Use of photovoltaic systems in the construction of wooden houses in a sustainable standard

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Abstract. The paper deals with the analysis of the efficiency and application of photovoltaic systems in the roof plane and in the perimeter walls in the construction of wooden houses in a sustainable standard. The installation of photovoltaic systems is a source of renewable energy in the construction of zero energy buildings with minimal emissions of environmental pollution. Semi-transparent photovoltaics integrated in the building (BIPV) is one of the technologies that has the potential to increase the energy efficiency of the building and at the same time aesthetically complete the design of the building. This work deals with the construction and material solution of BIPV systems, including BIPV glazing products, tiles and modules and their application in the architectural solution of a model building.

1. Introduction

Achieving sustainable development has been a major goal of the international community since 1992, when the UN Conference on Environment and Development was held in Rio de Janeiro (Earth Summit). The summit document sets out the principles for addressing the sustainable development of the territory in terms of social, environmental and economic growth. In the Europe, the Strategy 2020, which is one of the main economic reforms of the European Union, defines requirements such as sustainability in the construction and operation of buildings, including their demolition. One of the main goals of the strategy, which the EU countries have committed themselves to meeting, is that from 31 December 2020, all new buildings will have energy consumption approaching zero. [1] Regulation of the European Parliament and of the Council of the EU no. 305/2011. This criterion can only be achieved through the use of active technologies, that could transform energy from renewable sources in buildings for its operational needs. Solar energy is the most available source for optimizing the thermal microclimate and operating technical equipment in buildings. If the potential for the use of solar radiation from exposed surfaces in the production of energy during the operation of buildings is increased, the amount of environmental emissions from non-renewable sources that escape into the air during the operation of heating and cooling systems will be significantly reduced. Sunlight is an unlimited source of energy. The latest European Union report on the State of Photovoltaics of 2019 [2] states that the average cost of generating direct current (DC) electricity produced by photovoltaic modules has fallen below € 0.02 (€) per kilowatt hour in many places around the world (kWh). The current problem of electricity production from PV modules is the high costs associated with its transport to the place of consumption. For this reason, building an integrated photovoltaic system (BIPV) at the point of consumption is ideal. BIPV systems are photovoltaic cells that are integrated into heat-exchange building envelopes, such as roofs or facades. Such a system performs two tasks in
the building at the same time. First, it is the final structural-material solution of the heat-exchange packaging of the building itself with the function of weather protection and they are early fulfilling the function of thermal, acoustic and fire insulation of the building. The second task of the BIPV system is to provide electricity for the operation of the building. They become the energy generator of the building [3,4]. The BIPV system supplies energy where the end user needs it. The system for storing the generated direct current is in a battery or in the public electricity network. It is ideal to store energy in batteries directly in the building, which can cover the night's electricity consumption in a building for heating, cooling or artificial lighting. In terms of environmental impact on the environment, the integration of PV panels into building envelopes is an ideal solution - the electricity generator is at the place of its consumption and their installation is without the need for additional occupation of agricultural land [5,6].

2. Use of photovoltaic systems in the building envelope

We divide the use of photovoltaic systems in the building in terms of their application on the heat exchange envelope, the method of their installation and the components used. We divide photovoltaic energy systems in terms of their incorporation within the building envelope into applied PV panels - BAPV systems, and integrated systems in the construction of the heat exchange envelope - BIPV systems. BAPV systems are usually placed on a grate structure on the surface of the building envelope in grouped assemblies. With this installation system, the inclination, the area, the technology used and the orientation of the panels to the world side are decisive in terms of energy efficiency. As they are usually placed on facades and roofs additionally, they are a suitable solution for the reconstruction of energy systems of buildings during additional modernization of buildings. To increase their efficiency in heating buildings is possible. The use of BIPV systems is the optimal solution for new buildings. By incorporating integrated PV panels directly into the structure of the heat-exchanging building envelope or shielding lamellas, their effective area is usually significantly larger than in BAPV systems. They are most often applied to all-glass facades, which are oriented south, southeast, southwest in localities with a low degree of external shading by the surrounding urbanism or geo-relief. They are often located in the shading slats of sunshades, balustrades, awnings and the like. On roofs, they are most often applied to large-area skylights, glass roofs of atriums. With sloping roofs, they replace the classic roofing. When applying BIPV systems in general reconstruction of buildings - replacement of heat exchange envelope, it is possible with these technologies to achieve energy efficiency of a building with zero energy consumption (ZEB), or even plus energy buildings [7,8]. In terms of the elements used, they can be applied as - foil tiles, modules and glazing of solar cells. Application of PV systems in the heat exchange envelope of the building, see figure 1.

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**Figure 1.** Classification of BIPVs BAPVs products. [9].

PV systems can also be implemented as photovoltaic thermal systems (PVT), which are with active or passive ventilation, behind the panels with subsequent removal of hot air to the heating
system of the building. Cooling of PV modules is carried out using air or water. [10, 11, 12] In this way, the production of electrical and thermal energy in a building with higher efficiency is achieved [13, 14, 15]. For example, in a BIPV system with air ventilation in the gap of double-skin facades or roofs, a photovoltaic system is typically installed in front of the interior cladding of the heat exchange cladding. Fresh air in the summer naturally ventilates and cools the back of the BIPV system, increasing its efficiency in electricity generation. If the system uses this extracted hot air for heating purposes, it changes to a new configuration called the integrated photovoltaic heating system (BIPVT). Experimental assessment of the thermal performance of the BIPV ventilated wall is given in the study Chiu MS, Hou SP, Tzeng CT, Lai CM [16]. Examples of the use of different building facades with different focus on the distribution of energy production throughout the day are given in the literature [17,18]. The application of BIPV systems is not limited to a building, where, in addition to energy efficiency, it also performs a design function. It can also be used in other applications in vehicles - ships, cars, aircraft, where it contributes to their optimal performance in terms of energy consumption [19].

3. Methodology of the procedure

The optimization of the potential of BIPV and BAPV was based on studies and procedures reported in the literature [20, 21, 22].

There are currently four basic approaches available for assessing the potential of solar energy in photovoltaic systems. [22]. They are defined as theoretical, geographical, technical and economic potential. Theoretical potential is defined as all available solar radiation incident on the surface of the earth's surface, the distribution of which is without any geographical or technical restrictions. Geographical potential is a fraction of the theoretical potential, which is usable depending on the inclination of the panels and their orientation to the sides of the world. For the capitals of the EU countries, it is shown in figure 2 on the basis of data from [23].

Figure 2 shows the average annual potential of geographical solar radiation in creating surfaces for the placement of PV modules in the capitals of all Member States of the European Union (EU) together with the capitals of Norway and Switzerland. The analysis and calculated quantities are based on hourly data on incident solar radiation from 2005 to 2016 from the Photovoltaic Geographic Information System (PVGIS)

![Geographical solar irradiation potential on building skins of the capitals of the European Union](image_url)

Figure 2. The average annual geographical irradiation potential on building skins of the capitals of the European Union member states (EU) with Norway and Switzerland.
Technical potential is defined as a fraction of the geographical potential that is technically usable depending on the efficiency of the photovoltaic module technology. Economic potential is part of the technical potential that is economically feasible.

2.1 Photovoltaic system technologies and their technical potential

The division of PV systems can be based on the composition of solar cells and the type of connection to the grid (separate - accumulation in a battery, connected to the public grid, or hybrid by a combination of the previous two systems. (GaAs), thin-film technologies, multi-cord cells and emerging PV technologies. With a broad classification, monocrystalline and multi-crystalline are the two basic forms of crystalline technology. Compared to all other types of photovoltaic technologies, crystalline silicon technology has the highest representation in the construction market. Efficiency in the conversion of solar radiation into electricity see table 1.

| PV cell technology (abbreviation) | Theoretical effectiveness of the PV cell | Laboratory result of PV cell efficacy | Laboratory result of PV module efficiency | Market efficiency for the PV module |
|----------------------------------|------------------------------------------|--------------------------------------|------------------------------------------|------------------------------------|
| MonoCrystalline silicon (C-Si)   | 29.8%                                    | 250%                                 | 22.9%                                    | 14-17%; 20%                        |
| Multi-crystalline silicon (MC-Si)| NA                                       | 20.4%                                | 18.2%                                    | 12-15%                             |
| Copper Indium-Gallium Selenide (CIGS) | 31.6%                                  | 19.6%                                | 15.7%                                    | 11-13%                             |
| Telurid Cadmium (CdTe)           | 30.3%                                    | 16.7%                                | 12.8%                                    | 11-12%                             |
| Gallium Arsenide (GaAs)          | 31.2%                                    | 28.3%                                | 23.5%                                    | NA                                 |
| Multi-Junctional PV technology (Multi-J) | 55.9%                                  | 43.5%                                | 33.9%                                    | 25-30%                             |

The efficiency of solar systems is directly dependent on the intensity of solar radiation incident on the surface of the structure, depending on its inclination and orientation to the world side. Figure 2 shows an analysis of the average values of solar radiation intensity in the capitals of the EU countries, Norway and Switzerland without the influence of external shading on the surfaces of buildings, depending on their orientation to the sides of the world. From the geographical potential of the intensity of solar radiation for the surfaces of the building, the technical potential of the produced electricity can be calculated. In order to calculate the technical potential, it is necessary to specify the technology and efficiency of the PV module, which is specified by the technology manufacturer. For selected systems, see Table 1. The average overall efficiency of BIPV systems varies depending on the technology used, configuration, site climate, ventilation, orientation and slope. Based on the experimental projects carried out so far, the technical potential of BIPV is between 10% and 22% [25]. Thus, if we take the average efficiency of 18% for BIPV panels - which is the average efficiency of commercialized BIPV panels on the market and not the system, the technical potential can be easily calculated by multiplying the 18% efficiency by BIPV x geographical potential from figure 2. Based
on BIPV efficiency and data at figure 2 shows the technical potential of BIPV systems for European capitals in figure 3. In the future, it is expected that their efficiency will increase with the development of new PV module technologies. The expected life of a PV system is defined as the period during which the panels will generate electricity for at least 80% of their rated output. According to the manufacturers, the current BIPV systems have a warranty of about 30 years.

**Figure 3.** The average annual technical potential of the BIPV system of the capitals of the European Union member states (EU) with Norway and Switzerland.

4. **Model solution of a PV system in a family wooden house in terms of their technical potential**

The model solution compares the efficiency of the solution, of the location and technology of BIPV on the heat exchange envelope of the family wooden house in terms of their area, so that its energy consumption for the operation of the house throughout the year is ensured from the energy produced by PV. The family house has a gable wall with a glass wall facing south, its area is 28 m². This wall is without external shielding and is ideal for placing a BIPV system. In terms of light comfort in the living room and visual contact of people with the exterior, the distribution of daylight is provided from the sides. To the west to the terrace are situated French windows with a height of 2.4 m, to the east in the dining room part of the window with a height of 1.5 m. The family house has a sloping roof, while the roof planes are oriented east - west. The second option is to place the BIPV system in the roof plane of the saddle roof with an orientation to the west. The geometry and layout of the apartment can be seen in figure 5.

**Figure 4.** Area optimization of BIPV modules depending on their orientation on the heat exchange envelope of the building with zero energy consumption from non-renewable sources.
Figure 4 shows the economic efficiency of placing BIPVs in walls depending on their orientation to the sides of the world and in a sloping roof.

![Figure 4](image)

**Figure 5.** Example of a model solution for optimizing the location of a PV system in the envelope of a family house.

5. Results
In the case of family wooden houses, the optimal solution from the point of view of economic efficiency is the positioning of BIFV modules in the roof plane. In terms of equipment performance, it is ideal if the slope of the roof plane in our geographical location is in the range of 35-45 °. The second option, which is comparable to the variant of placing the BIPV on the roof, is the integration of BIPV modules into the southern gable wall in the model solution with regard to the boundary conditions of the area and the layout of the apartment. This solution will fundamentally affect the emotional quality of the living room space and the overall design of the building.

6. Conclusions
Current studies show that the lifespan of BIPV systems can be up to 50 years [26, 27], the return on the initial increased investment costs when installing them in the building is paid by their operation within 10 years. From the point of view of the service life of wooden houses, which are also realized for a service life of 50 years, the installation of BIPV on the casing of ZERO wooden houses is the optimal solution. PV systems in the building will provide at least 80% of their original projected electricity generation capacity during their lifetime. At present, more than 80% of BIPV systems in the world are installed on the roofs of buildings, the rest are PV systems mounted on facades [28]. BIPV products for facades are less widespread [29]. This is related to the optimization of the microclimate in protected areas. If they are located in front of the windows, they fundamentally limit the distribution of daylight in protected areas and the visual contact of people with the exterior. The second major limitation in terms of their effectiveness in their application in the perimeter walls is the external...
shading of the surrounding urbanism. In dense street buildings, their effectiveness is considerably limited.

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