PROCESS

The process starts with a volumetric study (heights, views, construction details) considering all typologies of the building complex. The buildings are modelled in the Rhinoceros environment - a commercial CAD application software (student license around 195 EUR) – using Grasshopper, a visual programming language for parametric modelling.

Then, an urban solar analysis is needed to identify the suitable surfaces for PV integration and the estimation of the annual energy yield. Radiance-based plug-ins such as DIVA [3] and Ladybug [4] are suitable for this process. Basic information regarding the occupancy schedules, equipment and internal gains for each building typology are used for estimating the electricity demand and optimal sizing (installed capacity, orientation, etc.) the BIPV systems.

In parallel, building energy calculations are provided by Honeybee [5] or ClimateStudio. Both tools use the EnergyPlus engine [6] - a whole building energy simulation program - widely used both in research and industry. Users can experiment and explore different materilas and parameters and conclude to the design that minimizes the Energy Use Intensity (EUI) of the building complex. In addition, BIPV systems are proposed taking into account not only the generated electricity, but also their effect on the built environment (thermal, daylighting).

Calculated metrics for the final design will provide information on energy balance and potential for energy self-sufficiency leading to Zero-Energy Building target.

SOLAR ANALYSIS

Details about the shape, dimension and building materials as well as obstacles and construction in the perimeter of the building are collected and 3D model of the building complex is prepared in Rhino. With the Ladybug [4] tools, the students can import and analyse standard weather data, draw diagrams like Sun-path, run radiation analysis, and shadow study. For the design of BIPV this is particularly important, especially for environments where shadow paths can dramatically reduce the PV generation. In our case, Ladybug [4] tool is used to conduct grid-based solar irradiation analysis.

Building surfaces were divided according to the dimensions of the PV modules and the software calculates the hourly irradiation (in Wh/m^2) at every sensor of the analysis grid, during one year period. Each of these surfaces receive different amount of solar radiation, based on the orientation, tilt angle and shadows or reflections from nearby objects. Simulation results can be presented as colored irradiation maps (Fig.2) indicating all the suitable surfaces that PVs can be integrated. Based on the irradiation differences and shading patterns, different string matching scenarios can be proposed by the students.

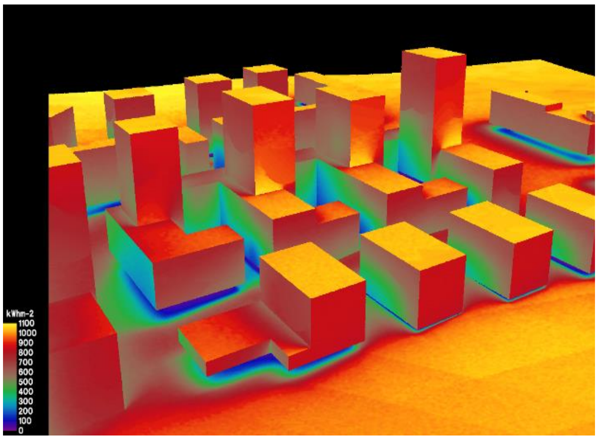

Fig.2: Annual solar radiation (kWh/m^{2}a) map for Zizkov building surfaces prepared in DIVA.

SURFACE SELECTION

Once the radiation values on each surface are available, they can be use to identify suitable surfaces for PV integration. For this purpose, an irradiation threshold is commonly used indicating the minimum amount of annual radiation required for an effective BIPV installation. Such thresholds are somewhat arbitrary; mainly based on financial aspects according to the following equation (Eq.1):

$$PBT = \frac{PV_{cost}\ [€/m^2]}{Threshold\ \left[\frac{kWh}{m^2\ year}\right] * \eta_{ref} * PR * E_{cost}\ [\frac{€}{kWh}]} \qquad (1)$$

Where:
PBT = Payback time,
PV_{cost} = PV system cost,
η = PV conversion efficiency,
PR = performance ratio and
E_{cost} = grid selling price

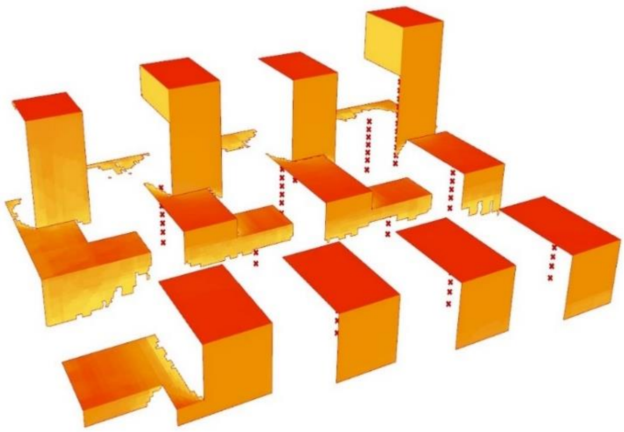

Fig.3: Illustration of the PV-suitable surfaces using irradiation thresholds (650kWh/m^2 annually) with Ladybug tool.

Here, the students can observe how the selected irradiation thresholds affect the relative fraction (percentage) of the surfaces and thus the PV capacity that could be installed in each building. An example of the available surfaces considering an irradiation threshold of 650kWh/m^2 is presented in Fig.3. Commonly, a conservative value of 1000 kWh/m^2 per year is assumed for the roofs and 800 kWh/m^2 per year for facades [7]. Considering the technological progress and enormous decline of PV costs within last decade, lower values such as 650 kWh/m^2 are still reasonable. However, final desicions regarding the PV surface areas will be taken considering the results from the energy balance calculations in later stage.

PV POTENTIAL

Honeybee is a free plug-in that integrates EnergyPlus to Grasshopper and includes PV simulation components. With the PV component the students need to define the efficiency and effective area of these PV panels. Then they can connect the PV panels to a 'PV simulation' component to link them to EnergyPlus. Based on the area of the suitable surfaces a simple model can be applied to quantify the annual energy output (E_{PV}) of each building block according to Eq.2:

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

Where:
η = PV conversion efficiency,
PR = performance ratio
$n_{threshold}$ = number of surfaces exceeding threshold,
I_i = cumulative insolation (kWh/m2.year) and
A_i = relative area (m2) of surface i.

For more accurate PV modelling EnergyPlus offer two more options; a) the "Equivalent One-Diode" and b) "Sandia" models. Modules´ parameters can be extracted from Sandia and CEC module libraries. Based on the type of PV integration, EnergyPlus allows for different ways of integrating with heat transfer surfaces and models and calculating phtotovoltaic cell temperature. The students can select among different options offered throuth the 'integrationMode' parameter shown in Fig.4.

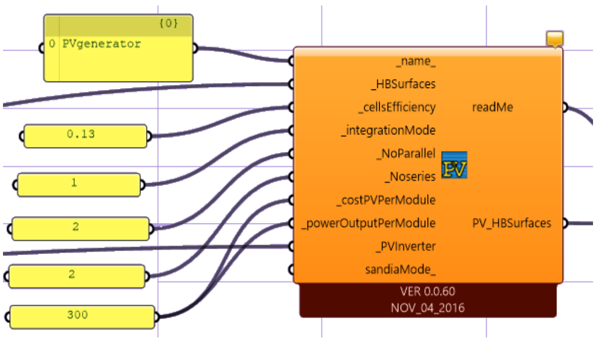

Fig.4: PV generator settings for Honeybee component.

Hourly solar radiation together with the modules´ parameters and inverter technical characteristics will be used to simulate the energy performance for each configuration considered earlier and obtain optimal solution. This could vary according to the objectives i.e. maximizing annual energy yield, load matching, etc.

ELECTRICITY DEMAND

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

Occupancy schedules are selected to define the presence of peoples in a zone and the use of electric equipment. Typical profiles (Fig.5) for various building typologies can be found in standard library and can be selected via drop-down menus.

In adittion, custom definitions can be prepared by students. This is done by providing an array of 24 values between 0 and 1 (Fraction schedule). The next step is to define a Week Schedule with a typical differentiation between working days and weekends. Ultimately, the Week Schedules are combined to define a Year Schedule. Figure 6 illustrates a complete setup and the relative components in the Grasshopper environment.

Subsequently, representative values for the equipment power density are selected for the estimation of the electricity demand (in kWh/m^2). Lighting energy can also be considered based on the selected values for lighting power density, dimming control and representative illuminance threshold for the interior spaces.

Based on the peak loads and selected objectives, PV systems can be 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 PV generation for the whole building complex can be made through the calculation of load match index [8]. According to the Eq.3 it indicates the average hourly contribution of the PV systems on the building loads (in hourly time intervals).

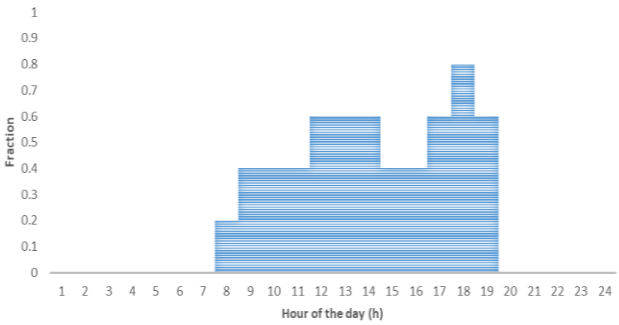

Fig.5: Normalized schedule for commercial building according to SIA2024 [9].

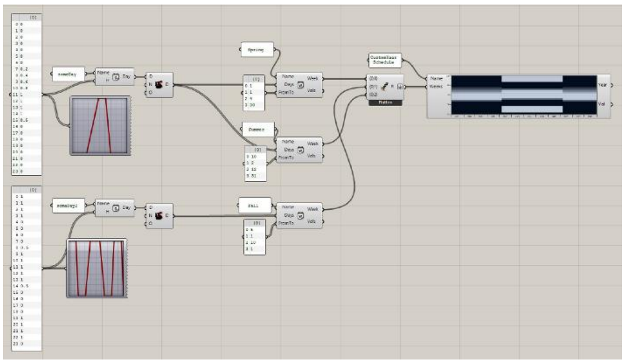

Fig.6: Complete setup for annual schedule definition in Grasshopper environment.

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

Where:
i = time interval (hour, day, month),
g_i = instantaneous on-site electricity generation,
l_i = instantaneous electricity demand and
n = sum of time steps over a year period

THERMAL ENERGY DEMAND

EnergyPlus was used to simulate the energy consumption for heating, cooling, ventilation and lighting in buildings. This is done in Grasshopper environment through the use of ClimateStudio and/or Honeybee [5] tools. In this process, the model takes into account the envelope transmission losses, infiltration, ventilation and the solar gains, but also interal flows such as heat emitted from occupants and equipment (Fig.7). These flows are not always in balance and hence heating, cooling and ventilation systems are required to provide a comfortable indoor environment.

Here, students can calculate the energy balance of each building, considering heat gains and losses, an example of which is presented in Fig.8. The students can also investigate the effect of key design parameters on the Energy Use Intensity (EUI) and make an early assessment.

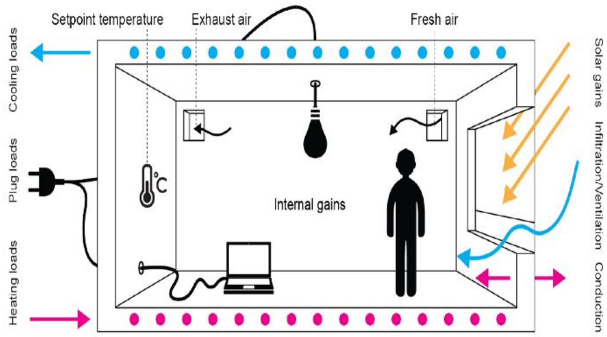

Fig.7: Main heat and mass transfer considered in a room [10].

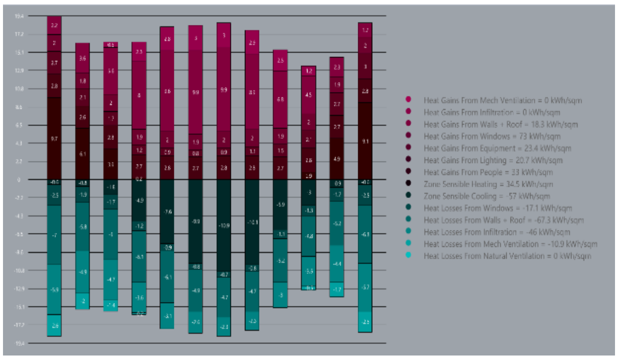

Fig.8: Energy balance of one building zone with the corresponding gains and losses.

Parameters for investigation include both a) envelope and b) system settings. The former corresponds to building envelope construction (insulation, thermal mass, etc.), window-to-wall ratio (WWR), insulating glazing units (U-value, SHGC, TVIS) and shading depth, while the latter include artificial lighting (density, dimming control), heating/cooling systems (gas-fired boiler, electric heating, heat pump) and ventilation strategies. Simulation inputs are fully parametric and can be coupled with optimization algorithms within Grasshopper. Results from selected strategies will be used together with the ones from previous stages to provide final recommendations regarding the design of the BIPV systems leading to Zero-Energy Building target.

CONCLUSION

The paper presented a methodology for the design of BIPV systems in the early design phase of near zero energy districts. Students can learn how to design, configure and optimize BIPV systems using open-source simulation tools. The process includes varyous methods from grid-based solar analysis and PV modelling up to whole building energy simulations and optimization process for BIPV systems.

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