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A Review Study About Photovoltaic Systems and the Energy Payback Time Calculation for Selected Modules

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ABSTRACT

The renewable energy can be utilized to satisfy the energy demand. Moreover, the solar energy as the most abundant energy resource among renewable energies plays a crucial role to provide the energy demand. The BIPV (building integrated photovoltaics) systems can be considered to supply the required energy demand from renewable sources. The essential advantage of BIPV systems is that they can be utilized as building component such as roof, window, shading systems and building façade and they can generate electricity simultaneously. Even though the photovoltaic technologies have been improved within past few years, however the utilization of the BIPV systems will be considered expensive. For this reason, the payback period calculation is considered a vital parameter in evaluating the BIPV systems. In this study, the overall energy consumption for producing one m^2 of a mono-crystalline photovoltaic module is calculated 1334 kWh. Additionally, the photovoltaic module data for three companies were investigated and the annual energy productions for one m^2 of each company's product were obtained. The results showed that the average energy payback time for 270 and 280 watt modules are 5.565 and 5.254 respectively. Moreover, the energy payback time for 290, 325 and 340 watt modules were calculated 4.903, 5.437 and 4.965 respectively.

1. INTRODUCTION

Nowadays, the electricity portrays a key role in a modern society. However, approximately 1.2 billion people in rural areas in Asia and Africa don't have access to electricity [1]. For this matter, the importance of the off-grid electricity production in rural areas will be accentuated and the renewable energy resources will be highlighted in this category. According to the international energy outlook, by 2021 the 825 GW electricity capacities from renewable energy resources will be installed in the comparison with the 2015 installed electricity capacity. Furthermore, the share of the renewable energy in global energy demand will be increased from 23 % in 2015 to 28 % in 2021 [2]. For the good economy and prosperity of any nation, energy is a key role player. However, most of the energy is obtained from fossil fuels, which in result create pollution by emitting greenhouse gases in the environment. In addition, these fossil-fuel resources are limited and non-renewable as these were prepared once in millions of years [3].

The electricity is one of the key demands for buildings that should be provided. The energy consumption in buildings is approximately one-third of global energy demand which results in the higher CO_2 emission [4,5]. The building energy demand is dependent on local weather condition to provide heating or cooling loads. The building's heating demand is usually satisfied by the combustion of fossil fuels. The electricity is considered as an alternative source to provide the energy demand of the buildings and commonly provide the cooling demand of the buildings [6]. Various sources can be considered to provide the energy demand and consequently, a number of scenarios can be outlined. The implementation of green buildings (zero energy buildings) can be a beneficial solution [7]. However, the energy demand for green buildings must be supplied from renewable energy sources to achieve the globally sustainable development goals. The global renewable energy utilization is growing and by the year 2040, approximately 60 % of global electricity demand is supplied from renewable energy sources [8].

The solar energy is significantly more abundant and available in comparison to other renewable energy resources [9]. The solar energy can be a perfect choice to satisfy the energy demand of the buildings since the solar energy provides both heat and electricity. The solar thermal systems can produce heat and the photovoltaic systems can convert the solar radiation to electricity. However, only 10 to 20 % of the solar radiation can be converted into electricity and the residue is available as heat in the module which results in decreasing of the photovoltaic system's efficiency. From the solar radiation incident on the surface of PV cells a range of about 80 % can be absorbed, however, only small portion of the absorbed incident solar energy is converted into electrical energy based on the conversion efficiency of the PV cell manufacturing technology [10]. The utilization of photovoltaic thermal hybrid systems can provide heat and electricity simultaneously.

PV cells absorb photons from the light source whose energy is captured by the electron and results in high electric potential resulting in electric current generation. However, all photons do not generate electric current as photons whose frequencies are much higher above threshold frequency are absorbed and results in generation of heat which increases cell temperature. As the temperature of cell rises above 25-27 ^{o}C, electrical energy starts to decrease because of heat expansion in system. It is reported that electrical output decreases by 0.4-0.65 % with one degree Celsius rise in temperature [11]. The

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*Corresponding Author's Email: mh.jahangir@ut.ac.ir (M.H. Jahangir) implementation of photovoltaic thermal systems would lead us one step closer to achieve the zero energy building goal [5,12]. There are some advantages concerning the implementation of the photovoltaic systems in comparison to other electricity production technologies such as zero emission of CO_2 or other greenhouse gases which cause the global warming and climate change [13], zero amount of threatening by-products- Hg, Pb, NO_X and SO_X [14], zero amount of radioactive wastes [15] and finally do not require water for electricity production [16]. However, non-silicon photovoltaic systems contain critical materials- Hydrochloric Acid, Sulfuric Acid, Nitric Acid, and arsenic which require the constant maintenance within their lifetime period [17].

1.1. The introduction of photovoltaic technologies

1.1.1. The crystal silicon technology

Silicon has been widely used in photovoltaic cell technologies. The first generation of photovoltaic cells was designed and manufactured by the utilization of crystal silicon structure. The electrical efficiency of solar cells was reached 17 % using microelectronics technology in 1970 [18]. The silicon crystals include regular structure and each atom is placed in a specified location in the crystal structure [19]. The silicon crystal structures can be categorized into mono-crystals and poly-crystals. The most popular material in solar photovoltaic technology is silicon for its unique characteristics and high efficiency which results in the 80 % share of materials used in solar cell manufacturing market [18].

1.1.1.1. Mono-crystals

The application of mono-crystalline photovoltaic panels is more than poly-crystalline panels due to higher efficiency. Zhao et al. [20] in 1998 reported the efficiency of mono-crystalline photovoltaic cells with wasp nest structure as 24.7 %. It should be noted that the efficiency of solar modules is lower than solar cells [18]. Monocrystalline modules are considered to be the most expensive crystalline modules in the market since the manufacturing process requires high technology and high energy consumptions and the rate of the process is very slow. In the past few years, the pure monocrystalline cells have been used for semiconductor industries which results in high expenses and long process period and the purity of the final product is higher than photovoltaic panels require [19]. The efficiency of the monocrystalline cells from various companies can be unequal. The typical efficiency of the monocrystalline cells based on National Renewable Energy Laboratory reports varies between 16 to 16.9 %. The highest efficiency of the monocrystalline cells is related to an American company -Sun Power- with the efficiency of 20 to 20.9 % and also a Japanese company -Sanyo Electric- with the efficiency of 19 to 19.9 % [18].

1.1.1.2. Polycrystalline

Zhao et al. in 1998 reported the efficiency of polycrystalline with bee nest structure by 19.8 %. The efficiency of polycrystalline cells is lower than a monocrystalline cell. However, the polycrystalline cells own a bigger market compared to monocrystalline cells since the cost of the polycrystalline cells is lower. The efficiency of polycrystalline cells alters from 15 to 16.9 %. The highest efficiency of polycrystalline cells is related to a Taiwanese company -New Solar Power- by 16.9 % [18].

1.1.2. Thin film technology

In the thin film technology, a thin layer of semiconductors will be laid on a solid substrate in order to reduce the usage of semiconductor materials and consequently, this will reduce the capital cost of the final product in comparison to crystalline cells. The most common materials in thin-film technology are Cadmium, Tellurium, Gallium, Arsenic and Titanium dioxide [9]. Barnet et al. stated that the efficiency of the polycrystalline cell using thin-film technology can be increased to 19 % [21]. The thin film process requires lower process temperature compared to crystalline cells. Moreover, another advantage of thin film technology will be the effortless contact of semiconductor materials to both flexible and rigid substrates such as glass, steel, and plastics. The reasonable cost and feasible manufacturing process of amorphous silicon technology favor in growing demand for such technology [19].

1.1.2.1. Amorphous

The amorphous silicon-such as silicon -Carbone, amorphous Si-Ga, and amorphous silicon nitride- is the most important type of non-crystalline material used in solar cell and frequently used in thin layer technology. However, in recent year, the popularity of amorphous silicon is decreasing [9]. The efficiency of the amorphous silicon is relatively 7 % and the amorphous silicon cell’s cost is lower than crystalline silicon cell [19]. the efficiency can be increased to 8 to 10 % by multi-junction design [9]. The highest efficiency of amorphous cells is related to an American company -Stion- with the efficiency of 13.8 % and another Spanish company -EPS Solar- with the efficiency of 11.8 % [18].

1.1.2.2. Cadmium- Tellurium

The thin-film solar cells contain Cadmium-Tellurium (CdTe) in order to provide the chemical stability of the solar cell. The energy gap of the CdTe is 1.44 eV. Moreover, the Cd is considered to be a poisonous material and it can be a potential threat to the environment. However, the solar cell contains a small amount of Cd which can be considered in safe range. The highest efficiency of solar cells containing CdTe is reported to be 17 % [19].

1.1.2.3. Copper, Indium, Gallium, Selenium

The combination of four elements Cu, In, Ga, and Se is considered as one of the most improved technologies among other solar technologies. The addition of such combination to solar cell structure can improve the energy gap of the solar cell from 1 to 1.1 eV. By 2006, the highest efficiency of the solar modules was reported 13 %. However, in 2014 the Siva power company reported the efficiency of 18.8 % which was approved by the National Laboratory of Renewable Energy [18].

1.1.2.4. Gallium-Arsenic

The structure of GaAs photovoltaic panels is similar to silicon solar cell. However, the efficiency of GaAs solar panels is higher and the thickness of the GaAs panels is lower than the silicon solar cells. As the result, the GaAs panels are lighter than monocrystalline and polycrystalline solar cells. The band gap energy of GaAs solar cells is 1.43 eV. The highest efficiencies of GaAs which was achieved by researchers are 28.8 % by Radboud University, 36.9 % by Sharp Company and 42.3 % by Spire Company (triple joint GaAs panels) [18].

1.1.3. Hybrid cells

The hybrid cell technology is based on the combination of crystalline and non-crystalline solar cells which result in the complexity of the production process [18]. Wu et al. discovered the highest efficiency to cost ration of hybrid solar cells [22]. For this reason, the highest efficiency of hybrid solar cells was introduced by Sanyo and Panasonic companies which introduced the efficiency of hybrid cells by 17.8 and 25.6 % respectively [18].

1.1.4. Organic (polymer) cell

The organic cells are considered a new generation of solar cells which decreased the capital cost of solar cell's production [23]. Kerbs demonstrated that the cost of the one cm^2 organic solar cell will be equal the 1 % of the cost of an identical monocrystalline solar cell [24]. However, the crucial challenges of organic solar cells are short lifetime and low efficiency [23]. The polymer layer would be placed between two electrodes. The aluminum is frequently used as an electrode with the energy gap of 4.2 eV [17].

1.1.5. Photosensitive solar cells

The new solar cell technologies have been taken seriously in recent years due to the low efficiency and economic and environmental issues [18]. The photosensitive solar cells contain two electrodes which at least one of them is transparent [25]. Originally, Deb in 1978 used the titanium oxide in photoelectrochemical process [18]. In that matter, the glass layer will be used which covered by a conductor layer (usually tin oxide or indium). The titanium oxide will be used to enhance the quantity of free charge carrier (electron) and consequently increase the electrical conductivity [26].

1.2. The introduction of integrated photovoltaic systems (BIPV)

1.2.1. History

In late 1970, the American ministry of energy announced its support for photovoltaic cell's industry as building construction material. By 1980, the related photovoltaic cell's companies such as Solarex, General Electric, and Sanyo Electric were expanded their business. However, the high manufacture cost and technical challenges led to the product reduction [23]. Humm and Toggweiler published one of the early papers on building integrated photovoltaic system in 1993 [27] while the US ministry of energy had proposed a program to support BIPV (building integrated photovoltaics) researches [28]. In 2000, a reference book on the BIPV projects in the US was released that compared 16 different international BIPV projects as technical and beauty point of view [29]. Building integrated PV (BIPV) is seen as one major opportunity for large market penetration of PV [30]. Furthermore, China introduced various support programs for sustainable energy and environment such as a 6.5 MW BIPV project in 2010 which is considered as one of the biggest building integrated photovoltaic affairs in the world [31]. Today, the photovoltaic cell manufacture companies intend to overcome the technical issues and economic barriers to achieve the product with higher quality and more reasonable price [32]. Taleb et al. [33], Zhai et al. [34], introduced novel methods to implement photovoltaic systems in modern building designs since the design of the building and windows have the crucial impact on the building energy performance [35,36]. The low cost of building construction material is one of the advantages of BIPVs in comparison to the other power generation systems which introduced the BIPVs as the pioneer in the photovoltaic industry [37]. Jelle et al. included artistry frame of reference to their researches and consequently concluded that the new photovoltaic technologies will lead to novel BIPV systems with lower cost and higher efficiency[38].

1.2.2. Description of BIPV system

The building integrated photovoltaic system is a concept in which photovoltaic panels are considered as power generation element and façade's cover simultaneously and as the result, photovoltaic panels can be implemented in different sections of the building such as walls, windows and roof [39] and the BIPV systems cannot be dissembled [40]. The key parameters such as photovoltaic panel's temperature, inclination angle, the shading effect and building heat capacitance should be considered to obtain a correct analysis of the BIPV performance [41]. Dapeng li et al. evaluated the solar potential for several urban buildings and the revealed that the solar potential of the building is directly related to the size of the buildings [42]. Figure 1 demonstrates a photovoltaic system integrated with the building. As it is shown, the air enters from the bottom of the BIPV and exits from the top side of the BIPV to control the temperature of the BIPV system and increase the performance of the system. In some cases, fans also can be implemented to moderate the temperature of the BIPV system [43].

As it is shown in Figure 2 the BIPV systems can be categorized based on the photovoltaic technologies, photovoltaic system's applications or the commercial names of the products. The photovoltaic system technologies can be demonstrated as silicon or non-silicon photovoltaic panels. Moreover, the photovoltaic systems can be utilized in building's roof or the building's façade. Traditional elements of building like roof tiles and windows can be replaced by BIPV modules and performing the same functions as well as generating electrical power. Finally, the photovoltaic system's commercial names can be divided into four categories-foils, tiles, modules and solar cell glazings [38].

1.2.3. The applications of BIPV systems

The photovoltaic modules can be utilized as the building façade which can be considered as modern art innovation and they are implemented as an alternative to conventional façade materials and the power can be generated simultaneously [7]. The BIPV used in the building façade will be usually located vertically and the output power is not noticeable, however the electricity generation can be considerable by implementation of the BIPV system on the building's roof. The former generation of photovoltaic panels can be utilized for opaque surfaces and the transparent and semi-transparent modules can be implemented as windows. Moreover, the colored organic solar cell's interest has been increased over the past years [7].

This module can be used as an alternative to conventional construction materials such as bar, tile, and metallic roofs. The BIPV systems can be implemented as curtains, shading, windows, and roofs which can be customized for specific applications with various transparency [45,46]. Among different application of BIPVs, the shadings are considered to be more efficient since it can provide electricity and decrease the HVAC loads simultaneously [47]. However, since the BIPVs cannot track the sun's direction, the power generation will vary during the day which can be considered as a disadvantage for these systems [7]. Another disadvantage of BIPVs is the complexity of the wire connections and the long startup time [41]. The various application of BIPV systems are given as Table 1. In this paper, after the overall introduction of the BIPV system technically and economically, the energy payback time of the system is investigated. By choosing different modules, the amount of energy payback time per year per square meter is compared with their energy payback time.

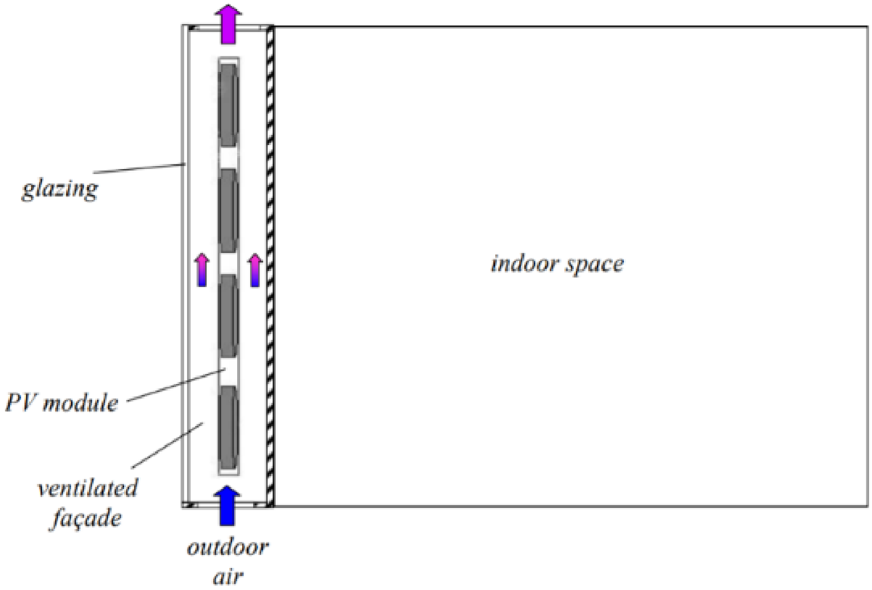


Figure 1. A schematic of a BIPV system [43].

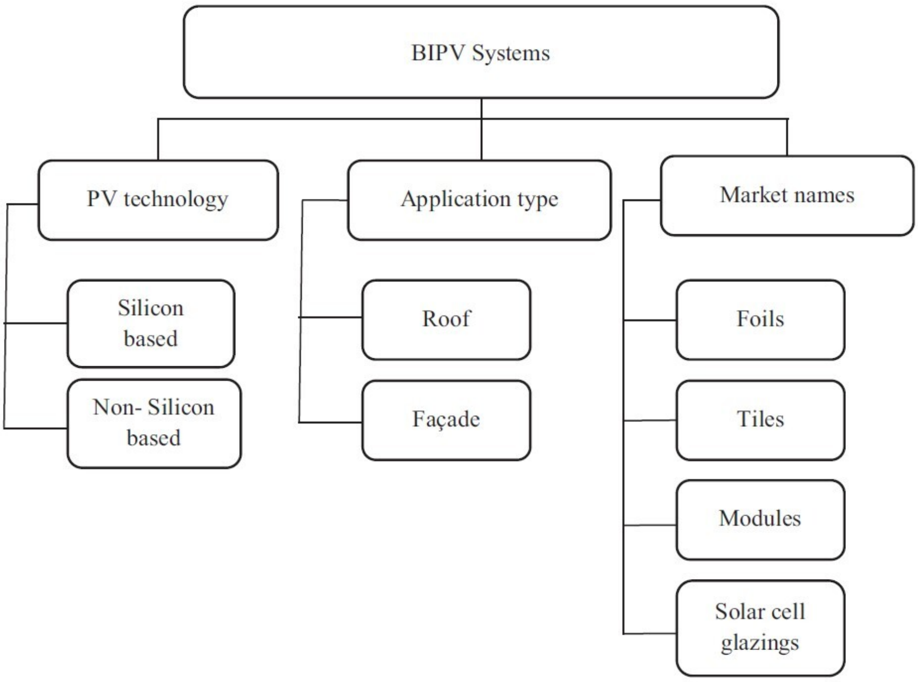


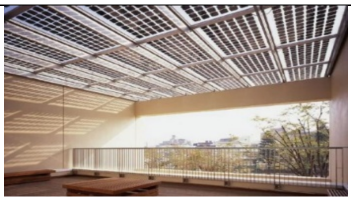
Figure 2. BIPV categorization [44].

2. THE BIPV TECHNICAL ANALYSIS AND ECONOMY EVALUATION

2.1. The modeling of the BIPV

The effective parameters such as the weather condition, temperature, humidity and other variable are considered carefully in the simulation procedure and the sensitivity analysis will be conducted to determine the importance of the parameters. In addition, the experimental results will be taken into account and both numerical and experimental results will be examined by the reference data from experimental studies [49].

Table 1. Different applications of the BIPV system [48].

Type	Application	Schematics
Glass roof	The utilization of glass roofs is one of the most appealing applications of BIPV systems. This arrangement provides the internal lighting and electricity demand simultaneously. Moreover, the architectural design can be very fascinating.	
The curved tiles	The BIPV tiles can cover the entire roof or a part of the roof. The appearance of the BIPV modules is very similar to the standard building tiles.	
The shading systems	Various types of BIPV modules can be utilized as the shading system. Moreover, in order to create proper shading effect, the BIPV unidirectional modules should be installed above the windows.	
Building external walls	The BIPV modules can be implemented as external walls for buildings.	
The roof modules	For this application, the BIPVs can be used as skylights to provide the natural light demand of the building and they can be replaced with another semi-transparent part of the roofs.	
Rooftop installation	The roof of the buildings usually provide vast areas to install the BIPV systems and the power generation of BIPVs will be higher in comparison to other cases.	
Semi-transparent facade	The transparent and semi-transparent façades will result in the higher heat transfer rate. The semi-transparent and transparent BIPV systems will provide the electrical and thermal demand of the building simultaneously.	

2.1.1. Thermal modeling of the BIPV system

2.1.1.1. Heat transfer across PV panel

The energy conservation equation in a photovoltaic layer is given in equation 1 and equation 2.

$$-\frac{\left(T_{epv}-T_{mpv}\right)}{\frac{R_{PV}}{2}}-\epsilon_{pv}\sigma\left(T_{epv}^{4}-T_{sky}^{4}\right)-h_{e}\left(T_{epv}-T_{out}\right)=0 \qquad (1)$$

$$M_{pv}\cdot C_{P_{pv}}\cdot\frac{dT_{mpv}}{dt}=\alpha_{pv}\cdot G+\frac{\left(T_{epv}-T_{mpv}\right)}{\frac{R_{PV}}{2}}-\frac{\left(T_{mpv}-T_{ipv}\right)}{\frac{R_{PV}}{2}} \qquad (2)$$

where T_{sky} is the sky's temperature, G is the solar radiation, T_{out} is the ambient temperature, σ is the Boltzmann constant, Cp_{pv} is the photovoltaic specific heat capacitance, h_e heat transfer coefficient, α_{pv} photovoltaic cell's absorption coefficient, R_{PV} is the photovoltaic thermal resistance, ϵ_{pv} is the photovoltaic emission coefficient, T_{mpv} is the photovoltaic module's temperature , T_{epv} is the final photovoltaic temperature, T_{ipv} is the initial photovoltaic temperature, M_{pv} is the photovoltaic panels weight [50,51].

2.1.1.2. Heat transfer within air gap

The heat transfer coefficient inside the air hole is relevant to the system's performance whether the gates are open or not. For the closed gate, the heat transfer coefficient is calculated based on the Kalogirou's method [52]. For the open gate, the heat transfer coefficient is calculated based on the Duffe and Bechmann's method [51]. The mean air velocity in the air gap will be calculated by Bernoulli equation solution where the air density is considered constant and the temperature distribution will be assumed linear [52].

The energy equation whining the air gap is described as equation 3 where h_{pvac} is the heat transfer coefficient between the photovoltaic and the air gap, h_r is the convection coefficient, T_{ac} is the air gap temperature, T_{ew} is the external wall's temperature, T_{mw} is the internal wall's temperature, M_{air} is the air mass, $C_{P_{air}}$ is the air specific heat capacitance, h_{wac} is the heat transfer coefficient between the air gap and the wall.

$$\frac{(T_{mpv} - T_{ipv})}{\frac{R_{PV}}{2}} - h_{pvac}(T_{ipv} - T_{ac}) - h_r(T_{ipv}^4 - T_{ew}^4) = 0 \tag{3}$$

$$M_{air} \cdot C_{P_{air}} \cdot \frac{dT_{ac}}{dt} = h_{pvac}(T_{ipv} - T_{ac}) + h_{wac}(T_{ac} - T_{ew}) \tag{4}$$

$$h_r(T_{ipv}^4 - T_{ew}^4) - h_{wac}(T_{ac} - T_{ew}) - \frac{(T_{ew} - T_{mw})}{\frac{R_w}{2}} = 0 \tag{5}$$

2.1.1.3. The heat transferred from the PCM wall

The energy equation for PCM walls can be given as equation 6 and equation 7 where h_i can be calculated based on the Santos et al. investigations and q_1 will be determined by Athienitis modeless [53,54].

$$M_w \cdot C_{P_w} \cdot \frac{dT_{mw}}{dt} = \frac{(T_{ew} - T_{mw})}{\frac{R_w}{2}} - \frac{(T_{mw} - T_{iw})}{\frac{R_w}{2}} + q_1 \tag{6}$$

$$\frac{(T_{mw} - T_{iw})}{\frac{R_w}{2}} - h_i(T_{iw} - T_{in}) = 0 \tag{7}$$

2.2. The exergy analysis

The exergy efficiency of the BIPV system can be given as follows:

$$\Psi = \frac{E_X}{E_{X_{solar}}} \tag{8}$$

where E_X is the BIPV exergy efficiency –mostly reveals as electrical term- and can be shown as follows [55,20,56]:

$$E_X = V_m I_m - \left[1 - \left(\frac{T_{amb}}{T_{mod}}\right)\right] Q \tag{9}$$

where T_{amb} is the ambient temperature, T_{mod} is the module's temperature, Q is the convection and radiation heat transfer from module to the ambient air and it can be shown as equation 10. Moreover, h_{ca} can be calculated as follows, where V_W is the wind velocity.

$$Q = h_{ca} A_{mod}(T_{mod} - T_{amb}) \tag{10}$$

$$h_{ca} = 5.7 + 3.8V_W \tag{11}$$

By merging the equation 10 in equation 11, equation 12 can be given as follows [20]:

$$E_X = V_m I_m - \left[1 - \left(\frac{T_{amb}}{T_{mod}}\right)\right] h_{ca} A_{mod}(T_{mod} - T_{amb}) \tag{12}$$

The solar exergy can be represented as $E_{X_{solar}}$ and it can be calculated as follows [55,20]:

$$E_{X_{solar}} = \left[1 - \left(\frac{T_{amb}}{T_{mod}}\right)\right] I_S A_{mod} \tag{13}$$

In addition, the exergy of a BIPV system can be calculated as follows [20]:

$$\Psi_{pv} = \frac{V_m I_m - \left[1 - \left(\frac{T_{amb}}{T_{mod}}\right)\right](5.7 + 3.8V_W) A_{mod}(T_{mod} - T_{amb})}{\left[1 - \left(\frac{T_{amb}}{T_{mod}}\right)\right] I_S A_{mod}} \tag{14}$$

Finally, the exergy efficiency can be calculated by Petela equation as follows[20,56]:

$$\Psi_{pv} = \frac{E_X = V_m I_m - \left[1 - \left(\frac{T_{amb}}{T_{mod}}\right)\right] h_{ca} A_{mod}(T_{mod} - T_{amb})}{[1 + \left(\frac{1}{3}\right)\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \left(\frac{4}{3}\right)\left(\frac{T_{amb}}{T_{sun}}\right)] I_S A_{mod}} \tag{15}$$

2.3. The economic analysis of BIPV systems

The installation of photovoltaic panels requires large areas. However, the BIPV systems will not face this issue due to the integration of photovoltaic panels with the building and utilization of BIPV systems will cause a minor enhancement of expense by 2 to 5 % [57,58]. The BIPV technology is expensive. Moreover, as the technology of photovoltaic panels improves, the capital cost of BIPV systems will be decreased [59]. The present size of BIPV market is about 2.3 GW with Europe constituting the largest market in particular due to attractive incentives in France, Italy and Germany [60].

The rapid decreasing of the material cost of photovoltaic panels led to significant changes in final BIPV system's cost due to improvement of the photovoltaic technology [61]. Koinegg et al. has estimated the cost of BIPV systems for building's façade and reported to be 950 to 10180 \$ per m^2 [62]. Paglaro et al. revealed that a 3 kW residential project in Europe will cost about 10.8 \$ per watt [63]. Bizzari et al. showed that a 256 kW project in Italy in 1980 with BIPV systems as windows, 24.5 \$ per watt was spent [61]. Sharples and Radhi demonstrated that a BIPV project in Middle East would cost 4.1 \$ per watt [64]. Moreover, Li et al. evaluated the cost of transparent BIPV systems to be 1286 \$/m^2 in China [65]. Aristizabal et al. conducted a case study of a 840 W BIPV rooftop system in Colombia and the cost of the project was estimated to be 10.3 \$/W [66]. Seng et al. evaluated a BIPV case study in Malaysia and estimated the project cost to be 8.4 \$/W [67]. A similar study in Malaysia was conducted by Rahman et al. on a 5.76 kW BIPV system and the project cost was reported to be 8.5 \$/W [68]. Chel et al. indicated the cost of a 2.3 kW BIPV system to be 7.2 \$/W in India [69]. Ikedi et al. performed a comprehensive study on PV system integrated with bricks and reported the 18 \$/W cost for a 1.57 kW project [70]. Another similar investigation was conducted by Hammond in Britain and results revealed that the cost of the 2.1 kW project will be 9 dollar per watt [71]. The result of previous investigations are presented as Table 2.

3. THE ENERGY PAYBACK TIME (EPBT) OF BIPV SYSTEM

3.1. The definition of EPBT and related parameters

The energy payback time of the BIPV systems provide an energy analysis of BIPV systems considering the energy consumption for BIPV production and energy generation of the BIPV system. This analysis will demonstrate the overall efficiency of the BIPV system in the BIPV lifetime period as follows:

$$EPBT = \frac{E_{S.E} + E_{BOS.E}}{E_{output}} \tag{16}$$

where E_{output} is the annual system's energy production and $E_{S.E} + E_{BOS.E}$ is the total lifetime system's energy consumption. The total energy consumption of the system include the total energy required to produce the raw materials, process energy requirement, and the transport energy consumption and system's installation. $\mathrm{E_{S.E}}$ is the energy consumption of photovoltaic modules and $\mathrm{E_{BOS.E}}$ is the total energy consumption of all utilities except the photovoltaic module. The detailed energy consumption of the system can be defined as follows:

$$\mathrm{E_{S.E}} = \mathrm{E_P} + \mathrm{E_S} + \mathrm{E_F} + \mathrm{E_T} + \mathrm{E_D} \tag{17}$$

where $\mathrm{E_P}$ is the energy consumption of purification process for silicon, $\mathrm{E_S}$ is the energy consumption of a silicon ingot process, $\mathrm{E_F}$ is the energy consumption of photovoltaic module fabrication, $\mathrm{E_T}$ is the energy required for transportation of photovoltaic modules from factory to desired installation site, $\mathrm{E_D}$ is the energy consumption of module's destruction and recycling.

The auxiliary utilities such as electrical cables and convertors and other electrical utilities should be considered in energy balance equations as follows:

$$\mathrm{E_{BOS.E}} = \mathrm{E_{EBOS}} + \mathrm{E_{MBOS}} \tag{18}$$

where $\mathrm{E_{EBOS}}$ is the electrical unit energy consumption and $\mathrm{E_{MBOS}}$ is the mechanical unit energy consumption [72].

Table 2. The results of research on BIPV economic analysis.

Project type	Capacity (kW)	Researcher	Country	Cost ($/W)	Cost ($/m^2)
Façade [62]	Not mentioned	Koinegg	Europe	-	950-10180
Roof module [63]	3	Paglaro	Europe	10.8	-
BIPV glazing [61]	256	Bizzari	Italy	24.5	-
Unspecified [64]	Unspecified	Sharples & Radhi	Middle-East	4.1	-
semi-transparent solar glazing system [65]	Unspecified	Li	China	-	1286
Roof module [66]	0.84	Aristizabal	Colombia	10.3	-
Unspecified [67]	Unspecified	Seng	Malaysia	8.4	-
Roof module [68]	5.76	Rahman	Malaysia	8.5	-
Roof module [69]	2.3	Chel	India	7.2	-
Roof tile [70]	1.57	Ikedi	Britain	18	-
Roof tile [71]	2.1	Hammond	Britain	9	-

3.2. The energy consumption calculation

The production process of photovoltaic modules consist of the melting process of silicon and a two-step conversion process -Si to MG-Si and Mg-Si to EG-Si-. The energy consumption of conversion processes to produce one kilogram MG-Si and EG-Si are 20 kWh and 100 kWh respectively and the process continues to achieve 90 % of reactant's total mass. Moreover, the total energy consumption to produce one kilogram of mono-crystalline photovoltaic modules is equal to 290 kWh where the process continues to achieve 72 % of reactant's total mass in previous stage. In addition, in order to produce one m^2 of monocrystalline photovoltaic solar cell, 1.448 kilogram monocrystalline silicon will be required [72,73]. Therefore, the energy consumption of the purification process of silicon per one m^2 of solar module can be calculated as follows:

$$\mathrm{E_P} = 290 \times 1.448 + 100 \times \frac{1.448}{0.72} + 20 \times \frac{\frac{1.448}{0.72}}{0.9} = 666\mathrm{kWh/m^2} \tag{19}$$

The energy consumption of cutting process for silicon bar -$\mathrm{E_S}$- is estimated to be 120 kWh per 1 m^2 solar cell and the energy consumption of photovoltaic module production -$\mathrm{E_F}$- is estimated to be 190 kWh per 1 m^2 of solar cells [74]. The total energy consumption of photovoltaic module's manufacture can be calculated as follows. The recycling process and transport energy consumption were neglected.

$$\mathrm{E_{S.E}} = 666 + 120 + 190 = 976\,\mathrm{kWh/m^2} \tag{20}$$

The energy consumption to create supporting structure for settlement of photovoltaic systems is 200 kWh/m^2 [75] and the energy consumption of invertor production is estimated to be 33 kWh/m^2. The energy consumption of auxiliary utilities and maintenance and etc., is estimated to be 125 kWh/m^2 [72].

$$\mathrm{E_{BOS.E}} = 200 + 33 + 125 = 358\,\mathrm{kWh/m^2} \tag{21}$$

Considering the equation 20 and equation 21, the following equation can be written:

$$\mathrm{E_E} = \mathrm{E_{S.E}} + \mathrm{E_{BOS.E}} = 976 + 358 = 1334\,\mathrm{kWh/m^2} \tag{22}$$

The energy consumption of BIPV rooftop systems is shown as Figure 3. The major energy requirement is related to the purification process of the silicon which almost covers the half of total energy consumption for BIPV system and the lowest energy consumption is related to inventor's energy consumption.

As it is shown in Figure 4, the 73 % of the total energy consumption is directly related to photovoltaic module's production and the 27 % of the total energy consumption will provide the energy requirement of sideways processes and auxiliary utilities.

3.3. The selection of photovoltaic modules and the payback time period calculation

In order to calculate the exact energy consumption of BIPV systems, the desired photovoltaic system should be pinned down. For this reason, the photovoltaic modules form three well-known solar companies –J.A. Solar, Yingli Solar and Jinko Solar- ware nominated. The characteristics of each module is presented in Tables 3 to 5. The values of the tables are achieved in STC (standard test condition) condition, 1000 W/m^2 solar irradiation, 1.5 A current and 25 °C temperature.

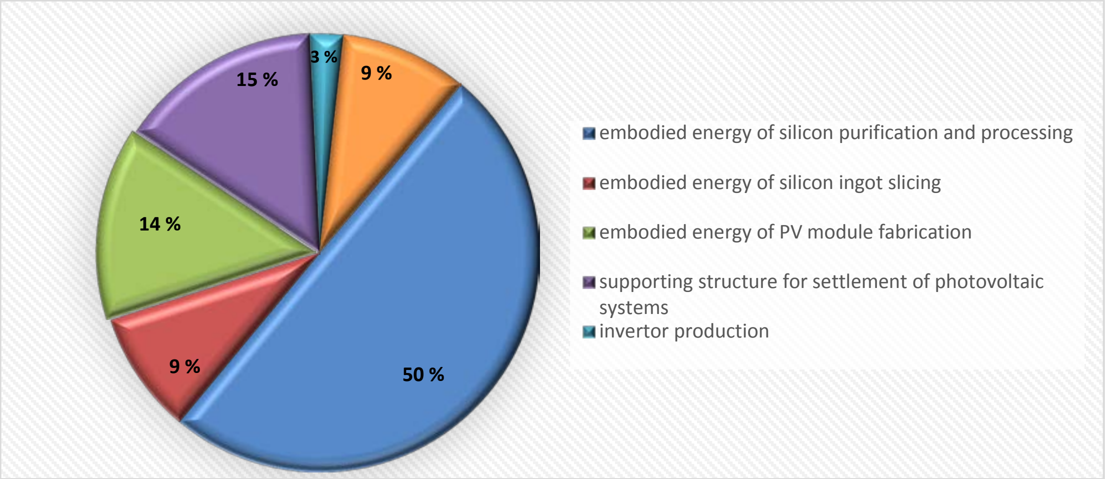


Figure 3. Consumption energy for the BIPV system.

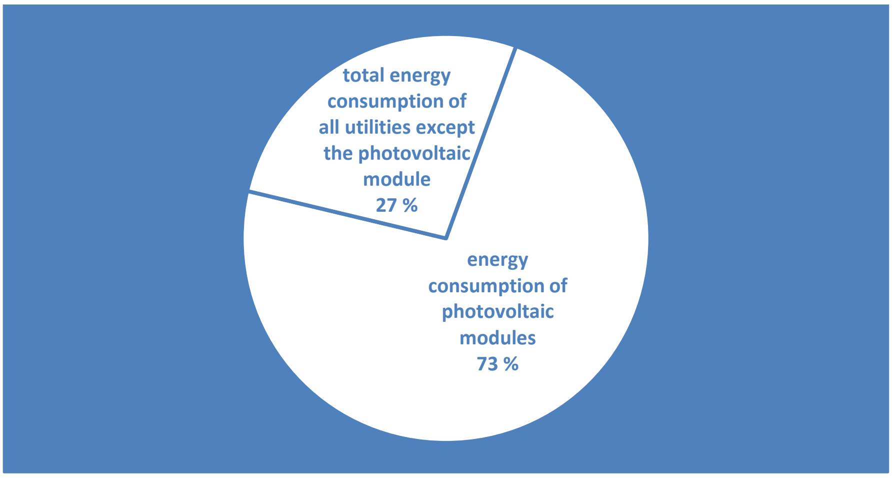


Figure 4. Distribution of energy consumption in the production of the module.

Table 3. Specifications of the modules studied from the J.A. Solar factory in the standard test conditions [76].

Parameters	**JAM6(K)-60-270/4BB**	**JAM6(K)-60-280/4BB**	**JAM6(K)-60-290/PR**	**JAM6(K)-72-325/4BB**	**JAM6(K)-72-340/4BB**
Maximum power (W)	270	280	290	325	340
Maximum power voltage (V_{MP}/V)	30.68	30.97	31.8	37.15	37.87
Maximum power current (I_{MP} /A)	8.8	9.04	9.12	8.75	8.98
Open circuit voltage (V_{OC}/V)	38.39	38.65	39.46	45.6	46.32
Short circuit current (I_{SC}/A)	9.29	9.49	9.57	9.33	9.6
Module efficiency (%)	16.51	17.12	17.74	16.73	17.5
Dimensions (m × m × m)	1.65×0.991×0.035	1.65×0.991×0.035	1.65×0.991×0.035	1.96×0.991×0.04	1.96×0.991×0.04
Weight (Kg)	18	18	18.7	23	23

Table 4. Specifications of the modules studied from the Jinko Solar factory in the standard test conditions [77].

Parameters	**JKM270M-60**	**JKM280M-60H-V**	**JKM290M-60**	**JKM325M-72**	**JKM340M-72**
Maximum power (W)	270	280	290	325	340
Maximum power voltage (V_{MP}/V)	31.4	31.8	32.2	38	38.7
Maximum power current (I_{MP} /A)	8.6	8.81	9.02	8.55	8.79
Open circuit voltage (V_{OC}/V)	38.4	38.6	38.8	45.6	47.1
Short circuit current (I_{SC}/A)	9.28	9.49	9.78	9.03	9.24
Module efficiency (%)	16.5	16.95	17.72	16.75	17.52
Dimensions (m × m × m)	1.65×0.992×0.04	1.665×0.992×0.04	1.65×0.992×0.04	1.956×0.992×0.04	1.956×0.992×0.04
Weight (Kg)	19	19	19	26.5	26.5

Table 5. Specifications of the modules studied from the Yingli Solar factory in the standard test conditions [78].

Parameters	**YL270-30b**	**YL280CG2530L-1**	**YL290CG2530F-1**	**YL325D-36b**	**YL340D-36b**
Maximum power (W)	270	280	290	325	340
Maximum power voltage (V_{MP}/V)	30.9	31.7	32.3	36.9	37.9
Maximum power current (I_{MP} /A)	8.73	8.83	8.98	8.81	8.97
Open circuit voltage (V_{OC}/V)	V38.6	V38.8	V39.2	V46.2	V47.3
Short circuit current (I_{SC}/A)	9.31	9.25	9.34	9.27	9.35
Module efficiency (%)	16.6	17	17.4	16.7	17.5
Dimensions (m × m × m)	1.64×0.99×0.035	1.66×0.992×0.06	1.666×0.998×0.032	1.96×0.99×0.04	1.96×0.99×0.04
Weight (Kg)	18.5	23	24.5	22	22

Considering the values of Table 3, 4 and 5, the energy consumption for each module's manufacture process can be calculated. Moreover, the payback energy period for each module can be calculated using equation 22 and the results can be shown as Tables 6, 7 and 8. As it is shown, the highest annual energy production is related to the J.A. Solar and Jinko Solar modules with 290 W capacity and Yingli Solar modules introduce 280 W solar panels. The lowest EPBT and highest energy production is related to JAM6 (K)-60-290/PR with 275.612 kWh energy production and 4.84 year EPBT period. On the other hand, the highest EPBT and the lowest energy production is related to JKM270M-60 with 238.427 kWh energy production and 5.595 year EPBT period. Figure 5 and Figure 6 present the annual energy production and EPBT period for each modules as follows.

Table 6. Generated energy per square meter and energy payback time in the modules of J.A. Solar factory.

Parameters	**JAM6(K)-60-270/4BB**	**JAM6(K)-60-280/4BB**	**JAM6(K)-60-290/PR**	**JAM6(K)-72-325/4BB**	**JAM6(K)-72-340/4BB**
Produced energy per year ($\frac{KWh}{m^2}$)	238.812	256.808	275.612	245.219	268.344
Energy payback time (year)	5.586	5.194	4.84	5.44	4.971

Table 7. Generated energy per square meter and energy payback time in the modules of Jinko Solar factory.

Parameters	**JKM270M-60**	**JKM280M-60H-V**	**JKM290M-60**	**JKM325M-72**	**JKM340M-72**
Produced energy per year ($\frac{KWh}{m^2}$)	238.427	251.713	275.024	245.766	268.928
Energy payback time (year)	5.595	5.299	4.85	5.428	4.96

Table 8. Generated energy per square meter and energy payback time in the modules of Yingli Solar factory.

Parameters	**YL270-30b**	**YL280CG2530L-1**	**YL290CG2530F-1**	**YL325D-36b**	**YL340D-36b**
Produced energy per year ($\frac{KWh}{m^2}$)	241.823	253.216	265.856	245.026	268.615
Energy payback time (year)	5.516	5.268	5.018	5.444	4.966

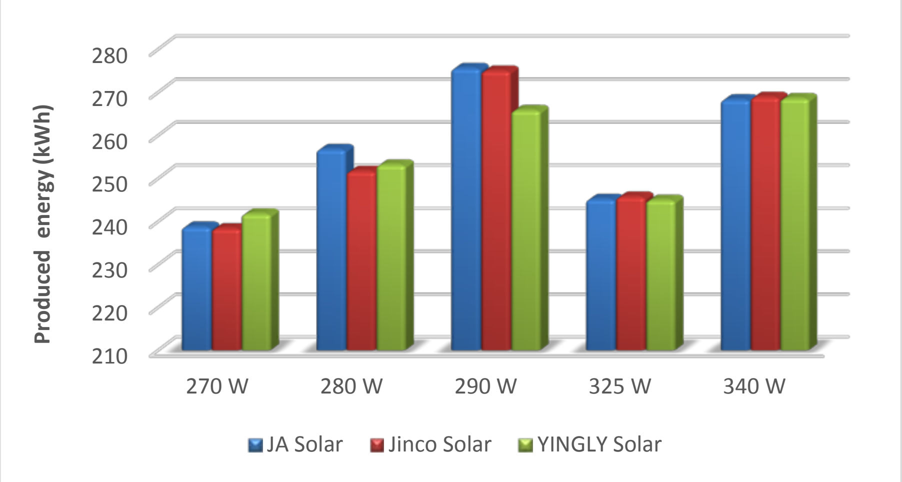


Figure 5. Produced energy by different modules in the year.

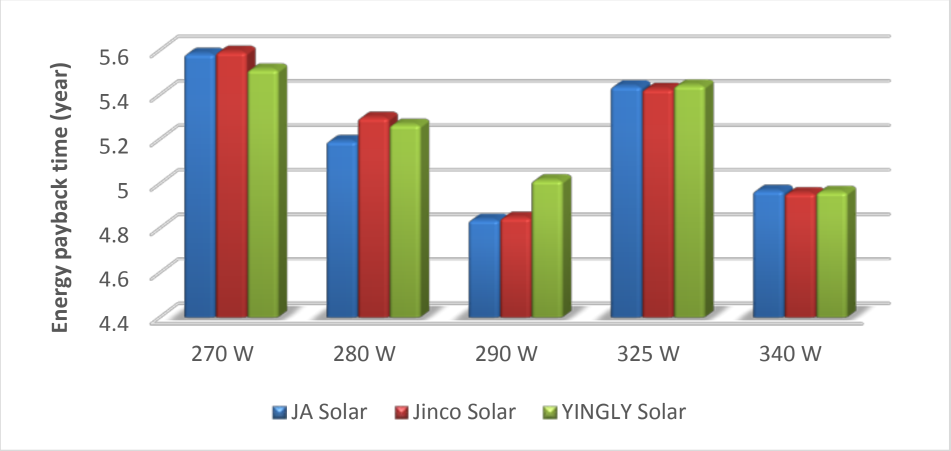


Figure 6. Energy payback time for different modules.

4. CONCLUSIONS

In the present study, various aspects of the BIPV systems were investigated. The solar energy as the most abundant renewable energy is considered an interesting alternative for providing building's energy demand. Moreover, the photovoltaic systems are considered as clean energy production systems and do not produce CO_2 and other greenhouse gases which causes the global warming issues. Furthermore, the photovoltaic systems are considered a desired choice to utilize in zero energy buildings. The BIPV systems is the solar photovoltaic modules which can be integrated to the building's façade as an alternative for other construction materials such as tiles. Roofs and windows. Since the photovoltaic modules are considered as a part of the building, they cannot be relocated or removed. Furthermore, the key parameters such as inclination angle, the shading effect and the thermal effect of the modules should be considered before the installation procedure. In order to simulate the thermal performance of the BIPV systems, three thermal resistance layers are considered -photovoltaic layer, air gap layer and the wall-. The efficiency of the BIPV system can be calculated due to the input solar energy. Various application for BIPV systems are introduced as rooftop BIPVs, BIPV tiles, semi-transparent BIPVs and the shading systems. The international market for BIPV systems increased from 1.8 billion dollars in 2009 to 8.7 billion dollars in 2016. Even though, the implementation of BIPV systems will increase the building material's expenses 2 to 5 % more than common building materials, the rapid improvement of photovoltaic technologies has led to the growing global interest to utilize BIPV systems. Based on the previous investigation in literature, the final capital cost to produce 1 watt electricity from BIPV windows, BIPV bricks and BIPV rooftop systems are estimated 24, 14 and 10 $ respectively. In the present study, the photovoltaic modules from three well-known solar companies were studied. Additionally, the photovoltaic module data for three companies were investigated and the annual energy production for one m^2 of each company's product were obtained. The results showed that the average energy payback time for 270 and 280 watt modules are 5.565 and 5.254 respectively. Moreover, the energy payback time for 290, 325 and 340 watt modules were calculated 4.903, 5.437 and 4.965 respectively. Furthermore, the highest annual energy production is related to the J.A. Solar and Jinko Solar modules with 290 W capacity and Yingli Solar modules introduce 280 W solar panels. The results showed that the lowest EPBT and highest energy production is related to JAM6 (K)-60-290/PR with 275.612 kWh energy production and 4.84 year EPBT period. On the other hand, the highest EPBT and the lowest energy production is related to JKM270M-60 with 238.427 kWh energy production and 5.595 year EPBT period.

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REFERENCES

1. http://www.reelcoop.com/, (accessed March 8, 2018).
2. International Energy Agency (IEA), Medium-Term renewable energy market report 2016, Executive summary, (2016), 13. (doi:10.1007/s13280-010-0059-7).
3. Fayaz, H., Rahim, N.A., Hasanuzzaman, M., Nasrin, R. and Rivai, A., "Numerical and experimental investigation of the effect of operating conditions on performance of PVT and PVT-PCM", ***Renewable Energy***, (2019). (doi:10.1016/j.renene.2019.05.041).
4. Good, C., Andresen, I. and Hestnes, A.G., "Solar energy for net zero energy buildings – A comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems", ***Solar Energy***, Vol. 122, (2015), 986-996. (doi:10.1016/J.SOLENER.2015.10.013).
5. Huide, F., Xuxin, Z., Lei, M., Tao, Z., Qixing, W. and Hongyuan, S., "A comparative study on three types of solar utilization technologies for buildings: Photovoltaic, solar thermal and hybrid photovoltaic/thermal systems", ***Energy Conversion and Management***, Vol. 140, (2017), 1-13. (doi:10.1016/J.ENCONMAN.2017.02.059).
6. Bauer, M., Mösle, P. and Schwarz, M., Green building : Guidebook for sustainable architecture, (2010). (doi:10.1007/9783642006357).
7. Jadhav, N.Y., Green and smart buildings, Advanced technology options, Springer, Singapore, (2016). (doi:10.1007/978-981-10-1002-6).
8. http://www.gbpn.org/laboratory/positive-energy-buildings, (accessed March 9, 2018).
9. Parida, B., Iniyan, S. and Goic, R., "A review of solar photovoltaic technologies", ***Renewable and Sustainable Energy Reviews***, Vol. 15, (2011), 1625-1636. (doi:10.1016/j.rser.2010.11.032).
10. Elminshawy, N.A.S., Mohamed, A.M.I., Morad, K., Elhenawy, Y. and Alrobaian, A.A., "Performance of PV panel coupled with geothermal air cooling system subjected to hot climatic", ***Applied Thermal Engineering***, (2019). (doi:10.1016/j.applthermaleng.2018.11.027).
11. Hassan, A., Wahab, A., Qasim, M.A., Janjua, M.M., Ali, M.A., Ali, H.M., Jadoon, T.R., Ali, E., Raza, A. and Javaid, N., "Thermal management and uniform temperature regulation of photovoltaic modules using hybrid phase change materials nanofluids system [2020]", ***Renewable Energy***, Vol. 145, No. 10, (2019), 282-293.
12. Michael, J.J., Iniyan, S. and Goic, R., "Flat plate solar photovoltaic-thermal (PV/T) systems: A reference guide", ***Renewable and***

Sustainable Energy Reviews, Vol. 51, (2015), 62-88. (doi:10.1016/ j.rser.2015.06.022)

13. Dell, J., Tierney, S., Franco, G., Newell, R.G., Richels, R., Weyant, J. and Wilbanks, T.J., "Chapter 4: Energy supply and use, Climate change impacts in the United States: The third national climate assessment", Melillo, J.M., Richmond, T.C. and Yohe, G.W. Eds., U.S. Global Change Research Program, (2014), 113-129. (doi:10.7930/ J0BG2KWD).

14. Freese, B., Clemmer, S. and Nogee, A., "Coal power in a warming world: A sensible transition to cleaner energy options", Cambridge, Union of Concerned Scientists, (2008).

15. Gronlund, L., Lochbaum, D. and Lyman, E., "Nuclear power in a warming world: Assessing the risks, addressing the challenges", Union of Concerned Scientists, (2007).

16. Averyt, K., Fisher, J., Huber-Lee, A., Lewis, A., Macknick, J., Madden, N., Rogers, J. and Tellinghuisen, S., "Freshwater use by U.S. power plants: Electricity's thirst for a precious resource", (2011). (http://www.ucsusa.org/sites/default/files/attach/2014/08/ew3-freshwater-use-by-us-power-plants.pdf).

17. Haynes, W.M., Lide, D.R. and Bruno, T., CRC Handbook of chemistry and physics, 97th Edition, CRC Press, (2017). (doi:10.1136/oem. 53.7.504).

18. Gul, M., Kotak, Y. and Muneer, T., "Review on recent trend of solar photovoltaic technology", ***Energy Exploration & Exploitation***, Vol. 34, (2016), 485-526. (doi:10.1177/0144598716650552).

19. Tiwari, G.N., Mishra, R.K. and Solanki, S.C., "Photovoltaic modules and their applications: A review on thermal modelling", ***Applied Energy***, Vol. 88, (2011), 2287-2304. (doi:10.1016/J.APENERGY. 2011.01.005).

20. Zhang, X., Zhao, X., Smith, S., Xu, J. and Yu, X., "Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies", ***Renewable and Sustainable Energy Reviews***, Vol. 16, (2012), 599-617. (doi:10.1016/J.RSER.2011.08.026).

21. Barnett, A.M., Rand, J.A., Hall, R.B., Bisaillon, J.C., Delledonne, E.J., Feyock, B.W., Ford, D.H., Ingram, A.E., Mauk, M.G., Yaskoff, J.P. and Sims, P.E., "High current, thin silicon-on-ceramic solar cell", ***Solar Energy Materials and Solar Cells***, Vol. 66, (2001), 45-50. (doi:10.1016/S0927-0248(00)00157-4).

22. Wu, L., Tian, W. and Jiang, X., "Silicon-based solar cell system with a hybrid PV module", ***Solar Energy Materials and Solar Cells***, Vol. 87, (2005), 637-645. (doi:10.1016/j.solmat.2004.09.018).

23. Li, G., Zhu, R. and Yang, Y., "Polymer solar cells", ***Nature Photonics***, Vol. 6, No. 3, (2012), 153-161. (doi:10.1038/nphoton.2012.11).

24. Krebs, F.C., Alstrup, J., Spanggaard, H., Larsen, K. and Kold, E., "Production of large-area polymer solar cells by industrial silk screen printing, lifetime considerations and lamination with polyethyleneterephthalate", ***Solar Energy Materials and Solar Cells***, Vol. 83, (2004), 293-300. (doi:10.1016/j.solmat.2004.02.031).

25. Nazeeruddin, M.K., Baranoff, E. and Grätzel, M., "Dye-sensitized solar cells: A brief overview", ***Solar Energy***, Vol. 85, (2011), 1172-1178. (doi:10.1016/j.solener.2011.01.018).

26. Kalyanasundaram, K., Dye-sensitized solar cells, CRC Press, (2010). (https://www.crcpress.com/Dye sensitized Solar Cells/ Kalyanasundaram/p/book/9781439808665) (accessed March 8, 2018).

27. Humm, O. and Toggweiler, P., Photovoltaik und architektur – Die integration von solarzellen in gebäudehüllen, Ed. Bundesamt für energiewirtschaft (BEW) und Bundesamt für konjunkturfragen (BfK), Basel, Harwood Academic Publishers, (1993).

28. Thomas, H.P. and Pierce, L.K., "Building integrated PV and PV /hybrid oroducts – The PV:BONUS experience", ***Proceedings of NCPV Program Review Meeting***, Lakewood, Colorado, (2001).

29. Eiffert, P. and Kiss, G.J., "Building-integrated photovoltaic designs for commercial and institutional structures A sourcebook for architects", National Renewable Energy Laboratory (NREL), Report BERL/BK-520-25272, Oakridge, TN, (2000), 92. (doi:http://www.nrel.gov/ docs/fy00osti/25272.pdf).

30. Kanta, K., Pitchumania, R., Shukla, A. and Sharma, A., "Analysis and design of air ventilated building integrated photovoltaic BIPV system incorporating phase change materials", ***Energy Conversion and Management***, Vol. 196, (2019), 149-164.

31. Schiermeier, Q., "Clean-energy credits tarnished", ***Nature***, Vol. 477, (2011), 517-518. (doi:10.1038/477517a).

32. Fraile, S.E., Montoro, D., Despotou, E., Latour, M., Slusarz, T., Weiss, I., Caneva, S., Helm, P., Goodal, J. and Fintikakis, N., "PV diffusion in the building sector", ***Proceedings of the 23th European Photovoltaic Solar Energy Conference and Exhibition***, (2008), 3300-3304.

33. Taleb, H.M. and Pitts, A.C., "The potential to exploit use of building-integrated photovoltaics in countries of the Gulf Cooperation Council", ***Renewable Energy***, Vol. 34, (2009), 1092-1099. (doi:10.1016/j.renene. 2008.07.002).

34. Zhai, X.Q., Wang, R.Z., Dai, Y.J., Wu, J.Y. and Ma, Q., "Experience on integration of solar thermal technologies with green buildings", ***Renewable Energy***, Vol. 33, (2008), 1904-1910. (doi:10.1016/ j.renene.2007.09.027).

35. Iqbal, I. and Al-Homoud, M.S., "Parametric analysis of alternative energy conservation measures in an office building in hot and humid climate", ***Building and Environment***, Vol. 42, (2007), 2166-2177. (doi:10.1016/j.buildenv.2006.04.011.

36. Lee, E.S. and Selkowitz, S.E., "The New York Times headquarters daylighting mockup: Monitored performance of the daylighting control system", ***Energy and Buildings***, Vol. 38, (2006), 914-929. (doi:10.1109/LPT.2006.872290).

37. Park, K.E., Kang, G.H., Kim, H.I., Yu, G.J. and Kim, J.T., "Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module", ***Energy***, Vol. 35, (2010), 2681-2687. (doi:10.1016/ j.energy.2009.07.019).

38. Jelle, B.P., Breivik, C. and Drolsum Røkenes, H., "Building integrated photovoltaic products: A state-of-the-art review and future research opportunities", ***Solar Energy Materials & Solar Cells***, Vol. 100, (2012), 69-96. (doi:10.1016/j.solmat.2011.12.016).

39. Ng, P.K. and Mithraratne, N., "Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics", ***Renewable and Sustainable Energy Reviews***, Vol. 31, (2014), 736-745. (doi:10.1016/j.rser.2013.12.044).

40. Wang, W., Liu, Y., Wu, X., Xu, Y., Yu, W., Zhao, C. and Zhong, Y., "Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai", ***Energy and Buildings***, Vol. 130, (2016), 98-106. (doi:10.1016/j.enbuild.2016.07.066).

41. Peng, C., Huang, Y. and Wu, Z., "Building-integrated photovoltaics (BIPV) in architectural design in China", ***Energy and Buildings***, Vol. 43, (2011), 3592-3598. (doi:10.1016/j.enbuild.2011.09.032).

42. Li, D., Liu, G. and Liao, S., "Solar potential in urban residential buildings", ***Solar Energy***, Vol. 111, (2015), 225-235. (doi:10.1016/ j.solener.2014.10.045).

43. Coelho, B. and Oliveira, A.C., "REELCOOP project: Research cooperation in renewable energy technologies for electricity generation", ***SolarPACES 2013***, Vol. 00, (2013), 26-29.

44. Biyik, E., Araz, M., Hepbasli, A., Shahrestani, M., Yao, R., Shao, L., Essah, E., Oliveira, A.C., del Caño, T., Rico, E., Lechón, J.L., Andrade, L., Mendes, A. and Atlı, Y.B., "A key review of building integrated photovoltaic (BIPV) systems", ***Engineering Science And Technology, an International Journal***, Vol. 20, No. 3, (2017), 833-858. (doi:10.1016/j.jestch.2017.01.009).

45. Barkaszi, S.F. and Dunlop, J.P., "Discussion of strategies for mounting photovoltaic arrays on rooftops", ***Proceedings of Solar Forum 2001, Solar Energy: The Power to Choose***, (2001), 333-338.

46. Crawford, R.H., Treloar, G.J., Fuller, R.J. and Bazilian, M., "Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit", ***Renewable and Sustainable Energy Reviews***, Vol. 10, (2006), 559-575. (doi:10.1016/j.rser.2004.11.005).

47. "Building integrated photovoltaics (BIPV)", (https://www.wbdg.org/resources/building-integrated-photovoltaics-bipv) (accessed March 8, 2018).

48. Debbarma, M., Sudhakar, K. and Baredar, P., "Comparison of BIPV and BIPVT: A review", ***Resource-Efficient Technologies***, Vol. 3, (2017), 263-271. (doi:10.1016/j.reffit.2016.11.013).

49. Lamnatou, C., Mondol, J.D., Chemisana, D. and Maurer, C., "Modelling and simulation of building-Integrated solar thermal systems: Behaviour of the coupled building/system configuration", ***Renewable and Sustainable Energy Reviews***, Vol. 48, (2015), 178-191. (doi:10.1016/j.rser.2015.03.075).

50. Test, F.L., Lessmann, R.C. and Johary, A., "Heat transfer during wind flow over rectangular bodies in the natural environment", ***Journal of Heat Transfer***, Vol. 103, (1981), 262. (doi:10.1115/1.3244451).

51. Duffie, J. and Beckman, W., Solar engineering of thermal processes, 4th ed., (2013). (doi:10.1115/1.2930068).

52. Jaber, S. and Ajib, S., "Optimum design of Trombe wall system in mediterranean region", ***Solar Energy,*** Vol. 85, (2011), 1891-1898. (doi:10.1016/j.solener.2011.04.025).

53. Soares, N., Costa, J.J., Gaspar, A.R. and Santos, P., "Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency", ***Energy and Buildings***, Vol. 59, (2013), 82-103. (doi:10.1016/J.ENBUILD.2012.12.042).

54. Athienitis, A.K., Liu, C., Hawes, D., Banu, D. and Feldman, D., "Investigation of the thermal performance of a passive solar test-room with wall latent heat storage", ***Building and Environment***, Vol. 32, (1997), 405-410. (doi:10.1016/S0360-1323(97)00009-7).

55. He, W., Zhang, Y. and Ji, J., "Comparative experiment study on photovoltaic and thermal solar system under natural circulation of water", ***Applied Thermal Engineering***, Vol. 31, (2011), 3369-3376. (doi:10.1016/J.APPLTHERMALENG.2011.06.021).

56. Radziemska, E., "Performance analysis of a photovoltaic-thermal integrated system", ***International Journal of Photoenergy***, (2009). (doi:10.1155/2009/732093).

57. Paul, D., Mandal, S.N., Mukherjee, D. and Bhadra Chaudhuri, S.R., "Optimization of significant insolation distribution parameters - A new approach towards BIPV system design", ***Renewable Energy***, Vol. 35, (2010), 2182-2191. (doi:10.1016/j.renene.2010.02.026).

58. Eiffert, P. and ImaginIt, L.L.C., "Guidelines for the economic evaluation of building- integrated photovoltaic power systems", International Energy Agency PVPS Task 7 : Photovoltaic power systems in the built environment, (2003), 52.

59. Sozer, H. and Elnimeiri, M., "Critical factors in reducing the cost of Building Integrated Photovoltaic (BIPV) systems", ***Architectural Science Review***, Vol. 50, (2007), 115-121. (doi:10.3763/asre.2007.5017).

60. Osseweijer, F.J.W., van den Hurk, L.B.P., Teunissen, E.J.H.M. and van Sark, W.G.J.H.M., "A comparative review of building integrated photovoltaics ecosystems in selected European countries", ***Renewable and Sustainable Energy Reviews***, (2018). (doi:10.1016/j.rser.2018.03.001).

61. Bizzarri, G., Gillott, M. and Belpoliti, V., "The potential of semitransparent photovoltaic devices for architectural integration: The development of device performance and improvement of the indoor environmental quality and comfort through case-study application", ***Sustainable Cities and Society***, Vol. 1, (2011), 178-185. (doi:10.1016/j.scs.2011.07.003).

62. Koinegg, J., Brudermann, T., Posch, A. and Mortzek, M., "It would be a shame if we did not take advantage of the spirit of the times...", An analysis of prospects and barriers of building integrated photovoltaics, www.Ingentaconnect.Com, (2013). (http://www.ingentaconnect.com/content/oekom/gaia/2013/00000022/00000001/art00011) (accessed March 8, 2018).

63. Pagliaro, M., Ciriminna, R. and Palmisano, G., "BIPV: Merging the photovoltaic with the construction industry", ***Progress in Photovoltaics: Research and Applications***, Vol. 18, (2010), 61-72. (doi:10.1002/pip.920).

64. Sharples, S. and Radhi, H., "Assessing the technical and economic performance of building integrated photovoltaics and their value to the GCC society", ***Renewable Energy***, Vol. 55, (2013), 150-159. (doi:10.1016/J.RENENE.2012.11.034).

65. Li, D.H.W., Cheung, K.L., Lam, T.N.T. and Chan, W.W.H., "A study of grid-connected photovoltaic (PV) system in Hong Kong", ***Applied Energy***, Vol. 90, (2012), 122-127. (doi:10.1016/j.apenergy.2011.01.054).

66. Aristizábal, A.J., Banguero, E. and Gordillo, G., "Performance and economic evaluation of the first grid-connected installation in Colombia, over 4 years of continuous operation", ***International Journal of Sustainable Energy***, Vol. 30, (2011), 34-46. (doi:10.1080/1478646X.2010.489948).

67. Seng, L.Y., Lalchand, G. and Sow Lin, G.M., "Economical, environmental and technical analysis of building integrated photovoltaic systems in Malaysia", ***Energy Policy***, Vol. 36, (2008), 2130-2142. (doi:10.1016/j.enpol.2008.02.016).

68. Rahman, M.M., Haur, L.K. and Rahman, H.Y., "Building Integrated Photovoltaic (BIPV) in Malaysia: An economic feasibility study", Vol. 45, (2012), 7683-7688. (http://www.elixirpublishers.com/articles/1350369798_45 (2012) 7683-7688.pdf).

69. Chel, A., Tiwari, G.N. and Chandra, A., "Simplified method of sizing and life cycle cost assessment of building integrated photovoltaic system", ***Energy and Buildings***, Vol. 41, (2009), 1172-1180. (doi:10.1016/j.enbuild.2009.06.004).

70. Ikedi, C.U., Okoroh, M.I., Dean, A. and Omer, S.A., "Impact assessment for Building Integrated Photovoltaic (BIPV)", ***Energy***, (2010), 1407-1415.

71. Hammond, G.P., Harajli, H.A., Jones, C.I. and Winnett, A.B., "Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations", ***Energy Policy,*** Vol. 40, (2012), 219-230. (doi:10.1016/J.ENPOL.2011.09.048).

72. Lu, L. and Yang, H.X., "Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong", ***Applied Energy***, Vol. 87, (2010), 3625-3631. (doi:10.1016/J.APENERGY.2010.06.011).

73. Kato, K., Murata, A. and Sakuta, K., "Energy pay-back time and life-cycle CO_2 emission of residential PV power system with silicon PV module", ***Progress in Photovoltaics: Research and Applications***, Vol. 6, (1998), 105-115. (doi:10.1002/(SICI)1099-159X(199803/04)6:2<105::AID-PIP212>3.0.CO;2-C).

74. Tiwari, G.N. and Ghosal, M.K., Renewable energy resources : Basic principles and applications, Alpha Science International, (2005). (https://books.google.com/books/about/Renewable_Energy_Resources.html?id=I8ApwaKRmf0C) (accessed March 8, 2018).

75. Yang, H., Burnett, J. and Ji, J., "Simple approach to cooling load component calculation through PV walls", ***Energy and Buildings***, Vol. 31, (2000), 285-290. (doi:10.1016/S0378-7788(99)00041-9).

76. http://www.jasolar.com/html/en/, (accessed March 8, 2018).

77. https://www.jinkosolar.com, (accessed March 8, 2018).

78. http://www.yinglisolar.com/uk/, (accessed March 8, 2018).