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APPLICATION OF SOLAR CELLS IN CONTEMPORARY ARCHITECTURE

Nikola Cekić[1,], Dragana Milosavljević[2], Tomislav Pavlović[2], Dragoljub Mirjanić[3]*

[1] University of Niš, Faculty of Civil Engineering and Architecture, Aleksandar Medvedev 14/111, 18000 Niš, Republic of Serbia
[2] University of Niš, Faculty of Sciences and Mathematics, Višegradska 33, 18 000 Niš, Republic of Serbia
[3] Academy of Science and Arts of the Republic of Srpska, Bana Lazarevića 1, 78 000 Banja Luka, Republic of Srpska

Abstract: The paper outlines the basic information on photovoltaic conversion of solar radiation on solar cells made of different materials (monocrystalline, polycrystalline, amorphous silicon, etc.), as well as on building integrated photovoltaic systems (BIPV). Moreover, examples of the use of solar cells in contemporary architecture worldwide, Serbia and the Republic of Srpska are given. In conclusion, it is emphasized that the solar cells are increasingly used as façade elements and a source of electrical energy in the building sector. In future cities solar cells and BIPV systems will play evermore an increasingly significant role in façade forming and electrical energy generation in the residential and other types of objects.

Keywords: solar cells, BIPV systems, contemporary architecture, eco-urban-architecture.

1. INTRODUCTION

A different, non-globalist pattern in conceptual formation of the buildings' façade planes, coupled with simultaneous observation and support of sensitive esthetic-geometrical differences in urban space, is based on the idea of a rational usage of energy and other natural resources, the new functional technologies providing a reduced, efficient consumption and progressively interesting design of layouts. The contemporary facades with high technical and technological performances provide exquisite potential in conceptualization of the sensitive culture of structure building. Eco-urban-architecture is on a quest for a new identity of „smart" façades and roofs, for an articulation based on multidisciplinary scientific principles and analyses of the material thermal properties in various façade systems. From theoretical standpoint, this means prioritizing the design of high-performance facades based on the climate conditions in micro-ambient environment as well as on the characteristics of sustainability. Apart from that, thermal behavior and resistance to weather conditions are very important, particularly resistance to humidity. Good contemporary design of solar facades includes thermal comfort in the interior space, quality lighting and acoustic stability in the environment. The latest city-building experiences of solar cells illustrate the implementation of double facades on the structures with technologically exclusive, artifact materials functioning as energy generators.

Recent studies focus on the environmental and strategic considerations of an impeccable position of the structure layout, adjustment and orientation of the façade planes forms to observe the position of the sun. Energy-efficient facades require the designers and planners to create more avant-garde philosophy of multicultural character of houses, squares and plazas and car parking areas design. Thus, it is necessary to implement scientifically proven contemporary materials and high technology. This calls for an examination of every macro and micro climate area so that a proper choice of type and form of solar cells can be made. An example of eco-urban-architectonically designed pavilion of the Federal Republic of Germany, at the world exhibition „EXPO 2015" in Milan, confirms the advent of new, very avant-garde solar technologies and contemporary environmental materials in civil engineering.

* Corresponding author: ncekic@yahoo.com

This will certainly radically expand the scientific borders and announce radical, scenic, adequately dynamic changes in the physical structures of the cities worldwide. Essential reformulations, permanent facades changes introducing flexible, robust, state-of-the-art materials − films with polymer photovoltaic solar cells to replace glazed surfaces, will certainly require new, highly demanding architectonic functions of the structures.

The appearance of physical structures in eco-urban-architecture substantially changed at the turn of centuries. Integration of solar cells in the architectonic designs of the structures façade planes brought about strategic-energy and historical-environmental changes. There were significant innovations concerning energy efficiency in using exterior and interior space as well as the immediate environment. The interpolated solar cells significantly and strategically defined a new non-stereotypic identity of the ambient entities and their esthetics. Their impact generates a different city-building, material-synthetic philosophy and the urban-art culture. Dramatic technical-technological changes in formation of the houses and installations took place in them. The innovations can be interpreted from the vertical and horizontal volumes, in spiritual and material-texture changes of the appearance of streets, squares, plazas and cities. A new age ensues from the global creation of the designing-planning values, within the matrices of environmental-urban architectonic agglomerations with a new historicity and an artifact, attractive morphology in a community fostering different spatial-conceptual forms of communication. The use of solar cells brings new challenges and creative conceptual solutions as well as scientific and professional intervention in redefining urban structure of the cities [1−3].

2. SOLAR CELLS IN ARCHITECTURE

Photovoltaic conversion of solar irradiation implies conversion of solar irradiation energy into electrical energy. Photovoltaic conversion of solar irradiation takes place in solar cells made of semiconducting materials, which are of simple construction, do not have movable parts, do not pollute the environment and display long shelf life. Photovoltaics constitutes a new study field for architects and engineers while the new designs develop new forms of building façade, roof system installation, efficient operation and other practical aspects. In contemporary architecture solar cells and solar modules are increasingly used as the roof and facade elements that embellish and simultaneously generate electrical energy for the given object and the net grid as well. Solar cells as the source of electrical energy are increasingly used in buildings to maximally reduce the consumption of electrical energy generated by power plants and to reduce the greenhouse gas emission. Contemporary architecture objects with solar cells are energy-independent and environment friendly [4-8]. Photovoltaics may be integrated into many different assemblies within a building envelope:

− Solar cells can be incorporated into the façade of a building, complementing or replacing a traditional view or spandrel glass. Often, these installations are vertical, reducing access to available solar resources, but a large surface area of a building can help compensate for the reduced power.

− Solar cells may be incorporated into awnings and saw-tooth designs on a building façade. These increase access to direct sunlight while providing additional architectural benefits such as passive shading.

− The use of solar cells in roofing systems can provide a direct replacement for batten and seam metal roofing and traditional 3-tab asphalt shingles.

− Using solar cells for skylight systems can enhance economical use of PV and present an exciting design feature [9].

Monocrystalline silicon cells are most efficient, requiring less surface area than other cell types to produce an equivalent amount of power. They also have a wide range of transparency options. Their disadvantages include higher costs, a requirement for ventilation to maximise performance and a distinctive geometric pattern. Monocrystalline cells are especially suitable for atrium roofs; partial vision glazing in façades, rooftop installations in houses and commercial sunshading or rooftop retrofits where the installation area is limited and maximum electricity generation is desired.

Polycrystalline silicon cells are less efficient than monocrystalline, however the lower cost per m^2 and a distinctive appearance make them a popular choice for relatively large, opaque installations serving as a strong design element. They have been extensively used in façade spandrel panels and sunshading elements on commercial buildings.

Amorphous silicon cells are based on ‘thin-film’ technology where a semi-conductor material is deposited on a substrate such as glass or plastic. This allows them to be physically integrated in a wider variety of applications, including into flexible membranes and as coatings on ordinary building products.

Copper indium gallium selenide (CIGS – or CIS without gallium) and cadmium telluride (CdTe) thin-film solar cells present a growingly penetrated market since their manufacturing processes are less costly than crystalline PVs. On the other hand, their efficiency is lower than crystalline solar cells. Thin film solar cells are less affected by higher operating temperatures and overcast skies than silicon cells and while a larger surface area is required for output, the cost of electricity per Watt peak is currently more attractive. However, this could change if the PV material commodity prices, for example the price of tellurium, increase.

The focus of the ‘third-generation’ PV technology innovation is on thin-film technologies that combine the high electrical efficiency of monocrystalline cells with the flexibility and lower costs of thin film manufacturing. These are expected to provide an increasingly attractive option for building-integrated applications. Light-absorbing dyes such as titanium dioxide and organic polymer solar cells hold promise for a very low-cost PV solution. However, they currently suffer from low efficiency output and as yet are unable to maintain their performance characteristics beyond three to five years [8−18].

Building integrated photovoltaic (BIPV) installations are able to serve as functional building materials in a number of applications, such as façades (cladding and curtain walls), roofing (solar tiles, slates, shingles and single-ply membranes), and windows (glazing, skylights and sunshades) [10]. The fundamental first step in any BIPV application is to maximize energy efficiency within the building’s energy demand or load. Thus, the entire energy system can be optimized. Holistically designed BIPV systems will reduce a building’s energy demand from the electric utility grid while generating electricity on site and performing as the weathering skin of the building. Roof and wall systems can provide R-value to diminish undesired thermal transference. Windows, skylights, and facade shelves can be designed to increase daylighting opportunities in interior spaces. PV awnings can be designed to reduce unwanted glare and heat gain. This integrated approach which brings together energy conservation, energy efficiency, building envelope design, and PV technology and placement, maximizes energy savings and makes the most of BIPV systems use [11].

Among various PV technologies presently available, monocrystalline, polycrystalline and amorphous silicon modules are the most commonly used for BIPV installations. From a design perspective, the choice of technology type will depend not only on the efficiency and cost, but also on the flexibility of application and integration.

Therefore, BIPV systems represent a powerful and versatile tool for achieving the ever increasing demand for zero energy and zero emission buildings of the near future, offering an aesthetical, economical and technical solution to integrate solar cells producing electricity within the climate envelopes of buildings [8−18].

3. SOME EXAMPLES OF BIPV SYSTEMS IN THE WORLD

3.1. Dubai's Vertical Village

The vertical district-village in Dubai has prominent sequences of solar panels in façade planes. They are an artifact means for collection of solar radiation and conversion into the energy required for the multifunctional structures. The designers believe that such a manner of building formation, apart from esthetics, can result in good, new sustainable structures. Most collectors are located on the south side of the location, to most efficiently receive solar rays with a potential of automatic adjustment of solar collector angle, tracking the sun. Buildings roofs have similar solar surfaces, kinetically adjustable for the optimum operation conditions. Guildings have a non-standard, futuristic, environmental-architectonic appearance with the spider web of solar panels. Future users will have a potential to enjoy nicely shaped, innovative and abundant modern interiors of the hotels, cinemas, trade centers and theaters. They will also enjoy the exterior landscaping of micro-ambient areas [19].

Figure 1. Dubai's Vertical Village Has a Skirt of Photovoltaics

3.2. Saint-Etienne, France, International Design Center

The city of design in Saint-Etienne, France has state-of-the-art photovoltaic panels in triangular pattern on the vertical and roof façade planes. This is a good example of the environmental architecture on the location of Saint-Etienne, where there was once a munitions factory. The historical complex is completely renovated and functionally interpolated into the historical tissue of the city with the new appearance of solar panels façade planes. The replenishment of night lighting, heating and circulation of air in the great, magnificent International Design Center is thus solved by transformation of the solar energy. The building is a monolithic, attractive, esthetic-visual physical structure, on a rectangular layout, 200 meters long. The façade skin is composed of 11 different equilateral, modulated triangles. The „Cite du Design“ is an international design center and an institution for communication and research. The project is located on the National Manufacture d'Armes, a site of a former munitions factory, in Saint-Étienne, France. Status: 2004-2009, opening 1st October 2009. Location: Saint-Etienne, Loire, France. Surface: 17,250 m² (net), 64,000 m^2 Cite Du Design. Awards: Prix Spécial de l'Équerre d'Argent pour la Cité du design de Saint-Étienne, 2010; Prix de la Construction Métallique, Bâtiments à usage tertiaire, and Ouvrages d'art, 2010 [20].

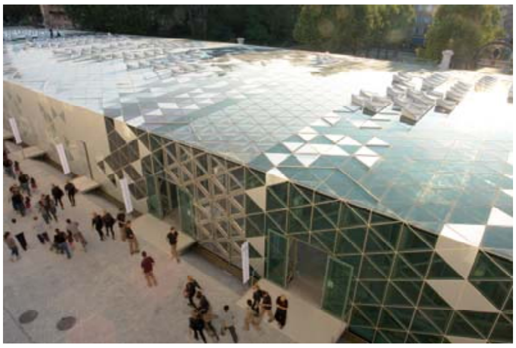

Figure 2. Saint-Etienne, France, International Design Center, LIN, lattice structure, solar panels, photovoltaic cells, energy efficient design, heat recovery. Inhabitat - Sustainable Design Innovation, Eco Architecture, Green Building

3.3. Incheon International Airport in Seoul

A triangular pattern with solar panels was implemented in design and realization of the building of Terminal 2, of the „Incheon“ International airport in Seoul on the curved roof surface, thus uniquely blending the façade at the ground level, to radically reduce the primary consumption of electric power. The passenger and cargo traffic will be considerably increased in this futuristically conceived terminal with 72 gates, in a 7.000.000 m^2 wide area. The structure will be completely ready for the Olympic Games in Pyeong Chang in 2018. The Terminal 2 hall was designed by the Gensler & HMGY in cooperation with the Heerim-Mooyoung-Gensler-Yungdo (HMGY) Consortium.

„We designed Terminal 2 with a great central garden in the interior - sizing two football pitches, were motivated by the Korean nature, and we offered an easy and practical usage to the people, wishing to announce new standards in airport design in the world“, said Keith Thompson, head of the Gensler company. The idea that airports are no longer only the aviation infrastructure, but also comfortable and energy efficient generators of the cities, is a new reference and a new concrete orientation in eco-urban-architecture [21].

Figure 3. Incheon International Airport in Seoul, South Korea, demonstrates the trend for curved structural forms in buildings

3.4. AG facade in Paris

An example of a façade design with solar panels in Paris, demonstrates how one interpolated urban-architectonic physical structure in Quai de Valmy street in 10th arrondissement produced a complex esthetic-visual, engineering-designing and historical discrepancy with the surrounding structures. The form of a newly designed structure was seen as physical space and a new technological work of art, whereby the simplified content was taken away from the historical and culturological coordinates. Photovoltaic panels efficiently provide thermal and electric energy for the users. Since December 2011, this has been the first housing building in Paris with photovoltaic panels containing 7200 solar cells and over 170m^2 panels on the frontal face protecting users in the interior space from noise and weather effects. There are no solar panels at the ground level [22−24].


Figure 4. A Sunways AG facade - Quai de Valmy 179 in Paris

3.5. Arizona State University's photovoltaic installations

The Arizona State University's photovoltaic installations are one of the largest commitments to solar energy by a university in the United States. In the period 2009-2013, 11 installations with total capacity of 1,231 kW and an average capacity of 123 kW, were fitted. Particularly indicative is the solar installation on the roof of the garage with three floors for 420 cars, which produces energy equivalent for 275 households. The advantages of such an installation are considerable. The university has a number of financial benefits in the society because of a rational and efficient energy status. Apart from that, the eco-urban-architecture appearance of artifact structures is considerably different. It is a harbinger of new hybrid designing era in engineering, which is a globalizing, non-static view of the world, with harmonic connection of structural elements [25,26].


Figure 5. Arizona State University's photovoltaic installations are one of the largest commitments to solar energy by a University in the United States

3.6. High-Rise Greens Sydney Skyline

The double glass curtain wall for the first high-rise 26 storey administrative-business building in Sydney, has managed to provide optimum daylight and solar control. The energy efficiency is prominent, showing twice as good results as the standard buildings with a single facade. Its vertical concept essentially differs from the other buildings in the environment. The building has an elliptical layout with 1600m^2 per floor. It is clad with dark, reflecting glass which looks like „Darth Vader“

mask. Darth Vader (born Anakin Skywalker) is a fictional character in the Star Wars universe. He appears in the original trilogy as a pivotal figure, as well as in the prequel trilogy as a central figure. It has a streamline design. In the central part there is a well ventilated atrium with an amoeboid layout, illuminated through the large glass surface, as well as the interior working space ventilated by the air circulation from the floor structures, towards the upper zones, which observes the highest environmental standards. The most contemporary materials and technology reducing dependence from the usage of artificial light, mechanical heating and cooling were implemented, thus ranking the iconic structure among the „smart" buildings. Particularly important are the solar panels on the roof of the structure, tracking the sun, which yield good energy results and aesthetically well define the fifth façade of the building [27,28].

Figure 6. Sustainable High-Rise Greens Sydney Skyline

3.7. All Valley Solar, Beijing China

An increasing number of the environmental hybrid and electric cars challenged planners, urban planners and architects in shaping the parking areas. Covering of stationary traffic areas using photovoltaic panels opens up a new potential for charging batteries of the users of such cars. The industrial designer and architect Neville Mars tried to design an interesting car reserve, where the cars, apart from being in the cool shade, will have a possibility to recharge from the source of generated electric energy. Solar panels are fitted on the posts with power sockets. After parking a car, a driver can easily connect the battery system and recharge it with environmental energy. The „solar forest", with a set of photovoltaic panels, apart from being useful has a very good, eco-urban-architectonic-esthetic, radically new geometry and recognizable non-rigid-angled geometrical composition similar to the natural forest forms thus representing a good platform for the future changes in the growing urban environments. It is particularly interesting for the region of China, having an accelerated economic growth, under the market conditions pressure, where, in 2003, Neville Mars opened the Foundation (DCF) in Beijing, a Center for solar research [29].

Figure 7. Pin by Ted Bavin on All Valley Solar

3.8. Photovoltaic Honeycomb Glass Screen Façade, New York

This design of 2008, of a building in one heavy-traffic street of New York is based on the honeycomb model according to the concept of the Japanese architects Daisuke Nagatomo and Minnie Jan, inspired by the natural world. The frontal façade wall has a glazed, undulating photovoltaic glass panel with a regular hexagonal geometry, while another panel on the honeycomb structure was installed facing the interior, carrying an efficient LED system for lighting and displaying variable colored images and information towards the exterior - the street. The honeycomb structure is very rigid, so that it can statically support the façade screen which can be used for entertainment. This attempt to interpolate a new eco-urban-architectonic structure and bring a metamorphosis in space is a new city-building stimulating strategy of permanent inauguration of contemporary materials and solar technologies in the micro-ambient space [30].

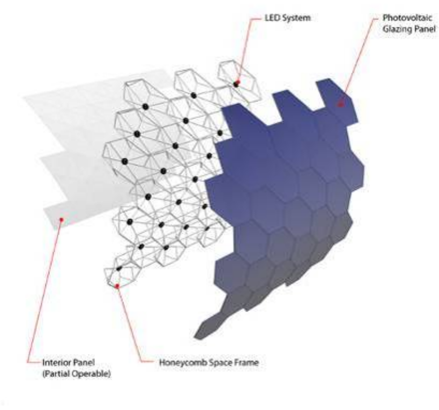

Figure 8. Photovoltaic Honeycomb Glass Screen Façade by Daisuke Nagatomo from Japan

3.9. GT Tower East in Seoul

The concept in the design of the attractive, flowing „twist“ façade of Seocho Garak Tower East - GT Tower, 130 meters high with 24 floors in Seoul, contains solar panels, which, apart from the transformation of solar energy, bring about a new visual quality and physiognomy of the micro-ambient space with mirrored, deformed visual effects. Technical details: Project Architect: Peter Couwenbergh. Floor area 54.530 m^2. Design and construction: Architect Het Architecten Consort. Developer: GT Construction − Hanbit Structural Engineering.

Even though it is located in a cramped space, this archi-sculptural tower of 2010 changes the character of the total geometry of vertical lines in the immediate environment. It is a new philosophy of formation and building of energy efficient, non-stereotypical physical structures with demanding prefabricated elements [30]. The designers found an inspiration for the appearance of the geometrically fluid façade in the forms of the traditional Korean ceramics undulating the frontal glazed façade to create the contrast and dynamics. At night, the tower is illuminated with several thousand LEDs accentuating the unique appearance of the structure through the variation of light coloration [31,32].

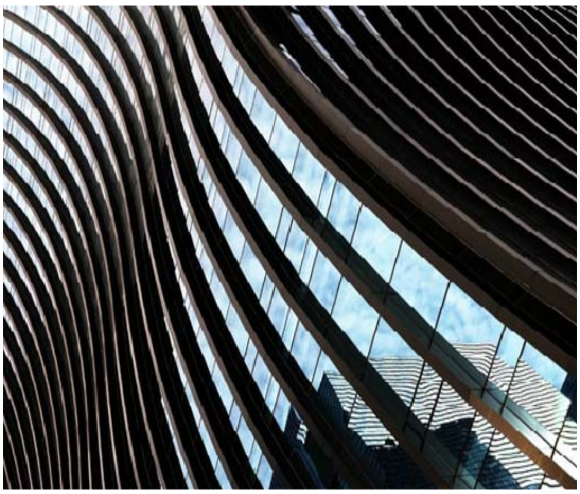

Figure 9. Seocho Garak Tower East. GT Tower East is a 130-meter high contemporary office tower designed by the Dutch architectural firm Architecten Consort and located in Seoul, South Korea

3.10. EXPO 2015 in Milan - German Pavilion

The key motto of the world exhibition „EXPO 2015" in Milan is Feeding the planet − Energy for life. The Universal Exposition brought together 145 countries representing 94% of the world's population. They participate either via self-built pavilions or in the context of Clusters. Three international organisations, 13 NGOs and 5 corporate pavilions are also participating in the event. The largest and most attractive eco-urban-architectonic-technological pavilion in the complex – 2680 m^2, belonging to the Federal Republic of Germany, Architects: Schmidhuber**.** On behalf of the Federal Ministry of Economics and Energy, Messe Frankfurt has entrusted the German Pavilion Expo 2015 Milan Consortium (ARGE) with the realization of the German pavilion. The ARGE, as general contractor, is responsible for designing, planning and construction of the German pavilion and the exhibition. The Schmidhuber architectural office in Munich is responsible for the spatial concept, architecture and general planning, Milla & Partner in Stuttgart for the content concept as well as the design of the exhibition and media. Nussli in Roth (near Nuremberg) is responsible for the project management and construction. The exterior warped façade surfaces were formed by the flexible, lightweight robust, state-of-the-art material − film with polymer photovoltaic solar cells, which provides exquisite air conditioning of the building and energy generation. Science fiction came true. The sunlight is transformed into a stream of charged particles generating electric power. The new phenomenal procedure with the printed electronic components was made possible by combining several types of materials, including application of high-quality plastics. All the materials have different electric and optical properties. The implemented innovative technology has an important function in reducing the external usage of energy in construction industry and over time proves to be a considerable resource-saver. For the architecture of tomorrow, this discovery is of an extraordinary importance. This triggers a fascinating potential of the sustainable physical structure, provides a number of functional advantages in eco-urban-architectonic equipping, remodeling, reconstructions and modernizations of urban areas [27,33,34].

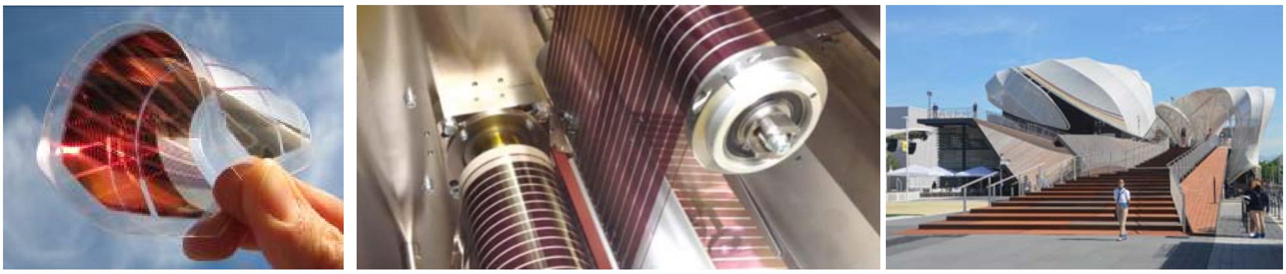

Figure 10. EXPO 2015: Field of polymer solar cells in the German Pavilion

4. SOME EXAMPLES OF BIPV SYSTEMS IN SERBIA

Recently, Serbia and the Republic of Srpska have more intensively started to use solar cells for the generation of electrical energy.

Serbia has up to now installed more than 200 independent PV systems of 1-60 kWp. Moreover, Serbia has installed several small rooftop PV solar plants connected to the grid: on the roof of *Mihajlo Pupin Institute* in Belgrade (50 kWp), on the secondary electrotechnical school *Rade Končar* in Belgrade (5 kWp), on the daycare centre in Bezanijska Kosa (3 kWp), on the Faculty of Sciences and Mathematics in Niš (2 kWp), on the building of the *Elektromehanika Ltd*. in Nis (30 kWp), on the residential house in a village Batusinac (10 kWp), on the residential house in a village Malca (20 kWp), on the Faculty of Technical Science in Novi Sad (FTS1 of 9.6 kWp, FTS2 of 15.9 kWp), on the commercial building of the *Elektrovat Ltd*. in Čačak (54.72 kWp), on the Faculty of Technical Science in Čačak (1.05 kWp), on the private company *Hemofrigo* in Leskovac (60 kWp), on the private company *Domit* in Leskovac (34.32 kWp), on a private object in the village Bobiste near Leskovac (30 kWp), on the *Technical School* in Pirot (4.59 kWp), on a private object in the village of Cortanovci (10 kWp), on a private house in Backa Topola (7.5 kWp), on the secondary technical school in Varvarin (5 kWp), on the secondary technical school *Mihajlo Pupin* in Kula (5 kWp), on the primary school *Dusan Jerkovic* in Ruma (3 kWp), etc [35].

Figure 11. PV solar plant of 20 kWp in Belgrade

Figure 12. PV solar plant of 10 kWp in the village of Cortanovci

5. SOME EXAMPLES OF BIPV SYSTEMS IN THE REPUBLIC OF SRPSKA

In the past 3 years, the Republic of Srpska has installed more than 20 grid-on PV solar plants of 2-250 kWp. Moreover, the Republic of Srpska has installed several small rooftop PV solar plants connected to the grid: on the roof of the company *Fratelo Trade A.D.* in Banja Lika (45 kWp and 107.5 kWp), on the *BLC* College in Banja Lika (20 kWp i 10 kWp), on the roof of the company *Tesla doo* in Modrica (120 kWp i 120 kWp), on the roof of the company *Verano Motors* in Banja Luka (48 kWp), on the primary school *Nikola Tesla* in Banja Luka (10 kWp), on the roof of the company Madra doo in Celinac (2x50 kWp), on the roof of the company *Neutron doo* in Bjeljina (180 kWp), on the roof of the company *MI-TRIVAS doo* in Prnjavor (50 kWp), on the oil refinery *Modrica* in Modrica (110 kWp), on the roof of the company *BMB DELTA doo* in Gradiska (50 kWp), on the roof of the *Cultural Center* in Gradiska (10 kWp), etc [35].

Figure 13. Rooftop on-grid PV solar plant of 50 kWp MADRA 2

Figure 14. Rooftop on-grid PV solar plant of 50 kWp MI-TRAVIS

6. CONCLUSION

On the basis of all aforementioned it can be concluded that solar cells made of monocrystalline, polycrystalline, amorphous silicon, GaAs, CdTe, CIS and other thin film materials are used nowadays for the photovoltaic conversion of solar radiation. By means of solar cells and other elements on-grid and off-grid BIPV systems are formed as façade elements and the sources of pure electrical energy. The paper gives examples of the use of solar cells in contemporary architecture worldwide, Serbia and the Republic of Srpska clearly showing that even nowadays solar cells are playing an increasingly important part in the aesthetic shaping of the facades of the modern residential and other types of objects and in providing electrical energy for them, or passing in it on to the utility grid. Worldwide, BIPV systems have been installed on numerous old and modern objects efficiently converting solar energy into the electrical energy. Having in mind that solar cells have been increasingly used in modern architecture, it is quite obvious that in the cities of the future they will represent an important façade element and an independent source of electrical energy generation. In this context, it is important to emphasize that up to now more than 200 PV systems have been installed in Serbia on the private residential and other types of objects and that the trend of using BIPV systems is going upwards. Also, in the past few years numerous BIPV systems have been installed in the Republic of Srpska and their use is increasingly rising.

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ПРИМЕНА СОЛАРНИХ ЋЕЛИЈА У САВРЕМЕНОЈ АРХИТЕКТУРИ

Сажетак: У раду су дате основне информације о фотонапонској конверзији Сунчевог зрачења на соларним ћелијама од различитих материјала (монокристални, поликристални и аморфни силицијум итд.), као и о фотонапонским системима интегрисаним у зграде. У даљем тексту су дати примери коришћења соларних ћелија у савременој архитектури у свету, Србији и Републици Српској. У закључку је истакнуто да се соларне ћелије сваким даном све више користе као фасадни елементи и извори електричне енергије у грађевинарству. У градовима будућности соларне ћелије и фотонапонски системи ће играти све значајнију улогу у обликовању фасада и добијању електричне енергије на стамбеним и другим објектима.

Кључне речи: соларне ћелије, фотонапонски системи, савремена архитектура, еко-урбана архитектура.