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A Comprehensive Global Review of Building Integrated Photovoltaic Systems

Saudi Arabia has embarked on diversification of its existing energy portfolio through renewableables, mainly solar photovoltaic and thermal, and wind power. This study presents an overview of how different areas around the world utilized building-integrated solar photovoltaic applications to recommend appropriate and suitable options for implementation in Saudi Arabia and the Middle East region. With this objective, the power utility will have three-fold benefits (i) clean and economic power availability for off-grid remotely located dwellings, (ii) cutting down the emissions of greenhouse gases, and (iii) conserving the fixed reserves of fossil fuels, which are being used mainly for power production around the world. The study shows that building-integrated applications are most common in Asian and European countries. Moreover, it is observed that monocrystalline and polycrystalline photovoltaic materials are both technologically and economically suitable for such applications.

Keywords: Solar Photovoltaics, Building Integrated Photovoltaic Systems, Energy, Renewable Energy, Cost of Energy.

1. INTRODUCTION

Photovoltaic (PV) solar technology is a promising and elegant means of producing electricity directly from the sun at any site where PV panels and sunlight exist together. It is a solid-state technology, does not having any moving part, emitting no harmful gases, requiring bare minimum maintenance, having almost no material depletion, being easy to install, and last but not the least producing energy silently. The solar energy applications, both photovoltaic and solar thermal include PV hybrid power systems [1], solar power in shipping [2], greenhouses and solar stills [3] and [4], solar water heating [5], solar chimney [6] and [7], solar concentrators [8], and solar hot water storage [9]. With all these advantages and wide range of applications, there is a consensus among experts and policymakers that PV systems, capable of providing power at the point of use, are on the road of widespread commercialization [10]. The global PV installed capacity increased by 20.1% in 2019 (580.2 GW) compared to that in 2018 (483.1 GW). The cumulative global PV installed capacities between 2009 and 2019 are shown in Fig. 1, [11]. The largest cumulative PV capacity of 274.6 GW is observed in Asia with major contributions by China (175.0 GW), Japan (55.5 GW), India (26.8 GW), South Korea (7.8 GW), Thailand (2.7 GW), and Taiwan (2.6 GW). Europe is the second-

largest contributor of cumulative PV installed capacity of 119.3 GW with significant shares of Germany (45.9 GW), Italy (20.12 GW), the U.K. (13.4 GW), France (9.4 GW), Turkey (5 GW), Spain (4.7 GW), the Netherlands (4.1 GW) and Belgium (4.0 GW). Among these distributed applications, building integrated PV systems (BIPV) for individual building and houses are getting popular. The cumulative percent increase of annual PV installed capacity shows a decreasing pattern (Fig. 2) from 78.17% in 2010 to 20.10% in 2019.

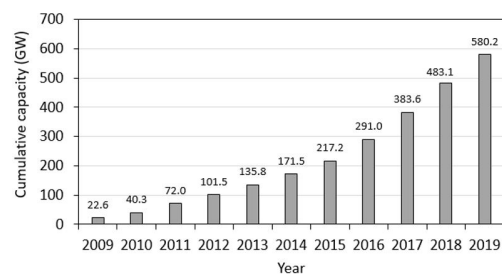


Figure 1. Cumulative global PV installed capacities

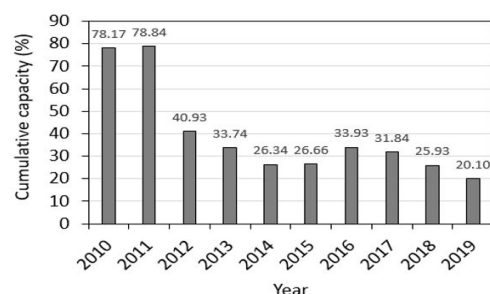


Figure 2. Annual percent cumulative global PV installed capacities variation

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2. DESCRIPTION OF A BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) SYSTEM

A BIPV system consists of integrating photovoltaics modules into the building envelope, such as the rooftops, the façade, walkways, parking areas, and so on. These systems provide savings in materials reduce electricity bills and fuel burning for power generation. This results in fossil fuel conservation and reduction in greenhouse gases emissions. Usually, BIPV systems are interfaced with the available utility grid, but can be used off-grid as well. A grid-tied BIPV system is 100% efficient and is unlimited in capacity and benefits. Both the building owners and the utility benefit from such a system. A typical schematic setup of a BIPV system for grid-tied/isolated grid is shown in Fig. 3. The PV cells or panels can be integrated with vertical walls of the buildings, facades, and rooftops, examples are shown in Fig. 4. BIPV systems mainly consist of the following main components [12]:

- photovoltaic (PV) panels or modules or arrays
- a charge controller, to regulate the power into and out of the battery bank in the case of a standalone system
- a power storage system either battery bank or the utility grid
- DC to AC converter
- backup power, usually diesel generator in case of standalone systems
- supports, mounting hardware, wiring, and safety disconnects

3. AN OVERVIEW OF SOLAR PHOTOVOLTAIC INSTALLATIONS IN SAUDI ARABIA

Saudi Arabia is a vast country (total area of 2,149,690 km², 100% land) and has high intensities of solar radiation and long sunshine durations. This country and the neighboring nations are very much suitable for small to large PV based applications. Saudi Arabia has huge open desert land, which can be utilized economically to develop very large grid-tied PV power plants. In urban areas, BIPV systems can be deployed in multi-story buildings and individual houses which are connected to the grid. On the other hand, in remote areas BIPV systems can also be used as an isolated system with diesel or battery power backup options.

The existing Saudi national power grid in Saudi Arabia can absorb an additional 13.5 GW of new power generation according to [13]. The renewable energy-based parks or power plants are expected to be spread all over the Kingdom in the near future, as shown in Fig. 5. According to a press release [14], a giant solar park of 2.6 GW (Faisaliah Solar Power Project) total installed capacity is proposed for Mecca region. It will be completed in several phases and the first park is said to be of 600 MW installed capacity. The first green-powered gas well (Fig. 6), a photovoltaic system with battery backup, was commissioned on July 24, 2019 in Wa'ad Al-Shamal, Saudi Arabia [15]. It has a five-year battery life cycle and is capable of providing uninterrupted power supply to a large electrical load created by the use of blower motors, methanol injection

pumps, HVAC, and other systems. The first phase of a grid-connected PV power plant of 13.65 MWp capacity was commissioned recently in Layla, Al-Aflaj, Saudi Arabia [16]. This project, when completed after the second phase of 40 MW capacity, will result in savings of 4 million barrels of diesel fuel and 1.7 million tons' reduction in CO₂ emissions. This power plant (shown in Fig. 7) can cover 10% of the power needs of Al-Aflaj area. A PV power plant with 10.5 MWp capacity is operational in Saudi Aramco premises in Dhahran and is connected to the grid [17]. A total of 121,250 thin-film solar PV panels along with associated connection boxes are installed on parking shades (Fig. 8).

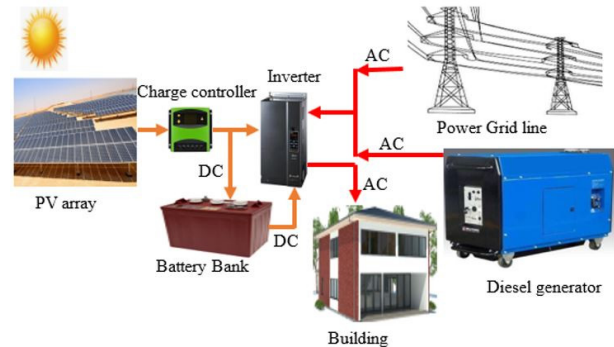


Figure 3. A typical BIPV system for grid-tied/isolated connection



Figure 4. Examples of BIPV systems designs

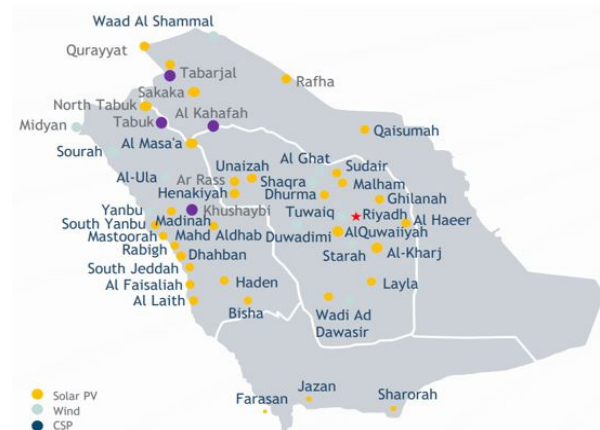


Figure 5. Projected locations of renewable energy based power plant deployment [13]



Figure 6. First green powered gas well in Saudi Arabia [15]



Figure 7. Layla solar photovoltaic power plant, Layla, Al-Aflaj, Saudi Arabia [16]



Figure 8. Photo of a 10 MWp installed capacity grid-connected PV power plant in Saudi Aramco, Dhahran, Saudi Arabia [17]

In Farasan Island, 500 kW installed capacity PV power plant (Fig. 9) was inaugurated on October 1, 2011. It is saving 28,000 barrels of diesel fuel transport to the island and is producing approximately 864,000 kWh of electricity annually. A grid-connected solar park Phase 1 of 3.5 MW installed capacity is located in Riyadh and belongs to King Abdullah Petroleum Studies and Research Center (KAPSARC). This plant uses 12,684 panels from China's Suntech Power Holdings Co. Ltd. and was constructed in a record time of 20 months over an area of 55,000 m². The 1.8 MW capacity extension was completed in Phase 2, covering a land area of 26,000 m² and started operation in early 2014. The total capacity of this plant is 5.3 MW. It is providing around 8,540 MWh of electricity annually to the KAPSARC's medium voltage grid (Fig. 10).

There are many ongoing and planned PV power plant projects in Saudi Arabia. The planned PV plants in near future include Sakaka 300.0 MW plant (Fig. 11) in Al-Jouf area [17], Saudi Aramco's 300.0 MW plant, K.A. CARE 500.0 MW plant, KACST PV desalination power plant of 10.0 MW capacity in Khafji, and K.A. CARE 50.0 MW PV power plant for Royal Commission of Jubail and Yanbo. There are more PV power plants (Madinah 50.0, Rafha 20.0, Al-Faisaliah 600.0, Jeddah 300.0, Rabigh 300.0, and Qurrayat 200.0 MW) underway for which the contracts have been awarded to different

national and international bidders [18]. With this background and hands-on experience, it can be said that Saudi Arabia has a vast scope of developing small to large BIPV's for both rural and urban areas and is expected to provide expertise in this field to the neighboring nations.



Figure 9. Photo of a 500 kW installed capacity PV power plant in Farasan Island near Gizan, Saudi Arabia

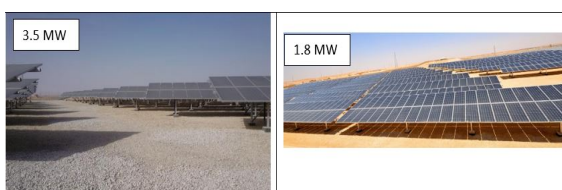


Figure 10. KAPSARC's 5.3 MW installed capacity PV power plant in Riyadh



Figure 11. Sakaka solar power plant [17].

4. METHODOLOGICAL APPROACH FOR THE CURRENT REVIEW

Relevant material for this review paper is obtained from internet, news media, published papers in journal and conference proceedings, completed project reports, and progress reports of the real-time working BIPV systems. The information, on various aspects of BIPV, will be analyzed to recommend suitable BIPV systems for Saudi Arabia and the region. The scope of the present work is to abreast the scientific community to know about:

- the most popular technology (monocrystalline, polycrystalline, thin film, etc.) being used in such systems
- existing BIPV system sizes being used around the globe, efficiency, effect of temperature and dust on the efficiency
- statistics of grid-tied and off-grid BIPV systems
- type of integration of PV with buildings being used (façade or roof-top) globally and continentally
- the panel cleaning technologies being used and associated costs
- capital cost, payback period, and cost of energy

5. GLOBAL POPULARITY, TECHNOLOGIES, EFFICIENCIES, AND COST OF ENERGY OF BIPVS

More than 100 research studies, both simulation and experimental, conducted in different parts of the world are reviewed and analyzed. A continental percent distribution of BIPV's is depicted in Fig. 12. It is seen that maximum applications (50%) are observed in Asia while 15% in Africa and 28% in Europe. In the Middle East also the applications of BIPV's are getting popular, as seen from the studies appeared in the literature. Among the technologies used for these applications; monocrystalline, polycrystalline, and thin film type BIPV's constitute around 57%, 29%, and 15% global share, respectively. The application types of BIPV's include rooftops (95%) and façade type (5%). The mean efficiencies of polycrystalline, monocrystalline and thin film technologies reviewed in this survey are found to be 13.62%, 12.8%, and 10.89%; respectively (Fig. 13).

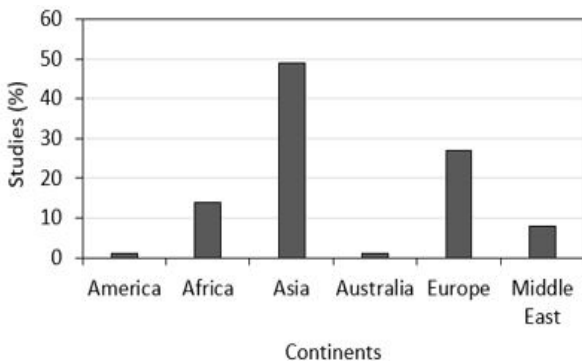


Figure 1. Continental popularity of BIPV's

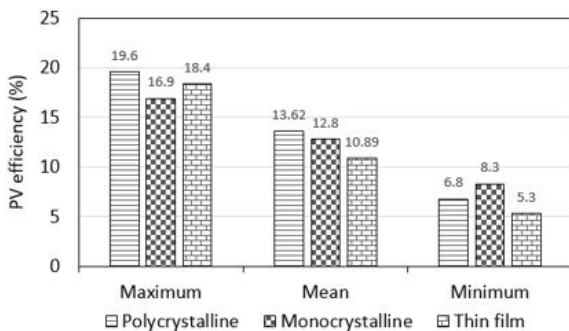


Figure 2. Efficiencies of different photovoltaic technologies used in BIPV's

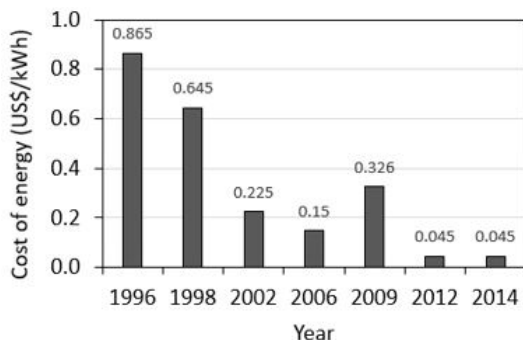


Figure 3. Cost of energy of monocrystalline based BIPV's

Efficiency wise, polycrystalline type of PV panels are the most efficient. The maximum and minimum values are also shown in this figure. The cost of energy of building-integrated monocrystalline based photovoltaic

panel systems has shown a gradual decrease. However, no definite trend is noticed in the case of polycrystalline based BIPV's; as shown in Figs. 14 and 15. However, it is evident that, based on COE, polycrystalline technology is more economical than monocrystalline.

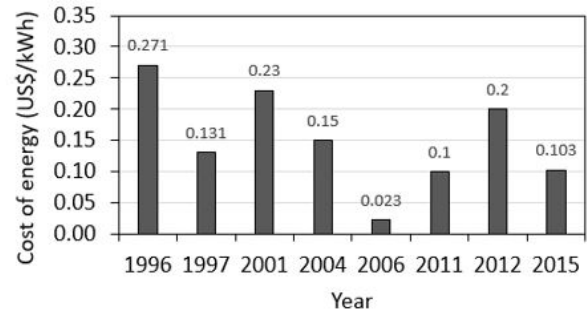


Figure 4. Cost of energy of polycrystalline based BIPV's

6. CONTINENTAL REVIEW OF BIPVS CAPACITIES, ENERGY YIELDS, EFFICIENCIES, COST OF ENERGY, PAYBACK PERIODS, AND LIFETIME

In trying to utilize the global solar radiation for generating electricity using PV systems in different parts of the world, the technology and the efficiency of the modules and the environment where the module would be installed have a great impact on the power output of the BIPV system. To better understand the existing performances of BIPV systems, this section concentrates on prevalent BIPV sizes, efficiencies in relation to climatic conditions, annual energy yield, and cost of energy, last but not the least the payback periods on a continental basis.

6.1 American Region

In the American region, the research database shows that Southern American displays a high solar radiation. The coastal zone of northern Chile (Antofagasta) is one of the regions with a high level of solar radiation in the world. However, the effect of this radiation on PV modules in Antofagasta is not well analyzed due to lack of data availability. As a result of this effect, in 2015, Ferrada et al. [19] analyzed two PV modules: i.e. amorphous/microcrystalline silicon a-(Si/lc-Si) tandem thin films and monocrystalline silicon (mono-Si) within a period of 16 months at the University of Antofagasta. The installed capacities of these modules were 3.36kWp and 3.33kWp with efficiencies of 8.9% and 14.6%. Furthermore, the annual energy outputs from these systems were reported as 1,690kWh/kWp and 1,760kWh/kWp. De Lima et al. [20] conducted an annual performance evaluation of 2.2 kWp PV system installed in the state University of Ceará, Fortaleza Brazil. The annual energy output of the system was 1,685.5kWh with module efficiency of 13.3%.

In the American region, a few case studies were found in our limited search, the prevalent capacities were ranged from 2 to 3.5kWp and monocrystalline cell types were reported having the higher efficiencies of 14.6%.

6.2 African Region

In the African region, efforts have been made to mitigate the amount of CO₂ and to utilize the abundance of solar

energy across African continent through implementing the PV modules. Different researchers carried-out both experimental and theoretical studies to compare and analyze the performance and working principle of these implemented PV modules. In 2010 Dabou et al. [21] evaluated the consequence of weather conditions on grid-connected PV modules using a 1.75 kWp system made up of mono-crystalline modules installed at the Unit of Research in Renewable Energy (URERMS) southwest of Algeria. The experimental results at a temperature of 41.1 °C showed that the system had an efficiency of 13.5%. In 2007, Cherfa et al. [22] evaluated the performance of a grid-connected 9.540 kWp capacity of monocrystalline roof-mounted PV panels (Fig. 16) and reported an annual energy output of 11872 kWh with efficiency of 12% in Algeria. Laib et al. [23] studied the performance of a roof-mounted 1.2 kWp PV system for residential building in northern region of Algeria. The installed system generated 2,253 kWh of energy annually. Necaibia et al. [24] studied the outdoor performance of a grid-tied 2.5 kWp PV system reported an annual output of 4322.65 kWh with an efficiency of 15.87% in Algeria.

El-shimy [25] examined a 29 sites in Egypt for the implementation of 10 MWp PV system on an area of 57,562 m². The systems comprised of mono-Si (Heterojunction with Intrinsic Thin-layer technology) modules with an efficiency of 17.4% and the initial cost of 103,740,822 US\$. The results showed that Wahat Kharga site was the most profitable with the annual energy yield of 26.35 GWh and lifetime of 25 years. Baghdadi et al. [26] compared the performance of three PV technologies (mono-crystalline 2.04kWp, polycrystalline 2.04kWp, and amorphous 1.86kWp) comprising of a total of 5.94 kWp and installed on the rooftop of a building in the Faculty of Science, Tetouan-Morocco. The study reported a respective total energy output of 3834.7, 3833.8, and 3618.8 kWh/yr at an efficiency of 15.2%, 15.2%, and 9.87%. El Fathi et al. [27] evaluated the performance of 7.2 kWp standalone rooftop PV system for 16 households in Morocco. The system was made of crystalline silicon cells with an efficiency of 18.1%. Also, in Morocco Allohi et al. [28] analyzed 2 kWp rooftop PV system (Fig. 17) made of monocrystalline and polycrystalline technologies and reported an efficiency of 15.2% and LCOE of 0.073 and 0.082 USD/kWh; respectively. The payback periods of these systems were reported to be 11.10 and 12.69 yrs with an assumed lifetime of 25 yrs. Salem and Kinab [29] theoretically analyzed a 17.6 kWp BIPV system installed in a commercial building under Mediterranean climatic conditions, Lebanon. The installed system produced 26.95 MWh of energy annually.



Figure 5. Roof mounted monocrystalline technology BIPV demonstration plant in Algeria [22]

Ulrich et al. [30] analyzed a stand-alone PV system for rural electrification in Ethiopia under local climatic condition. The system was made of two arrays with total capacity of 220 Wp and produced 190 kWh annually with 9.9% efficiency and had a life time of 25 yrs. Kassahun [31] analyzed 35 locations for the implementation of 5 MW PV system on a total area of 34,364 m² in Ethiopia using HOMER and RETScreen software. The proposed PV systems were comprised of 23,256 Heterojunction with Intrinsic Thin-layer (HIT) panels with 17.1% efficiency. The study reported that the system was able to generate a total of 8,674 MWh of energy annually at a COE of 200 USD/MWh with 25 yrs life time and 14.5 yrs payback period. The total investment cost of the proposed system was 19,767,600 USD.

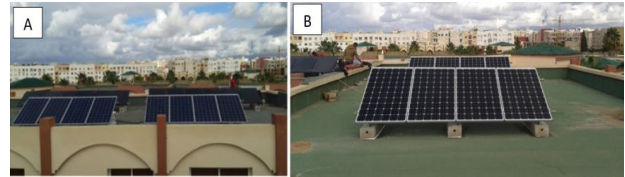


Figure 6. Polycrystalline (A) and polycrystalline (B) roof mounted PV systems in Morocco [28]

In 2013, Cheikh et al. [32] presented an analysis of a 15 MWp large-scale PV plant in Mauritania. The system is comprised of thin-film (amorphous and micro amorphous silicon) panels with daily average energy production of 2.755 MWh in January and 4.831 MWh in October. In the same year, Okello et al. [33] compared the performance of a 3.2 kWp BIPV system in Nelson Mandela Metropolitan University (NMMU), South Africa. The system had polycrystalline silicon modules connected in series with total annual energy production of 5,757 kWh and efficiency of 13.72%. Quansah et al. [34] presented the outdoor performance of five solar PV technologies (Fig. 18) with combined total capacity of 20 kWp installed on the rooftop of a building in Ghana. The study concluded that polycrystalline (pc-Si) was the best option while Indium Disulphide (CIS) was the least preferred technology. Muyiwa [35] evaluated 80 kWp capacity grid connected system using HOMER software in Nigeria. The system had 72 polycrystalline modules with efficiency of 14.7%. The system generated 331,536 kWh energy annually at levelized cost of energy (LCOE) of 0.103 USD/kWh with an initial investment of 2,322 USD and lifetime of 25 yrs.

In African region, a review of 15 papers (experimental and simulation studies) found monocrystalline technology (efficiencies varying from 12.0 to 15.87%) most popular followed by polycrystalline, HIT, amorphous, and crystalline silicon with average system efficiencies of 15.0, 17.0, 12.5, and 18.1%; respectively. The cost of energy varied from 0.02 to 0.103 USD/kWh with average payback period of 13 years. For experimental cases, the sizes of the systems varied from less than 2.0 kWp to 220 kWp while for simulation studies these were in MW sizes. In almost all the cases, the working life of the BIPVs was reported as 25 years.

6.3 Asian Region

Many projects on renewable energy were initiated by government in Asian region to improve the applications

of renewable energy and reduction of greenhouse effects on the climate. Bhuiyan et al. [36] conducted the economic feasibility analysis of stand-alone residential system (47 Wp x 6 PV) for rural and remote areas of Bangladesh. The proposed system was able to generate 4,672 kWh of energy with a capital investment of 770 US\$ with an expected working life of 20 years. The study reported that PV systems are more economically feasible in rural than in remote areas. In another attempt, Mondal and Islam, [37] used GeoSpatial toolkit to analyze financial feasibility of 1.0 MWp PV system in Bangladesh. The system was designed using 5,714 monocrystalline panels with 25 yrs lifetime installed at an initial investment 14015.0 US\$. The proposed system was estimated to produce 1,729 MWh of energy annually at 13.9% system efficiency and 1,423 tons of greenhouse gases reduction.

In 1997, the first BIPV system (100 kWp) was implemented in Korea at Samsung Institute of Engineering and Construction Technology (SIECT), Seung et al. [38]. This system was made of polycrystalline and single crystalline modules with efficiencies of 12% and 14%. The total daily energy production was 206, 205, and 237 kWh in June, July, and August, respectively. In 1999, Hong Kong government installed a BIPV system with 8.0 kWp capacity to supply around 41% of annual load (16,700 kWh) of a building. The system consisted of 100 crystalline silicon modules with 13% efficiency installed on the rooftop and the walls of the building (Fig. 19). Result showed that the system could have 20 years payback period at an energy cost of 0.19-0.26 USD/kWh, Yang et al. [39]. Jung et al. [40] analyzed four PV systems, 3kWp capacity each, made of two multicrystalline and two monocrystalline panels in Korea. The resulting energy output and the respective efficiencies are summarized in Table 1. Kim et al. [41] analyzed performance of two grid connected polycrystalline BIPVs of 20 kWp installed capacity in Kiemyung University's Osan Building and Dongho Elementary School in Daegu Metropolitan City, Korea (Fig. 20). BIPVs at school and Osan building produced 25,848 and 40,094 kWh of electricity annually at a COE of 0.824 and 0.531 USD/kWh.

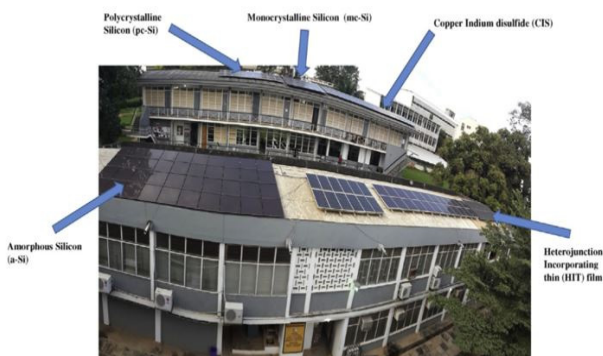


Figure 7. Technologies demonstration project Nelson Mandela Metropolitan University (NMMU), South Africa [34]

Lu and Yang [42] compared the energy and greenhouse-gases payback times of a 22 kWp rated power BIPV system in Hong Kong with an annual energy output of 28,154 kWh. The system was found to have payback periods of 7.3 and 5.2 years with module

efficiency of 13.3% and an estimated lifespan of 20-30 years. Meng et al. [43] compared the energy performance of CdTe PV and a-Si PV windows in Hong Kong and reported annual energy output densities of 52.3 kWh/m² and 41.8 kWh/m² with module efficiencies of 7.1% and 5.9%, respectively. In Hong Kong, Li et al. [44] reported the annual energy output and the cost of semi-transparent photovoltaic solar cells, made of amorphous silicon implemented in office building, as 1,203 MWh and US\$ 1,286/MWh, respectively. Chow et al. [45] evaluated the annual performance of a polycrystalline BIPV system in Hong Kong with heating collector system for warm climate application. The study reported annual energy saving of 322.9 kWh with a panel efficiency of 13%, payback period of 13.8 yrs.



Figure 8. First BIPV system in Hong Kong [39]



Figure 9. BIPVs installed in Dongo Elementary School (Left) and Osan Building (Right), [41]

Table 1. Annual energy output and the efficiency of four 3 kWp installed capacity PV systems in Korea.

System Type	Capacity (kWp)	Energy (MWh)	Efficiency (%)
Multi	3	4.13	10.1
Mono	3	3.51	9.2
Mono	3	3.98	9.5
Multi	3	3.68	9.5

Similarly, Tian et al. [46] analyzed the energy saving potential of semi-transparent PV (STPV) window made of amorphous silicon (a-silicon) at four sites in Southwest China. The energy generated at these sites was reported to be 402.1, 314.1, 233.55, and 216.5 kWh at Lhasa, Kunming, Chengdu, Guiyang sites, respectively. A home-based grid-connected roof-mounted photovoltaic system (2.992 kWp capacity made up of 22 polycrystalline modules, Fig. 21) was implemented on an area of 22 m² in China and its performance was reported by Xinfang Wu et al. [47] over a period of 3 years from 2007-2009. The authors used PVSYS software for performance analysis and reported an annual energy yield of 3,189.13 kWh at an array efficiency of 11.34%. In 2015, Li et al. [48] evaluated the perfor-

mance of 2.02 kWp off-grid PV system in Kunming and Yunnan provinces of China using PVSYS software. The system was made of 192 monocrystalline PV modules with life time of 10 yrs. Peishi et al. [49] performed the life cycle assessment (LCA) of 1 MWp on-grid ground-mounted multi-si PV modules based solar station in China. The system consisted of 4,568 modules spread over an area of 7,537.2 m² and produced 2,313.33 MWh of energy annually with a payback period of 2.3 years and lifetime of 30 years.

Huang and Yu [50] studied the energy payback time of three BIPV systems made of single crystalline, multi-crystalline, and amorphous crystalline type of panels. The results showed that these technologies had respective efficiencies of 14%, 13.2%, and 6.6% with a payback period ranging from 3.0 to 7.4 years over an expected life cycle of 30 years in China. Wang et al. [51] compared the performance (environmental and economic) of building attached (BAPV, 3 kWp, poly-si) and building-integrated (BIPV, 10 kWp, mono-si) PV systems in Shanghai, China for a life cycle of 25 years. The results (Table 2) showed an annual energy output of 3114.3 and 9890.7 kWh, average efficiencies of 10.8 and 11.2%, and an energy payback period of 4.2 and 3.1 years; respectively.



Figure 10. 3kW BIPV system in Shanghai, China [47]

In Malaysia, various PV projects were implemented under Malaysia Building Integrated Photovoltaic (MBIPV) program and their technical, economic and environmental analysis were presented. Among these, 1 kWp PV systems with an installation cost of USD 6.57/Wp and LCOE of USD 0.066/kWh were able to produce 1,100 kWh annually with an expected lifespan of 30 years, Yun et al. [52]. Such type of PV systems can help in reducing around 17.57 tons of greenhouse gases over the life span. Vigneswaran et al. [53] evaluated the cost of stand-alone PV systems consisting of three types of technologies in Malaysia by considering a peak load of 6.62 kWh and a life span of 25 years (Table 3). It is evident from the data given in Table 3 that monocrystalline technology is still the best economically with a minimum cost of 16,249 USD.

Humada et al. [54] compared two 5 kWp BIPV (c-Si and CIS, Fig. 22.) systems installed on the rooftop of the solar lab building at the National University of Malaysia. The respective annual energy yield and the efficiency from mono-crystalline silicon (c- Si) and copper-indium-diselenid (CIS) were reported to be 353.568 kWh and 10.7% and 434.512 kWh and 13.2%.

The system cost was 38,076 USD COE and payback period of 0.045 USD/kWh and 28.44 years. Farhoodnea et al. [55] assessed 3kWp PV system comprised of 25 polycrystalline PV modules installed at Universiti Kebangsaan Malaysia. The system produced 343 kWh energy with 11% efficiency and an expected lifetime of 25 years and an overall cost of 6987 USD. Khatib et al. [56] reported annual energy output of 370.48 kWh at an efficiency of 12.72% from a 5 kWp installed capacity BIPV system (multi-crystalline) in tropical climatic conditions of Malaysia.

Table 2. Summary of BAPV and BIPV systems in Shanghai, China. [51]

Type	PV-Module	Capacity (kWp)	Energy (kWh)	Efficiency (%)	Cost (USD/kW)	EPBT (yrs)	Life Time (yrs)
BAPV	Poly-si	3	3114.3	10.8	1872.5	4.2	25
BIPV	Mono-si	10	9890.7	11.2	1947.4	3.1	25

Table 3. Data related to PV projects in Malaysia [53]

Type of PV cell	Efficiency (%)		initial capital investment (RM)	
			Total net present value (USD)	Average cost (USD)
Monocrystalline	High	16.9	15,818	16,259
	Low	11.9	16,704	
Polycrystalline	High	13.5	16,375	16,451
	Low	12.1	16,532	
Thin-film	High	8.6	16,589	17,104
	Low	6.9	17,625	

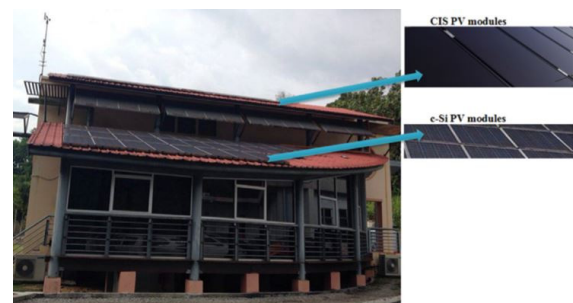


Fig. 11. Photograph of a 5kW installed capacity BIPV in Malaysia [54]

The fastest emerging industry in India is solar power with a record of 35.12 GWp installed capacity by June 2020. In 2003, the Indian government implemented a 200 kWp installed capacity PV power plant at a cost of 1.04 million USD. This plant consists of 2,620 polycrystalline modules with a system efficiency of 8.3% and produces annually 154,424.4 kWh of electricity, Vikrant et al. [57]. Agrawal and Tiwari, [58] compared the performance and life cycle costs of BIPVT and BIPV systems using different solar cell technologies in New Delhi, India. The results are summarized in Table 4, below. It is evident from the data given in Table 4 that BIPVT systems, irrespective of the cell technology, generated electricity at a lower unit price compared to BIPV. Kumar et al. [59] reported an annual energy output of 161.6 MWh at an efficiency of 13.17% from grid-connected Si-poly PV panels of 100 kWp capacity in India using PVSYS simulation tool. Padmavathi et al. [60] used measured data for evaluating a 3.0 MW capa-

city grid connected PV plant made of 13,368 monocrystalline silicon module with 13.25% efficiency and producing average annual energy of 4,116 MWh. Kumar et al. [61] presented a techno-economic analysis of a 20 kWp PV system comprised of polycrystalline modules of 14.1% efficiency for an industrial application. The capital cost of the project was USD 33,624.0 and the plant generated 30,140 kWh of energy annually at a COE of 0.20 USD/kWh over a life span of 25 yrs.

Dobaria et al. [62] evaluated a 5.05 kWp grid-tied rooftop PV system comprised of 22 polycrystalline modules with total annual energy yield of 8,261.8 kWh. A large-scale grid-connected 10 MW capacity polycrystalline PV power plant in India was reported to produce 15,798.2 MWh of energy annually with an efficiency of 14.06% Kumar and Sudhakar [63]. Shukla et al. [64] analyzed a 110 kWp grid connected plant made of c-Si/a-Si/CdTe/CSI for a hostel building in India and reported monthly energy generation of 314.2 kWh with life time of 25 years. Ahsan et al. [65] presented the performance of a 1 kWp capacity Si-polycrystalline based PV system for a small house in India. The said system was installed at a capital cost of around 1,150 USD and produced 3,102 kWh of electricity annually at a COE of 0.014 USD/kWh for an expected life of 25 years. Similar type of studies have been reported in the literature for various projects in India [66–71] and can be referred from for detail reading.

Table 4. Performance comparison of BIPVT and BIPV systems for New Delhi, India.

PV technology	Module efficiency (%)	BIPVT System			BIPV system	Plant life (years)
		Energy output (kWh)	Efficiency (%)	COE US\$/kWh	COE US\$/kWh	
c-Si	16	15,131	14.91	0.1190	0.1338	30
p-Si	14	13,141	13.19	0.1143	0.1309	30
r-Si	12	11,179	11.50	0.1189	0.1395	30
a-Si	6	6,066	7.13	0.1009	0.1260	20
CdTe	8	7,958	8.75	0.1182	0.1416	15
CIGS	10	9,578	10.13	0.2654	0.3195	5

Ketjoy et al. [72] evaluated the performance of a 10 kWp PV system under hot and humidity climate conditions of Thailand of three technologies viz., Amorphous Silicon (a-Si), Poly Crystalline Silicon (p-Si), and Hybrid Silicon (HIT) and reported average efficiencies of 5.89, 10.59, and 13.41%. Chokmaviroj et al. [73] analyzed a 500 kWp PV system which produce of 383.3 MWh energy annually at an efficiency of 13% in Thailand. Boonmee et al. [74] reported the performance of a 5 kWp system (Fig. 23) consisting of 84 amorphous PV panels in Thailand. Kannan et al. [75] evaluated a 2.7 kWp roof top mono-crystalline based PV system in Singapore and reported an annual energy output of 2,600 kWh with module efficiency of 11.86%, a payback period of 6.7 years and a life-time of 25 years.

In the Asian region, 38 BIPV related (experimental and simulation) studies are considered. Among PV technologies, polycrystalline, monocrystalline, amorphous silicon, crystalline silicon, and others (CdTe, CIS, HIT, etc.) are identified as popular ones in Asia with a number of cases of 22, 12, 8, 2, 9; respectively. The respective average system efficiencies, of the cases

reported here, are 12.53, 12.84, 7.74, 13.15, and 9.18%. However, the COE values vary from as low as 0.014 USD/kWh to 0.824 USD/kWh depending on the technology type and the size of the plants (<1.0 kW to 500 kW with an average of 28.14 kW). The payback periods varied from 2.3 to 13.8 years. Most of the studies reported the plant life between 20 and 25 years and in the extreme case 5 years only.



Figure 12. Building-integrated photovoltaic system of 4.872kW rated capacity in Thailand [74].

6.4 Australian Region

The installation of PV system has increased exponentially in an Oceania region in recent times. In 2011 Yan et al. [76] analyzed the performance of a 1.22 MWp capacity roof-mounted PV system installed at the University of Queensland (Fig. 24), Brisbane Australia. The authors reported an annual energy output of 20 MWh from polycrystalline technology-based plant. Emmanuel et al. [77] presented the techno-economic evaluation of 10 kWp rooftop PV system implemented at Maungaraki School, Wellington, New Zealand in 2014. The said system was made up of 40 monocrystalline panels at a capital investment cost of 19,600 USD and produced 910.13 kWh annually with a payback period of 6.4 yrs. Crawford et al. [78] reported the payback periods with and without heat recovery, for a 75 Wp BIPV system, as 7.5 and 16.5 years for c-si technology. However, for a-si technology, the payback was 4.3 years with heat recovery in Australia.

In this continent, hybrid power system related studies are limited with installed capacities of few tens of watts to 1.22 MW only. The PV technologies used in these reported cases were polycrystalline and monocrystalline.

6.5 European Region

The need for carbon-free atmosphere and abundance of renewable energy resulted in the implementation of BIPVs across European countries. Oliver and Jackson [79] performed a comparative analysis of the energy and related economics of rooftop BIPVs in England in 2009. The systems considered were the central PV, BIPV, and Net BIPV. The study revealed that despite of higher output performance of a central PV plant, less embodied energy was required per kWh of electricity generated by the BIPV system. This may be accounted for a significant amount of energy embodied in the balance of plant components of a central PV plant compared to a BIPV system. Additionally, there is no embodied

energy required for transmission and distribution of the electricity from a BIPV system to the point of use. Hammond et al. [80] reported annual energy output of 1,720 kWh (COE=0.348 USD/kWh) from a 2.1 kWp sized mono-crystalline BIPV roof tile system in southern England. The analyzed system had 25 years lifespan and was built at a cost of 14,972.06 USD. Erge et al. [81] studied different sizes (1, 5, 20, and 1000 kWp) of BIPVs in Germany (Fig. 25) and reported respective COE's of 0.87, 0.66, 0.56, and 0.49 USD/kWh based on the energy output of 700 kWh/kWp, 25 years of working life, and 3% interest rate without tax. These figures directly indicate the effect of scale on the COE. As the plant capacity increases, the COE also goes down.

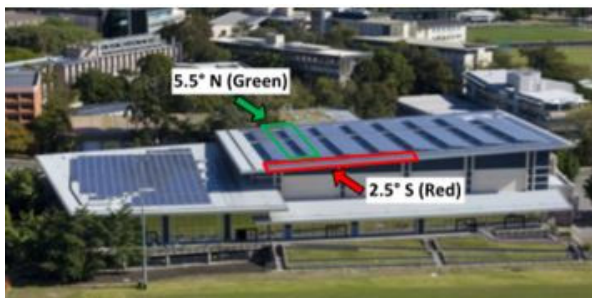


Figure 13. BIPV system of 1.22MWp installed at University of Queensland [76]

Alper et al. [82] studied a grid-connected rooftop PV system of 84.75kWp capacity (339 monocrystalline modules with 15.37% efficiency) in Turkey. The system produced 90,289 kWh/yr energy annually at a COE of 0.0808USD/kWh and a payback period of 12.52 yrs. Another rooftop multi-crystalline PV system of 2.73 kWp capacity (10.13% efficiency), spread over an area of 27 m², was reported to produce 182.83 kWh of electricity annually in Turkey, Eke and Demircan [83]. Duman and Güler [84] used HOMER to analyze 5 kWp rooftop PV system and reported a payback period of 8 years at a capital cost of 6350 USD in Turkey. Ozden et al. [85] compared the long-term performance of three PV technologies (mono crystalline Si, an amorphous Si and CdTe thin-film; Fig. 26) with respective installed capacities of 1.14, 1.26, and 1.215 kWp. The study reported the average efficiencies over a period of 44 months of these technologies as 11.86, 6.40, and 5.30% in Turkey.

In northern Greece, Bakos et al. [86] described the first BIPV system of 2.25 kWp power and presented its techno-economic analysis using RETs software. The system cost was 26,593.20 USD and it generated annually 4,000 kWh of energy. In 2013, Roumpakias et al. [87] presented the performance of 99.84 kWp rooftop PV system after six years of successful operation in central Greece. The system consisted of 416 monocrystalline panels with an efficiency of 13.3% and the generated annually 19,481.66kWh of electricity. In Europe, such studies have been reported in the literature like Mondol et al. [88] and Ayompe et al. [89] for Ireland (see Figure 18); Aste et al. [90], Malvoni et al [91], Ghiani et al. [92], Congedo [93], Micheli et al. [94], and Mellit and Pavan [95] for Italy; Cucumo [96] for Calabria; Schoen [97], Ritzen et al. [98], and Ritzen et al. [99] for Netherland; Adaramola [100] for Norway;

Dufo-lo [101] for Spain; and Milosavljević et al. [102] for Serbia.

European researchers have put great efforts in understanding the BIPV system characteristics both experimentally and theoretically. Mainly, monocrystalline technology has been used in Europe based on the present survey. The BIPV sizes ranged from less than 2 kWp to 1000 kWp with system efficiencies of 4.5 to 15.5%. Other technologies, though a few cases, used in European countries include s-si, a-si, CdTe and polycrystalline. The economy of scale has a significant effect on COE of BIPVs means as the size or capacity increases the COE decreases.



Figure 14. A grid-connected BIPV under 100,000-Roof-Solar-Programme in Germany [81]



Figure 15. Grid-connected BIPV systems (mono-silicon, monocrystalline, and CdTe) installed and tested in Anatolian, climatic conditions [85]

6.6 Middle East Region

Last but not the least, this section provides outcomes of some of the studies reported in the literature on BIPVs in the Middle East Region to abreast the readers with the present status of these systems in the region of interest for the present authors. Radhi [103] analyzed a 134.2 kWp façade-integrated photovoltaic system made of a single crystalline silicon cell in a commercial building in the United Arab Emirates (UAE) and reported an annual energy yield of 1,450 kWh at an efficiency of 15.2%. Al-Sabounchi et al. [104] presented the performance of a rooftop BIPV system consisting of 36 kWp capacity made of 180 multicrystalline modules with an expected life time of 25 yrs in Abu Dhabi Dubai. Al Otaibi et al. [105] reported the performance of 85.05 kWp and 21.6 kWp BIPVs consisting of copper indium gallium selenide (CIGS) thin-film modules (efficiency = 14%) in Kuwait (Fig. 27) with total annual energy output of 136.5 and 35.2 MWh; respectively. Ahmed [106] reported the energy output and cost performance of a 1.0MWp capacity PV plant under local climatic conditions of Kuwait for monocrystalline, polycrystalline, and two

thin-film (CdTe and CdS/CdTe) PV technologies. The respective panel efficiencies of these panels were 18.33, 16.45, 17, 13.94%. The study reported the localized cost of energy for these technologies as 0.0685, 0.0682, 0.0630, and 0.0688 USD/kWh; respectively.

In Riyadh, the capital city of Saudi Arabia, Saleh [107] reported a range of COE (0.013 to 0.053 USD/kWh) for a 6 kWp system (with 8.26 to 10.06% efficiency) consisted of 6 arrays with expected life of 25 yrs and a capital investment of 53,922 USD. Other relevant studies in Saudi Arabian context may be referred to Rehman and El-Amin [108] and Rehman et al. [109]. Ali [110] analyzed a 5.8 kW PV system and reported an efficiency of 18% and energy yield of 8311 kWh per annum in Iraqi climatic conditions. In Oman, Kazem et al. [111] analyzed the performance of a 1.4 kWp rooftop grid connected PV system with efficiency of 13% and 25 years of life time. The system costed USD 10,020, and annually produced 2625.18 kWh of energy at a COE of 0.045 USD/kWh and a payback period 11.17 years. A similar type study was reported by Albadi [112] of a 1.4 kWp polycrystalline PV panels (Efficiency 15%) in Oman in 2012.



Figure 16. Roofmounted BIPV system at Sawda School tested under harsh environmental conditions in Kuwait [105]

In that past, not much has been observed on building integrated photovoltaic and general PV systems installation and the simulation studies in this part of the world. Few studies are found in Kuwait, Oman, United Arab Emirates, Iraq, and Saudi Arabia; and are included in this section on BIPV systems. The system capacities reported in this region vary from 1.0 to 1000.0 kW with system efficiencies ranging from 13.0 to 18.0%. Mainly polycrystalline and monocrystalline technologies are found prevalent in this region with few examples of CIGS and thin film applications. The COE is observed to range from 0.013 to 0.053 USD/kWh with expected working life of 20 to 25 years.

7. CLEANING FREQUENCY ON GLOBAL AND REGIONAL BASIS

The exposure of solar PV panels to the surrounding atmosphere and local weather conditions causes deposition of air-borne particles, bird droppings, dirt, dust, pollutant, and pollens. These particles accumulate on the surface of the panels over a time if proper and periodic cleaning is not performed. With the passage of time, the PV output efficiency is negatively affected and power output decreases from 2% to 60% depending on

the environmental conditions, time of exposure, and material properties of the panels [113]. To improve the performance of these solar panels, cleaning is inevitable. Research shows that the efficiency of the panels improves from 0.81% to 4.7% when cleaned in a dry summer without rainfall throughout the year and up to 9.8% using an automated cleaning machine [113].



Figure 17. A 1.4 kW BIPV system installed on a building at Suhar University, Oman [111]

Both manual and automated techniques are used for cleaning PV panel's surface. In general, the cleaning activities account for half of operation and maintenance expenditure. Rainwater is the most popular and natural method for cleaning PV panels since the emergence of PV panel installation. During recent past, manual cleaning techniques have been developed and used. Fig. 29 shows a typical manual and robotic way of cleaning building integrated PV panels and large grid connected PV plants. These techniques require the operator to use cleaning kits to remove the sedimented particles from the surface of the panels. Some of the manual cleaning kits include multiple extension poles, brushes, carrying bags, ropes, cloth, hose connection, etc. However, with the development of new technologies, manual cleaning methods are being replaced gradually with sophisticated methods like robotics, electrostatic, and ultrasonic. A lot of research has been conducted to improve the cleaning methods from manual to automated ones.

Robot is the multi-purpose cleaning technique that can be used for cleaning both small and large PV arrays. The robotic systems are comprised of actuator, gears, drivers that move on the surface of the module for cleaning purpose. This system has a virtual operator and it cleans the panels more effectively than a manual technique. The integration of automation with robotic cleaning system reduces the interfacing of human. Different types of robotic cleaning technique exist which include water-based robotic cleaning system, waterless robotic cleaning system and automated water sprinkler systems [113]. Vasiljev et al. [114] proposed an Ultrasonic system for cleaning PV panels. This system can be called an acoustic Piezoelectric system in which water is being used for cleaning the PV surface. Around 0.1 to 1.0mm water layer is spread on the surface during the rarefaction cycle of wave compression and can penetrate tiny crevices and hard-to-reach areas by other cleaning techniques. Horenstein et al. [115], [116] presented an electrostatic self-cleaning technique based on electrodynamic screen (EDS) where a transparent surface electrode is used to remove accumulated dust from the surface of the panels. The authors observed that the energy needed for EDS cleaning would be $\leq 1.0\text{Wh}/1.0\text{m}^2/\text{cleaning cycle}$ without using water or manual operator. Furthermore, the surface of the solar

panel can be coated with a self-cleaning translucent nano-film material to prevent the deposition of dust. This nanomaterial is made of super hydrophilicity or superhydrophobic material [117], [118].



Figure 18. Manual and robotic cleaning (large PV plant) demonstration photos

The cost of cleaning solar panels is related to the location, local labor costs, the number of solar panels to be cleaned, at what height are the panels installed, condition of the panels, and ease of accessibility of the panels. According to one reporting [119], on an average solar panel cleaning may cost around 200 USD and these processes may vary from 173-225 USD. A homeowner may end up paying as low as 91 USD and as high as 400 USD for panel cleaning depending on the locality, height, and accessibility [119]. Usually, solar panels can be cleaned for just around 200 USD, depending on the area to be cleaned. However, it is advisable that one should opt cleaning quotation based on per unit cleaning. According to sources [120], per panel cleaning fee may be somewhere around 5.0 to 20.0 USD. Table 5 summarizes approximate prevailing costs of cleaning depending on the number of PV panels and the duration of cleaning.

Table 5. Cost of PV panels cleaning [120].

Number of panels to be cleaned	Duration (Minutes)	Cost (USD)
<20 panels on the ground	10-30	67-110
<40 panels on the ground	10-30	80-130
<20 panels one floor	20-40	130-200
<40 panels one floor	60-90	~200
>40 panels	60-120	200-400

8. CONCLUSIONS AND RECOMMENDATIONS

An overview of BIPV related studies and installed capacities of application and technology types exhibits a long-term, comprehensive, and enriched experience both in terms of expertise and infrastructure. The applications range from pole lights to multi-megawatt sized grid-connected power plants in Saudi Arabia. This experience will be very useful in implementing the building-integrated photovoltaic systems in varied and harsh climatic conditions of Saudi Arabia. Having said that, the knowledge base developed in this review paper will be very useful for the Kingdom and the region in different ways as summarized below:

- Globally, as observed from the literature, monocrystalline is the most commonly used technology for building integrated PV systems of all sizes and the next popularly used technology is reported to be polycrystalline. The rest of the technologies, which are scantily used in this perspective, include c-si, a-si, CdTe, CIG, CIGS, and HIT.
- BIPVs are most common in Asia in the first place, Europe the next region with a large number of these

applications, and African countries fall at number three. Other regions have reported fewer applications and studied BIPV systems.

- The prevalent BIPV application sizes are around 2.0kW in America, 2 to 220kW in African countries, 9.0 to 13.0kW in Asian countries, few watts to more than 1.0MW in Australia, 2.0 to 1000.0kW in Europe, and 1.0 to 1000.0kW in the Middle East region.
- In general, the average system efficiencies are reported to be 5.0 to 18.0% depending on the climatic conditions of the region.
- The cost of energy is found to vary from 0.013 to 0.824 USD/kWh depending on the plant size and the climatic zone.
- A few studies have reported the payback periods between 4 and 15 years on an average gain based on the size of the plant and the location.
- Almost all the studies have assumed the life of the plant as 20 to 25 years with few extremes having reported 5 and 30 years.
- Last but not the least, all of the systems reviewed and reported in this paper are fixed oriented systems.

The present study recommends and encourages the end users to build BIPV systems for single independent houses of 2.0 to 5.0kW installed capacities using either monocrystalline or polycrystalline technologies. Multi-storied buildings with apartments can also opt for around 100kW sized BIPV systems using the above technologies with fixed configuration. With regard to cleaning of the panels, it is suggested that the owner itself can easily clean panels mounted on flat roofs, if possible. If not, then it can be subcontracted to some local cleaning company at a moderate price of 50 to 70USD per hour for installed capacities of less than 20 panels.

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NOMENCLATURE

a-(Si/Ic)	Amorphous/microcrystalline silicon thin films
°C	Celsius
BAPV	Building Attached PV systems
BIPV	Building Integrated PV systems
BIPVT	Building Integrated PV systems Thermal
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Indium Disulphide
COE	Cost of Energy
CO ₂	Carbon dioxide
DC	Direct current
EDS	Electrodynamic screen
EPBT	Energy payback period
GW	Gigawatts
GWh	Gigawatts hour
HIT	Heterojunction with Intrinsic thin layer

HVAC	Heating Ventilation and Air Conditioning
kW	kilowatts
kWh	kilowatts hour
LCA	Life cycle assessment
LCOE	levelized cost of energy
mono-Si	Monocrystalline Silicon
multi-Si	Multi silicon
MW	Megawatts
MWh	Megawatts hour
MWp	Megawatts peak
pc-Si	Polycrystalline
PV	Photovoltaic
PVSYST	Photovoltaic System
STPV	Semi-transparent

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СВЕОБУХВАТНИ ГЛОБАЛНИ ПРЕГЛЕД СОЛАРНОГ ЕНЕРГЕТСКОГ СИСТЕМА ИНТЕГРИСАНОГ У ЗГРАДУ

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Саудијска Арабија је започела диверзификацију постојећег енергетског портфеља путем обновљивих извора претежно соларне фотонапонске и топлотне енергије, као и енергије ветра. Даје се преглед области у свету према коришћењу соларних фотонапонских апликација интегрисаних у зграду и препоруке одговарајућих и погодних опција за примену у Саудијској Арабији и региону Блиског Истока. Са оваквим циљем електроенергетски систем остварује троструку корист: 1. чисту и економичну стабилност напајања за станове који се налазе изван мреже, 2. редуkcију емисије гасова стаклене баште, 3. конзервисање одређених резерви фосилних горива која се у целом свету највише користе за производњу енергије. Истраживање је показало да се фотонапонске апликације најчешће користе у Азији и Европи. Такође је потврђено да су монокристални и поликристални фотонапонски материјали како економски тако и технолошки најпогоднији за овакве апликације.