

DESIGN AND CONSTRUCTION POSSIBILITIES FOR PHOTOVOLTAIC INTEGRATION IN ENVELOPES OF NEW AND EXISTING BUILDINGS

Aleksandra Krstić

Sun is the renewable energy source whose usage exerts influence on architectural design. Facade concepts of energy efficient buildings are developed producing new facade structures and components. Photovoltaic systems, as elements of active solar systems are discussed in the paper and particular attention is paid to building integrated systems, as they influence building appearance. Classification and analyzes of PV systems - materials, supporting systems, coatings and design principles are presented in the paper. The purpose of this paper is discussion on design and construction possibilities for PV integration in envelopes of new and existing buildings. Possibilities for structural variability of envelopes with PV integrated systems are described in the paper.

Keywords: *PV integration in architecture, building integrated PV, building appearance, design possibilities, design principles, structural variability.*

INTRODUCTION

The public become aware of the effects of climate change and environmental pollution. Buildings, as consumers of around 40% of global energy production, mostly generated from conventional energy sources, significantly contribute to environmental pollution. Implementation of Renewable Energy Sources and Rational Use of Energy in building design can reduce energy use in buildings, consumption of pollutant energy sources and thereby reduce CO₂ emissions. Sun is renewable energy source whose usage exerts influence on architectural design and building concepts. Main role take south facing exterior screens. Concepts of energy efficient buildings are developed producing new facade structures and components. Passive, active and hybrid solar systems can be separated. In the case of active solar conceptions building components are classified according to their function, such as: solar collectors and photovoltaic systems. The first transform solar energy into thermal

energy while the second convert it into electric energy.

Photovoltaic systems are discussed in the paper. They can be used in design of new buildings or refurbishment of existing buildings in order to improve the energy performances. But it requires proper thermal performances achieved by building construction and detailing. In the developed world, with the existing power grid infrastructure, PV in buildings is regarded as major application area for photovoltaics (Nordmann, 2005). In order to encourage the use of PV in buildings, a well created plan of organizing and promoting PV installations has to be carried out. Government that regulates energy and building, by national indicative targets and legislation can encourage the use of PV in buildings. The government stimulates building integrated PV systems development by supporting research and demonstration programs.. Programs generated for the public support enable citizens to be informed about PV power and PV in buildings. Once people are informed of

possibilities to improve their quality of life by investing in environmentally friendly renewables, combined with economically sound projects, there is no limit for citizens' enthusiasm and involvement (Cristiansen, 2006). Major problem is that PV is still more expensive than it need be. The low-cost mass production of PV can be justified through simply regulating that new buildings are solar powered PV (Mallon, 1999). It can also provide a transition of the related industry which could be made open to different building designs and performances and competitive for conventional building claddings. Listed actions require to be carried out by experts among which PV dedicated architects play an important role.

The influence of PV systems on appearances of buildings and settlements is significant. The application of photovoltaic components to building envelopes is a challenge to architects. Production of PV systems is new provocation and orientation for building industry. Design and construction possibilities for PV integration in envelopes of new and existing buildings are

discussed in the paper. Design of energy efficient houses with PV systems requires proper information on photovoltaic systems by the architects and students of architecture. The paper presents initiation and contribution to that process. Classification and analyzes of PV systems - materials, supporting systems, coatings and design principles are presented in the paper. The purpose of this paper is also to describe possibilities for structural variability of envelopes with building integrated PV modules.

RELEVANT ASPECTS IN DESIGN PROCESS

Basic information about material, structure, function and design possibilities of PV systems is sufficient for the design process, and major facts are briefly mentioned in this section. From architectural aspect, different performances of photovoltaic systems can be required regarding: *Location possibilities, Function possibilities, Dimensions and form, Color and appearance of modules, Light permeability, Construction possibilities.* Various possibilities for fulfillment of listed performances result in variability of building envelopes with PV systems.

Application of PV devices to a building envelope enables zero land consumption. Regarding *location on building*, roof and facade "standoff" and "building-integrated" PV systems are available (Fig. 1a, b and 2a, b). They strongly influence building appearance in a different way. In the first case they are independent devices applied on roof or facade structure. In the second case, building-integrated PV systems are building components which can substitute usual roof or facade cover materials. Development of technologies, materials, support systems and coatings is continuous, giving freedom for architectural design.

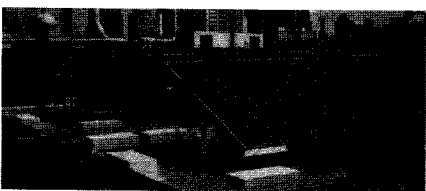


Fig. 1a. Roof "standoff" PV system



Fig. 1b. Facade "standoff" PV system

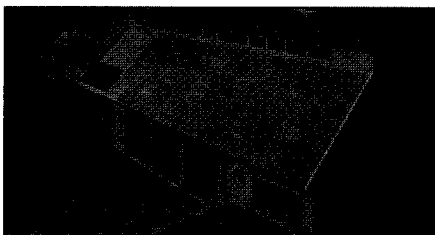


Fig. 2a. Roof "building-integrated" PV system

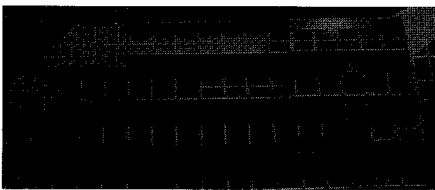


Fig. 2b. Facade "building-integrated" PV system

Function possibilities for PV systems are various. The main function is production of electricity. Photovoltaic system concept is based on the direct conversion of sunlight to electricity. Batteries store energy for use when the sun is not shining. The basic element of a photovoltaic power system is the solar cell made of a semiconductor material, usually silicon. It is photosensitive and produces electrical current in the presence of photons, or energy from light. The efficiency of monocrystalline silicon is the highest (14-18%), of polycrystalline somewhat less (12-15%), and amorphous modules have the worst efficiency (4,5-6%). The same features stands for durability. Photovoltaic cells generate commercially valuable electricity operating in parallel with the existing electricity network. Exchange of electricity to and from the network is possible. Individual solar cells are combined to create PV modules that produce a specific amount of power. Many interconnected PV modules (the number varies, depending on the demanded amount of power) are called an array.

While standoff PV systems have poor scope of functions (in addition to electricity production can be used as shading devices), building integrated systems are characterized by functional complexity. As external layer of building envelope, they provide thermal, acoustic and humidity insulation, wind protection, in some cases fire and security protection, protection from sunrays and produce electric energy. Application of building integrated PV modules removes the need for conventional cladding materials and is reflected in investment costs. For example, Thomas Nordmann comments that, compared with an ordinary roof mounted installation (standoff systems), which is placed on top of a conventional roof, part of the basic concept of a true BIPV installation is to share the cost of the building envelope because the installation has a double function (Nordmann, 2005). His opinion is that the main potential of double function in the area of balance of system (BOS) is in the area of module costs and installation costs, where it should be 30% of the total system cost.

Factors that affect PV output and can be influenced by designers are: tilt, azimuth, shadowing, temperature.

System efficiency is influenced by orientation and inclination of PV modules. A favorable orientation is south. Deviation to southeast and southwest up to 30° is suitable. PV modules can be placed in horizontal position, vertical position or inclined. Choice of inclination is influenced by latitude value and orientation. Maximum available irradiation is received by a south-facing unobstructed PV panels oriented at a tilt equivalent to the local latitude, while east and west-facing PV panels perform relatively well at steep angles or vertical orientation and still yield 60% of optimally inclined south oriented PV systems; It points out that a range of orientations and tilts give 95% of the maximum output; A role of thumb is that 1m² of monocrystalline PV array reasonably positioned and in an efficient system will give about 100kWh/y (Sich, Erge, 1996). For Belgrade, PV power production estimate is shown in the Fig. 3.

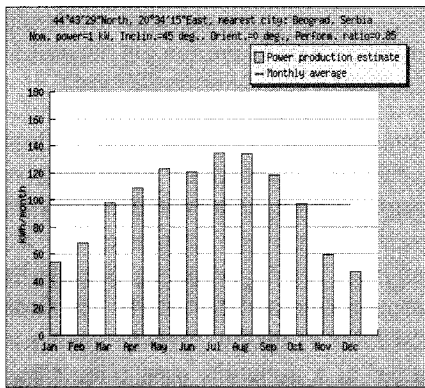


Fig. 3. PV power production estimate, location Belgrade

It is not recommended to apply PV systems on periodically shaded surfaces of building envelope because it results in negative effect on system efficiency and can cause damages, as glass cracks. In order to obtain system efficiency the overheat of PV modules has to be prevented. It appeared that building integrated modules can reach 20–40°C above ambient in conditions of high radiation; For each 1°C increase in cell temperature above 25°C, the power output decrease by about 04–05% (Sich, Erge, 1996). Ventilation, normally natural ventilation, needs to be provided to remove heat from the modules. A role of thumb is to provide an air gap of minimum 100mm.

Variations in *dimensions and forms* of PV modules are dependent on glass characteristics and require further development. Solar cells are embedded with special clear cast resin between two glass panels, air-tight and protected against corrosion. Extremely great changes occur in glass industry where the introduction of modern solutions, i.e. special types of glass enables the design of large glazed surfaces with integrated PV modules, providing pleasant indoor atmosphere as well as building appearance (Fig. 4a). With regard to form, flat modules are mostly in use, but twisted, mostly concave and convex shapes (Fig. 4b), are also available and very frequently present in contemporary architecture.

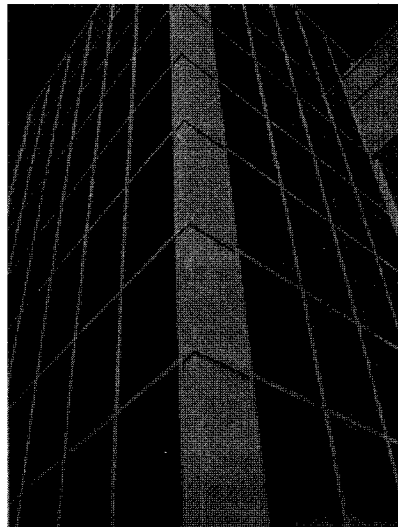


Figure 4a. Large size PV modules

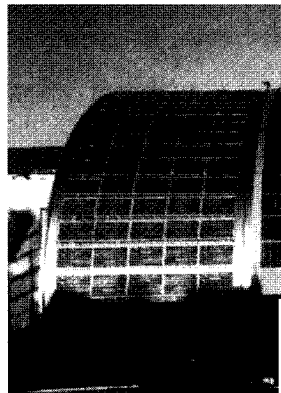


Fig. 4b. Convex shape of PV modules

Talking about dimensions some problems can be noticed. The suppliers in the PV industry produce their modules in individual, non standard sizes. It means that architect is forced to design its application in favor of a certain product before the call for tender. But it is contrary to approach accepted by building industry that elements being specified by size become part of the tendering process. For the building industry we need "open" PV systems, the production of not just standardized modules but modules that will fit in with other industries that use – or could use – PV modules (Nordmann, 2005).

Color and appearance of PV modules depend on material of solar cells. There are two basic types of PV modules commercially available today: those made from crystalline silicon (mono- and multi- or polycrystalline) and those made from amorphous silicon (a-Si). The first type is the dominant commercial product. Mono-crystalline modules are

recognizable by their black mono-crystalline cells. Polycrystalline modules can be recognized by blue, glittering polycrystalline cells. They could be opaque and semitransparent. Amorphous modules can be opaque and semitransparent. Amorphous module opaque is recognizable by its brown non-transparent look, while semitransparent by its brown-transparent look. Using double-layer antireflection coatings a broad range of colors of PV modules can be obtained – gold, steel blue, dark blue, pink, green (Spiegel, Bucher, Willeke, 1996), allowing architects' flexibility for integration of PV cells into building facade and providing a good match to the environment.

Various *light permeability* and interesting light effects inside a building can be produced through the use of amorphous, light permeable solar cells or the variation of the arrangements and distances between the cells (Fig. 5a, b). A typical crystalline cell is 100x100mm.



a)



b)

Fig. 5. Light permeability produced through the variation of the arrangements and distances between the PV cells; a) facade permeability, b) roof permeability

Regarding *construction possibilities* different solutions are present in case of "standoff" and "building integrated" systems.

"Standoff" mounting modules and arrays can be applied on new roof or facade construction or refurbished existing building envelope. A key element is standoff bracket, attached directly to the module frame or to rails or channels which support a matrix of modules. Various support systems are available, for vertical, sloped and flat surfaces, as shown in Fig. 6a. The space between the module or array and facade or roof material is ventilated by convection. Cooling the modules and arrays enhances their efficiency. If modules are mounted onto flat roofs building appearance is not affected. Modules applied to facade and pitched roof influence building appearance and visual effect depends on type and design of module and support structure (Fig. 6b).

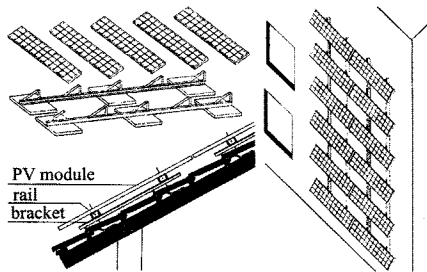


Fig. 6a. Different locations of "standoff" PV modules and support systems

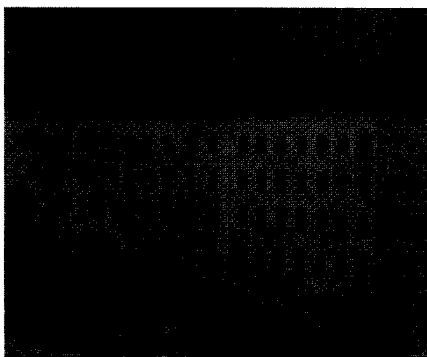


Fig. 6b. Influence of "standoff" roof modules on building appearance

"Building-integrated" PV components replace conventional building materials and labor, reducing the installed cost of the PV system. They are mostly in use for new roof or facade

construction while less in case of building refurbishment.

Building integrated modules can be treated as an envelope (Fig. 7a) or as a finishing layer of the envelope structure (Fig. 7b). They provide thermal, acoustic, wind and humidity insulation, sometimes fire and security protection, and produce electric energy and in some cases thermal energy also (Fig. 7c). Due to functional complexity facades with integrated PV modules can be treated as multifunctional structures.

Product development is proceeding in following areas: Facade integrated systems, Multifunctional PV facades, Shading devices with PV and Roof integrated systems.

PV Integrated Facades

Facade integrated systems include integral vertical and sloped glazing modules and arrays. Also, modules integrated to awnings can be considered.

Photovoltaic facade is type of glazed facades. PV modules can be integrated into the most of the contemporary suspended facade systems (Fig. 7 a, b). Suspended facades (curtain

walls) are light structures which are leaned against the building structure and suspends in front of it.

Glazing layer consists of two kinds of structural components - sections and glass sheets as shown in the Fig. 8 (Krstic, 1998). If they are treated as individual components that are assembled in site the glazing is made by simple prefabricated components and needs scaffold for its erection. When the structure is formed as a frame with glass plates filling, glass partitions - panels (complex prefabricated components) they can be joined directly and indirectly. Wooden, metal and plastic sections can be used. Metal and plastic sections are light and have smaller measures than wooden sections. Metal sections, customary in use have to be constructed of two parts solving the heat bridge problem and preventing condensation. By diversity of dimensions, shapes, colors and materials (wood, plastic or metal) of sections and frames it is possible to make different facade designs. They can also be hidden by glass, making a new appearance.

Glass sheets are PV modules. The appearance of modules depends on the material they are made from, crystalline silicon, mono- and

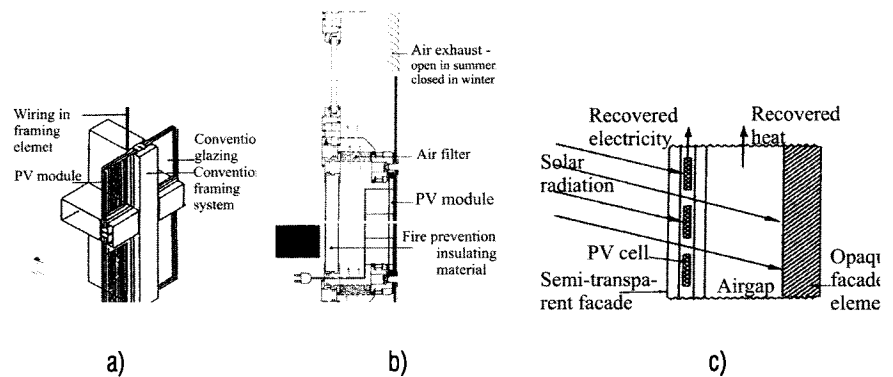


Fig. 7. Different structures of facades with integrated PV modules

- a) PV modules as a building envelope,
- b) PV modules as a finishing layer of the envelope structure,
- c) Structure that produces electric and thermal energy.

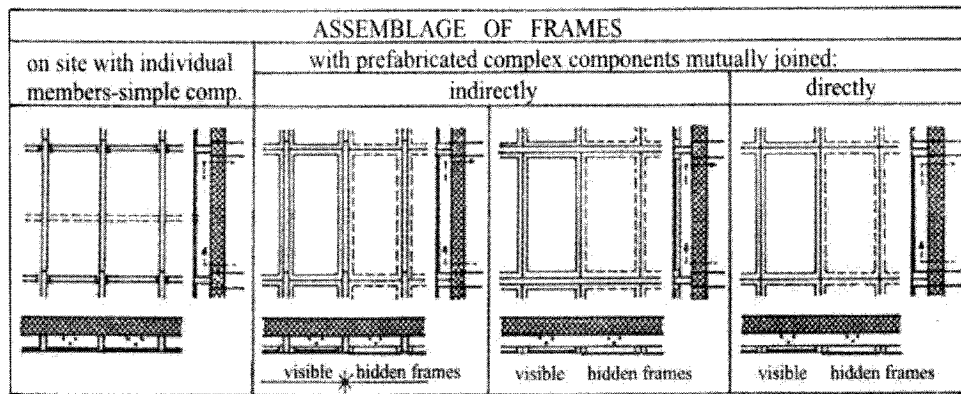


Fig. 8. Suspended facade assemblage possibilities

polycrystalline, or amorphous silicon, "opaque" or "semitransparent". PV modules can be produced in sizes that provide large areas to be covered without a horizontal glass separation (Fig. 4a, 9).



Fig.9. Assemblage process of large size PV modules

layer intended for air flow. The thermal energy – hot air supplied in the middle layer can be used for building heating using a system based on a ventilated PV wall principle, as shown in Fig. 10. Large mono-crystalline and multi-crystalline encapsulated PV modules as well as semi-transparent amorphous-silicon thin film solar cells, which can control the light entering the building, are presently considered as excellent models. Assemblage of multifunctional modules (M-modules) by using curtain wall technologies is acceptable and usage of frame structures is favorable (Fig. 8).



Fig 10. Multifunctional Photovoltaic Facades

Shading Devices with PV

Shading devices, with integrated PV cells, convert solar energy into electric power and at the same time prevent admittance of sun rays and overheating of a room in summer, or allow passing sun rays into room in winter. PV modules, as shading devices, are placed in front of the glazed surfaces in such a way to provide sufficient lighting of the room, operable windows and ventilation of facade structure. As facade external layer, usually movable, PV shading elements can perform as

weather protection and combine, conversion of sunlight into electricity and useful warmed air. Solar cells are integrated into safety glass.

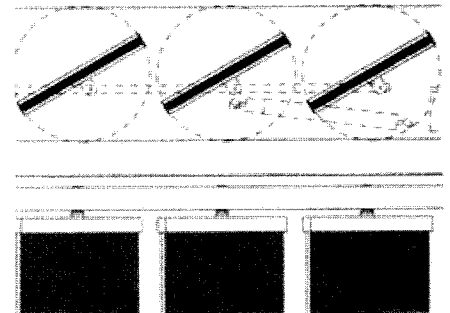
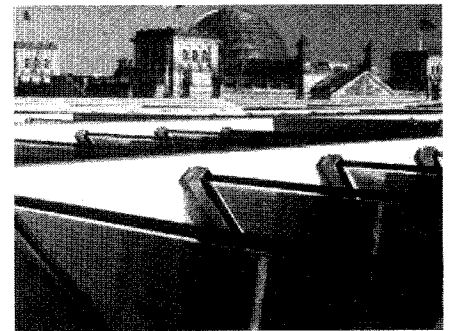


Fig. 11. Roof shading devices with PV cells

Shading is provided by semi-transparency of modules or cells arrangement. The most effective are horizontal overhangs for south orientation while for east and west orientations are suitable vertically placed shading elements. Shading devices with integrated PV modules influence a building, roof and facade appearance (Fig. 11, 12). In the case of movable shading elements building envelope becomes a changeable structure adaptable to day and season changes - "alive" structure. Movable PV shading elements applied on glazed roof proved as excellent protection against sun rays. Further they enable creation

Multifunctional Photovoltaic Facades

Development of multifunctional solar facades that produce electrical and thermal energy and provide protection against inclement weather, light and noise is actual and interested in industrial production. Solar module consists of three layers. The external glazed layer where PV modules are encapsulated and internal layer, as an insulating partition are separated with the

of vivid effects by sunlight, daylight and shade to the interior.

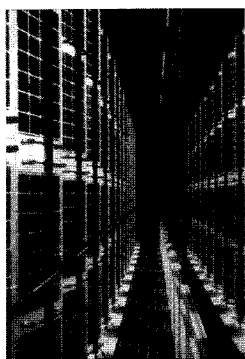
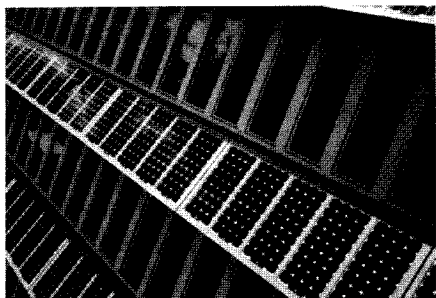


Fig 12. Facade shading devices with PV cells

Roof Integrated Systems

Roof integrated PV systems can appear as: integral roof modules and roofing tiles and shingles (Krstic, 2006). Integral roof PV modules appear as glazed structure, while roofing PV tiles and shingles appear as roofer. Both can cover whole roof surface or can partly substitute roofer.

Integral roof modules are usually combined to create arrays as shown in the Fig. 13. This roof system concept is similar to facade integrated system in sense of modules structure and techniques of mounting. With appropriate mounting and sealing techniques, the array serves the roof's weatherproofing function. The mounting system consists of frameworks of extrusions which provide support for the modules, a watertight seal and air channels which discharge heat buildup through a ridge vent. Air gap is placed between external glazed PV layer and internal solid, light or massive, roof construction. Such structure with opaque modules is customary solution in case of solid, non-transparent, roof. For transparent roof, the usage of "semitransparent" PV modules mounted like suspended wall structure is customary solution. In the first case PV

modules represent a finishing layer of the envelope, while in the second they are a roof envelope. In the first case, if warmed air is distributed into the internal space, roof structure can be treated as solar collector that produces electric and thermal energy.

Roofing tile elements, with integrated photovoltaic modules resemble and replace a normal roof tiles, providing weather protection. They can be mounted directly on the battens and overlap each other at the top and bottom (Fig. 14a). The frame of the solar roof tile is made of high quality acrylic glass, colored to provide protection against ultra-violet radiation. The photovoltaic cells in mono-crystalline silicon are enclosed between a reinforced fiber-glass layer and the external glass covering. Because of weather protection, top and bottom headers are needed. The complete construction covers area equivalent to 5 normal tiles. The problems of condensation and overheat can be avoided by improving the internal air circulation under PV roof tiles. The assembly can be simplified to such an extent that it can be mounted by regular craftsman.

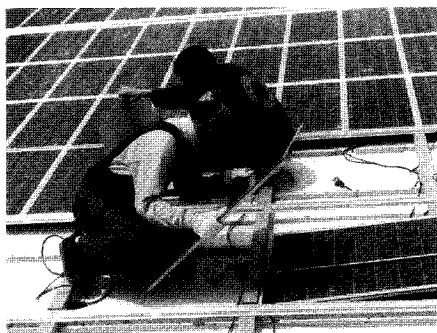


Fig. 13. Integral roof modules

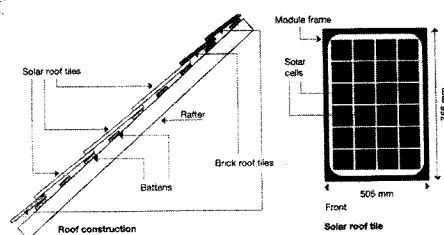


Figure 14a. A type of roofing PV tiles

PV shingles, as well as bituminous shingle roof cladding, need roof boarding to be constructed with ventilated air gap underneath (Fig. 14b).



Fig 14b. Roofing PV shingles

Roofing PV tiles and shingles have more acceptable price than integral roof modules. Their shapes and dimensions fit into standard roofers.

CONCLUSION

Building integrated PV modules, that convert sunlight into electric power, contribute to less consumption of conventional fuels that are environment polluters. The electricity produced by every square meter of PV can effectively displace emissions of more than two tones of CO₂ to the atmosphere over its lifetime; wider use of PV power in buildings can help to reduce such environmental impacts of buildings that are responsible for generating over 50per cent of all emissions of greenhouse gases globally (Roaf, Fuentes, Thomas, 2003).

Dissemination of PV integration in building has to be supported by government, building industry and experts among whom PV dedicated architects play an important role.

In order to encourage the use of PV in buildings, design and construction possibilities

for PV integration in envelopes of new and existing buildings are discussed in the paper. Presented classifications and analyzes of PV systems - materials, supporting systems,

coatings and design principles, as well as possibilities for design and structural variability of envelopes with building integrated PV modules, point out that application of photovoltaic components to building envelopes is a challenge to architects. Production of PV systems is a new provocation and orientation for building industry.

Designers have a key influence on the following factors that affect PV output: tilt, azimuth, shadowing, temperature. System efficiency is strongly influenced by orientation and inclination of PV modules. A favorable orientation is south. Deviation to southeast and southwest up to 30° is suitable. PV modules can be placed in horizontal position, vertical position or inclined. Choice of inclination is influenced by latitude value. The best solar yield is usually obtained on surfaces oriented to the equator and tilted by the degree corresponding to the local latitude. It is not recommended to apply PV systems on periodically shaded surfaces of a building envelope because it produces negative effects on system efficiency and can cause damages, as glass cracks. Various possibilities for design of PV integrated roof and facades are available giving freedom for architectural design.

References

- Cristiansen, E., 2006., Copenhagen's solar co-op, Denmark promotes a new model of PV financing, *Renewable Energy World*, Vol. 9, No 1, pp. 99-100.
- Krstic, A., 1998., Measures and techniques for bioclimatic rehabilitation of existing buildings aimed to produce energy rational and efficient buildings, *Proceedings of 2^o International Conference for Teachers of Architecture*, Universita' degli studi fi Firenze, Florence, pp. 2.05.
- Krstic, A., 2006., Multifunkcionalne krovne strukture energetske efikasne zgrade (Multifunctional roof structures of the energy efficient buildings), *Arhitektura i urbanizam*, 18/19, IAUS, Beograd, pp. 34-47.
- Mallon, K., 1999., PV – Breaking the solar "impasse", *Renewable Energy World*, Vol. 2, No. 6, pp. 95-96.
- Nordmann, T., 2005., Built-in future, *Renewable Energy World*, Review issue 2005-2006, Vol. 8, No. 4, pp. 236-247.
- Roaf, S., Fuentes, M., Thomas, S., 2003., *Ecohouse 2: A Design Guide*, Architectural Press, pp. 195-197.
- Sich, F. and Erge, T. ŠEds.Ć, 1996, *Photovoltaics in Buildings*, James&James, London, pp. 28.
- Spiegel, M., E. Bucher, E., Willeke, G., 1996., Colored Antireflection Coatings for High Efficiency PV Modules, *4th European Conference on Solar Energy in Architecture and Urban Planning*, H.S.Stephens&Associates, Berlin, pp. 623-628.