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Reducing the Effects of Climate Change Using Building-Integrated and Building-Applied Photovoltaics in the Power Supply

Springer

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World Renewable Energy Congress & Network (WREC/WREN)
Brighton, UK

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Introduction

The main aim of this book is to showcase the highly successful application of photovoltaic technology (PV) in the built environment to produce electricity. This success is noteworthy given the existential crisis the planet faces through untrammelled climate change. At the end of 2021, PV global capacity reached 940 GW, at the end of 2022 it had reached 1100 GW, and at the end of 2023 it is predicted to reach 1456 GW. Thus, at the end of 2022 record levels of installations have been reached in China, 392.61 GW; in Germany 66.5 GW; USA 142.3 GW; UK 14.3 GW.

Nowadays there is no country in the word without some PV installation. This is due to the much-reduced installation costs and free sunshine. The EU countries are proposing to make the use of PV mandatory in all new buildings which will be built after 2025. The French Senate in April 2023 approved legislation that makes it mandatory for all existing and new car parks with 80 spaces or more to be covered by PV panels.

Great technological advances have been made in every aspect of PV applications in buildings. For example, one Chinese company is producing PV panels of 315 Watts weighing 11 kg by reducing glass cover thickness to 1.6 mm. Helmholtz-Zentrum Berlin (HZB) technology in Berlin developed a Tandem Cell consisting of Crystalline Silicone topped a Perovskite cell, giving 32.5% efficiency, whilst battery storage systems utilizing lithium – iron and phosphate now have a recycling efficiency of 98% after 15 years of operation. More recently, PV farms are no longer confined to land installations but are now applied on floating lakes, rivers, and shallow seashore. For example, German BayWa r.e. AG have built a 3 MW floating photovoltaic (FPV) system for Quarzwerke GmbH in Haltern am See. North Rhine-Westphalia; a floating farm to date by Sirindhorn Dam near Bangkok supplies electricity – 60 GWh per year and is the largest global floating farm. In 2020, global floating PV had reached 1.3 GW.

In this book, we consider PV is considered an essential part of building materials. Fourteen different countries and at different regions have been selected and investigated for the use of PV to generate power, namely: Brazil, the Netherlands, Austria, Poland, Argentina, Iran, Germany, Malaysia, Oman, Bahrain, India, Australia, United Kingdom, and Egypt.

It is predicted that by 2030, 40% of global electricity will be generated by PV, a figure which two decades ago would have been considered a dream. It is fully recommended now adays that all architects and builders should acquirerd themselves with the basic use of PV in buildings.

March 2023 Ali Sayigh

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Photovoltaics and the Built Environment in Brazil

Antonia Sônia A. C. Diniz, Joyce Correna Carlo, Suellen C. S. Costa, and L. L. Kazmerski

1 Introduction and Background

Brazil has a diverse electricity-generation matrix. Through November 2022, the installed capacity was ~190 GW, divided among 9000 power plants [1–4]. Brazil's electricity supply is based mainly upon renewable-energy resources. For decades, hydropower has been the main source of electrical power and through 2021 represented about 62% of total capacity [2]. Wind (12.5%) and bioenergy (7.2%) accounted for the next largest renewable energy contributions [1, 4]. At the end of 2021, installed photovoltaics (PV) exceeded 13 GW [5, 6]—and the growth in Brazil's cumulative PV is presented in Fig. 1. Though the 2021 PV capacity was only at 7.7% on the electrical power generation in the country (about 18-TWh in terms of the electricity generation), solar-PV electricity is the fastest growing of the renewable sources. Brazil stands as the 11th largest producer of solar electricity in the world [6]. In 2021, Brazil added 5.7 GW of PV to its electric-power system, ranking fifth in the world in installations that year and has been identified as among the top-10 emerging PV world markets [6]. The incredible growth of Brazil's solar PV is certainly indicated by the announcement that PV now surpassed the electric-power capacity of wind at the end of 2022 [1]. The Ministério de Minas Energia, Empresa de Pesquisa Energética—MME/EPE—"Brazil 2031 Ten-Year Energy

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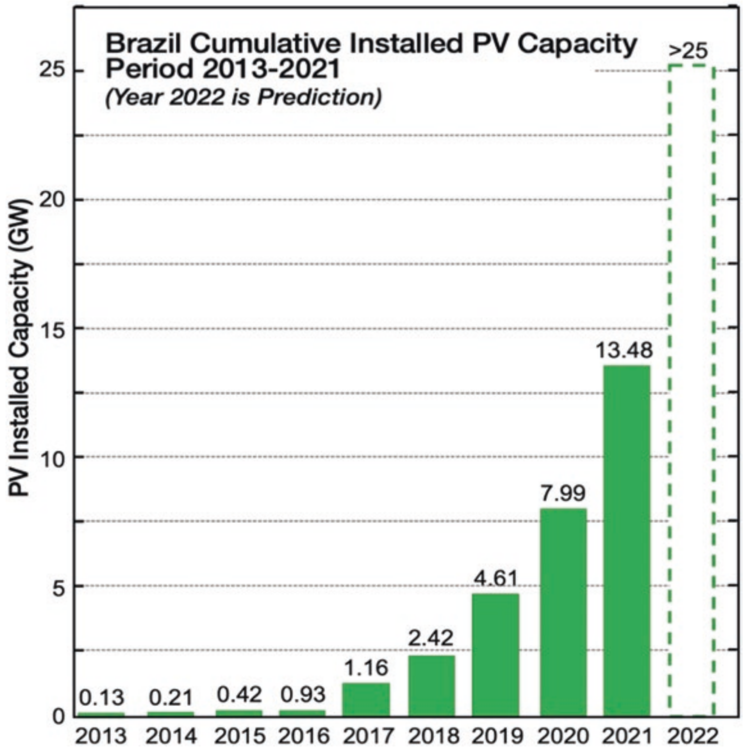

Fig. 1 Brazil's cumulative installed PV capacity over past decade. Brazil is on track to add 12 GW in 2022, leading to an installed capacity exceeding 25 GW. These data follow publications of Brazil's *Associação Brasileira de Energia Solar* (ABENS)l (http://www.abens.org.br). Brazil now is predicted to reach 54 GW by 2026

Expansion Plan" targets solar PV to exceed 67 TWh from distributed and centralized sources [7, 8]. It should be also expected that these targets will grow with the new government administration starting in 2023 and the mounting concerns for the environment and global climate change [8–10]. In general, PV will hold a significant portion of Brazil's energy sectors with contributions ranging from its current sizeable electric-power focus to expanding transportation and building segments that have vast potential [3, 4].

This chapter focuses on one sector of Brazil's growing investments in PV, that of the built environment. It is an area worldwide that PV has not yet played a substantial role, but the needs, state of development, and suitability of "buildings" make it a prime focus for growing investments to bring about a 100% renewable-electricity portfolio by mid-century [9, 10]. In particular, the dominance of hydropower in the Brazil electricity framework has highlighted some vulnerabilities. The onset of droughts has had effects on the operations of the hydro plant—leading to interruptions and equipment issues. The need for adequate power demand response opens the electricity suppliers to potentially rely more on fossil-fuel generation, building dependencies on non-renewable resources at the time the world is moving to combat climate change. This chapter highlights the evolution and recent growth of PV installations in Brazil and the potential for significant growth in the buildings sector. Certainly, the incredible decrease in PV module and system prices over the past decade makes this electricity source attractive for applications not thought to be competitive, such as air conditioning, cooking, hot water delivery, and even heating [11]. This new PV attention is also augmented by favorable policy and regulations, local meteorological and climate conditions, and economic and social considerations. The specific effects of government strategies are discussed, such as the Normative Resolution n° 482 published in 2012 by Brazilian Electricity Regulatory Agency (ANEEL) that regulated the net metering of photovoltaic and other renewable energy technologies classified as micro (≤75 kW) and mini (>75 kW and ≤ 1 MW) distributed generation (DG), the electricity auctions (started in 2014), and also the Incentive Program for Distributed Micro-Mini Generation [8]. The benefits of available commercial technology products are described and evaluated. Importantly, PV's growing impact and potential in the building sector is analyzed. The status, relative benefits, and trends of building-integrated and building-applied PV (BIPV and BAPV) are evaluated. Rooftop versus micro- and mini-grids are assessed for various social and building conditions—with some considerations of constraints for such PV systems in the Brazil Equatorial locations and various climate conditions. The effects of these aspects are compared with building applications and investments in other countries [11]. The potential and future for PV in the Brazil built-environment markets are considered and forecast. Special insight is also directed toward the coupling of innovation in the PV technologies and their special position in elevating the architectural and economic value and acceptance of solar PV in the buildings sector. Insights and projections for PV in the Brazil built environment are discussed relevant to worldwide prospects.

2 Brazil's Regulations and Policies

Often, the dominating considerations for PV deployment and innovations are the *technical* aspects. Certainly, component materials suitability/availability, device performance, reliability, and operating lifetime are essential to the viability of any electricity source. But of equal importance to the wide-ranging deployments are the policies and regulations that control and can incentivize and accelerate the adoption and use of energy resources. Table 1 summarizes some important regulations, laws, and policies that affected the adoption of PV in Brazil's electricity distributed-generation (DG) structure, including its built environment. A selection of these laws, programs, and regulations is discussed in this section in terms of their effects on the adoption of PV deployment and benefits to the buildings' markets.

During 2000–2020, Brazil's hydroelectric plants experienced a series of problems. Due to several long draught periods and a continuous increase in the demand for electricity, in 2002 this primary electricity source was forced to curtail services,

Table 1 Summary of selected laws and regulations that address DG and PV implementation in the Brazil electricity sector discussed in Sects. 2 and 6

Year	Law/Regulation/Policy	Ref.	Comments
2000/ (2016)	Law no. 9991/(law no. 13.280, amendment)	[19, 20]	Established that 1% of the annual net profit of the concessionaries and permissionaries be applied to R&D and energy-efficiency projects
2003	MME: Luz para Todos	[21, 22]	Implements electricity "universalization" in rural areas, where >80% of the people live without electricity. Includes: (1) extension of the distribution grid, (2) autonomous off-grid, isolated electricity generation using micro-grids, and (3) individual (stand-alone) electricity systems
2004	ANEEL resolution 012/2004	[22]	Provides for the use of individual decentralized energy systems, including PV systems in homes: Includes mini- and micro-hydro power plants, biomass, thermal, PV, wind energy, and hybrids
2004	Brazil law 10,848/2004	[15]	To increase the country's energy security, to promote diversification of the national electrical mix, to promote energy efficiency measures, and to foster universal access to electricity
2004	CEPEL led: Brazil-US program of assistance for rural development in Brazil	[23, 24]	Evaluated the feasibility of different PV technologies in Ceará, Pernambuco, and Minas Gerais (CEPEL and U.S. DOE)
	PRODEEM: Energy program for small communities (includes*:* *Luz Solar* & *luz no saber (*Minas Gerais)	[25]	Provided objective for electricity to 90% of all rural households by 2008
2020	Decree no. 93570	[25, 26]	Extended electricity universalization target to 2022
2011	ANEEL strategic call for R&D no. 13	[23]	Supported technical and commercial arrangements for solar-PV generation, aimed at integrating PV in the Brazilian electrical power matrix. This call mobilized partnership between universities and 17 electric utilities
2012	ANEEL normative 482/2012	[27]	Introduced: (1) net metering compensation scheme for micro- (≤75 kW) and mini- (>75 kW and ≤ 1 MW) DG and qualified co-generation from renewable sources (solar); (2) electricity auctions (started in 2014); and (3) the incentive program for DG
2015	ANEEL resolution 687/2015	[29]	Changes to norm. 482/2012: (1) improved registration process for new PV-DG systems; (2) electricity credits validation expanded from 36 months to 60 months; and (3) A new power range for micro-generation (up to 75 kW) and mini-generation (above 75 kW and below 5 MW). But complicated solar PV in poor urban areas

(continued)

Table 1 (continued)

Year	Law/Regulation/Policy	Ref.	Comments
2017	ANEEL resolution 786/2017	[22, 23]	(1) installed power limit for microgeneration from water sources increased; (2) projects previously classified as commercial or utility committed, no longer classified as DG
2022	Brazil law no 14,300	[82]	Facilitated formation of cooperatives mandated distributors/developers to invest in low-income areas (e.g., favelas)

and customers were subject to strict electricity rationing measures [12, 13]. Additionally, social and environmental concerns limited the building of more hydroelectric dams [14]. To mitigate this serious problem, Brazil's electric-power sector was reformed through Brazil Law 10,848/2004 [15] in 2004 to increase the country's energy security, to promote the diversification of the national electrical matrix, to advocate energy efficiency measures, and to foster universal access to electricity. This legal framework also created the energy auctions, one of the primary policy instruments for diversifying its energy sector and increasing Brazil's renewable-power supply [16, 17].

The Brazil National Energy Efficiency Program has been very important for the research and development of renewable technologies [18]. ANEEL Law No. 9991 (July 2000) [19] and amending Law No. 13,280 (May 2016) [20] established that 1% of the annual net profit of the utilities, *concessionaries* (electric companies that only provide distribution), and *permissionaries* (locally owned concessionaries) must be applied to R&D and energy efficiency projects and related government funds (e.g., energy research fund, called CT-ENERG). Solar-thermal water heating has been strongly supported by the energy-efficiency program as a demand-side management technology to reduce the peak-hour demand (caused by electrical showers). Most concessionaries mandated that electrically heated showers be replaced by solar collector systems. The requirement to invest in R&D projects also provided wider support for solar thermal electrical generation, PV grid connections—and investments in solar buildings, including improved materials, insulation, and smart windows.

In 2003, Brazil's federal government (Ministry of Mines and Energy-MME) established the prominent National Program of Electric Energy Universalization for All (*Programa Luz para Todos*–Light for All Program) [21]. It implements electricity universalization in rural areas, where at that time, around 80% of the people lived without electricity. The objective is to benefit the rural isolated communities that have no access to electricity from the utility. One main feature is to ensure that low-income families would not be charged to grid extension costs [21]. Most of those benefiting from this program live long distances from the existing electricity-grid. The program prioritizes houses of low-income families, rural schools, "quilombolas"—the indigenous people, settlements, riverside dwellers, small farmers, families in extractive reserves affected by undertakings in the electricity sector, rural schools, and community water wells. Based on several successful renewable-energy projects, the *Luz para Todos* program set up 3 alternatives for electricity supplies to rural areas: (1) Extension of the distribution grid to rural homes, (2) Autonomous off-grid electricity generation (isolated) using micro-grid to rural villages, and (3) Individual (stand-alone) electricity supplies.

The Brazilian electric-energy regulation agency (ANEEL) introduced its first resolution (Res. 012/2004) to provide for the use of individual decentralized-energy systems, including PV home systems (stand-alone) [22] This framework supports technologies such as mini- and micro-hydro power plants, biomass, thermal, PV, and wind energy. Hybrid systems that encompass two or more of these technologies are included. The relative competitiveness of the different technologies for a rural-electricity supply depends on the local climatic and geographic conditions, as well as the electricity consumption density (defined as kWh/km^2/month) of the area to be supplied. In general, the average price for electricity increases with declining consumption and length of the distribution grid. Among the autonomous, off-grid technologies, PV has been used in both hybrid stand-alone and micro-grid systems [21, 22].

Luz para Todos was the first official government program that specifically addressed PV in buildings. However, before its enactment, several other programs evaluated solar technology feasibility. The earlier pioneering experimental "Program of Assistance for Rural Development in Brazil" evaluated the feasibility of different PV technologies in Ceará, Pernambuco, and Minas Gerais, led by CEPEL (Electricity Research Centre) in Brazil and the U.S. Department of Energy (USDOE) with its National Renewable Energy Laboratory (NREL) [23, 24].

PRODEEM's "Energy Program for Small Communities" (Programa de Desenvolvimento Energético de Estados e Municipios), and various State programs such as *Luz Solar* (home electrification) and *Luz no Saber* (electrification of schools) in Minas [25] were specifically beneficial to building's solar-energy use. A typical rural household and rural PV-electrified school through the *Luz Solar* and the *Luz no Saber* programs are shown in Fig. 2a, b, respectively. These programs were

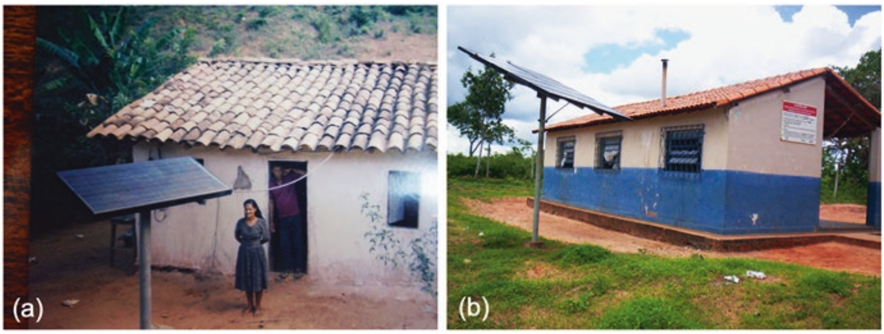

Fig. 2 Typical PV-electrified buildings through the (**a**) *Luz Solar* (single-family rural household); and (**b**) *Luz no Saber* programs (school). The PV was in these cases was not applied on the room in order to ensure security, structural integrity, and safety. Some homes did also have the PV systems roof-mounted if these three criteria were satisfied

established to provide electricity to 90% of all rural households by 2008. But the target date had to be extended by ANEEL Decree No. 93570 through 2022 because 300-thousand low-income rural families (especially in the North and Northeast) remained without electricity [25, 26].

Financing for renewable energy programs has been a barrier to solar deployment throughout the world. Several Brazil financing mechanisms for rural electrification have been enacted or extended from previous laws or initiatives under *Luz para Todos* [27]. Sectoral funds are available as grants from the Energy Development Account (CEE, Conta de Desenvovimento Energético), or as soft loans as part of the Global Reversion Reserve (RGR, Reserva Global de Reversão) [28] for concessionaries. Through 2021, 13-million households and more than 3-million consumer units located in rural regions in Brazil were served (again primarily in the North and Northeast) by the *Luz para Todos*. More than 6-thousand are PV stand-alone and 19 are PV mini-grid systems. Figure 3 shows one-representative household that was part of *Luz para Todos* [27].

The tipping point for grid-connected PV systems occurred in 2011 with the ANEEL "Strategic Call for R&D no. 13." This "Call" supported technical and commercial arrangements for solar-PV generation, aimed at integrating PV in the Brazilian electrical power matrix. The "Call" mobilized partnerships between universities and 17 electric utilities. These strategic projects analyzed the suitability of PV technologies for Brazil's electricity market, possible impacts on the electric-power system, and studies of the most suitable locations for the installation of solar plants considering solar irradiance levels [27]. In 2012, the Normative 482/2012 published by ANEEL was approved [27]. It introduced (1) the net metering scheme (compensation) in the country for micro- (≤75 kW) and mini- (>75 kW and ≤ 1 MW) distributed generation (DG) and qualified co-generation from renewable sources. It allowed the renewable energy system owner to feed excess PV electricity into the electrical grid and obtain energy credits (measured in kWh, non-monetary) that can be used during a 36-month period (2), Electricity auctions (started in 2014), and (3) the Incentive Program for Distributed Micro−/Mini Generation [41, 42]. This resolution was considered a noteworthy regulation mark for distributed generation of solar PV energy in Brazil [27].

Fig. 3 Example of PV household installation as part of *Luz para Todos* for home without access to electricity

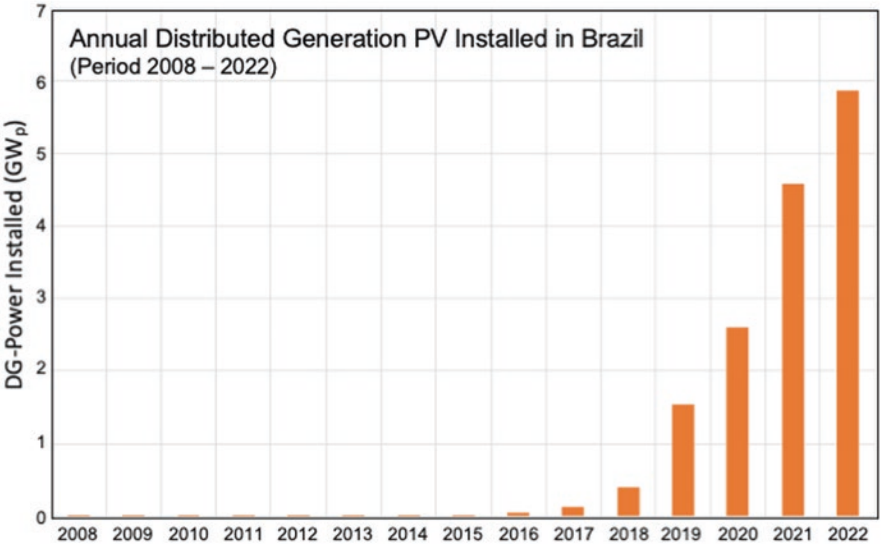

Fig. 4 Annual Distributed Generation (DG) PV-growth in Brazil as a function of time for the period 2007 to 2022

In 2015, a revision to ANEEL Normative 482/2012 led to resolution 687/2015. It enabled new PV-related businesses and promoted more flexibility for prosumers 29]. The main additions were: (1) Registration of new PV-DG systems was shortened from 82 days to 34 days, with the beneficial result of a more rapid approval process**;** (2) Electricity credit valid periods expanded from 36 months to 60 months (allowing more time for the consumer to use the credits); and (3) A new power range for micro-generation (up to 75 kW) and mini-generation (above 75 kW and below 5 MW) were defined (ANEEL, 2015) [29]. These changes in Brazilian net metering brought by Resolution 687/2015 were very beneficial to DG, responsible for the exponential growth of DG staring in 2014 (Fig. 4).

These policies, laws, and regulations, summarized in Table 1, evolved over the past two decades. In recent years, the laws have become more favorable to renewables and to PV in the built environment. Policy is critical to accelerating the use and acceptance of PV, whether as a plant or as a DG-electricity source on a residence connected to the grid.

3 Climate Conditions and Solar Resources

Climate is important for designing and use in the built environment. It not only affects the buildings' human comfort concerns, but for PV applications, it can significantly affect the power and related financial investments required. Brazil is the fifth largest country by area in the world, covering some 8.5 M km^2. As such, it has

Table 2 Climatic zones according to Köppen-Geiger and latitudes of occurrence [31]

Climate Zone	Latitude	
	North	South
Equatorial or tropical (A)	0° and 25°	0° and 25°
Arid and semi-arid (B)	30°	30°
Subtropical (C)	30° and 60°	30° and 60°
Snow (D)	60–70°	–
Polar (E)	70°	70°

a diversity of climatic zones due to its extensive territory, different landforms, and geographic location. Climate zones are defined by location, owing to the 1931-pioneering Köppen publication [30] that identified different "zones" according to latitude, as shown in Table 2. In this section, a high-level description of the climate diversity may complicate building design and PV incorporation in Brazil.

Brazil is predominately located between the Equator and the Tropic of Capricorn. Hot and humid conditions prevail throughout the territory, with higher temperatures close to the Equator as a result of the more intense solar irradiation received in this region. The Köppen-Geiger model shown in Fig. 5 divides Brazil into three climate groups, A, B, and C, which characterize equatorial climate (blue), semi-arid climate (orange/red), and warm temperate climate (green) [31]. These climate zones are further divided into subgroups according to precipitation rates and air temperature. All parameters are important for PV building requirements.

Figure 6 shows the typical weather-related conditions with the average temperature for the coldest month of the year, July, and the distribution of the annual average temperature [32]. Figure 7 presents the accumulated precipitation data for the month of July, the winter season in the southern hemisphere, and for the month of January, the summer season.

The comparisons of Figs. 6 and 7 show that even in the coldest month of the year, the North, part of the Midwest, Northeast, and Southeast regions have average temperatures above 18 °C. And in none of the months of the year, temperatures are less than this value. These climate characteristics of the regions include them in the large Group A, according to the climatic methodology of Köppen-Geiger [31]. The Group A zone is the largest geographical area, accounting for approximately 81% of the Brazilian territory. The main reason for climate group A to dominate the country climate is the lack of limiting factors of altitude, rainfall, and higher temperature in these areas [33]. Among the subgroups, the Aw climate zone is the most representative of the country, accounting for approximately 26% [33].

Part of the Northeast region is included in climate Group B, due to higher temperatures and low precipitation, indicating higher potential for droughts in the summer and winter periods. The climatic zone of Group B presents an annual average temperature greater than 22 °C and the annual accumulated precipitation can reach values lower than 800 mm. This group spread through the states of Bahia, Sergipe, Alagoas, Pernambuco, Ceará, Piauí, the coast of Rio Grande do Norte, and a small part of the territory of Paraiba.

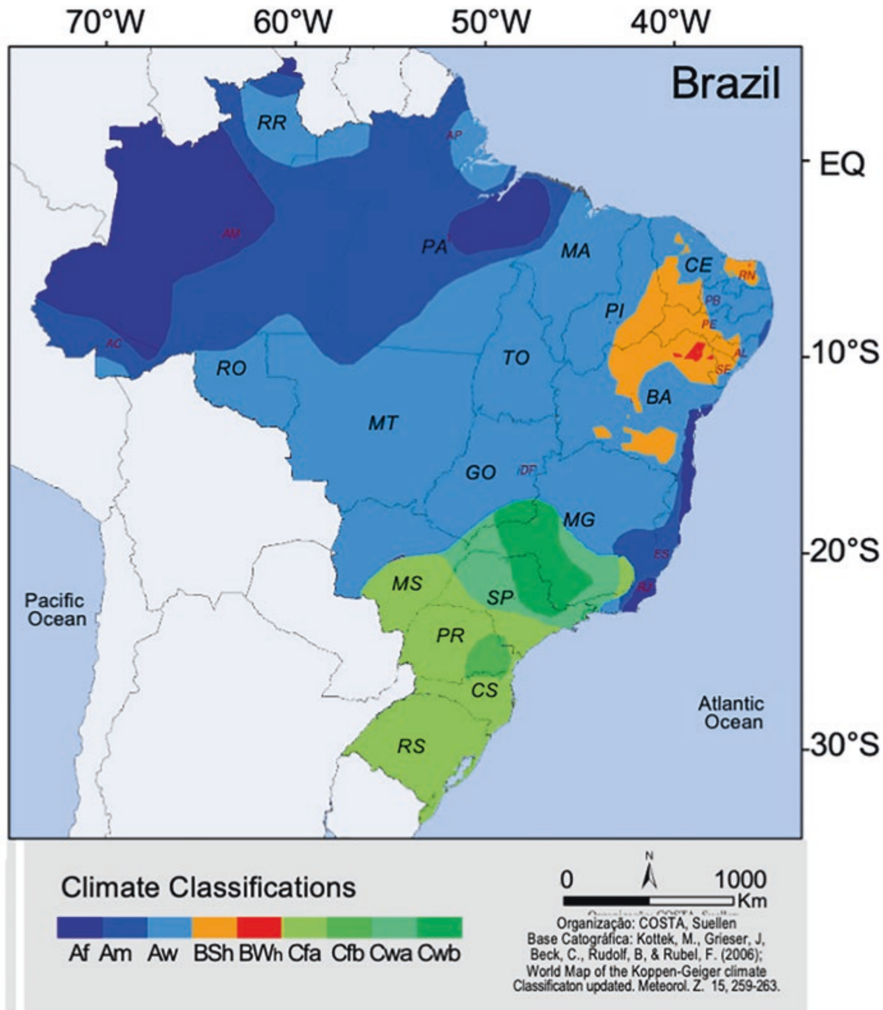

Fig. 5 Köppen-Geiger climate classification for Brazil [31]

The South region and a small extension of the Southeast region of Brazil have average temperatures below 18 °C for the coldest month of the year and are classified in climate Group C. Group C covers ~13% of Brazil's territory. This is mainly in the southern regions of the country, typified by plateaus and mountains.

In summary, climate Groups A and B are distinguished by average annual temperature above 25 °C. Precipitation rates above 3000-mm represent sub-climates Af, Am, Cfa, and Cfb. Annual precipitation is higher in the north of the country, with rainfall and temperatures decreasing toward the south. Certainly, meteorological variables of temperature and solar and the regions in the semi-arid climate zone (B) have the highest levels of solar irradiance (above 2250 kWh/m^2), followed by

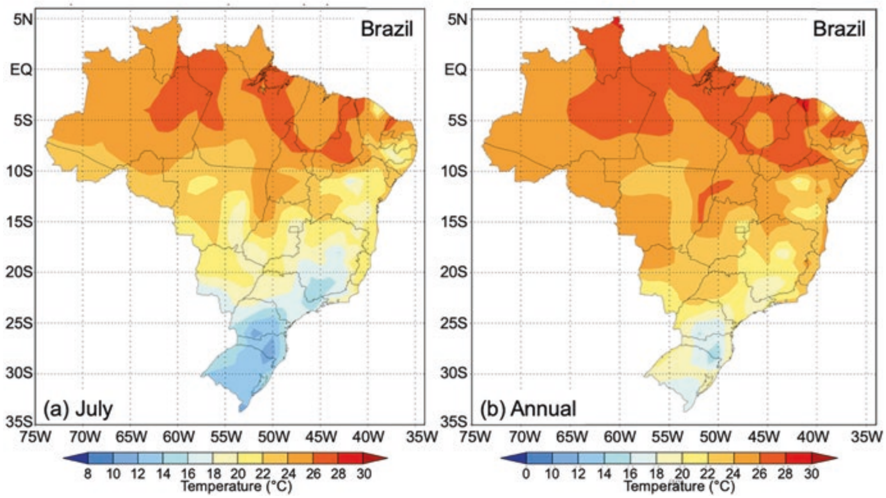

Fig. 6 Average temperatures for Brazil: (**a**) Average monthly temperature for the month of July (winter), and (**b**) Average annual temperature [32]

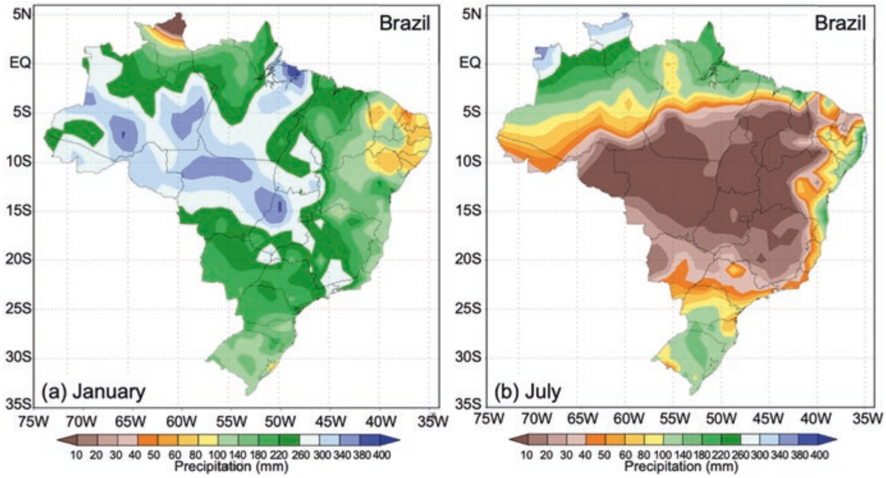

Fig. 7 Accumulated precipitation: (**a**) Month of January (Summer – rainy), and (**b**) July (Winter – dry) [32]

the Equatorial zone (A) with annual irradiance levels between 1750 and 2250 kWh/m^2 [34, 35]. The solar resource and corresponding PV-power maps of Fig. 8 certainly reinforce the fact that PV is an excellent electricity choice throughout Brazil.

As for the higher suitability of photovoltaic technology, the Northeast, the Southeast, and the Midwest regions are currently the primary areas for installations—despite higher temperatures that occur in some areas. Coastal areas in the South can have issues with humidity and clouds, which lower the PV

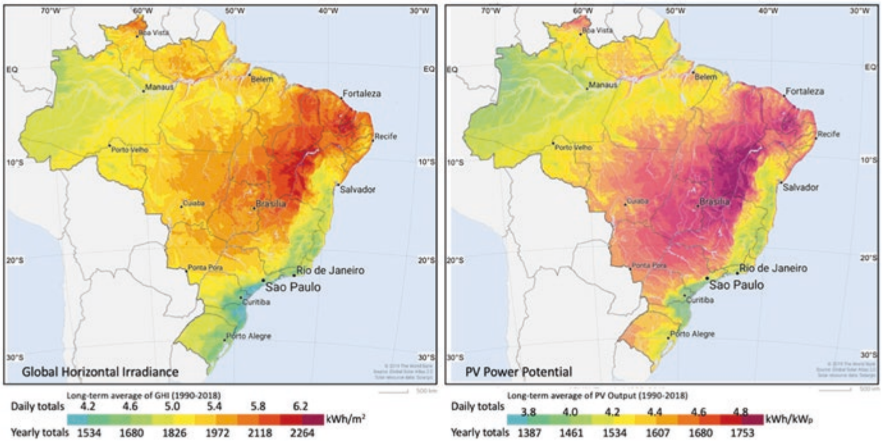

Fig. 8 Global horizontal irradiation (left) and photovoltaic power potential (right) for Brazil [34]

potential—though PV can still be a significant contributor to electricity generation. However, the major urban population centers provide viable solar resource locations for PV for the built environment.

4 PV and the Built Environment in Brazil: Applications and Relationships to Climate

"PV in the built environment" encompasses many facets for effective and cost-competitive utilizations. Urban areas are much different and more complex than suburban or rural localities. High-rise buildings impose different constraints than low-profile constructions such as single-family dwellings. Businesses usually have different energy and time-of-day requirements than family apartments or houses. Financial or income levels can impose limitations for solar adoption across the board. Consumer knowledge and understanding can be critical for confidence building and buy-in of new technology. And very important, the price and architectural value of PV in the built environment can be a tipping point for significant change to take place. *Most important* is that building-PV has to be coupled with building ***energy efficiency***. Energy efficiency is the most desirable, lowest cost, and biggest impact area in lowering the building's energy consumption, related costs, and human comfort. And mandating building efficiency with PV use can exploit some aspects of PV technology beneficial for building energy conservation—as well as lowering the levels of building electricity needs for this somewhat capital-intensive technology component.

General Discussion of Building Considerations

Many aspects of building types, structure, design, use, and location are important for the effective use of PV for building electricity requirements. Of course, the climate and solar resource parameters have to be considered for system sizing as well as technology suitability. The considerations include the details of the surrounding structures that might limit the availability of solar irradiance. In this section, urban (most times high-density, high-rise types) and suburban/rural (lower density, lower profile) sectors are analyzed and discussed for PV suitability.

Shadowing caused by the high-density and high-rise buildings in urban centers is troublesome and a major obstacle to exploiting photovoltaics in cities. Constraints include the building shape and orientation that are critical for incorporation and electricity generation of the PV. Urban laws engender verticalization and densification in central areas. These areas attract businesses with greater ability to invest in PV power compared with private residents in apartments or condominiums. A problem is the verticalization of the city centers leading to small roof area and large façades. For dense building areas, such factors limit solar access and are not generally compatible for substantial or even adequate PV electricity generation.

In low-latitude countries like Brazil, the roof offers the greatest potential for harnessing solar energy [36]. Large roof surface buildings are generally low, podium-shaped buildings which, ironically, are more subject to shading from their surroundings. High-rise, tower-shaped buildings usually have vast façades but receive little solar radiation compared to low-rise building roofs. Both the commercial and residential sectors display examples of both building types. In the residential sector, these tower and podium typologies are more often discussed in terms of single-family and multi-family buildings, representing 88% and 11% of all homes in the country, respectively.

The Brazilian climate displays favorable conditions for adopting ecosystem services like solar energy and natural ventilation. Although the ubiquity of air conditioners has increased in recent decades, natural ventilation is still dominant in residences, used at the very least in hybrid mode with air-conditioning. Since natural ventilation depends on window operation, photovoltaic systems on façades are constrained to the available area available on façades. Roofs generally do not face these problems as zenithal openings are rare. And for Equatorial regions, flat roofs come with benefits for support, installation, orientation, and cost.

In the Brazil urban landscape, there are three major constraints to adopting photovoltaics: (1) The density of urban buildings provides severe shadowing over considerable buildings areas; (2) the most suitable, limited-shadow area for photovoltaic installations is usually on their roofs with the façades providing low solar irradiance for any PV; and (3) the even desirable roof area available for PV modules is frequently limited by other architectural elements such as ventilation, protection and safety components, and air conditioning and handling. These factors are considered in the analysis and discussion in the following sections to evaluate potential obstacles to adopting photovoltaic systems specifically in Brazilian residential and commercial buildings. *(ASIDE: Certainly, capital price is always an issue for the consumer, but PV prices have fallen to competitive levels in most regions of the world making PV the least expensive of the renewable-electricity technologies and lower than most non-renewable power-production choices.)*

Characterization of Building Electricity Consumption

Commercial and public buildings consume the most electricity in the building sector and are expected to account for 70% of the final energy consumption of all buildings by 2031 [37]. In contrast, the Brazil residential energy sector shares a sizeable portion of its use with natural gas for cooking and solar thermal or natural gas for water heating.

It is projected that the increase in the number of residential consumer units in Brazil will be 16% from 2021 to 2031, with an 18% increase in the average consumption for each residence [38]. This combination results in a 30–49% increase in electricity consumption depending on the scenario, with an average annual growth of 3.3%. With the projected annual increase of 0.5% in the population of Brazil [37], an improvement in the living standards is anticipated based on related experience in residential electricity use. A more significant increase is projected in the commercial sector, with the electricity consumption ranging from 40% to 63% and an annual average of 4.3% increase over the decade due to the economic consequences of COVID-19 [38].

Air-conditioned commercial and public buildings have electricity patterns closely coupled with the local climate as expected. An example is presented in Fig. 9 for corporate high-rise buildings ("towers") at various locations in Brazil. The

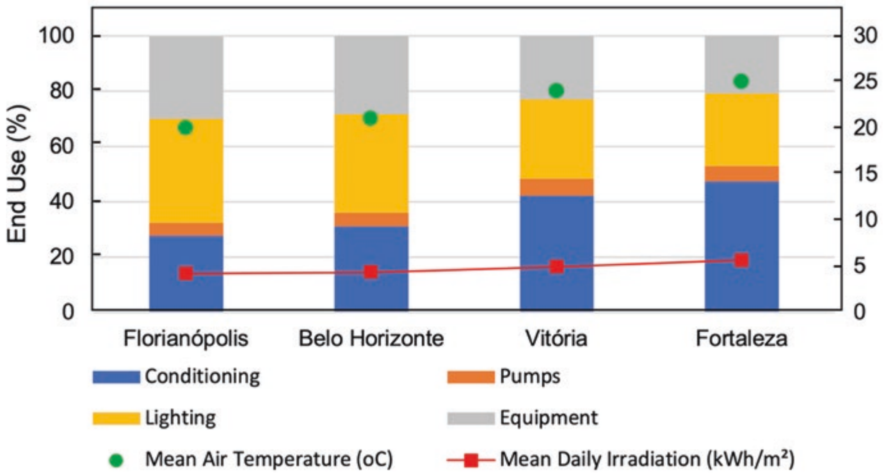

Fig. 9 End uses of a business-building of the tower type simulated in different Brazilian climates

consumptions do not meet the benchmark for high energy-efficiency for this class of building. The end uses are divided into pumps, air handling and office equipment, lighting, and air conditioning (mostly for cooling) [39]. The share of consumption caused by air conditioning follows the average annual mean ambient temperature that, in this case, ranges from 20 to 25 °C. The air conditioning electricity-use accounts for 28–47% of the building load, while that for lighting, 26–38%. Ambient comfort is the largest investment in such situations.

As the commercial and residential energy consumption continues to increase, technology improvements are being incorporated to offset added electricity usage. One recent advance is that of artificial intelligence (AI) air conditioning, which provides machine-learning unit control for more efficiency and levels of comfort. This mechanism avoids losses and excessive electricity use that can occur without sensing changes or relying only on direct human control.

The pattern of Brazil's increased energy use is exampled by equipment ownership, which has increased from 0.16 units per household in 2005 to 0.18 in 2019. In turn, the consumption share of air conditioning in dwellings grew from 12% to 16.5% over this same period. However, this average consumption is directly tied to income, ranging from 10.4% (lower income) to 35.5% (higher income) in 2019 [37]. With this in mind, [40] combined the differences in family income with two family lifestyles: traditional and contemporary, and three consumption patterns determined by Brazilian climates: predominantly cold (Bento Gonçalves, RS), seasonal with distinct summer and winter (São Paulo, SP), and predominantly hot (Belém, PA). The typical average monthly consumption of dwellings is presented in Fig. 10. The traditional lifestyle naturally presents a higher consumption since it is

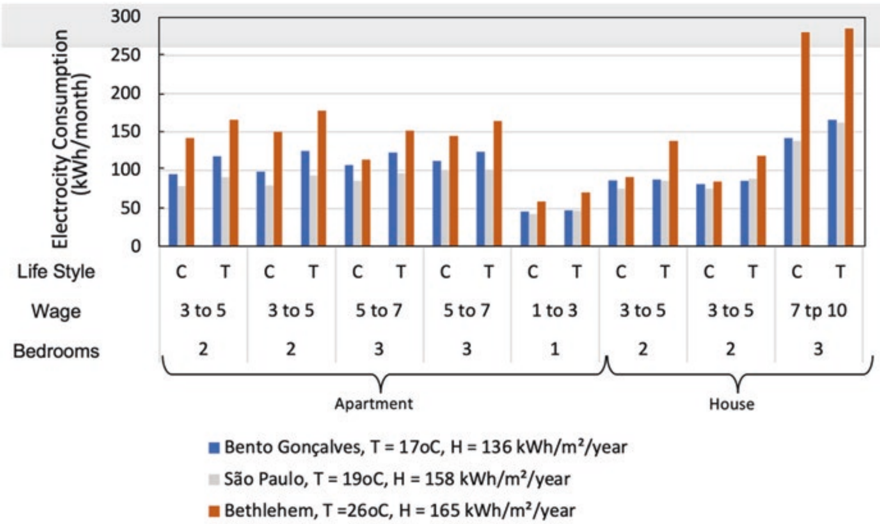

Fig. 10 Consumption patterns by climate and family lifestyle (*C* contemporary, *T* traditional) for five multi-family and three single-family housing models, based on projections for 2020

defined by spending more time at home than the contemporary style. However, climate and family income are the main factors determining consumption differences. Family income is related to the ability to acquire equipment, to the number of residents and, as shown in Fig. 10, the number of bedrooms. Furthermore, the first five cases in Fig. 9 refer to flats in multi-family buildings, while the last three refer to single-family houses.

Rodrigues et al. [40] analyzed the end uses as functions of regional and climate projections reported for 2020 [41]. Figure 11 compares the end uses by climate type with the reported average national projections [37]. When comparing consumption rates in the same income range, a root-mean-square error (RMSE) of 11% and a mean bias error (MBE) of 8% were found, with 288 samples compared to 48 averages from the PDE 2031. This considers the categories: lighting, leisure, water heating, food conservation, environmental comfort, and general services. In contrast, the differences between the reported averages [40] and the reported national averages [37] for 48 samples dropped to 7% RMSE and 5% MBE (see Fig. 12). Therefore, after confirmation of the consumption patterns in Fig. 9 by the benchmarking and Fig. 10 by national projections, they were adopted for discussing the photovoltaic potential according to the building type. In turn, the Brazilian building categories do not present a sufficiently relevant climatic differentiation by region. Thus, standard models were adopted for all the locations discussed [42].

This analysis was carried out within the framework of Brazilian electricity tariff policies. The most widely adopted tariff in Brazil for the commercial sector is *hourly seasonal*, while the conventional residential tariff does not present hourly or annual price variations. In 2011 a voluntary "white tariff" with hourly variation was introduced in the residential sector, but it had little effect and adoption due to its small differences in off-peak hours compared to the conventional one [43].

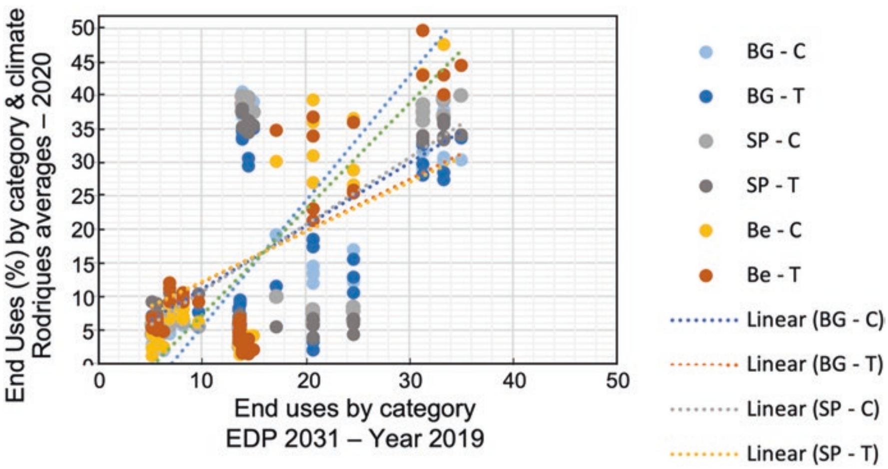

Fig. 11 Difference between the end uses of the consumption patterns of Fig. 10, which are differentiated by climate and the national average projections of PDE 2031

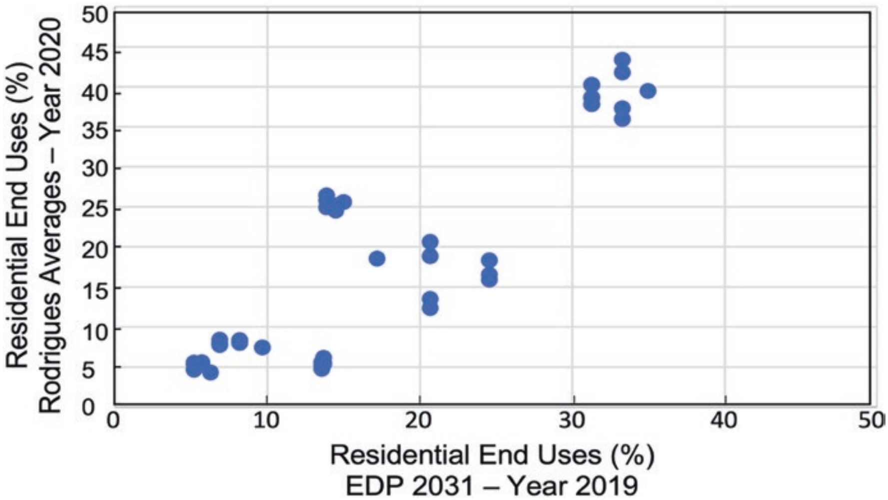

Fig. 12 Difference between average end uses of consumption patterns in Fig. 9, without differentiation by climate and the national average projections of PDE 2031

Photovoltaics in Buildings: Energy Patterns

For commercial buildings in areas with no obstructions causing shading, the "podium" shape (also known as pedestal or platform construction) is the most advantageous for photovoltaic generation. Podium structures have been the common construction type since the 1960s. This is because of their high-performance benefits, including long-term durability, low-maintenance, and fast-track site erection. This structure has been typical for residential apartments, hostels, prisons, schools, and a range of other commercial buildings. The "tower" buildings analyzed in Fig. 9, when fitted (simulation) with thin-film PV systems on its façades, only generated ~10% of the consumption for the evaluated climates. This accounts for 27% to 32% of the consumption by lighting or between 17% and 36% of the consumption by the air conditioning system of the building. But an analysis for a podium-type supermarket in the same bioclimatic zone of Belo Horizonte [44] reaches 31% of the total building electricity needs.

For the tower building in Fig. 10, the installation of thin-film PV on the glazed surfaces caused an additional thermal load on the buildings in Florianópolis (Lat 27°67′ S) and Belo Horizonte (19°55′ S). In turn, this increased the air conditioning load by 8% and 3%, respectively. Consequently, these cities reduced their energy balance total (Fig. 13), although photovoltaic generation ensured a positive yield. Thus, the benefits of photovoltaic energy require accounting for increases in thermal system consumption.

Single- or multiple-family residences present different situations. Considering the residential building configurations (stock structures) in Fig. 14, the energy payback times were estimated. They were evaluated in 55 cities between latitudes 14°

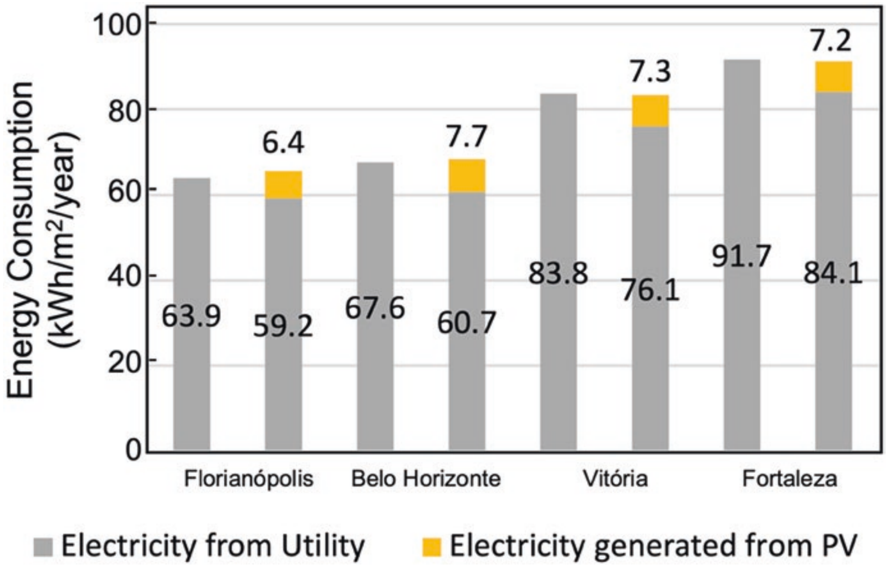

Fig. 13 Electricity-consumption billed concessionary and consumption resulting from the photovoltaic generation of thin films on the façades

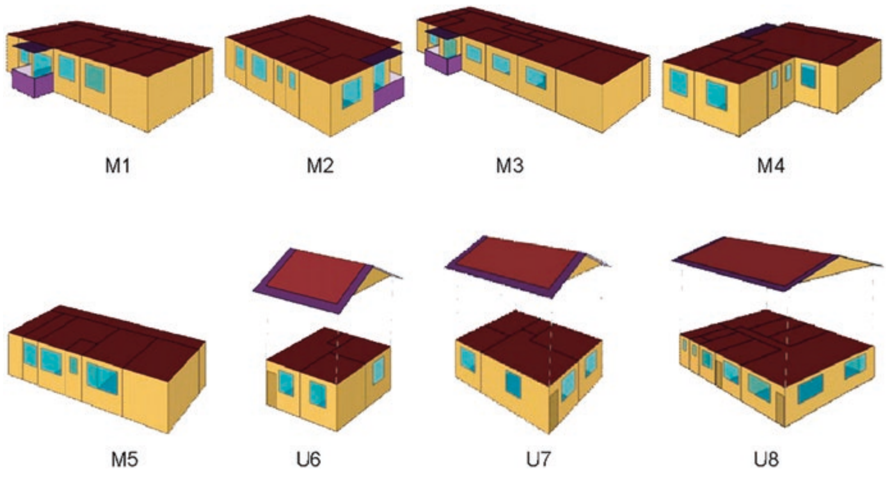

Fig. 14 Shapes of the study's representative multi-family and single-family dwellings

S and 28° S and 7 of the 8 Brazilian bioclimatic zones—ABNT, 2005 (Fig. 15). These data compare "cooling degree days" and the annual average of the daily totals of global horizontal irradiation. Monocrystalline-Si PV (Area: 1.98 m^2) modules were configured on the northern façades of the multi-family dwellings (M1 to M5) and the north-facing roof areas of the single-family dwellings (U6 to U8). The

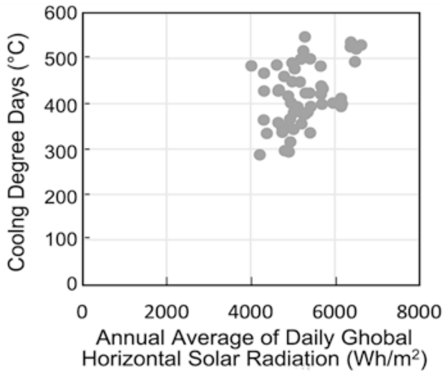

Fig. 15 Characterization of climates between latitudes 14° and 28° S by global horizontal irradiation and by the cooling degree days at a base temperature of 10 °C

Table 3 Characteristics of the representative dwellings

	M1	M2	M3	M4	M5	U6	U7	U8
Area (m^2)	53.3	60.8	66.8	67.7	33.2	30.7	55.5	142.9
Dorms	2	2	3	3	1	2	2	3
Residents	3	3	4	4	2	3	3	4
Consumption (kWh/month)	80–200	80–200	80–200	80–200	0–80	80–200	80–200	200–500

consumption patterns were equivalent to those in Fig. 10 but adjusted according to the climate and characteristics summarized in Table 3.

The photovoltaic systems were dimensioned to meet the monthly consumption of the building, minus the minimum conventional residential tariff's worth of electricity. This tariff refers to the cost of the availability of the distribution network and is equivalent to 30, 50, or 100 kWh/month according to the building's number of power phases. The area available for module installation on the façade or roof was the constraint to the photovoltaic sizing.

Finally, the financial electricity-billing use of the 440 cases with and without the contribution of PV generation was calculated. Figure 16 shows that there were cases of positive energy balance in dwellings M5, U6, U7, and U8. The positive balance of M5 was due to the low consumption typical of a single resident, which frequently only reaches up to the minimum monthly consumption. In the other dwellings, the positive balance was due to the availability of the roof area combined with the high solar heights that ensure greater intensity of solar radiation on low slope surfaces. When comparing these results to the payback in Fig. 17, dwelling M5 emerges as the least promising due to low consumption. Although there are climates in which dwellings M1 to M4 obtain low paybacks, only the geometries of the single-family dwellings U6 to U8 guarantee advantageous investments.

For the remaining cases, flat dwellings (M1 to M4), 42% have payback times equal to or less than 6 years, which can be considered a time limit for investments that will still fall within the family budget. None of these cases presented a payback ≤3 years, considered suitable for investments in the residential sector.

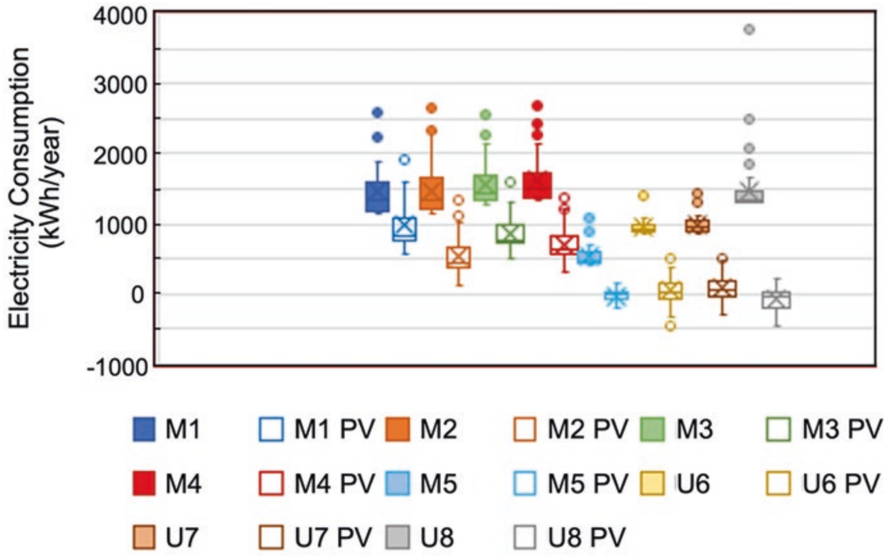

Fig. 16 Electricity consumption as billed by the energy utility companies, of the case study dwellings with and without photovoltaic energy

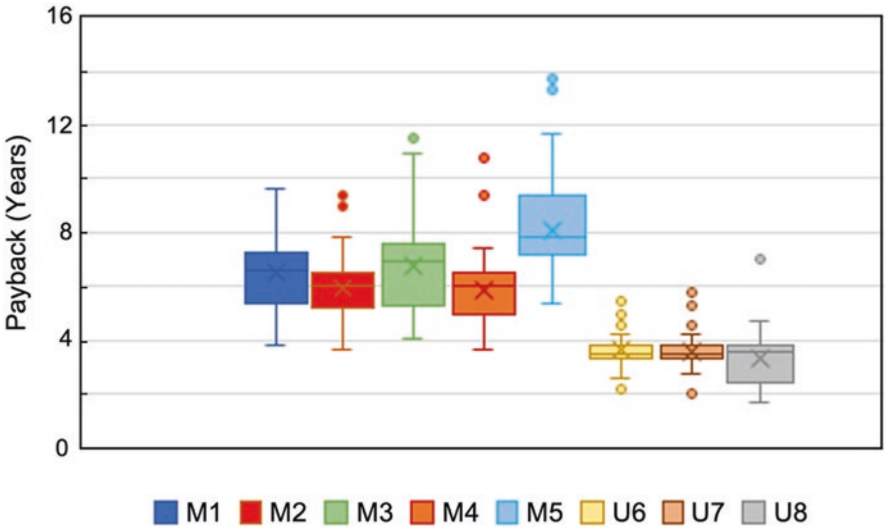

Fig. 17 Electricity consumption as billed by the energy utility companies for the case study dwellings with and without photovoltaic energy

Although the present economic scenario may be marginal for these dwellings, climate change scenarios may reduce the payback times in the coming years for these buildings. Air conditioning for cooling is a growing problem in the residential sector, both due to the increased penetration of splits in dwellings and the forecasts of future scenarios. In these, the total home consumption in Brazil will grow from 30% to 49% over 10 years growth in the consumer air-conditioning markets. While new, more energy-efficient electronics are improvements in the system efficiency and meeting comfort levels, many of the thermal comfort needs could be met by passive strategies thermal comfort, which, in principle, could be achieved with passive strategies.

5 BIPV/BAPV in Brazil: Examples and Issues

The markets and interest involving the installation of PV on residential and commercial buildings are increasing in Brazil. There are growing concerns for the environment in Brazil, issues of power outages and brownouts (many associated with increasing periods of drought affecting the hydroelectricity), and growing electricity prices that make this technology attractive to the consumer that have led the consumer and developers to seriously consider PV. The use of BAPV in particular has been increasing, spurred by the lower cost of PV panels, the lower cost if incorporated in the initial design and construction [4, 10, 11], the growing awareness of the viability of this technology by the consumer, and the availability of small PV systems in the "home improvement" and other retail outlets. A few BIPV and BAPV installations are exampled in the section to give some look into how this PV is being used in its still initial stages in the build environment in this South American country.

A Mini-Tour of BAPV and BIPV in Brazil

Among the first grid-connected BIPV systems was that at Universidad Federal Santa Catarina (UFSC) LabSolar in 1997 (Fig. 18) [45]. This pioneering system utilized a 2-kWp amorphous Si:H (a-Si:H) thin-film technology. This thin-film PV design utilized opaque and semi-transparent glass-PV laminates. In this period of time, the a-Si:H technology was the leading thin-film PV alternative, with products developed specifically for roofing materials [46]. The requirements and benefits for BIPV in the urban building structures (façades, rooftops), especially grid-tied, have been covered in the literature [47, 48, 49]. PV prices that make this technology attractive to the consumer provide the potential for BIPV.

The Brazil single-family residential sector is typified by low-angle roofs using red ceramic tiles or grey to white-colored cement. The most common installations are 1-kW to 4-kW (Fig. 19a–c), though larger systems are becoming more common (Fig. 19d). Brazil also has a large commercial production of solar thermal hot-water systems that have been used extensively and successfully on residences, condominiums, and commercial buildings. These are certified following the government standard [44].

Fig. 18 The first grid-connected BIPV system in Brazil, installed on the LabSolar building in 1997 at the Federal University of Santa Catarina (UFSC) in Florianopolis, Brazil. This was one of several BAPV and BIPV systems pioneered at the university over the past two decades. (Source: Dr. Ricardo Rüther, UFSC, and Ref. [47])

BIPV has to be considered a priority for the future of the built environment. Not only because PV has already become a cost-effective electric-power technology in most parts of the world [4], but it can add architectural and aesthetic value to buildings, rather than just using "cookie-cutter" modules on building areas that are visible. The building-integrated approach can add financial value to the property. In many cases, the use of PV is less expensive than many architectural approaches. A PV façade is more economical than using marble or granite. Transparent PV windows can help engineer the light needed and serve to reflect portions of the sunlight that would provide unwanted heat to the building. The future of BIPV lies in the fact that it can provide the needed power as a roof, façade, window shade, etc., and it is just considered the normal building structure. A casual observer may not know it is "PV," but it provides efficient, clean electricity.

BIPV is starting to be part of the urban Brazil areas. Two interesting examples are presented in Figs. 20a, b. The first is the "Museu da Amanhã" in Rio de Janeiro [50]. This modern architectural structure has skillfully woven into the façade, 5492 crystalline-Si PV units in 48 circuits with a power of 181.2 kWp—providing about 9% of the building's electricity. The theme of the museum reflects the reality of PV technology—"Amanhã é hoje," the future is here. The second is for an office complex "TOTVS" in São Paulo [51]. The glass façade is lined 200 m^2 of thin-film organic PV (OPV) sheets. This emerging technology is an example of the ideal

Fig. 19 Examples of BAPV in Brazil: (**a**) 4-kW on red tile roof; (**b**) 3 KW on cement roof; (**c**) 4 kW on galvanized steel roof; and (**d**) 6 kW on tile roof

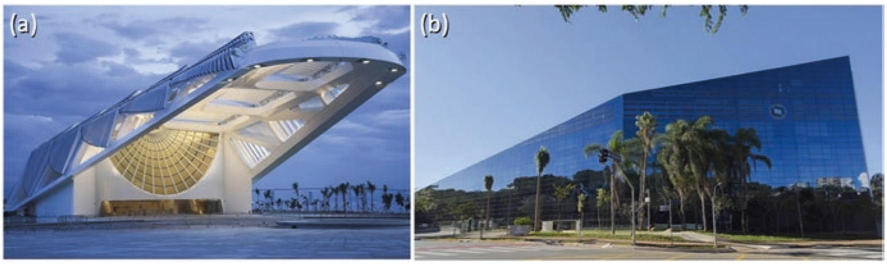

Fig. 20 Examples of BIPV in commercial buildings in Brazil: (a) Museo da Amanhã in Rio de Janeiro with 181.2-kW of crystalline-Si PV; and (b) TOTVS office building in São Paulo with a 200-m^2 area façade of organic PV (OPV)

match for thin films, which are almost transparent, produce the power from the sunlight, are low cost to produce, and can conform to any surface because of their flexibility. In this case, the OPV is produced in Brazil [52]; an example of the current trend toward producing the solar product in the region that the PV is used.

One final set of examples presented for the two airports: *Santos Dumont* in Rio de Janeiro [53], Fig. 21a, and *Hercílio Luz International Airport* in Florianopolis,

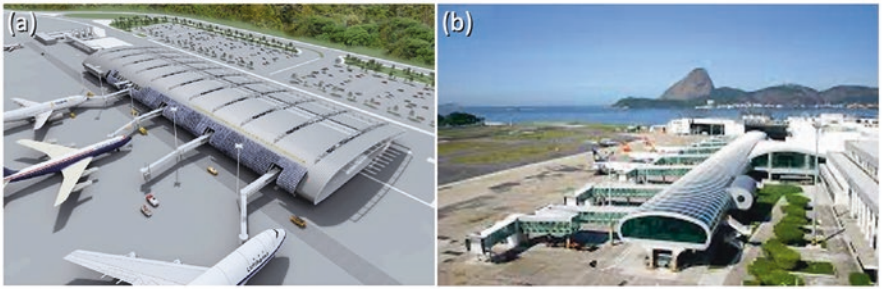

Fig. 21 Airport terminal integrated PV: (**a**) Hercílio Luz International Airport in Florianopolis, (**b**) Santos Dumont in Rio de Janeiro

Fig. 21b. These are really examples of the blend of BIPV and BAPV, with the latter solar components [54] installed in areas that are not very visible to the airport public. Both airports are situated at lower latitudes, with the large-area curved roof providing good acceptance for the sun orientation. The PV sun baffles (architecture term "brise soleil") extend over the windows and building surfaces as well at Florianopolis, which has 1.5 MWp solar installed.

Finally, one cannot mention the built environment and photovoltaics in Brazil without showing PV used in the "futebol" stadiums. For the World Cup in 2014, 4 stadiums were equipped with PV. One example is shown for *Mineirão* in Belo Horizonte in Fig. 22. Because of the structure of the existing stadiums, it was difficult to have the PV visible to the public as planned. However, the facilities provided monitoring kiosks that feature the PV installations, described is function and power levels, and showed what the current production of electricity is there. Mineirão has 6000 modules in its PV power plant—enough to completely power the stadium or 1200 Brazilian households [55]. In fact, the annual electricity needs of the stadium are 1600 MWh, and the PV produced 10% more than this. The extra power is directed to the customers of the "utility" (CEMIG) that built the power plant.

Issues: Soiling and Shading

Windows and façades in buildings are subject to ambient particulate accumulation and have to be cleaned periodically for aesthetics and for optimizing natural lighting in the living spaces or the offices. BAPV panels and BIPV surfaces likewise are subject to soiling, and in this case, the soiling limits the irradiation impinging on the solar converter's surface and decreases the needed power output. The degree to which this affects the panel's performance depends upon the location, local environmental conditions, orientation of the panels, and the condition of the panel's surface (usually glass with some anti-reflection coating). The issues of soiling, associated cleaning methods, and required cleaning periods to minimize power and financial losses have been reported extensively [34, 56–59]. Soiling mitigation cases specific

Fig. 22 Mineirão Stadium in Belo Horizonte, Brazil (1.3 MW crystalline-Si PV). One of four Brazil football stadiums integrated with PV for the 2014 World Cup

to buildings have been investigated—having applications to both normal “windows” and building PV-installations [60, 61].

One case study for Minas Gerais, Brazil, provides some insights into the effects on the importance of location, weather conditions, and especially the issues relating to emissions caused by vehicular traffic in urban areas [62]. This report is for BAPV on a commercial building and compares performance to ground-mounted systems. The performances of a similar power output monocrystalline-Si and poly- (also termed mult-) crystalline Si systems installed in Belo Horizonte were compared (Figs. 23 and 24). The 3.15-kWp monocrystalline-Si technology system was ground-mounted, with a tilt equal to the latitude of 20° in 2010, in a region away from high-traffic roads. The 3.64-kWp polycrystalline Si system was installed in the same year and with the same 20° tilt on the roof of a building close to a high-traffic road. Electrical and thermal parameters, and incident solar irradiance data on the inclined photovoltaic module were monitored during Spring time periods. The first observation is that rain provides a natural cleaning of the modules. The data showed that the output power of the systems increased after the rain, due to the natural cleaning of the modules.

A comparative performance analysis showed that the polycrystalline silicon technology system had a lower performance ratio (0.55–0.57) than the monocrystalline silicon technology system (0.68–0.76). This result can be justified due to the

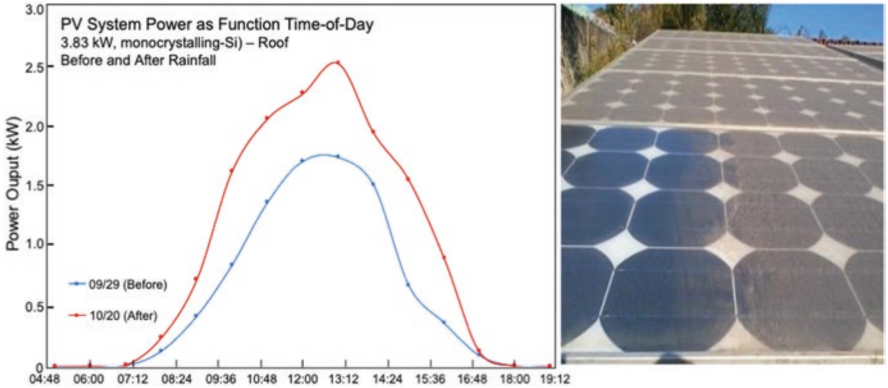

Fig. 23 Power output before and after rainfall from PV system of 3.15-kW_p (monocrystalline-Si) DG installed on roof in Belo Horizonte, Brazil

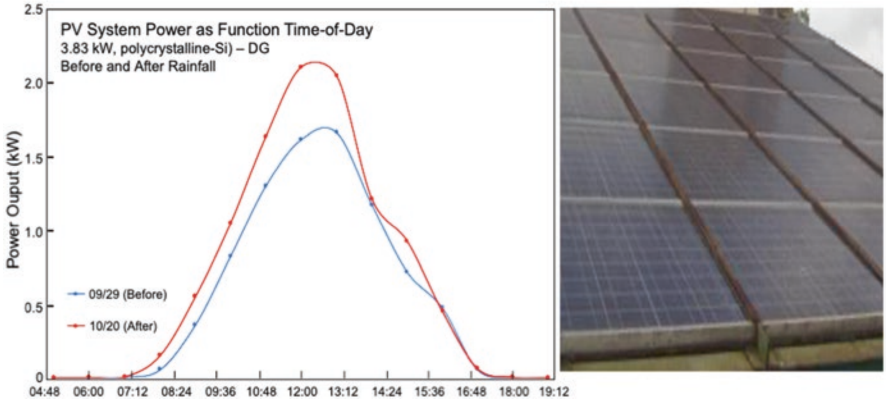

Fig. 24 Power output before and after rainfall from DG PV system of 3.63-kW_p (polycrystalline-Si) DG installed ground-mounted in Belo Horizonte, Brazil

dirt deposited on it, which showed high adhesion to the surface due to the existence of organic matter and a high percentage of carbon, evidencing the presence of a biofilm formed by microorganisms that are difficult to remove by natural cleaning, such as rain and wind [63–66].

Issues: Early Experiences with Rooftop Installations

For the residential PV rooftop sector in particular, Brazil has experienced some issues relating to proper installations and certification. These issues have been experienced in other countries when the new PV buildings' markets started to expand.

Many systems under-perform because they have either been improperly installed or were designed for other climates, applications, or roofing configurations and materials [67–69]. Of course, environmental and location factors are important, the potentially negative performance factors shading [70, 71], cell/module aging [18–20], damage to due handling [21], climate, and ambient temperatures [72].

The operating temperature of the module is a critical factor for ensuring best-possible performance. For typical rooftop installations, the temperature is most affected by the roofing material and the separation between the module and the roof surface. Simulation of a roof-mounted PV-system can be used to optimize real PV-module power-generation by determining the correct installation parameters forecasting the system's capability [71, 73]. As an example, the common roof materials used in Belo Horizonte, Brazil, buildings are red ceramic, cement fiber, and galvanized steel. One study of these modeled crystalline-Si modules mounted on each of these roof types (see Fig. 25 showing installed PV on roofs as part of survey and experimental evaluation set-up in Minas Gerais) determined the optimal separation for the local conditions [73].

The ideal installation distance varies depending on the roof material. In the case of red ceramic tile, the ideal distance is calculated to be between 10-cm and 20-cm; for fiber cement the ideal installation distance of the PV module is around 10 cm, and in the case of galvanized steel the ideal installation distance of the PV module is between 10-cm and 20-cm. These have been experimentally validated. Interestingly, at the 30-cm distance between the PV module and the roof, an increase

Fig. 25 (**a**) Two PV roof installations in Minas Gerais (formed part of survey); and (**b**) Installations for determining the optimum module-roof separation for 3 common roofing materials in Belo Horizonte, Brazil. Left to right: Red-ceramic tile; galvanized steel, cement (based upon the report of Guimaraes [73])

in temperature was recorded for all materials, suggesting that large installation distances might not be desirable [73].

Models predict that the placement of the PV panel directly on the roof (i.e., 0-cm separation) is a configuration that should be avoided. This is a convention discouraged by most installers and suppliers to avoid the loss of power output due to potential higher panel temperatures [53]. Mounting with no separation results in the largest module temperatures for any of the 3 roofing materials. Although field (no-roof mounted) modules (mounted at the latitude near 20°) at this site operate typically <50 °C, direct roof mounting results in modules with temperatures 55 °C to more than 70 °C. Though for the fiber cement thermal properties are best roof-panel operations in these studies, losses of at least 3–4% in module power were observed over the reference field-mounted modules. For the case of galvanized steel, the measured power losses were 10–15% for the modules mounted with no separation. In a survey of the PV roof system installers in 2019–2020, (41%) indicated that they mount panels directly on the roof. These installations lose useful and considerable power for the consumers. There are, of course, also worries about long-term degradation or failure of these modules operating at higher temperatures under conditions that can be avoided. In the survey, 29% responded that 10 cm between PV generator and roof is used, 12% answered that it depends on what the installation location would permit (e.g., obstructions, ability to support the modules, security, etc.), 6% answered that the distance is 15 cm or more, and 12% answered that this "distance is not important."

The best installation (separation) depends also on the roofing material. For example, the optimal separation is about 10 cm for the fiber cement and the red tile roofs and 20–30 cm for the galvanized steel. For all cases, the module temperature rises for separations greater than the optimal one due to increased radiation from larger exposure to roof areas. And in all cases, the roof-mounted PV panels operate at higher temperatures than those that are field-mounted [73].

The installation landscape in Brazil has been changing rapidly with the influence of the government and university laboratories, the manufacturers, and the initiation of certification procedures. The early-stage experience with installations is similar to what other countries have experienced. However, as knowledge, increased use of technology, and training advance, the occurrences of incorrect installations are diminishing.

6 Concerns and Promise for the Working-Class Neighborhoods

Electricity service to the poorer and working-class neighborhoods in Brazil remains a concern [74]. The growth of these "favelas" began in the 1950s when many people migrated from the rural areas to the cities, mainly seeking jobs, improved living, and better wages. However, due to their lack of adequate financial resources, many of this population established themselves in their own-built communities that lacked adequate roads, sewerage, water, medical support facilities—and especially electricity. These favelas are present primarily throughout the larger cities (Rio, São Paul, etc.), where today the largest such areas exist. But favelas have now extended into most states in Brazil. Services to these communities have improved in the past several decades, but still about 20% of the favela populations do not have electricity. The government has promoted metered service to the communities, but with the financial limitations of most of the families, electricity if still "stolen" to provide essential needs. It has to be realized that these are built-environment communities in which the people are in need of reliable electrical service in order to provide even the minimal improvements in their lifestyle. PV has been investigated as an alternative to serve this purpose [75, 76].

Despite the potential for PV in these poorly served communities, the use of this seemingly well-paired technology to the application really faces some major barriers and questions:

- Through these communities benefit from the exceptional Brazil solar resource (Sect. 3), how can it be used effectively and economically to provide and maintain this clean electricity?
- How can the risks (installation, theft, breakage, regulations, maintenance, etc.) be mitigated or eliminated to ensure constant and reliable service?
- How to finance and continue this service in communities that can have high economic limitations.
- At what level can solar be used in these communities with the potential limitations of solar-oriented roof space, solar availability, building structure support for solar installations, and the concerns that environmental issues (heavy rains, land movements, floods) can destroy the entire infrastructure?
- Are the current Brazil legal and regulative condition (Sect. 2) restricting or promoting the use of PV in these higher-risk areas?
- Can the residents buy into this technology, competing with the illegal "business as usual" methods in getting the electricity for free. What programs are needed to help these communities understand the value to improving their lifestyles and social conditions?

Most of these questions have already started being addressed (and continue to be answered with the increase PV availability) for the favela use of solar by the government, by research groups, by the utilities that serve these communities, and in many cases by the residents themselves. BAPV presents a viable electrical power approach. A recent report at the World Conference on Solar Energy Conversion (WCPEC-8) evaluated the solar roof potential in on large favela in Niteroi (near Rio de Janeiro) that may be typical of these neighborhoods [77]. Caetano et al. found that ~30% or more of the roofs were suitably oriented to accept PV panels for very good power output [77]. The report did raise concerns about the structural integrity to support installations, but noted that in some dwellings (exclusive of environmental calamities), this may not be a problem—but may call for additional work on the structures. For most of these communities that exist in densely packed urban areas, adjacent open land for the installation of mini-power plants is not available as an alternative.

The favelas in Rio may best serve as examples of the BAPV potential in this special type of built environment. The favelas were hit particularly hard with frequent and extended electricity outages in the 2015–2020 timeframe [76, 77]. In 2021, a small group from the communities of Babilónia and Chapéu Mangueira formed *Percília e Lúcio* solar cooperative, having raised some $19 K through a collective funding campaign to establish solar PV electricity to serve the community, began their solar enterprise [78–81]. The installation includes 58 PV panels, mounted on the 177 m^2 roof area in Babilônia (Fig. 26). The electricity generates 35,000 kWh annually, enough for ~35 houses. The PV power is fed to the electricity grid, Light S/A in Rio, which in turn, provides discounts in the energy bill of residences and businesses associated with the cooperative for the electricity generated from the PV installations. With the low-income levels of the population, this is a substantial contribution that can be measured at ~10% of the annual income of those consumers.

This BAPV accomplishment is but a small example of what is possible to assist these under-served communities in gaining needed and reliable electricity. The PV electrify has not only had the economic benefit from lowering the monthly bills for these consumers but has also created jobs thought the work of the cooperative. But the expansion and duplication of this effort is not easy under current Brazilian regulations (Normative No 687, 2015, in Section 2 and Table 3). Communities are required to have permits to share small-scale energy generation. These legal

Fig. 26 Partial view of PV module installation in Babilônia community (Rio de Janeiro)

requirements stipulate that there be two or more consumers, a legal cooperative, and that the location of the PV be different from the place where the energy will be consumed. It is time-consuming and inconvenient to comply with these regulations—which are certainly not within the power of PV to bring electricity to the point of use. In 2022, Brazil has implemented a new law (Lei No. 14.300, Section 2) that can help this PV application for the favela communities by making it easier for the cooperatives to be formed and mandating distributors/developers to invest in these low-income areas [82].

The incorporation of PV into the electricity structure of these poorer and working-class neighborhoods is a challenge. But the revolution toward providing clean, reliable solar power to these segments has begun. And BAPV is part of the first steps of this revolution.

7 Conclusions and Innovation and the Energy in Built Environment

Photovoltaic technology, like all electronics, is in a constant state of advancement. Innovation is key to bringing the needed next-generation of devices and systems to meet the economic and performance expectations of consumers and the world situation. Silicon PV technology continues to evolve with **innovation** in device understanding and engineering to ensure that every possible photon is captured, and every carrier survives long enough to contribute to the photoelectric process. Thin films have held great promise because of their efficient materials utilization, form factors, and potential for performance improvement. They have a current place in the power market, but innovation has recently produced advances in improvements in established and in new technology. All PV depends on innovation along the entire value chain from materials, through devices and manufacturing, to systems, standards, and policy. But PV has great prospects to advance beyond its current major focus on the power market. Concerns with land use have been diminished through the implementation of careful and smart "agrivoltaics," in PV power generation can enhance crop production while producing locally needed electricity, and "floating PV," which can utilize the available water areas of reservoirs and lakes. The built environment presents challenges and opportunities to not only help transform this important end high-energy consumption sector to use of clean, renewable electricity—and help the world advance toward a 100% renewable energy future.

The performance estimation of a photovoltaic system must consider the influence of local climatic conditions, as well as installation and maintenance conditions. Solar irradiance and ambient temperature are the climatic factors that directly affect the output current and voltage of a photovoltaic module, respectively. However, the wind speed, for example, can contribute both to the cooling of the module and to the cleaning of dirt deposited on this device depending on the direction of the wind that falls on it. For this reason, for the building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV) attention should be paid not only to the solar resource available in the locality, but also to evaluate the best installation conditions by proposing adequate distance of the modules from the surface, in order to promote free air circulation and, consequently, the exchange of heat between the photovoltaic and air (module cooling), install in places without shadow projection, adequate inclination (> 5° as suggested by manufacturers) in order to reduce the soiling deposition.

As PV continues to grow as part of our clean energy future—and potentially the major player in a 100% renewable-electricity future—the need for expanding the PV presence in the built environment becomes necessary. Just as Brazil is now emerging as a major market for PV, it will also emerge in the major use of PV in the built environment. This aspect has already materialized in the PV portfolio in Brazil. It can be anticipated that in the near term BAPV will dominate for the consumer, with BIPV finding a great place in the commercial and urban environments. Although a rationale mix of BIPV and BAPV has to be a prominent part of the future, it is a disruptive path from what we are doing today—needing significant resource investment and the buy-in from all participant segments.

Such a major transformation requires the engagement of PV scientists and engineers with architects and architectural engineers to make the best decisions and accelerate the transformation. Additionally, the manufacturing industry has to expand to provide products specifically designed for BIPV. Policy and decision-makers play an equal role to make this happen in a reasonable time. This will be a major paradigm shift in accomplishing this trend toward higher architectural value while continuing to provide high standards of performance. The opportunity exists. Currently, renewables account for about 29% of the world's electric-power area, but only about 2% of the much larger energy demand in the buildings sector [4]. And this is where the nexus of innovation in PV science and architecture is important. *There has to be both a movement toward energy efficiency in the built environment and better ways to bring solar technology into this important and large energy-consuming segment.* And a major target for the future has to be a major change in how we unite solar technology with buildings—specifically to make BIPV the major expectation for our built environment. This nexus cannot be "business as usual." But "amanhã é hoje"—tomorrow is today and the change has begun!

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Built Integrated Photovoltaic Application (BIPV): The Dutch Situation

Wim Zeiler

1 Introduction

Today's built environment and electrical power grid are part of an energy transition that prioritizes the use of renewable energy sources (RES). Buildings with integrated RES become energy producers and not only consume but also supply energy to the grid, creating multidirectional energy flows on lower grid levels. The increase in power grid-connected RES has resulted in to change in power generation characteristics. The total electricity grid transition and associated processes can be described as a change in the power grid from 'passive' to 'active', in which connected building services play an active role in the management of the power grid. More and more grid operations are dependent on the stochastic nature of RES like the sun and wind, their generation is therefore uncertain. New strategies for network operation are necessary to maintain grid stability.

The Netherlands has a liberalized and privatized energy market in which network operators and energy retailers are unbundled [2]. Only the grid infrastructure remains in the public domain, which is operated by seven different regional grid operators and one national operator Tennet. Solar PV energy holds immense potential for the future European energy mix, driven by falling costs (reaching USD 4 cents/kWh in 2019 according to Lazard) and scalability on rooftops, carports, water surfaces, and many other innovative applications. The National Energy and Climate Plans (NECP) can facilitate a cost-effective solar deployment and define future goals. The national goals established in 2019 are set on 49% emission reduction by 2030 and 95% by 2050. The innovation policy does not mention goals for specific technologies as the principle is to achieve these goals in the most

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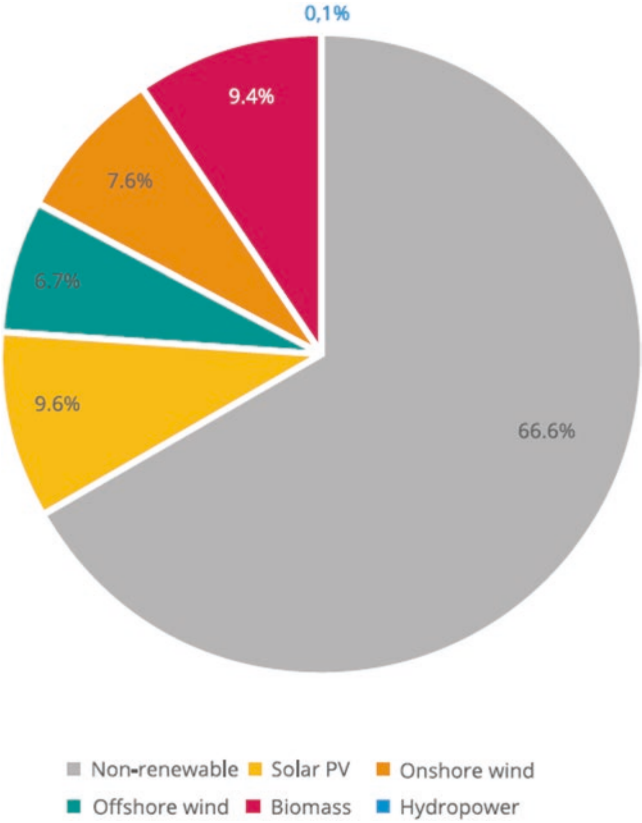


Fig. 1 Share of solar power in the electricity mix in the Netherlands [7].

cost-efficient way while maintaining energy security and a reasonable energy price. At the moment all three objectives are under pressure. The electricity demand for heating & cooling in the built environment and industry is also increasing and is expected to double by 2030, which will enhance the role of solar energy as a cornerstone of the energy transition. In 2021, 9.6% of net electricity production was from solar power [7]. The sun is therefore the main category of renewable power within the electricity mix. Together, renewable sources were responsible for 33% of electricity demand, see Fig. 1.

2 Climate Conditions

The Netherlands is located near the North Sea and enjoys a moderate maritime (or oceanic) climate. This means generally mild winters and cool summers. Throughout the country, mean winter temperatures are about 3 °C, and mean summer

Table 1 Average climate conditions of the last 5 years [10]

	Temperature [°C]	Sunhours [h]	Windspeed [m/s]	Global radiation [J/m^2]
2017	11	1764,3	4,5	383,538
2018	11,3	2088,9	4,5	418,248
2019	11,3	1964,1	4,5	404,463
2020	11,7	2025,8	4,9	416,735
2021	10,5	1799,9	4,3	385,579

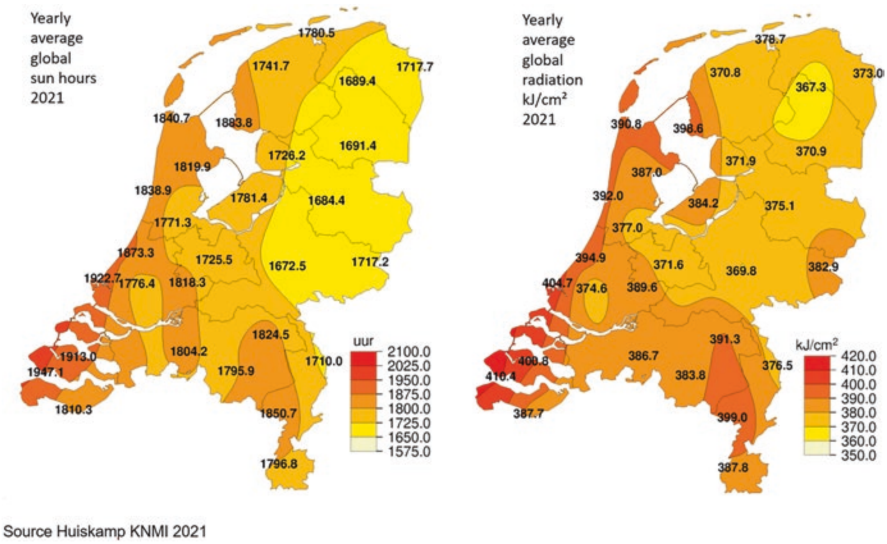


Fig. 2 Yearly average global sun hours and global radiation for 2021. [8]

Table 2 Total use of sum energy, respectively power and heat [10]

	Total [TJ]	Power [TJ]	Heat [TJ]
2016	6913	5767	1147
2017	9080	7936	1144
2018	14,510	13,354	1156
2019	20,617	19,437	1180
2020	32,729	31,553	1176
2021	41,972	40,796	1176

temperatures are around 17 °C, see Table 1 for the average climate conditions of the last 5 years. Coastal regions have more hours of sunshine than inland regions and a relatively small annual and diurnal temperature range. Precipitation, such as rain, is common throughout the year, which means there is no dry season. The difference in average yearly global sun hours and yearly average global radiation is relatively small, as it is a small country, see Fig. 2. The use of solar power is much higher than that of heat and growing fast, see Table 2.

3 Dutch PV Market

In 2021 the Dutch solar PV market continued growing at the same pace as the years before with an estimated added installed capacity just over 3.6 GWp installed (preliminary figures) which leads to a total cumulative installed capacity of 14.3 GWp [2]. These figures are based on a market survey by DNE Research in the Solar Trend Report 2022. See the updated chart from the RVO. The official figures are provided and updated regularly in the Electricity Balance Sheet published by the Central Bureau for Statistics (CBS). After Germany, the largest solar market in Europe, a position it held for most of the time over the last 20 years [16], Europe's new No. 2 in 2020 is the Netherlands, see Fig. 3. Germany has more solar installed per capita (651 W) than any other European Union country but the Netherlands has been catching up very quickly on this metric, coming close with 539 W/capita, after each citizen installed an average of 384 W in 2019.

The successful advance of solar power is reflected in the annual figures. With 11.2 Twh, solar power has become the main renewable source of electricity. In addition, with a total installed capacity of 14.3 GW, there is sufficient output for more than two modern solar panels per capita. No other country in Europe can match that.

The vast majority of solar panels are installed on roofs. In the new capacity, the residential sector provides a solid annual base. The number of households with solar panels passed the 1.5 million mark in the second half of 2021. In total, 1.3 GW of newly installed capacity was added to the residential part of the sector.

Alongside roof installations, more and more power in the commercial sector is being connected on land. In 2021, 3632 MWp of solar power was installed in the Netherlands. Total installed solar power has grown exponentially in the past number of years. In 2021, total installed capacity grew with 34% to 14.3 GW, see Fig. 4 [7].

At this moment, large roofs of commercial premises and auxiliary buildings make up 3.0 GWp of solar power capacity, even though the potential space on this type of roof is 20 times higher. As a result the biggest market segment was commercial rooftops [16], which reached nearly 50%. The residential market, though in

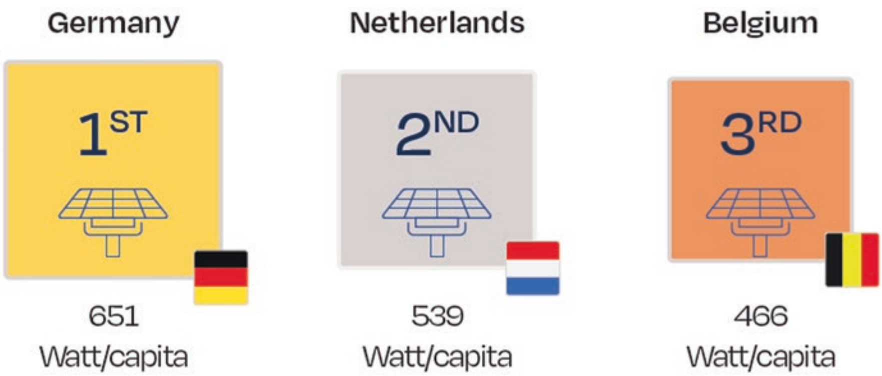


Fig. 3 Europe's top 3 installed average power per capita [16]

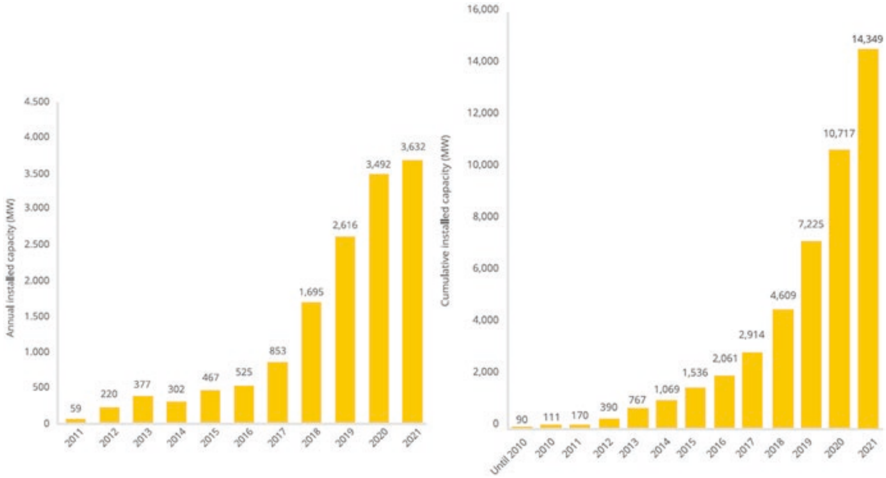


Fig. 4 Annual installed solar power capacity & total installed solar power capacity in the Netherlands [7]

absolute terms stable, saw its portion shrink by about 10% points down to nearly 30%. The market segment of ground-mounted solar parks remained at around 20%, with the largest PV plant so far, a 110 MW in Groningen, becoming operational this year. There is an increasing interest in multifunctional use of space, like floating solar or solar carports, with the largest solar panel carport of 35 MW having recently started construction [16]. The forecast is that the solar market in the Netherlands will continue to grow at a stable rate of over 3 GWp per year notwithstanding the increasing pressure on the electricity grid and land resources. Creative ways are being found to avoid and solve these issues while working on higher efficiencies and integration of solar PV.

4 Building Integrated Photo Voltaics

Most parts of the building envelope (roofs and facades) are suitable for the integration of renewable energy generating devices, a great potential of utilizing PV in existing buildings is still unused. Research teams around the globe have taken on the challenge of generating knowledge and providing solutions related to the integration of photovoltaic technologies in buildings [5]. The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) which carries out a comprehensive program of energy co-operation among its 23 member countries. Since 1993 the participants of IEA Photovoltaic Power Systems Program (IEA-PVPS) have been conducting a variety of joint projects in the applications of photovoltaic conversion of solar energy into electricity. IEA-PVPS Task 15 focuses on creating an enabling framework to accelerate the penetration of BIPV products in the global market of renewables and building components. Building integrated PV (BIPV) is seen by them as one of the five major tracks for large market penetration of PV, besides price decrease, efficiency improvement, lifespan, and electricity storage [5].

PV installations at a building level can either be added to the building envelope, which is called building added PV (BAPV) (Fig. 5, left), or they can be integrated in the building envelope, named building integrated PV (BIPV) (Fig. 5, right).

In 2016, the first standard for BIPV systems (EN-50583 2:2016: “Photovoltaics in buildings – Part 2: BIPV systems”) was introduced which gave rather technical definitions [Ritzen]

> *Photovoltaic systems are considered to be building-integrated, if the PV modules they utilize fulfill the criteria for BIPV modules as defined in EN 50583-1 and thus form a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011.*
>
> *Building Attached Photovoltaic system – BAPV system. Photovoltaic systems are considered to be building attached, if the PV modules they utilize do not fulfil the criteria for BIPV modules as defined in EN 50583-1.*

In general, a BIPV system has the installation technically and aesthetically integrated, contributing to a homogeneous coverage of the building surface.

In the beginning, the Dutch saw the application of BIPV as a demonstration of innovative research and sustainable strategy which made good public relations. Some remarkable projects were realized.

Source
https://www.jpvaneesteren.nl/nl/projecten/project-hoofdkantoor-eneco
https://edge.tech/developments/eneco

Fig. 5 Façade integrated building integrated PV (left) and roof-mounted building added PV(right) in Rotterdam, the Netherlands

5 Dutch Iconic BIPV Examples from the Past

In 1988 the first solar house in the Netherlands was a system of 2.5 kW PV array coupled to a 10 kW battery, see Fig. 6 left [6]. It was an autonomous system dimensioned for winter demand and functioned very well. It had to be replaced by a new system in 2016 so after 28 years! To get the same capacity it was now possible to do it with nearly half of the panels as can be seen in Fig. 6 right. However, at that time still, the necessary technology had to be developed further.

The Dutch first net zero energy building, built in 1993 had a fully integrated PV implementation on the roof combined with thermal solar collectors, see Fig. 7 right. The roof of the house carries 3.4 kWp in photovoltaic cells, connected to the public grid, and a 12 m^2 active (thermal) solar collector [3, 17]. A measurement program in 1995 showed the energy consumption of 1070 m^3 natural gas equivalent was more than balanced by the energy production of 1146 m^3 natural gas equivalent and proved that the house met the designer's "zero-energy" target [3, 11].

In 1999 the world's largest PV project in the built environment was built in the Netherlands with together 500 houses equipped with PV as well as schools and sports facilities in the new district Nieuwland in Amersfoort, see Fig. 8. In total 1.35 MWp of PV modules integrated into facades and the roofs, about 12,300 m^2 of PV. Solar optimization was taken into account in the urban planning phase with the land being parceled out to provide as many roof surfaces as possible suitable for the installation of solar panels. All the urban planners, architects, and developers involved were required to cooperate in the implementation of the solar power project. The district was divided into 12 development areas and each developer had its

Fig. 6 Left situation first Dutch solar house 1988 and right the situation after the renovation in 2016

Fig. 7 First Dutch Zero-energy house Woudbrugge 1993 [3]

Fig. 8 Different BIPV projects as part of the district Nieuwland. (Source: Cace J., Horst E. ter, 2008, Grootschalige PV projecten in Nederland. Nieuw Sloten, Amsterdam en Nieuwland, Amersfoot, Workshop Grootschalige implementatie van zonnestroom in onze steden, ECN, 29 mei 2008)

own architect because one of the goals of the project was to investigate the effects of various forms of ownership and management of the solar system. The performance of 463 decentralized PV systems with a total installed peak power of 1.2 MWp has been evaluated for a period of 5 years (2001–2006). The evaluated systems are situated in eight sections and are characterized by different architectural designs, tilt, and azimuth angles. In six of the sections, the majority of the systems perform well. Data indicate that in those cases there is no substantial lowering of the performance during 5 years. However, several individual systems in those sectors do not perform well. Often defects in the PV system or changes in the roof construction are the cause. For example, string errors are not recognized as such and as a

Source Projectvorstellung Waterkwarties Nieuwland in Amersfoort, NL Duijvestein K.,

Fig. 9 Energy balance houses district Nieuwland

Fig. 10 First Dutch NZEB school with its BIPV

consequence not repaired. In two other sections, the performance of the systems is insufficient, but no clear explanation could be found.

Extraordinary were the so-called Energie balans woningen, energy balance houses, which aimed to be energy-neutral, see Fig. 9.

The first Dutch NZEB school was built in 2000, see Fig. 10, and is a nice example of integrating the PV panels in a green roof. The school's electricity consumption of around 14.650 kWh is supplied by 145 m^2 PV panels on the roof while its heating needs around 4000 m^3 gas ~ 16.000 kWh covered by participation in a wind turbine park.

Floriade Haarlemmermeer 2002

For the Floriade in Haarlemmermeer, in 2002, almost the entire roof of a hall of almost 30,000 m^2, see Fig. 11, was equipped with semi-transparent solar panels (PV modules). With more than 19,000 panels, the installed photovoltaic generation capacity is 2.3 MWp, making it the largest PV roof in the world at that time!

Source: https://www.smiemansprojecten.com/nl/projecten/floriade

Fig. 11 Entrance building Floriade Haarlemmermeer

2014 The Edge – Amsterdam

This was the world's greenest-rated office space of its time, with a BREEAM score of 98.36%, and probably the smartest, too. The building is fitted with 28,000 sensors that track movement, lighting levels, humidity, and temperature, see Fig. 12. The southern wall is a checkerboard of solar panels and windows. Thick load-bearing concrete helps regulate heat, and deeply recessed windows reduce the need for shades, despite direct exposure to the sun. The roof is also covered with panels a total of 450 'PowerGlaz' solar panels with a total installed capacity of more than 100 kW peak. The building produces more electricity than it consumes as a result of its energy-saving design and use of solar and geothermal energy.

Source https://www.oranjedakenergy.nl/project/the-edge-energieneutraal-kantoor/

Fig. 12 The Edge Amsterdam

2014 House of Tomorrow Today (HoTT) – Heeze-Leende

The House of Tomorrow Today (HoTT), see Fig. 13, is an experimental house realized according to rather new sustainable visions like Smart Building (Slimbouwen) and Active House, but with tangible (today's) technology [12]. HoTT holds 19 roof windows and large-scale façade openings. All roof windows and east and west façade windows are automated sunscreen systems. South façade openings are shaded in the summertime by roof overhangs. Every room has two façades with large window openings, exceeding 5%. The south-oriented roof with 95 m^2 PV panels produces 15,000 kWh/y energy for (mainly floor) heating and domestic use, leaving a comfortable surplus for an electric car. Six solar collectors produce hot water. Heating and active cooling (only in the case of PV production) are provided by an air and water heat pump (COP 4.5). Overall insulation level (U value) is for roofs, façades, and ground level floor equally 0.15 W/m^2K. Partition walls and floors are 0.4 W/m^2K. Windows are triple glazed partly highly efficient double glazed (both around 0.8–0.9 W/m^2K). To avoid draught and to reduce energy consumption the house is made airtight and this was blower door tested.

Source: https://www.activehouse.info/cases/house-of-tomorrow-today-hott/

Fig. 13 House of Tomorrow Today Heeze-Leende

2018 Apartments De Willem en De Zwijger – Best

The first 5-layer zero-on-the-meter (NOM) apartments De Willem en de Zwijger in Best have been voted Most Sustainable Project of 2018. The apartments are equipped with BIPV. About 750 m^2 CIGS modules are integrated into the façade and another 500 m^2 CIGS modules are integrated into the balcony balustrades. On the roof of the apartment buildings, additional PV modules are installed [15] see Fig. 14.

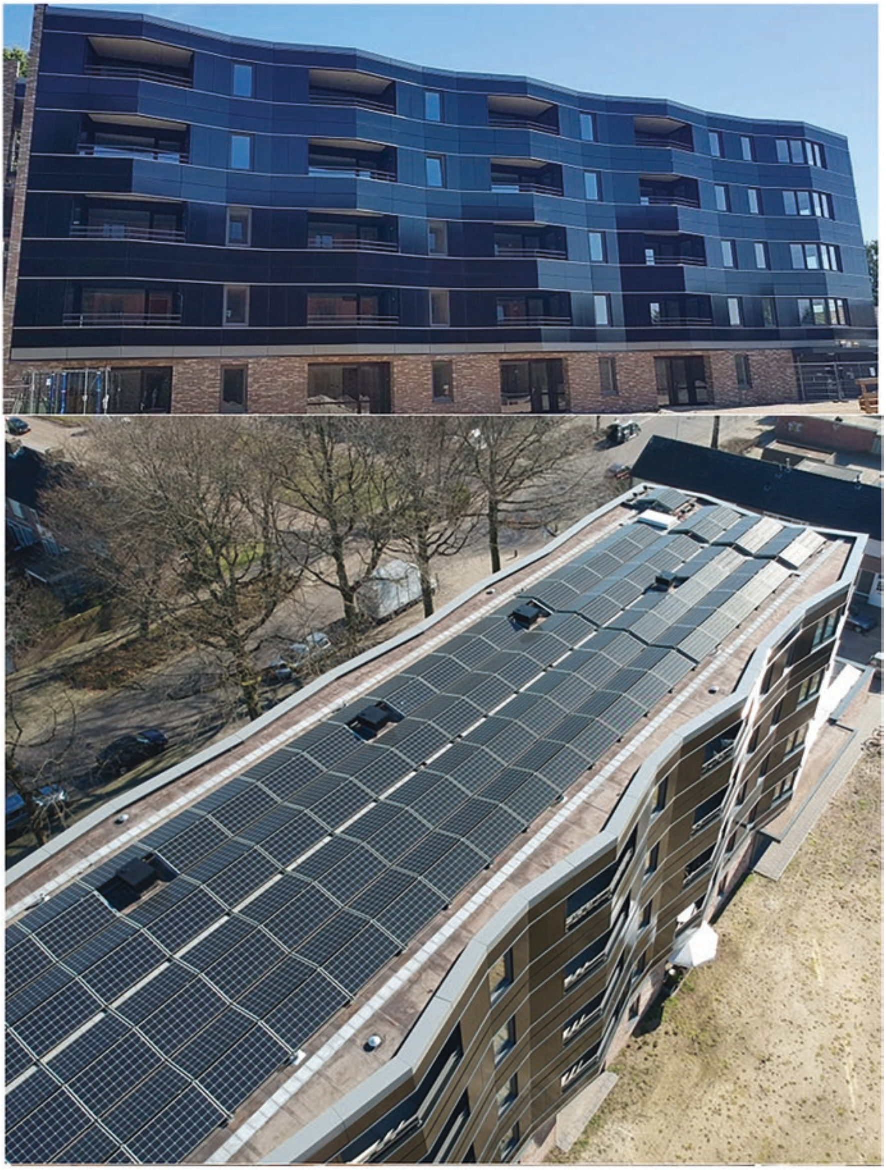


Foto source · EigenEnergie.net

Fig. 14 Roof, façade, and balcony BIPV Apartments De Willem en De Zwijger

6 Recent Dutch Iconic Examples

2020 House of Tomorrow Today 2.0 (HoTT2.0) – Monfort

House of Tomorrow Today 2.0 (abbreviated HoTT 2.0) is aiming to optimize the HoTT concept and to prove its economic feasibility [13]. The way to achieve a feasible concept was an industrial approach based on the so-called Slimbouwen (Smart building) approach which divides the process into four sequential parts, namely frame, envelope, services, and finishing. Especially the uncoupling of services is crucial in achieving an industrial process. Special attention is paid to daylight all over the house (daylight level 23% (ground floor)-25% (first floor)) and with quite some roof windows in the northern roof. The house is ventilated by mechanical extraction and a natural inlet. The ventilation is controlled by measuring the CO_2 concentration per space and also by air humidity. In addition, the house contains nine so-called night vents (façade hatches) automatically controlled in order to cool down the house in hot periods by night in combination with automated roof windows. The heat and also cooling in the summertime are provided by a high-end geothermal heat pump with a COP of 4.5. The heat is distributed all over the ground-level spaces by a liquid-based floor heating system controlled per room.

The timber façade has all around the house a ventilated cavity, in the southern roof the underneath ventilated PV panels functions as a sunscreen for the roof. In the concept, the energy losses are however compensated with solar panels on the southern roof (42 panels, 68 m^2). In practice in the first full year, the system was producing 11,700 kWh (Fig. 15).

2021 van Caem Transporten – Waalwijk

The largest BIPV façade installation in the Netherlands on a commercial building [14]. The installation covers 540 m^2 and uses the innovative Click&Go installation system. The solar façade consists of 240 frameless solar panels and 256 aluminum composite cassettes from Plastica. The estimated annual energy production (kWh) of the Van Caem BIPV façade is 62,000 kWh per year (Fig. 16).

2021 Echo, TU Delft – Delft

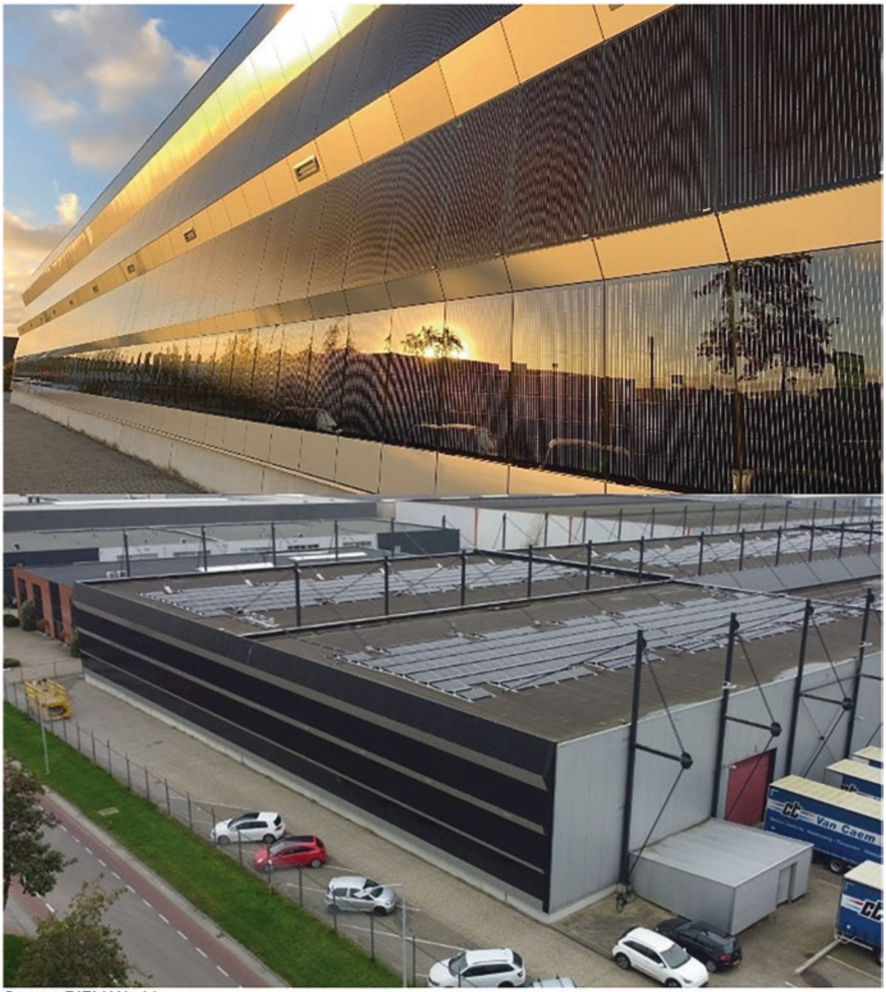
For Echo, the new interfaculty building for TU Delft, UNStudio, in collaboration with Arup and BBN, created a design that fully supports different educational typologies and teaching methods with a sustainable building in which adaptability and the wellbeing of the user are central. Transparency was essential to the design of Echo. It not only ensures maximum daylight inside the building but also creates a

Fig. 15 BIPV roof of the House of Tomorrow Today 2.0

visual connection to the surrounding nature. However, to avoid heat gain, it is also essential to prevent excess sunlight penetration. Overheating of the building is prevented by a combination of sun protection and the low solar penetration factor of the glass. In addition, the deep horizontal aluminum awnings keep out excess solar heat. 1200 solar panels installed on the roof, smart HVAC installations, good insulation, and a heat and cold storage system ensure that Echo will be able to provide on average 2% more energy than it requires for its daily operations (Fig. 17).

2021 Aeres Hogeschool – Almere

The seed for the greenest university of applied sciences in the Netherlands was planted some 10 years ago when the municipality of Almere announced its wish to establish higher education in the city, and Aeres saw the opportunity. After Almere was awarded the organization of the Floriade 2022 World Horticultural Expo, a logical context gradually emerged. The theme of the Floriade 'Growing Green Cities' fitted in the Aeres's mission 'Let the city live' perfectly, and ties in seamlessly with their education and research program. An educational building with its



Source BIPV World
https://bipv.world/projecten/nederland-van-caem-transporten#

Fig. 16 BIPV Facade van Caem Transporten – Waalwijk

own unique signature that shows what they do and where there is plenty of room to accommodate the growth in student numbers of the Faculty of Food, Nature and Urban Green of Aeres University of Applied Science. The specific education and research portfolio about the knowledge areas of green, energy, health and nutrition is rapidly gaining social relevance. This attracts many new students [1].

It had to be an example of what can be possible when trying to combine architectural appearance and sustainable technology to reach for a circular and energy-neutral building. For the complete building, inside and outside, a sustainable, circular concept has been implemented. Natural building materials have been used,

Photos: ©Evabloem / ©Hufton+Crow

Fig. 17 Interfaculty Echo building TU Delft

and green plants have been installed which should ensure CO_2 storage and water drainage storage. A kind of ‘green lung’ with different kinds of green walls, plants, and small trees moves as a landscape through the building from the entrance to the roof. This is a living lab part of the educational practice research, see Figs. 18 and 19.

To supply the many greenery plants on the roof and the facades with water, water storage facilities have been installed both underground and on the roof. All the rainwater is collected in these storage facilities and sent to the plants via smart, data-controlled, web-based systems. The reuse of rainwater and thus water storage are an integral part of the design, see Fig. 20 [9].

The façade on the west side with a view of the skyline of Almere Stad is practically completely covered with solar panels. On the west side overlooking the

Fig. 18 'Green lung' which is situated through the building

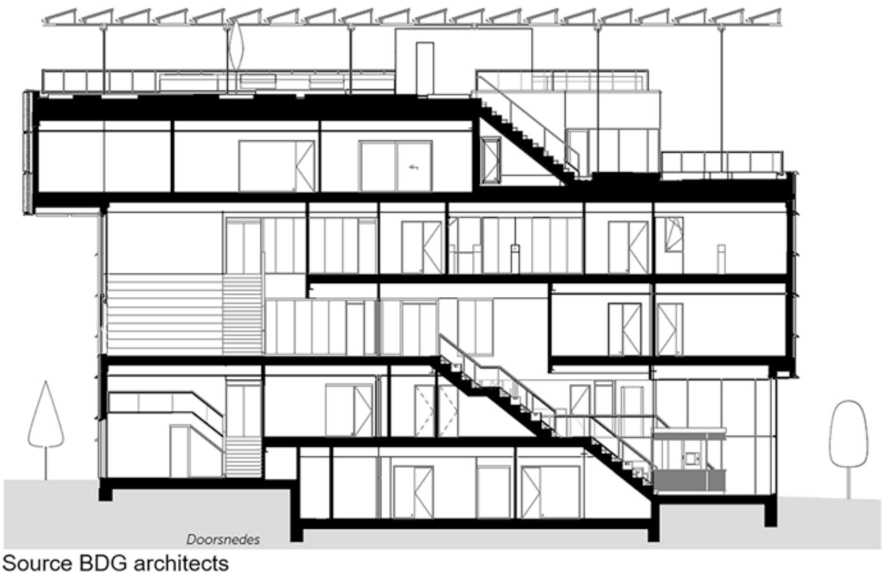


Fig. 19 Cross section with the staircases of the 'Green lung'

Fig. 20 Integral design greenery and water storage system

Floriade green city park the building has a green façade. As a result, this school building has two characteristic appearances, one side is expressing nature full of greenery while the other side is expressing technology fully covered with PV panels, see Fig. 21. As such it proves it is possible to combine them and make a harmony to reach synergy between nature and technology.

A total of 712 BIPV Powerglaz panels were installed for both the roof and the façade, 400 panels for the roof and 312 panels for the façade. Powerglaz consists of several layers of glass between which solar cells are laminated, see details given in Figs. 22 and 24 and Table 3. The total capacity is more than 156,000 Wp of which 88,000 Wp is installed in the roof. The fully customized panels for the roof and in the façade are supplied with different cell investments. The BIPV panels for the façade have a lower cell investment for the windows, i.e. more light and viewing permeability has been created (50–40% instead of 24%), for example, the classrooms, see Fig. 23.

The panels on the roof of the University of Applied Sciences in Almere are integrated into an imposing steel construction, which functions as a tropical roof, see Fig. 25. In order to generate as much energy as possible without detracting from the design, it was decided to apply two different cell types. The panels above the stairs and handling areas have a light transmission of 50%, for the other panels this is 24%.

The project was awarded the BIPV Award 2021 for the best building integrated PV in the Benelux (Netherlands, Belgium, and Luxemburg) as well as the Public Circular Award 2022, see Fig. 26.

Especially also this last award is a valuable award for the textbook definition of the circular building of the future. The jury indicated that it appreciated the exemplary function of this new building for its students. The future generation is

Fig. 21 The two different sides of Ares Hogeschool; nature and technology

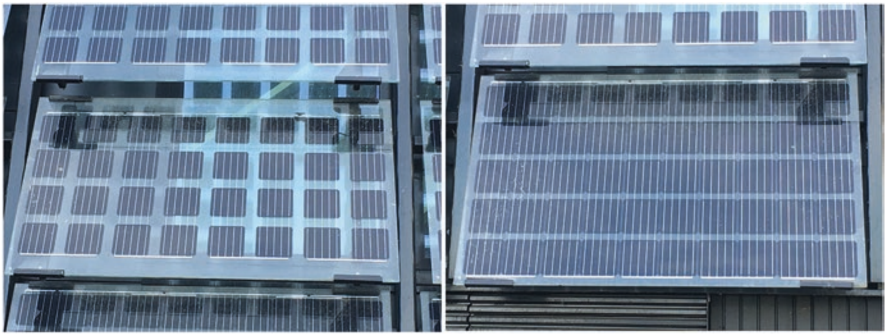


Fig. 22 Different PV panels in the façade with different transparency

Table 3 Different types of PV panels applied at Aeres

Number of cells	Peak power	Transparency
50	250 Wp	24
40	200 Wp	40
32	160 Wp	50

Source BDG architects, Hermans energy solutions

Fig. 23 PV panels in the façade with high transparency in classrooms

important in the shift to a circular economy. Aeres University of Applied Sciences reflects this in an environment that is healthy and has a positive impact on student performance.

7 Discussion

To reduce the effects of climate change, the energy system needs to be restructured drastically in the coming years. The growth of solar PV over the years has led to a change of focus in the implementation and innovation programs toward system integration, societal integration of solar PV, and its carbon footprint [2].

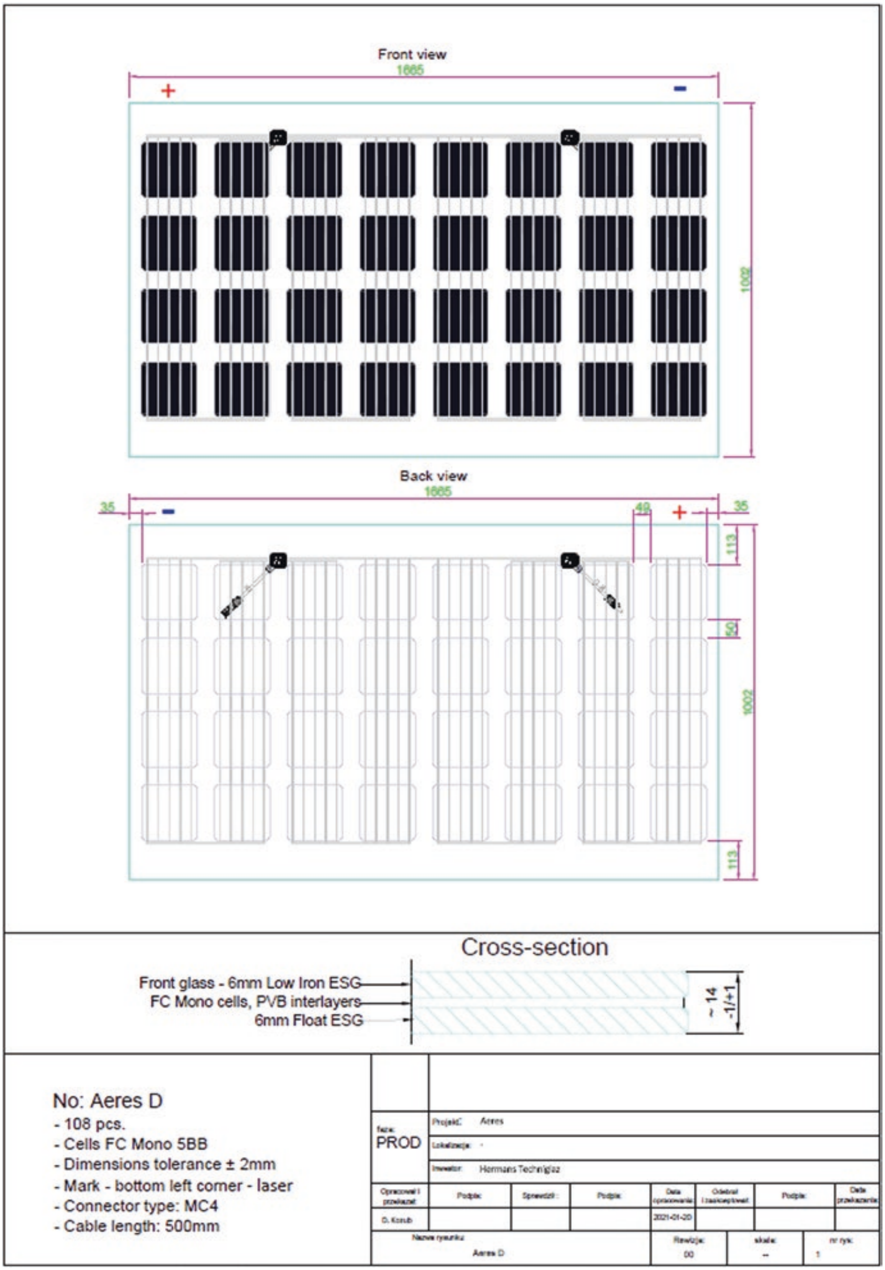


Fig. 24 Details applied 32 cells PV panels Aeres transparency 50%

Fig. 25 The ‘tropical roof’ of Ares Hogeschool

Fig. 26 BIPV Award 2021 for Hermans energy solutions for their contribution to the BIPV systems of the Ares building and the Public Circular Award 2022 [18]

In Rethinking Energy 2020–2030: 100% Solar, Wind, and Batteries is Just the Beginning [4] an energy system is sketched with 100% renewable energy from solar and wind, supplemented with battery storage would look. It differs radically from the current because it is completely decentralized [7]. Simulations demonstrate that such a system would work to stabilize electricity production when using 100% solar and wind power with battery storage. In the past, this was never an option because it would be too expensive or because of insufficient space to accommodate it [7]. However, due to the fall in costs of solar panels and battery systems of more than 80% up until 2020, 100% renewable energy from solar and wind energy paired with energy storage is "physically and economically affordable" throughout the "vast majority" of inhabited regions worldwide by 2030 [7]. This idea also offers the Netherlands a new perspective. Decentralized energy production – with solar power taking the lead role – combined with storage will provide the majority of energy and lead to a new balance [7]. The Netherlands is a small and densely populated country with limited available space for generating capacity. Fortunately, the potential of solar panels on residential and commercial roofs is huge.

Grid congestion has become widespread and has led to a backlog of solar power plants and led to forced curtailment in the domestic market. Investments in grid reinforcement are underway but given the long lead times, compared to the development of solar parks, grid operators will not catch up with the existing backlog in the coming decade. Alternative ways are being explored to make use of the existing electricity network including frequency management, cable polling, etc.

8 Conclusions

An energy system with 100% renewable electricity from solar and wind, with energy storage could be possible. BIPV is seen as a necessary step in coping with the energy challenge in the next decades by realizing energy generation with the roof and façade surface. Some interesting BIPV projects from the past and some more recent projects are shown as well as one iconic project in more detail. Proving the possibilities for a more sustainable built environment while also making it possible to reach synergy between technology, BIPV, and architectural concept.

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Building-Attached and Building-Integrated Photovoltaic Systems in Austria

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1 Introduction

Building attached (BAPV) and building integrated (BIPV) PV systems in Austria have had a tradition since the late 1980s. Starting at alpine mountain huts i, PV systems in buildings have been spreading slowly but continuously over the whole country. Already in 1991, the Austrian government passed the *200 kW-PV-rooftop programme* that meant to accelerate the deployment of PV in buildings. Since then, almost all PV systems built in Austria have been subsidised in one way or the other, mainly by investment subsidies or feed-in tariffs.

The core objective of this paper is to review the development of PV in buildings in Austria, to identify the major highlights, to document the development of the costs and to discuss further prospects in the next years.

2 A Short History of PV in Buildings in Austria

The first PV systems were installed in Austria in the late 1980s. Most of these were building-attached systems in remote areas of Salisbury and Upper Austria for autonomous supply of mountain huts in alpine regions. These systems had of course batteries for the short-term storage of electricity. The power of these alpine hut PV

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systems was between about 1.2 kWp and 2.5 kWp. Yet also some grid-connected projects were installed in the early 1990s mainly in schools in Vienna, St. Pölten and Linz-Leonding. The largest project at this time was at a technical school in St. Pölten with 20 kWp and a PV area of about 190 m^2. Other (small) autonomous projects were installed on the Danube island in Vienna and a fire-brigade building in Korneuburg. Table 1 provides a survey of the first Austrian BAPV-projects from 1985 to 1991.

The Austrian 200 kW rooftop programme was an initiative for practical testing of small, decentralised grid-connected PV systems in the years 1992 to 1999. The association of Austrian Electricity Companies (today Österreichs Energie), the Federal Ministry for Economic Affairs and the local energy supply companies organised this so-called *Breitentest* and provided funding for the systems. The Federal Ministry of Science and Transport commissioned an accompanying scientific research programme [1]. The investment costs of a photovoltaic system in 1992 were about €7300 per kWp, the average yield was determined for several systems in Upper Austria as about 825 kWh/kWp, for details see [2] and [3].

Sociological research entitled "Motives and obstacles for the spread of small decentralised photovoltaic systems", was carried out on behalf of the Ministry of Economic Affairs, see [4].

For the first time after this early phase of innovators and stand-alone systems, the Austrian photovoltaic market experienced an upsurge in 2003 when the green electricity bill (Ökostromgesetz) was passed. It collapsed again due to the 15 MW_{peak} capping of feed-in tariffs in 2004. The PV market stagnated from 2014 to 2018, after the absolute highest market diffusion in 2013 due to an extra funding process. After an increase in the following years (2019: 247 MW_{peak}, 2020: 340.8 MW_{peak}), there was a substantial increase in 2021. As shown in Fig. 1, PV plants with a total capacity of 739.7 MW_{peak} were installed in 2021, which represents a significant increase of 117% compared to 2020.

Hence, in 2021 the total amount of installed PV capacity in Austria was 2782.6 MWp. This represents an increase of 36.2%. As a consequence, the sum of electricity generated by PV plants amounted to about 2800 GWh in 2021 and lead to a reduction in CO_{2equ} emissions of about one million tons.

3 Current Types of PV Systems

Next it is shown how the type of PV system appears. It is split up in BIPV/BAPV, ground-mounted systems and grid-connected vs autonomous systems. Currently, about 0.3% of Austrian PV capacity is generated in autonomous stand-alone systems. Figure 2 shows the percentage of placement of newly installed PV capacity in 2021. It is obvious that the by far largest share of about 80% are building attached rooftop systems.

Table 1 Building-attached PV projects of early adopters in the 1980s and early 1990s in Austria

	Peak capacity (kWp)	Module area (m^2)	Battery size (Ah)	Grid-connected/ autonomous	Global insol (kWh/m^2)	Altitude (m)	Start of operation	Region
Alpine huts:								
Baumgartlalm	2.45 kWp	22.5 m^2	1750	Autonomous	1090	1402	1986	Salisbury
Kanzelhöhe	1.9 kWp	20 m^2	n.a.	Autonomous	1160	1500	1989	Carinthia
Hochleckenhaus	2 kWp	25 m^2	1000	Autonomous	1068	1573	1985	Upper Austria
Kesselbachfassung	1.5 kWp	12.8 m^2	1800	Autonomous	1293	1850	1989	Salisbury
Hofmannshütte	1.2 kWp	10 m^2	300	Autonomous	1344	2438	1988	Carinthia
Schools:								
HTL St. Pölten	20 kWp	190 m^2	150	Both[a]	1080	350	1989	Lower Austria
HTL Leonding	1.5 kWp	26 m^2	No	Grid-connected	1054	300	1990	Upper Austria
HTBL Wien X	10.4 kWp	84 m^2	No	Grid-connected	1090	244	1990	Vienna
Other buildings:								
Forsthaus Donauinsel	0.45 kWp	4.45 m^2	300	Autonomous	1090	203	1990	Vienna
FF Korneuburg	0.4 kWp	3.22 m^2	200	Autonomous	1051	167	1989	Lower Austria
SFH Obermayr	1.2 kWp	12 m^2	No	Grid-connected	1070	300	1989	Upper Austria

[a]This project is partly grid-connected and partly stand-alone

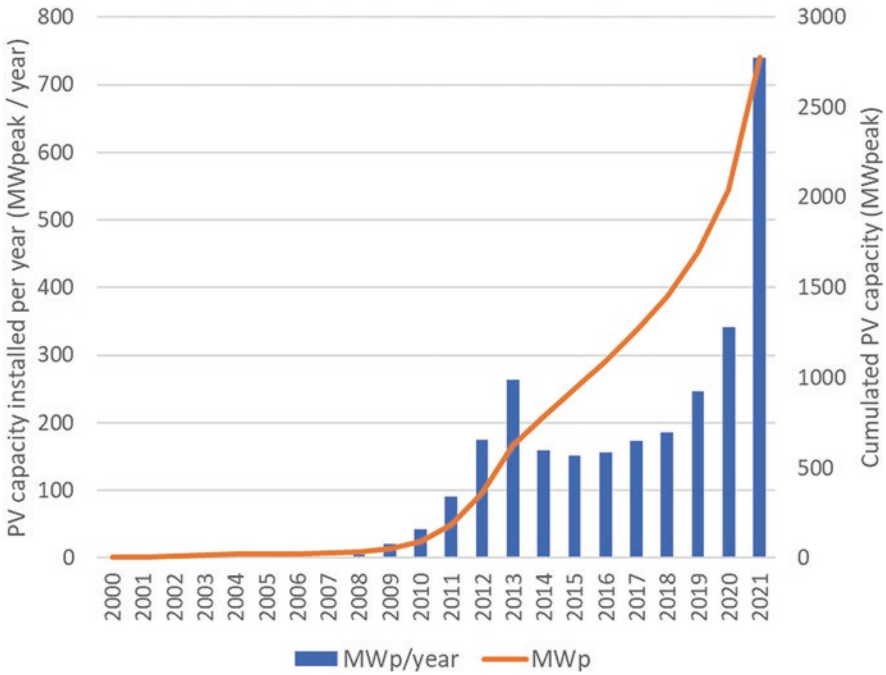

Fig. 1 Market development of photovoltaic systems installed in Austria until 2021. (Source: [5])

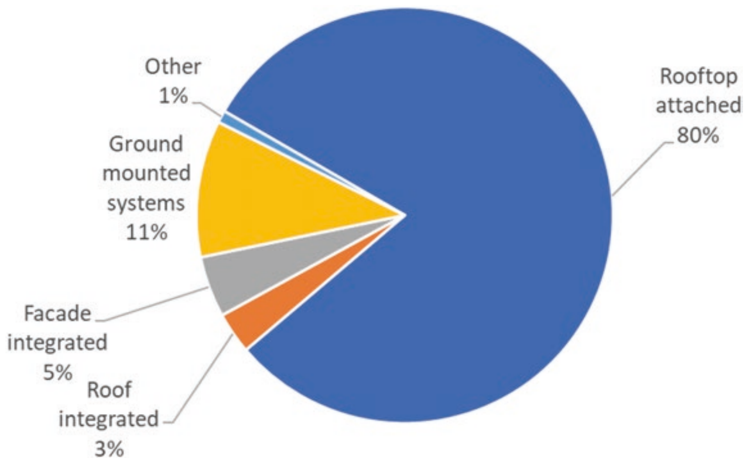

Fig. 2 Placement of photovoltaic systems installed in Austria in 2021. (Source: [5])

4 Meteorological Data of Austria

Regarding the solar insolation in Austria the distribution of the global insolation in kWh/m^2 is illustrated in Fig. 3. As seen the highest radiation figures – larger than 1300 kWh/m^2 – exist in the alpine areas on the higher mountains, where no significant residential areas exist. For the largest part of people living in populated areas the yearly insolation is between 1000 and 1200 kWh/m^2.

The monthly insolation for different areas in Austria is shown in Fig. 4. It can be seen that in the winter months the monthly insolation is between about 20 and 60 kWh/m^2month. In the summer months, the monthly insolation is between about 140 and 180 kWh/m^2month. Overall, the weighted average of solar insolation in settlements is about 1050 kWh/year.

5 Detailed Description of a Single Case Study for an Austrian Building-Integrated PV System

In this chapter, a specific case study of a roof-integrated 3 kW-PV-system in Enns, Upper Austria is described. Figure 5 depicts the roof integration of this case study during construction in 2002. The performances over the months of a specific year are illustrated in Fig. 6. This figure shows the monthly balances of PV generation, PV feed-in to the grid, PV own use and electricity taken from the public grid. It is clearly seen, that in the months April to August all of these parameters are more favourable from the PV systems point-of-view.

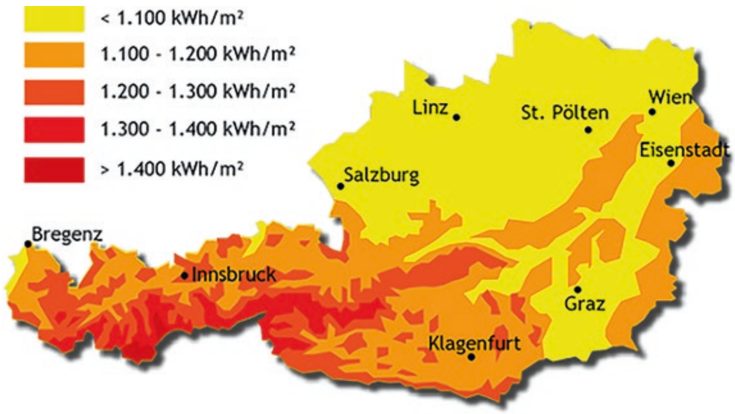

Fig. 3 Distribution of global insolation in Austria. (Source: [6])

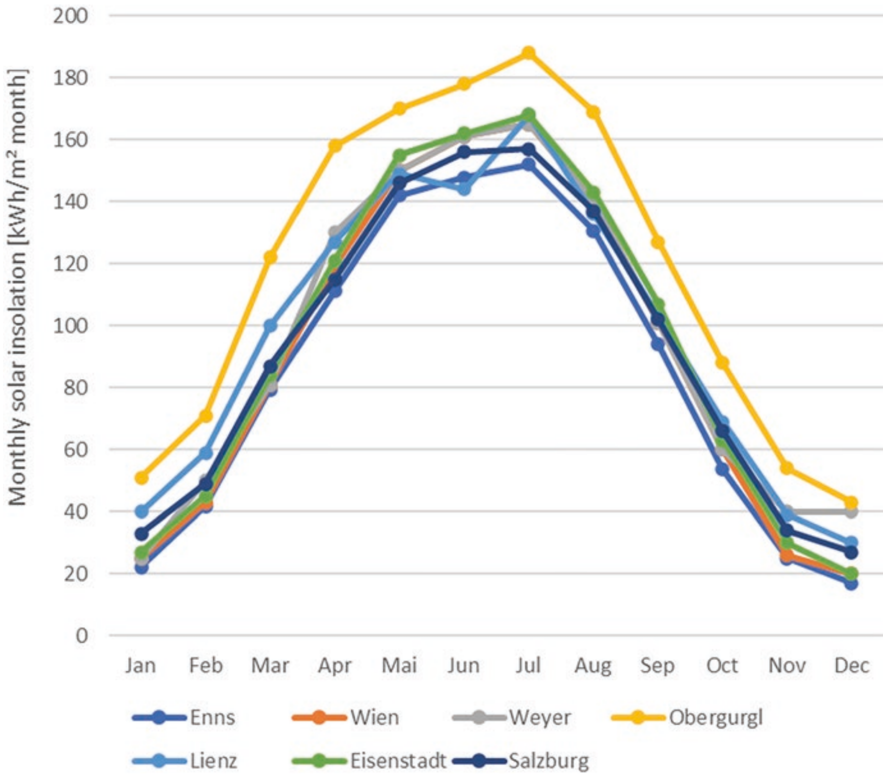

Fig. 4 Monthly insolation on the horizontal surface of selected villages in Austria. (Source: [7])

Fig. 5 Roof integration of the case study of a 3 kW-PV-system in Enns, Upper Austria

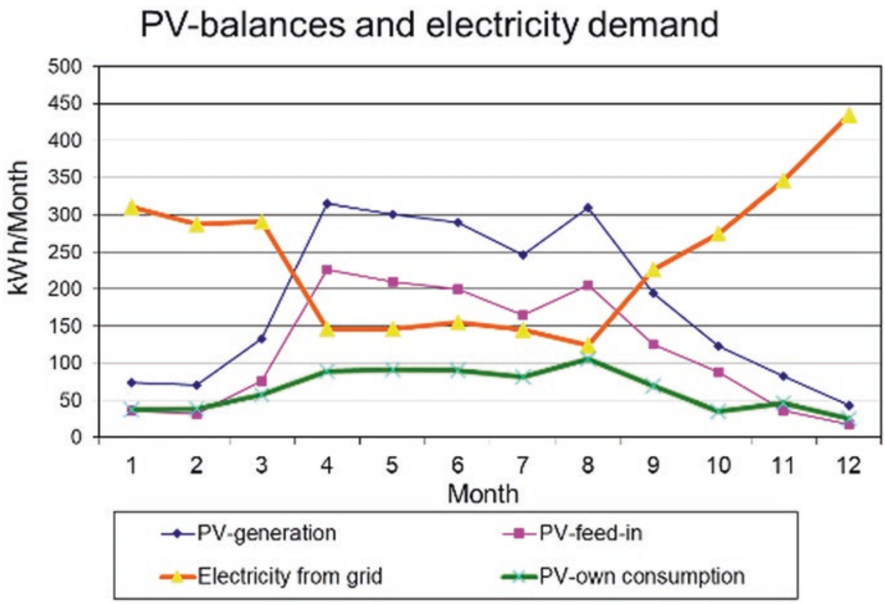

Fig. 6 Monthly balances of the case study of a 3 kW-PV-system in Enns, Upper Austria [5]

6 The Historical Development of Module and System Costs and the State of Grid Parity

The development of PV system prices of 5 kWpeak grid-connected plants between 2011 and 2021 is shown in Fig. 7. While in 2011 the average price was around 3000 EUR/kWpeak for the year 2021, a price of around 1543 EUR/kWpeak was surveyed for turnkey installed 5 kWpeak plants. This represents an increase in the average system price of a 5 kWpeak system of around 2.4% compared to 2020. As shown in Biermayr et al. 2022 [5] with increasing plant size (in relation to installed capacity), the specific system prices decrease. The share of the average module purchase price per kWpeak in the average complete system price of a 5 kWpeak system was about 30%, see Fig. 7.

In the years 2011 to 2016, falling module prices also led to falling prices for turnkey photovoltaic systems, see Fig. 7. This figure also shows that the module prices have decreased more than the system prices. Over the last few years system prices have hardly changed. In this respect, no significant additional cost reduction can be assumed in the coming years.

The development of grid parity of BAPV systems (3 kWp) in Austria from 2002 until 2022 is depicted in Fig. 8. The steepest decrease of the costs has been between 2009 and 2012 mainly because of the successful feed-in tariff programme in the neighbour country Germany which had a remarkable effect also on the Austrian market. Since about 2016 for small BAPV systems grid parity exists. Since this year own generation of PV electricity is (on average) cheaper than purchase from the grid.

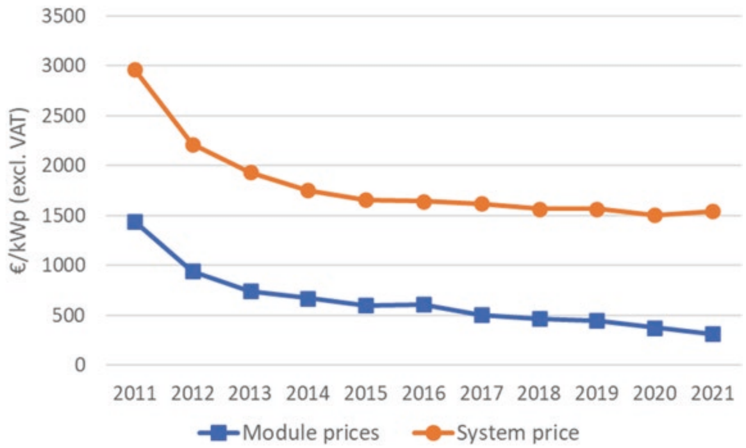

Fig. 7 Price development of modules and of systems (5 kWpeak grid-connected plants) per kWp between 2011 and 2021 (average figures, numbers excl. VAT)

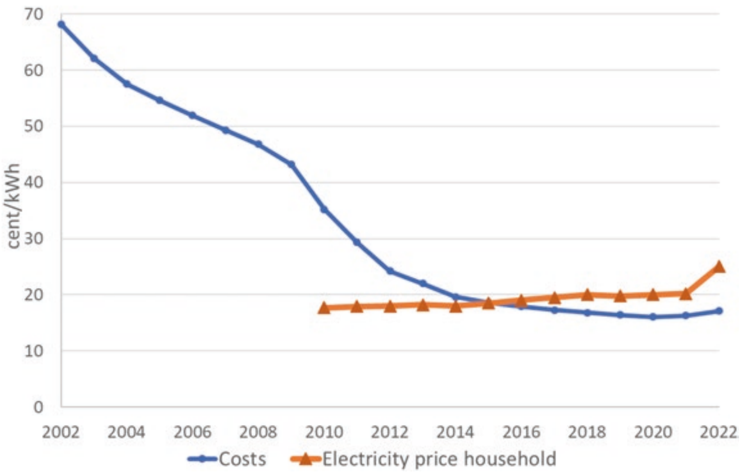

Fig. 8 Development of grid parity of BAPV systems (3 kWp) in Austria until 2022 (2022: preliminary numbers)

While up to about 2020 the grid-parity effect was driven by the cost decrease of the PV system, afterwards the electricity price increase was the major driving force.

7 Promotion of PV in Buildings in Austria

Historically, since the 1990s PV in buildings has been subsidised in Austria. The first comprehensive promotion programme was the 200 kWp-rooftop programme completed in 1996 [4]. The most recent subsidy programme for PV over the last

Table 2 Development of the feed-in tariff and the investment subsidy in Austria 2016 to 2021, [9]

Year	2016	2017	2018	2019	2020	2021
Feed-in tariff [ct/kWh]	8.24	7.91	7.91	7.67	7.67	7.06
Max. Investment subsidy [€/kWp]	375	250	250	250	250	250

decade consisted of a combined feed-in tariff and an investment grant whereby the subsidy is only granted for building systems between 5 kWp and 200 kWp, see [8]. The feed-in tariff is granted for 13 years. The development of the subsidy amounts for the feed-in tariffs as well as for the maximum investment subsidies are shown in Table 2 for the period 2016–2021, whereby the actual amount of the investment subsidy is always capped at 30% of the eligible investment costs.

Starting in 2018, applications for tariff subsidies were ranked according to self-supply percentage in the first week of application [9]. This measure resulted in more plants being subsidised, as the tariff subsidy for the respective photovoltaic plants was reduced by the percentage of self-supply. So far, it could be observed that the subsidy quotas for photovoltaics were partly allocated relatively quickly. For the year 2021, 5327 of 8998 applications could be considered in the quota according to the current status (as of 12.02.2021). Plants that had indicated a self-supply share of less than 17% could no longer be considered, as the quota of plants with a higher self-supply share was exhausted [9]. Also, in 2021, the waiting list for subsidies was reduced as soon as quotas became free due to the non-implementation of photovoltaic plants that originally received a subsidy commitment.

Since the 2017 amendment to the ÖSG, an additional funding line for pure investment funding for photovoltaic systems and electricity storage was introduced (§ 27a ÖSG 2012). This subsidy was endowed with €15 million annually for the years 2018 and 2019, with €9 million earmarked for photovoltaic systems and €6 million for electricity storage systems. This quota was increased to €36 million for the years 2020, 2021 and 2022, with €24 million primarily earmarked for the construction or expansion of photovoltaic systems [9]. Photovoltaic systems with a peak capacity of up to 100 kWp can be subsidised with a maximum of 250 €/kWp and a capacity of more than 100 kWp up to 500 kWp with 200 €/kWp. Photovoltaic systems on green areas are excluded from this support [9].

Likewise, the Climate and Energy Fund, federal provinces and individual municipalities award further limited or contingent investment subsidies for photovoltaic systems.

8 PV Storage Systems

In the year 2021 a total of 8755 PV storage systems were installed in Austria, representing an installed capacity of 130 MWh (net capacity) of storage. Of these, 72.8% received a subsidy and 27.2% were installed without subsidies. Figure 9 shows the market development of PV battery storage systems in Austria until 2021. Since

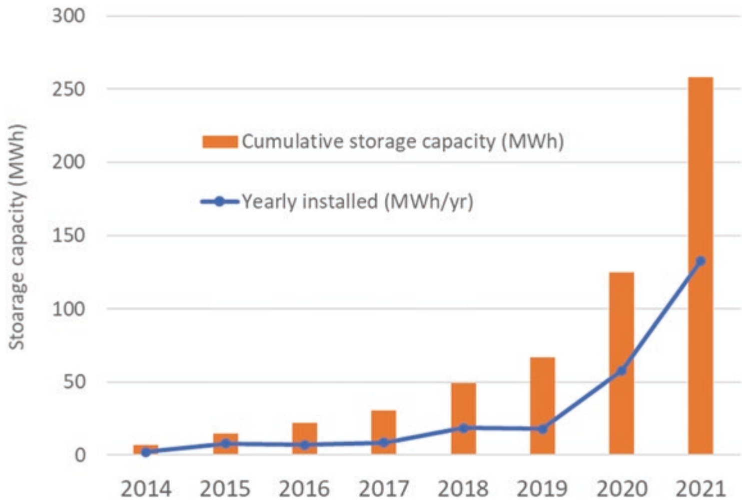

Fig. 9 Market development of PV battery storage systems in Austria until 2021. (Source [5])

2014, a total of 20,662 PV storage systems with a net capacity of about 250 MWh were installed.

The average system price for a PV battery storage system increased 12.7% from 914 EUR/kWh net capacity to 1030 EUR/kWh net capacity excl. VAT. A look at the purchasing prices shows a similar pattern. Also, the average purchasing price for a PV battery storage system increased by 13.3% from 539 EUR/kWh net capacity to 611 EUR/kWh net capacity.

9 Future Perspectives: Government and/or Local Authority Plans of Using PV in Buildings in Austria

Currently, in 2023 the major energy policy goal in Austria is set with 100% electricity by renewable energy sources by 2030 (balanced generation) and climate neutrality by 2040. In recent years, depending on the yearly situation, around 75% of electricity in Austria has been generated by renewable energy sources, mainly due to the high proportion of hydropower and the contributions from wind and biomass, as well as about 3% from photovoltaic systems. This level is intended to be increased up to 12 TWh by 2030 [7].

With the Renewable Energy Sources Expansion Act passed in summer 2021, the funding landscape for photovoltaic and electricity storage has changed. Beginning in 2022, either a market premium per kWh or an investment subsidy may be used to support a PV system. The market premium is the new subsidy for PV electricity fed into the grid and thus replaces the previously available feed-in tariff (current feed-in tariff contracts remain untouched).

The market premium is applicable for new PV systems or extensions greater than 10 kWp. It is a surcharge on the reference market value (roughly comparable to the average electricity price traded on the market). In the course of the application, the applicant must report electricity necessary to make his PV system profitable (takes place via a bid in the course of the general tendering round). The subsidy applications are ranked according to the registered electricity price (cents per kWh). This means that the applications are awarded, starting with the project with the lowest registered electricity price, until the funding volume of the tender is exhausted. A maximum value for the registered electricity price is specified by the legislature. Registered bids with a higher electricity price are invalid. The market premium is paid monthly over a period of 20 years. There are at least two auction rounds per year with a total annual auction volume of at least 700 MW.

Regarding BAPV and BIPV the investment-support is important. It is applicable to new PV systems and extensions up to 1000 kWp as well as electricity storage of up to 50 kWh (at least 0.5 kWh/kWp). The amount of the investment subsidy for PV systems varies with the size of the system. The amount of the investment subsidy for electricity storage is fixed. The minimum size of the electricity storage is linked to the performance of the PV system. A fixed subsidy is available only for PV systems up to 10 kWp.

The Austrian PV-Technology platform has been supported by Austrian government since 2012. This platform brings together about 30 Austrian-based industries and commercial entities, active in the production of PV relevant components and sub-components, as well as the relevant research community, in order to promote innovations. The transfer of latest scientific results to the industry by innovation workshops, trainee programs and conferences, joint national and international research projects, and other similar activities is part of the work program. The target of "PV Integration" now covers many different types of integration of PV into the building-, mobility- and agricultural sector [10].

Austria has several dedicated PV module producers, manufacturing standard PV modules as well as modules for specific building integration or solar-lighting. Other local producers in the value chain have a focus on high-quality materials in the module, the mounting or in the entire PV system including storage. The PV home market is predominately focusing on building adapted systems, larger ground-mounted PV systems are more and more installed, however legal restrictions and acceptance of the people are frequently limiting factors [10].

The fundamental development perspective of photovoltaics with a focus on the application areas of buildings/urban areas, mobility, agriculture and industry, is outlined in the Photovoltaic Technology Roadmap of the BMVIT from 2016 and 2018 [11] and [12]. This roadmap shows what can become possible if the framework conditions are adapted accordingly. Currently, it is no longer predominantly a question of costs that causes actual development to lag behind the roadmap paths, but rather a question of suitable framework conditions.

A major chance for PV is expected from local energy communities. These are just to be implemented by the new energy law, which fulfils the corresponding EU Renewable Energy directive. It foresees the distribution grid level as a boundary condition with some incentives, such as a reduced grid fee (only for the locally used electricity) and reduction in electricity taxes. Several hundred energy communities are under development with PV nearly always as the main electricity producer.

One of the strongest barriers is likely to be the priority for own use, which leads to suitable roofs not being fully utilised, or rarely used properties (holiday homes, etc.) not being used at all, as the expected production is often reduced to the possibility of self-used electricity in order to minimise the low remunerated feed-ins into the grid. The additional barrier of a levy for self-consumption for annual production greater than 25,000 kWh was removed in 2019, providing minor relief for commercial and industrial installations. The increased feed-in tariffs and the model of energy communities could alleviate this situation somewhat in the coming years, but long-term plannability would be desirable.

The planning and construction industry continue to cite bureaucratic barriers such as plant licenses, the need to obtain permits, and the often difficult-to-understand costs of connecting to the grid. Reduction to the bare essentials and increased transparency of the grid status on site and of grid expansion plans could help here. The role of E-Control as an arbitration body is essential in this context. The new Electricity Act has made things easier in this respect, for example with the flat-rate grid access fees.

Technological goals of the roadmap, such as an increased focus in Austria on BIPV, are currently only being pursued at a low level. Research funding for technological developments in photovoltaics in this promising niche must be expanded. The "1 Million PV Roofs Programme" mentioned in the most recent Austrian government programme of 2022 shows a way how building-related potentials should be used as a priority. Significant changes in the framework conditions should be made in the PV building sector (reducing the priority for own use by encouraging energy communities, introducing obligations, changing building regulations, etc.).

10 Conclusions

Today, there is still a huge potential for PV systems in buildings in Austria. Integration is important from two points of view, aesthetic and architectural. This brings new challenge for energy and local load management. It is expected that this approach will be accepted by population due to the local added value and local job creation.

One of the most important factors in the course of the strong upswing will be to expand the capacities in planning and construction. Accordingly, whereby the aspect of training and thus ensuring high quality in the trade of planners and installers but also in the field of architecture and construction will be central. For 2050, market shares of photovoltaic systems are expected to reach up to half of Austria's electricity demand, which will grow significantly by then. Whereby the continuous of training of planners and installers will be very important.

A discussion process coordinated with all key players would be conducive to generating a common picture for Austria to achieve climate neutrality. The further development of storage technologies and Power2X has an influence on the PV potentials that can be achieved. In addition to economic developments, social and societal developments and attitudes also influence the question of the necessary PV capacity to achieve a climate-neutral Austria.

The amount of PV area required for this will also be determined by the further development of efficiency levels.

Currently, the level on the market is about 20% while in the laboratory efficiencies of about 45% are reached. While it is unrealistic to reach this 45% for technologies available on the market in the coming years further increase in PV system efficiency of at least up to 25% should be achieved by 2050. This makes a remarkable decrease in terms of space requirement per unit of power by 2050s plausible. Nevertheless, almost all potentials available will have to be exhausted if 50% of the Austrian electricity demand should be covered by PV. Every suitable external surface in the built environment will contribute by default to electricity production through PV cells incorporated into façades, roof elements, windows, solar and noise protection devices, etc. Parking areas will be covered with PV as standard, PV systems will also provide shade in the agricultural sector in synergy with food production and thus reduce the need for irrigation, or promote biodiversity on fallow land. In mobility, which will then be almost exclusively electrically powered, photovoltaics may play an important role through direct integration in lightweight vehicles, by supplying the charging infrastructure and contributing to hydrogen production. Making the energy system more flexible by exploiting all load management potentials and by expanding storage facilities will be an important prerequisite for this transformation. The long-term demands for electricity grid infrastructure resulting from the dynamic market development of photovoltaics are dependent on the further innovations and cost of PV technologies, as well as the development of storage technologies and its costs including short- (e.g. batteries) and long-term storage (e.g. hydrogen).

Annex A (Table 3)

Table 3 Yearly installed PV capacity in Austria kWp per year

	Grid-connected kWp/year	Stand-alone kWp/yahr	Summe
1992	187	338	525
1993	159	85	244
1994	107	167	274
1995	133	165	298
1996	245	133	378
1997	365	104	469
1998	452	201	653

(continued)

Table 3 (continued)

	Grid-connected kWp/year	Stand-alone kWp/yahr	Summe
1999	541	200	741
2000	1030	256	1286
2001	1044	186	1230
2002	4094	127	4221
2003	6303	169	6472
2004	3755	514	4269
2005	2711	250	2961
2006	1290	274	1564
2007	2061	55	2116
2008	4553	133	4686
2009	19,961	248	20,209
2010	42,695	207	42,902
2011	90,984	690	91,674
2012	175,493	220	175,713
2013	262,621	468	263,089
2014	158,974	299	159,273
2015	151,806	46	151,852
2016	154,802	952	155,754
2017	172,479	476	172,955
2018	185,927	234	186,161
2019	246,461	500	246,961
2020	340,341	500	340,841
2021	739,168	500	739,668

Source: [5]

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Photovoltaic Systems: A Challenge or an Opportunity for the Polish Energy Sector During Its Transformation

Dorota Chwieduk

1 Introduction

To present the possibility of utilization of any renewable energy in any country, first it is necessary to describe the theoretical potential of such energy in specific geographical and local conditions [1]. When possible applications of photovoltaic systems are analyzed, it is necessary to present climatic conditions with a focus on the availability of solar energy. It should be underlined that analyzing only the average annual solar irradiation conditions, it may seem that the utilization of solar energy in Poland cannot be a very effective solution. However, relying only on averaged values does not reflect the dynamics of phenomena and does not show the real possibility of utilization of solar energy in various types of energy systems. Therefore, more detailed solar radiation data should be considered and analyzed to give clear recommendations for possible applications and modes of operation of the PV systems, and to predict the technical potential for these systems [2].

To answer a question formulated in the title of the chapter and decide if the application of photovoltaic systems is a challenge or an opportunity for the Polish energy sector during its transformation, it is good to describe the present state of the Polish energy sector. Then it is necessary to present briefly what is going in energy policy in the country. Different supporting mechanisms can always foster the introduction of new technologies into the energy market. In addition, a strong impulse for deployment of renewable energy technologies should be the need to comply with international legal regulations that strengthen the use of environmentally clean solutions, like photovoltaic technologies. In the case of European Union member states, the

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energy efficiency and clean environment policies have priority. As a result, the implementation of the set of quantitative and qualitative goals regarding the share of renewable energy in the energy consumption balance and the reduction of greenhouse gas emissions and other harmful compounds has got the highest importance.

The present state of application of the PV systems in Poland is presented in this chapter. At the beginning, most of the applications of PV systems have been seen on the micro-scale in single-family houses. However, recently the number of large PV power plants has been increasing continuously. The PV systems in the country are mainly on-grid systems without any storage. In the on-grid PV systems if electricity is not used at the same time when it is generated it has to be transferred to the grid. Such on-grid systems make up the vast majority of all operating PV systems in the country. This situation has been caused mainly by the national Act for the renewable energy systems [3], which was introduced several years ago and gave a support for such microsystems (theoretically with installed capacity less than 50 kW, but in reality of a few kW). According to this regulation the grid was used as a virtual storage. As a result the grid can be overloaded, when many micro-scale systems supply electricity at the same time. In the case of complex regional projects, when several dozen buildings are equipped with photovoltaic installations, the problem of overloading the old grids started to be quite serious. Consequently, their failure rate has increased. Outdated power grids are not able to accept a large amount of energy coming from many micro-installations at the same time. Therefore, there is an urgent need of upgrading not only the old inefficient power plants but also the grid.

2 Polish Climatic Conditions

The territory of the Republic of Poland is equal to 322,577 km^2, and the land area (including inland water) is 311,904 km^2. Poland is situated on the huge Northern European Plain, with the Baltic Sea in the north and Carpathian Mountains in the south. It lies open to the east and west. Poland is located between 49° and 54.5° N latitudes in a moderate climate zone influenced by both the Atlantic and Continental climate. Poland's location causes it to be affected by different atmospheric fronts that result in frequent heavy cloud formation. The averaged mean yearly temperature is equal to 7.9 °C, average annual global solar radiation is in range 950–1150 kWh/m^2. The annual solar hours are on average equal to 1600 that is about 18% of the total number of hours per year [4].

The climatic conditions of Poland are characterized by high variability over the time of the availability of solar radiation. The highest level of solar irradiation is in the northern part of the country, i.e., in Pomerania, and in the south-eastern part, i.e., the Lubelskie Region. The highest solar irradiation is in June when the night time is shortest and it lasts 7 hours and 14 minutes. The lowest irradiation is in December when the night time is longest and it lasts 16 hours and 20 minutes. In Warsaw (central Poland) solar insolation conditions are not very good and the average annual irradiation is about 962 kWh/m^2. The highest average monthly solar irradiation is in

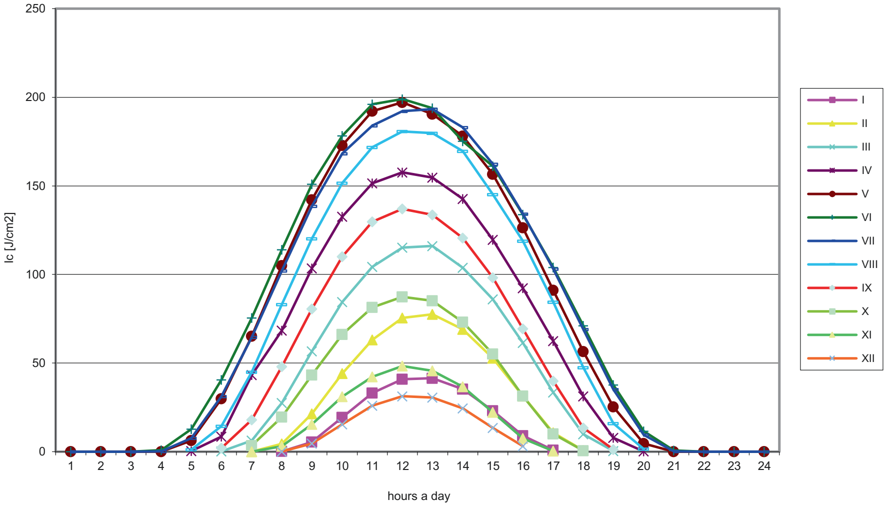

Fig. 1 Daily distribution of average hourly sums of global solar radiation for all months of an average year for Warsaw

June, like all over the country and equals to 160 kWh/m^2 and the lowest is in December and equals to 11 kWh/m^2 [5, 6]. Figure 1 presents daily distribution of average hourly sums of global solar radiation for all months of a year for Warsaw.

The huge difference in solar insolation conditions between winter and summer can be easily seen in Fig. 1. This very uneven distribution of solar radiation during a year is caused by the location of Poland, related to its latitude and location in the central-eastern Europe, where the moderate weather conditions are strongly influenced by the continental climate. Because of that, summers are relatively hot and winters cold. So large differences in daily distribution of solar radiation for all months of the averaged year indicate that inclination of a surface exposed to incident solar radiation is very important to assure the highest solar energy gains throughout a year.

The annual and diurnal course of solar radiation, as is well known, depends mainly on astronomical factors and atmosphere state [1, 7]. The most evident is the relation between the elevation of the Sun and the day length, the highest values being observed in summer, the lowest in winter months. Cloudiness and transparency of the atmosphere for the large dispersion of the diurnal and hourly values are mainly responsible. Figure 2 presents the Sun Charts for Warsaw and it is evident that the course of the charts is analogous to monthly distribution of average hourly sums of global solar radiation presented in Fig. 1.

The climatic conditions of Poland are characterized by high fluctuations of solar radiation availability in the time. About 80% of annual solar radiation is available from April to October and only 20% in the remaining 5 months. In winter, a day lasts 6–7 hours, while in summer it can be nearly 19 hours. Moreover, an average annual percentage of the direct solar radiation amounts only for 46%. In summer the

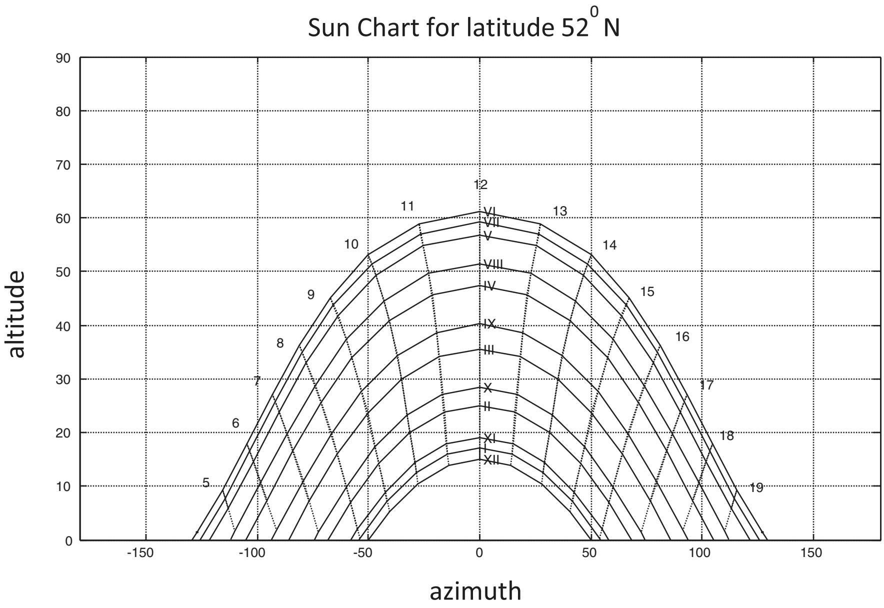

Fig. 2 Sun charts for Warsaw

share of direct radiation is higher and accounts for 56%, but in a period from November to January average diffuse radiation varies from 65% to 71%, and sometimes in December it can reach 80% [5].

Figure 3 shows daily distribution of average hourly sums of diffuse solar radiation on a horizontal surface for all months of a year for Warsaw. This figure can be compared with Fig. 1 to see how high is a share of diffuse solar radiation throughout the year and especially in winter months.

Figure 4 presents monthly distribution of mean monthly sums of global and diffuse solar radiation for an averaged year for Warsaw.

Generally, the surface orientation of any solar receiver normally corresponds to south in the southern hemisphere (and north in the southern hemisphere). However, with the increase in latitude describing the geographical location of a given place on the globe, the importance of the inclination of a surface receiving solar radiation increases. The position of the Sun relative to a surface exposed to incident solar radiation is described in terms of several spherical angles by appropriate relationships [1, 7]. The calculations of solar radiation incident on surfaces with different azimuth and inclination angles for Polish climatic conditions have been performed using such relationships and applying the average hourly solar radiation data for Warsaw [5].

In Poland the influence of inclination of the incident surface on solar irradiation level is evident for the whole year [8]. In summer the most irradiated surfaces have small inclination angles of 10–15°. If the slope is larger then the solar gains are smaller accordingly. Vertical surfaces (the maximum slope) experience a significant

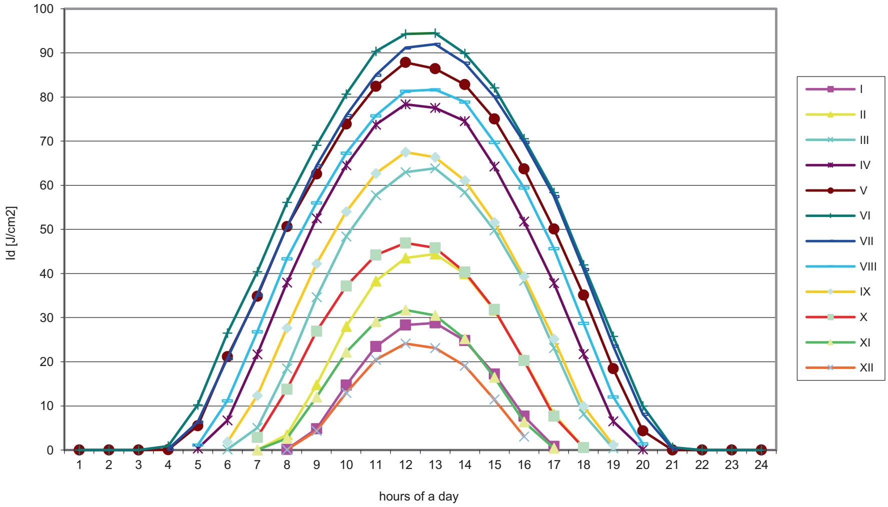

Fig. 3 Daily distribution of average hourly sums of diffuse solar radiation on a horizontal surface for months of a year for Warsaw

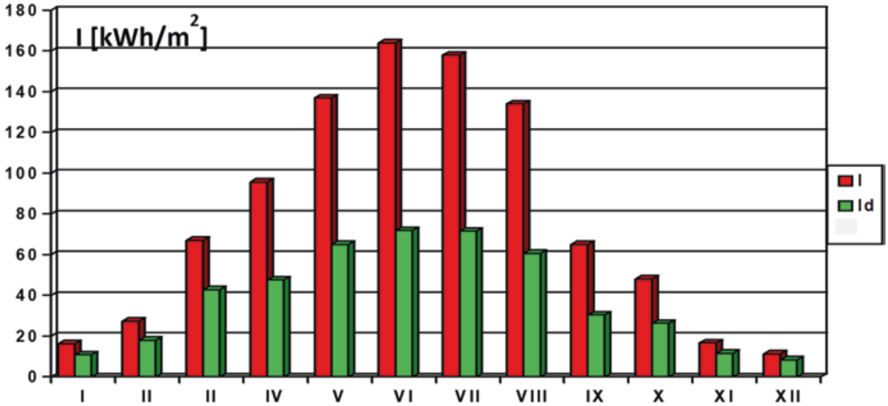

Fig. 4 Distribution of monthly sums of global solar radiation and diffuse radiation for Warsaw

reduction in received solar radiation and the summer solar energy peak, typical for horizontal surfaces, is reduced, especially for south-facing surfaces. In winter the situation is opposite and the best inclination is in the range 50°–70° directed to the south. In winter all surfaces facing south-east through north to south-west receive little solar irradiation, because they cannot see the direct component of solar radiation, what reduces a lot solar energy availability. Calculations carried out for the year-round solar radiation impact on any surface show that in the case of the isotropic solar radiation model the recommended inclination to receive maximum solar energy is equal to 30°, but in the case of using the anisotropic solar radiation model the inclination is 45°. The best orientation for the whole year operation of any solar receiver is for the azimuth angle of +15° (slightly to the west). This preferably for the West direction is particularly visible in the summer, when the most irradiated surfaces are directed to the south-west, and to a larger extent for azimuth angles from +30 to +90 degrees (the last one refers to the west direction). This phenomenon is caused by a larger share of direct radiation in the afternoon than the morning (in the morning there is often foggy, which weakens the global solar energy flux reaching the earth).

Thus knowing the structure of solar radiation in Poland, it is obvious that only the solar systems which use both direct and diffuse solar radiation can be effectively used in Polish solar radiation conditions. The PV modules use of course both forms of solar radiation, but insolation conditions create preferences for the use of PV installation connected directly to the grid or require the use of various forms and modes of energy storage.

Table 1 gives the mean monthly values of climatic parameters in Warsaw: ambient air temperature, wind velocity, rainfalls, solar radiation on horizontal surface with percentage of diffuse radiation [9]. It can be seen that the ambient air temperature during winter drops below zero, which forces the use of anti-freezing mixture instead of water in solar collector loops in solar thermal systems.

The availability of solar energy depends also on local conditions that can be influenced not only by the climatic parameters but also by local pollution conditions. Figure 5 presents the map of availability of solar energy in Poland that was prepared taking into account both climatic and environmental conditions connected mainly with pollution. The map in Fig. 5 was elaborated 30 years ago and presented in an expert evaluation report on availability of solar energy in the country [6]. That report was the first one official report on possible application of solar energy in the country. It dealt with solar thermal systems only, as photovoltaic technology was completely unknown in those days in the country (it was published 30 years ago). It was the first time when national energy report (solar energy namely) took into account environmental aspects presenting potential of utilization an energy technology. The report included a state of the environment, namely air pollution. The map in Fig. 5 was elaborated using the classification of country's regions regarding their environmental state. It is necessary to underline that this environmental situation has not been changed since then. Thus the best solar energy irradiation conditions

Table 1 The average climatic conditions in Warsaw

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Ambient temperature [°C]	−3.5	−2.6	1.2	7.8	13.8	17.3	19.1	18.2	13.9	8.1	3.0	−0.6
Average wind speed [m/s]	3.5	3.5	3.5	3.25	2.8	2.4	2.45	2.45	2.7	2.82	3.2	3.3
Rainfall [mm]	22	18	29	28	59	82	57	60	41	26	35	36
Solar monthly irradiation [MJ/m^2]	62	102	253	357	494	577	558	475	308	161	60	41
Diffuse radiation ratio [%]	66	65	53	50	47	42	44	44	46	54	67	71

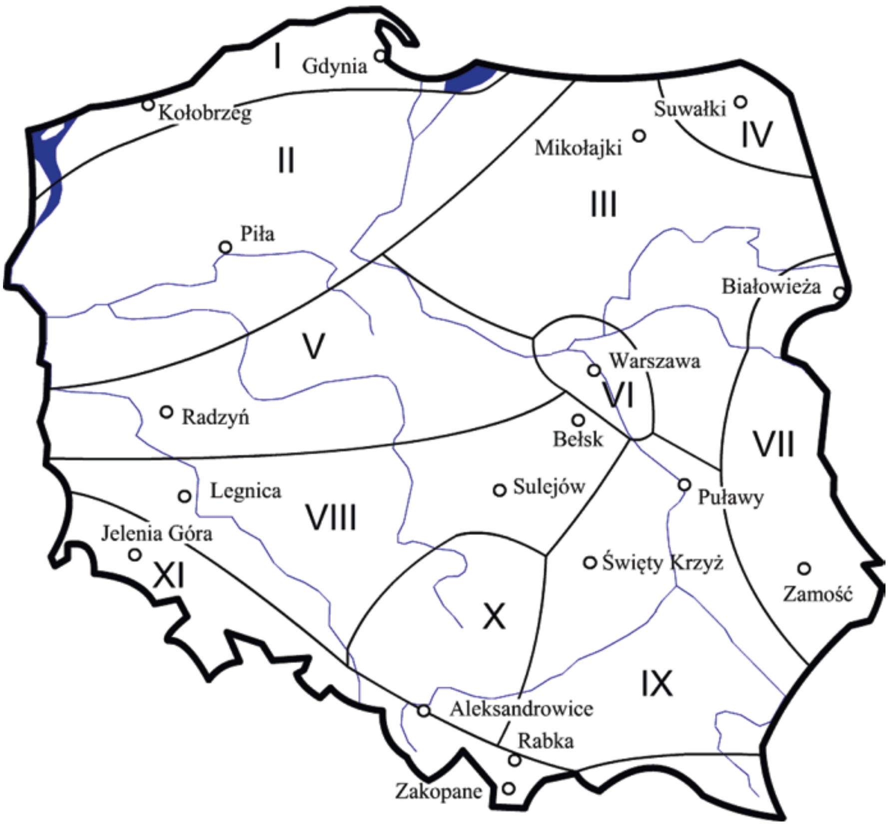

Fig. 5 Regions in Poland according to the availability of solar energy [6]

are in regions: Nadmorski (number I), Podlasko – Lubelski (number VII), Slasko – Mazowiecki (number VIII), and the worst in regions: Warszawski (number VI) and Gornoslaski (number X). The last one is an industrial region with mining and other heavy industry.

For many years not so much effort has been put to reduce environmental pollution. Fortunately, thanks to the accession to the European Union the environmental policy started being treated seriously. In the last years some strong actions have been undertaken, e.g., recently the Clean Air Program. Unluckily, the energy crises caused by the Russian war in Ukraine have stopped many of the important initiatives and actions for environment. Nowadays, the shortage of many fuels, mainly coal and gas can be seen. Due to the lack of these fuels, the government allowed to use traditional methods of burning solid fuels, including biomass of various origins and poor-quality coal, which until recently was forbidden to use at all.

The use of high-emission fuels is not only harmful to the environment and human health, but also significantly reduces the availability of solar radiation. High environmental pollution means the presence of dust in the atmosphere. Dust and pollution particles attach to other particles of the atmosphere, as a consequence, the number of large particles of highly polluted atmospheric aerosol increases. It can be added that traditionally atmospheric aerosol consists of liquid and solid substances, like pollen, bacteria, ashes, sea salt crystals, or soot. Photons of solar radiation, unable to penetrate directly to the earth's surface, are partly dispersed, but mainly absorbed by particles of polluted atmospheric aerosol. As a result of absorption, the internal energy of the molecules increases, which is then radiated as long-wave thermal radiation. As a consequence, the temperature of the atmosphere (hemisphere) increases, and the share of short-wave solar radiation decreases, so less solar radiation can be converted into a useful form of energy.

With reduced solar radiation flux, the ability of solar receivers to effectively gain solar energy is limited [10]. Useful energy gained by solar systems decreases, what is specially evident for photovoltaic modules. In case of solar thermal collectors their useful thermal energy does not drop so much, because apart from the short wave solar radiation they also utilize energy contained in the environment (solar collectors are not only solar receivers but heat exchangers as well). In case of photovoltaic modules, their electricity gains decrease significantly not only due to the lower level of short-wave solar radiation, but also because as the ambient air temperature increases, their efficiency decreases [11]. As a consequence, the power gained decreases and specific cooling methods are recommended to be used [12, 13]. Therefore, in many heavily polluted places on earth, mainly cities and industrialized areas, despite their geographical location (low latitudes), the energy gains of solar photovoltaic installations are not very high, often comparable to those obtained by PV installations operating at much higher latitudes.

3 The Background for Deployment of the PV Systems in the Country

The Past State of the Energy Sector and Its Main Energy Fuel Dependence

To present the background for application of photovoltaic technologies in any country it is necessary to analyze not only climatic conditions, but a state of the energy sector in the country and its main energy fuel dependence.

At the beginning of this chapter the past energy economy of Poland is briefly described to show how it is difficult to develop the energy transformation through the application of distributed energy sources based on renewables, like PV plants, if a country has used to be strongly dependent on one own fossil fuel and the use of which has been centralized for decades. Any changes to such a centralized system carry a high risk, mainly economic, but very often social, too, and not many politicians, decision decision-makers want to take the risk.

In Poland the prevailing view in the communistic energy policy in the last decades of the twentieth century was that the best form of development was to maintain the status quo when everything was planned and managed centrally. No actions, especially no energy transformation activities gave no risk. It was not thought at that time that the existing state of energy generation and transmission sector could not last forever. Maintenance and modernization activities were not a priority. The status quo situation led to the rapid aging of both the power generation blocks themselves and the power grids. What currently results in the lack of the possibility of their cooperation with modern renewable energy systems, when energy generation has a stochastic character, so it can change rapidly in time in unpredictable way, particularly when wind and solar energy are utilized.

The beginning of the economy transition started at the end of twentieth century in Poland, when Poland started to implement its accession plan to become a member of the European Union. In those days the stress was put on reduction of energy intensity of national product mainly through the ownership transformations in the national economy. Then to reduce energy consumption many energy-intensive industrial plants were simply closed down. In those years the economy showed a high dependence on coal (hard and brown), which came from its own domestic resources. The consumption of coal corresponded to 70% of the primary energy. The country was characterized by outstanding position of coal in the energy supply sector for decades. In the electricity generation sector it was especially evident. In those days in electricity production and supply Poland was practically self-sufficient. Coal (hard and brown) in 97% used to be a source of electricity (3% contribution was from hydro energy). The Polish power generation sector was and still is the largest in Central and Eastern Europe. About 97% of Polish electricity sector was generated in 55 coal power plants, of which 33 were combined heat and power (cogeneration CHP) plants [14]. So it is a huge challenge to transform such huge centralized energy sector based on one fossil fuel to distributed energy sources based on solar energy [15], which is widely recognized in the country as unstable and uncertain form of energy in meeting the needs of users.

The central heat supply played and still plays an important role in the Polish energy economy. Heat has been generated in the Combined Heat and Power stations and in Heat (only) Plants since decades. The fuel structure of direct consumption has not been changing significantly for many years. The large cities and factories have been supplied by thermal electric power stations using coal. However, in the new century, the new trends have been noticed, the slightly reduction of solid fuels share (hard and brown coal) to favor of liquid and gaseous fuels (gas, oil), which were imported ones.

District heating used to be and still is a major component of Poland's energy infrastructure. District heating networks supply more than half of Poland's residential heating needs, with 75% in urban areas. The largest district heating network in Europe and the second in the world is in Warsaw, where its total length is 1760 km [16].

It can be easily guessed, that in such economy based on coal, it was no interest in the application of renewables, especially that energy generation and supply sector was highly centralized and it was no place for energy-distributed systems like those based on renewables. However, the situation began to change with Poland's accession to the European Union in May 2004 and since then aspects of reconstruction of energy sector have become a must. As a result the energy efficiency and clean environment policies became more and more important and visible in the energy economy of the country.

And so the Polish government, willy-nilly, had to start creating conditions for the development of renewable energy technologies and their market. Initially, support for renewable energy was more theoretical than practical. Officially, it was declared necessary to increase the share of renewable energy in the country's fuel and primary energy balance, but no legal framework and financial support mechanisms were created to strengthen the role of renewable energy. In particular, there were great concerns about solar energy, as it was widely believed that economically viable energy investments were not possible under Polish climatic conditions. For many years, such a view resulted from the provisions of the National Strategy for the Development of RES, published in the late 1990s [17]. The strategy was adopted by the government and parliament of the country. This document, although it was supposed to promote the development of renewable energy, in fact only supported the use of biomass and contributed to a significant suspension of the development and use of other renewable energy sources for years. It was especially evident in case of photovoltaics. The document stated, among others, that in Polish conditions the use of photovoltaic systems would not be economically viable for at least the next 40 years. Unfortunately, often the lack of knowledge and purely vested interests can lead to create significant obstacles in the development of a given technology and its implementation in practice. It was just a case of photovoltaic technologies. The opinion that the use of PV technology is unprofitable is often visible in contemporary legal documents, such as the basic document for the development of the energy sector in the country, which is the Polish Energy Policy. Such an attitude of disbelief in the widespread effective use of solar energy through the use of photovoltaic technologies is still visible in new strategic government documents, for example, in the latest Polish Energy Policy – PEP until the year 2040 [18]. It can be said that photovoltaics has developed against all odds, and society itself has played an important role in the growth of PV applications.

Fortunately for utilization of solar photovoltaic systems, as well as other renewable energy technologies, in accordance with the European Union energy policy Polish energy sector had to change and move to environmentally friendly technologies. At the beginning, the best way to do that was seen mainly as to be focused on energy efficiency, what of course is always necessary and gives the base for effective utilization of modern renewable energy technologies. Luckily, after several years it turned out that without utilization of renewable energies, it is not possible to reduce energy consumption and environmental pollution highly enough.

4 The Transformation of the Energy Sector Thanks to Accession to European Union

The importance of energy conservation and necessity of using renewables have been indicated in the EU Directives, mainly *Directive of the European Parliament and of the Council on the energy performance of buildings* [19], *Directive of the European Parliament and of the Council on the Energy Efficiency* [20] and *Directive of the European Parliament and of the Council on the promotion of renewable energies* [21]. All those directives support the implementation of new, innovative technologies and modern options of energy conservation, enhancing the use of renewables. They have paid an important role for development of modern energy-saving distributed energy systems, including application of solar systems, and in such a way they help to intensify the pace of the energy transformation process.

Thanks to that legal framework introduced by the directives, reduction of energy consumption and in consequence the environmental pollution have become a priority of the Polish energy economy. However, as presented above, the transformation of large, centralized energy sector into distributed energy sector with energy systems of various sizes and based on different energy sources, mainly renewable energy sources, is not easy, and often seems to be practically impossible for many decision-makers. But thanks to the EU energy policy measures of rational use of energy, which combine energy efficiency from supply and demand sides the utilization of renewables, have been supported by financing mechanisms and regulative framework.

As mentioned before, the basic legal framework for the implementation of renewable energy in the country has been included in the Renewable Energy Act [4]. The Act went into force in the year 2015 and since then it has been amended dozens of times, the most of all national laws (the last change was in June 2022). This Act defines, among others: rules and conditions for conducting activities in the field of electricity generation from renewable energy sources, rules for the implementation of the national action plan in the field of energy from renewable sources or rules for international cooperation in the field of renewable energy sources and joint investment projects. The Act has created a good background for the development of micro-energy systems mainly photovoltaics. It defined the role of the prosumer and created the framework for his activity.

The Act formulated the modes of operation of the prosumer on the domestic energy market, giving huge regulatory support to micro-installations up to the installed capacity of 40 kW initially, and recently 50 kW. Consequently, the Act has given the background to introduce very beneficial financial mechanism for the end user, which is the prosumer. According to this Act till April 2022 the prosumers generating electricity in own PV systems could have used the grid as a virtual energy storage operating with 80% of efficiency. The Act introduced an energy billing system based on net metering and semi-annual billing, with the aforementioned treatment of the grid as an energy store. Such a legal situation caused a huge interest among inhabitants of small cities, villages, suburbs of the cities in investing in micro

Fig. 6 Examples of micro PV systems installed on a roof of a single-family house (right) and small hotel (left)

PV installations, which began to appear like mushrooms after the rain. Examples of such micro PV systems installed on a roof of a single-family house (right) and small hotel (left) are presented in Fig. 6. However, this scheme is not applied anymore. Currently, for new prosumers, the network is no longer treated as an energy store and individual prosumer contracts with energy distribution companies are concluded on the basis of a generally applicable price list.

The introduced regulatory scheme has been enhanced by specific energy–efficiency support mechanisms for renewables, like *Clean Air* or *My current,* which are national or regional projects managed by the National Fund for Environment Protection and Natural Resources or by appropriate regional Funds. They offer special grants and loans for investments in clean energy technologies. The highest share of such support is given to photovoltaics. Despite the fact that new contracts concluded by prosumers with energy distribution companies no longer have the option of using the grid as an energy storage, the number of new investments in photovoltaic micro-installations is still growing rapidly.

Ordinary inhabitants have started to invest in PV systems to be not only energy consumers but also the energy producers to have own energy source and to be responsible not only for the energy consumption, but also generation. The introduced support mechanisms helped to achieve significant benefits in energy consumption, and as a consequence, financial savings. This has contributed to the dissemination of photovoltaic technologies and the development of the domestic photovoltaic market in the country. Nowadays the name of prosumers has become popular and exists in the official regulation language, as has been mentioned before. It should be underlined that nowadays the photovoltaic systems are seen as a huge opportunity for Polish residents to be energy independent from the centralized energy systems and generate on their own the clean energy. It can be said that thanks to the Polish prosumers and their interest in application of the PV technologies, the energy sector has started undergoing its important transformation into decentralized decarbonized energy systems, mainly photovoltaic ones.

In case of large-scale photovoltaic systems the support has been stimulated by two mechanisms: certificates of origin and the auction system. Certificates of origin were introduced as a result of the implementation of the energy efficiency policy (and the EU Directive on energy efficiency [20]). However, they have not caused a huge deployment of the large Photovoltaic systems, even though the property rights of such green certificates could have been and still can be traded on the Polish Power Exchange stock. As a result of the introduction of the Renewable Energy Sources Act since 2016, the certificates have been gradually replaced by the auction systems. Significant changes to this support scheme were made through the amendments of the Act in the last years and development of a large-scale PV systems has been fostered a lot.

The Polish government has approved Poland's energy policy until 2040 (PEP2040) [18]. This document sets the framework for the energy transformation in the country, which is a priority if decarbonization of the Polish economy is to be achieved by the year 2050. It can be mentioned that there were a few years of delay in issuing this strategic document regarding the Polish energy sector, what is not good for the effective development of the energy sector. The document PEP 2040 presents solutions to meet EU climate and energy goals to assure the energy transition toward a zero-emissions economy. In the year 2030, a maximum 56% share of coal-fired power generation should be achieved and complete exit of such plants is expected in 2049. In the year 2030, a minimum 23% share of renewable energy in final energy consumption is planned.

According to PEP2040 by 2040, the heating needs of all households will be covered by district heat supply systems and zero- or low-emission individual energy systems. The latter are defined as systems using heat pumps or electricity. It can be seen that this is a turn toward the electrification of heating sector, where photovoltaics can play an important role. However, it is not mentioned in this strategic document.

It is expected that expansion of the new generation and network infrastructure will lead to the creation of an almost new power system by 2040, based largely on zero-emission sources. This is to be achieved thanks to the development of photovoltaics and offshore wind farms. However, the priority is given to the offshore wind farms due to "their greatest prospects for development". This last statement raises doubts among energy experts, especially those dealing with renewable energy, because the technology is relatively new in the world, and in Poland it has not been used at all so far. It is not good to rely only on imported technology, not to have own experts specialized in that field, and the logistic could be a huge challenge.

Decision-makers all the time do not believe in photovoltaics. According to the PEP2040, it is expected that in the year 2030 installed capacity of all PV plants will be 5–7 GW and in the year 2040 it will 10–16 GW. The document was published in April 2021. In that time the installed capacity of PV systems was already more than 5 GW, so it looks like the authors of that strategic document did not know what was going in the renewable energy sector in the country (they expected such capacity to be reached in 2030!).

Nowadays, the situation with the PV sector looks much better than it was ever expected by any creators of the Polish energy policy. The installed capacity of the PV systems has nearly fully reached the goal declared by the PEP2040 to be in 2040. At the end of 2022 it was at level of 12 GW, while the installed capacity in all generation sources in Poland reached 60 GW. Renewable energy sources accounted for almost 38% (22.6 GW). In the RES sector, photovoltaics ranks first with approximately 54% of the installed capacity [22]. A decade ago, at the end of 2012 the installed capacity in photovoltaics in Poland was 1.5 MW. At the end of 2019 it increased up to 1.6 GW (more than 10 times). Forecasts indicate that the closest milestone of 20 GW installed in PV in Poland will be reached by 2025 [23] (so it is much higher than the goal indicated by the PEP2040 to be reached in 2040).

The last 10 years of deployment of the PV technology are called "the golden decade of Polish photovoltaics". In recent years, the prices of PV installations have changed significantly and have become widely available on the domestic market. Nowadays, PV systems are one of the most acceptable new energy technologies. Solar thermal collectors take the first place, even if they are not so popular nowadays. Quite often new photovoltaic installations next to the previously installed solar thermal collectors can be seen, as it is presented in Fig. 7. Solar thermal collectors are located on a roof of the building, which belongs to the ski lift station. A light roofing structure is attached to the building and photovoltaic modules are

Fig. 7 New photovoltaic installations next to the previously installed solar thermal collectors on a building of the ski lift center

installed on it. The PV installation also represents the micro-system and operates on works on the principles of a prosumer installation.

Renewable energy market in Poland is dominated by photovoltaics. And photovoltaics is dominated by micro-scale systems, thanks to the investment boom that has been going on for several recent years, which was helped by support mechanisms for prosumers. At the end of August 2022, there were 1,132,259 renewable energy prosumers in Poland, of which almost 1,132,000 had photovoltaic installations. The installed capacity in RES micro-installations amounted to 8262.49 MW and was dominated by photovoltaic installations, whose capacity amounted to as much as 8259.43 MW [23]. Prosumers account for 80% of the installed capacity in photovoltaics and their role on the renewable energy market is undeniable in Poland.

5 Application of PV Systems in Poland

As mentioned before, the support mechanisms for micro-installations and individual solar energy prosumers were introduced in recent years and they have led to a huge increase in the number of photovoltaic installations with power from a few to a dozen or so kW, which were and are installed mainly in single-family houses. Photovoltaic systems at the micro scale are relatively easy to be installed, operate, and maintain. Their costs have been reduced significantly, while their efficiencies have been increased. Currently, there are many different technologies available on the market. However, the majority belongs to mono and polycrystalline silicon technologies. The photovoltaic market is currently dominated by micro-installations in the form of BAPV – Building Attached Photovoltaic systems (see Fig. 8).

Figure 8 presents Building Attached Photovoltaic system during its installation on the roof of the building. There are some PV modules already installed on the left side of the roof, while on the right side of the roof there is only the metal construction for further mounting PV modules on the roof. Quite often photovoltaic modules cannot be directly installed on a roof as BAPV systems and then they can be settled on the ground as the detached structures, see Fig. 9, or in the case of horizontal roofs can be placed on them on support mounting constructions, as shown in Fig. 10.

The concept of utilization of renewables in households is mostly based on the implementation of solar energy and heat pumps. This concept refers to new buildings, as well as old buildings under refurbishment. In such buildings the demand for heating (eventually for cooling) and lighting is reduced substantially. The energy is supplied to a building or it is generated in a building with high efficiency with high share of utilization of renewable energy sources. Then the final use of energy by residents is accomplished in effective way. As a result of the application of high thermal standards of the building envelope and its complementarity with the surrounding, and effective operation of energy devices, systems and receivers and smart energy management systems in a building, the final and primary energy consumption in buildings has been significantly reduced. Prosumers using the support system in which the grid is treated as a virtual storage of electrical energy can be

Fig. 8 Single-family house with BAPV system during its installation on the roof of the building

Fig. 9 PV modules settled on the ground as detached structures

practically self-sufficient. This is possible when the PV system is well dimensioned for the solar radiation conditions and the use of the solar energy gained. The best result in being energy self-sufficient is to use heat pump coupled with the PV system operation.

Fig. 10 PV modules placed on horizontal roof on support constructions

In the beginning of this century the solar energy applications in residential and tertiary sectors were connected only with the solar thermal active systems. Those systems were mostly used in the form of low-temperature heating systems with flat plate solar collectors, and later also with vacuum tube collectors. They supplied heat to Domestic Hot Water systems. Later the solar heating systems have been coupled with heat pumps to accomplish total heating needs for DHW and space heating. In those days application of solar thermal systems and heat pumps was not supported by any official regulations and supporting mechanisms. It was just a will of people to have own energy systems. In those years photovoltaic systems were rather completely unknown in the country and in addition they were very expensive.

It is necessary to underline that inclination of a surface exposed to incident solar radiation is very important to assure the high solar energy gains, what has been presented in the first part of this chapter, when climatic conditions were described. The large slope is especially recommended for the application of solar receivers operating in mountains in winter. Usually, the best slope for the annual operation of PV modules or solar collectors is in range 30–45°. In mountains it can be even more because of the snow, which can easily melt on a surface of larger inclination (see Fig. 11) than on a surface of small slope (see Fig. 12). It is necessary to mention, that both pictures were made at the same time in January in Polish mountains and two places are located in a distance of 100 m.

The support mechanisms for micro-installations and individual solar energy prosumers were introduced in recent years and they have led to a huge increase in the number of photovoltaic installations with power from a few to a dozen or so kW, which were and are installed mainly in single-family houses, as already presented. However, the interest in investing in PV systems in multifamily buildings is increasing [24]. This is mainly caused by the increase of electricity prices and new support mechanism for such buildings. Nowadays, grants are available for renewable energy projects (RES projects). They offer the support in the amount of 50% costs of purchase, assembly, construction, or modernization of a RES installation in a

Fig. 11 PV system located on a high slope of the hill in January in Polish mountains

Fig. 12 PV system located on a small slope of the hill in January in Polish mountains

multi-family building, with the upper limit of the support granted not specified. The PV systems are mainly mounted on roofs as the Building Attached Photovoltaic systems, when a roof is inclined, or they are attached to the supporting structures on horizontal roofs.

Up to now rather very rarely the BIPV – Building Integrated PhotoVoltaic systems are used. Some of them can be met in public buildings, as shown in Fig. 13. Sometimes the BIPV systems apply the PV technology called glass–to-glass, where they play an important role not only as electrical energy generator but also are main elements of a daylighting system and have a function of solar shading devices, as presented in Fig. 14.

Large-scale systems are usually built as photovoltaic farms with power from one to hundreds megawatts in the countryside. Nowadays, the largest photovoltaic farm with a capacity of 204 MW is located in Zwartów in Pomerania. It was commissioned in September 2022. The second place is occupied by the PV farm in Brudzewo with power of 70 MW. The third largest farm is in Witnica and has a capacity of

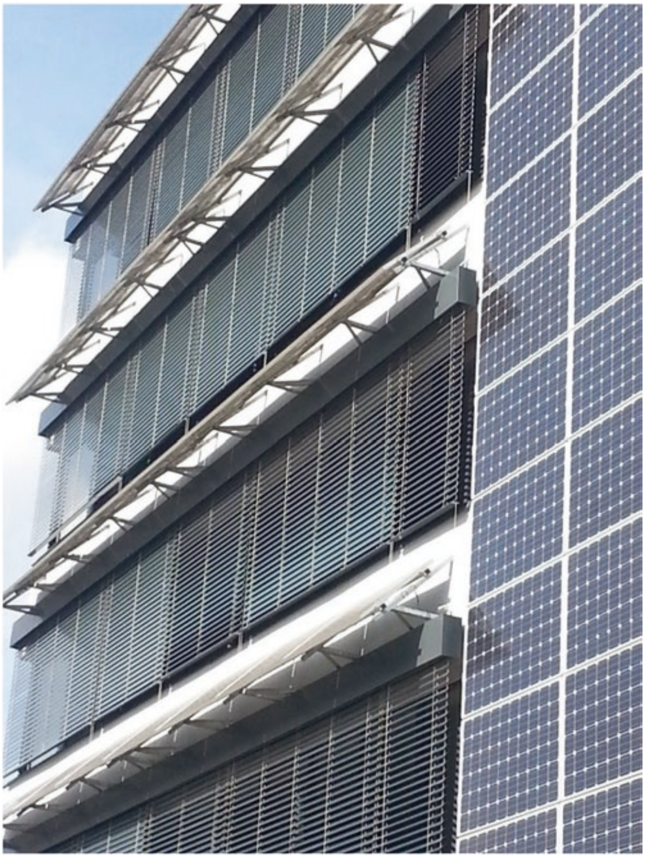

Fig. 13 BIPV – Building Integrated PV systems as cladding and solar shading devices

Fig. 14 BIPV system in a form of glass–to-glass technology

64 MW. All of them belong to different energy groups. Throughout the last year (2022) 362,159 new photovoltaic plants with a total capacity of 4269.8 MW were built. According to the Polish Power Grid company data the last year record was broken on September 7, when at 1 p.m. the photovoltaic plants operated with a capacity of 6711.3 MW. In August, 14,147 GWh of electricity was produced in Poland, of which 11,575 GWh (81%) was provided by conventional power plants, and 2477 GWh (17%) by RES [22]. Photovoltaics covered approximately 8% of energy demand in that months, which was characterized by the best solar irradiation conditions in the last year.

There are many plans for new investments in large-scale PV plants. New investments in photovoltaic installations with a capacity of several megawatts in areas that must undergo intensive reclamation process are characteristic. These include areas of former garbage dumps, mine heaps, areas after opencast lignite mining, etc. Here is great potential for such an environmental transformation of areas related to the extraction of fossil fuels and the place of their storage, into new environmentally clean areas intended for generating energy in a zero-emission way thanks to investments in PV installations constructed and operated in these areas. Nowadays, energy generation and distribution company implementing a photovoltaic farm in Mysłowice with a target capacity of 100 MW can be an example of such a modern ecological energy transition. Over 60,000 PV modules have already been installed in the reclaimed coal combustion waste landfill area, which is 73% planned installations. As a result, the farm is expected to provide 39,000 MWh of green energy annually, which will help reduce carbon dioxide (CO_2) emissions by 30,000 tons compared to generation in coal-fired plants [25].

6 Summary and Final Remarks

After the communist political system, the country underwent a systemic transformation. However, the transformation of energy sector goes very slowly. After many years of centralized energy economy based on using coal as basic raw material and lack of concern for the energy and environment conservation, the transition to distributed energy systems based on renewable energy sources presents a huge challenge for the energy sector. The situation of urban heating networks and centralized energy systems is especially difficult in large cities. Therefore, the energy transformation in big urban areas should be implemented gradually. The easiest way should be to develop distributed small renewable energy systems cooperating with the national power grid and step by step substitute the central district heating systems by such small RES systems where the photovoltaics can pay the basic role of energy generation system.

It should be underlined that utilization of renewables is well perceived by society. It is the previous monopolistic energy economy that causes the society to want to liberate itself from these old centrally controlled and managed energy structures. People strive to have their own independent energy systems and sources. And it is renewable energy that gives them such an opportunity. Therefore, from the beginning of the implementation of the new energy policy focused on energy efficiency and taking into account the possibility of using new renewable energy sources, it is the role of the inhabitants of cities and villages in the pursuit of energy independence and the use of their own renewable energy resources. Thus the regular energy consumers have become the main initiators to implement the renewable energy technologies.

Poland declared and confirmed in the national Energy Policy till 2040 [3] that the share of renewable energy for the heating and cooling will increase by 1.1% annually. For several dozen years, the central heating system provided easy and cheap access to heat for the entire city. This advantage of a very centralized operation of the heating system is now becoming the main obstacle in the fast, and energy and economic efficient transition to a modern low-temperature heating system of the fourth or fifth generation, where the heat pumps will be the main heating devices and they will be powered by the electricity generated by the photovoltaic and wind farms, as the process of electrification of the heat supply system is developing.

Concluding it can be said, that application of photovoltaic systems is for sure a challenge for the Polish energy sector, but the same time it is huge opportunity for its green transformation, going to zero-emission economy of the country so much experienced for many years by centralized energy sector based on utilization of fossil fuels applied with low efficiency of their conversion into final energy. It must be underlined, that any transition of economy of a country cannot go without acceptance of the society. The role of society in their support for investment in environmentally clean energy technologies can be seen, especially among young people. This is particularly reflected in small investments in own micro PV systems. The will of ordinary people to buy and use the PV systems is of course also related to the financial benefits that they can achieve thanks to the reduction in consumption of conventional energy based on fossil fuels, which costs a lot nowadays.

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Wind Tunnel Tests for BAPV Installations in Patagonia, Argentina

Carlos Víctor Manuel Labriola and Jorge Lassig

1 Meteorological Data of Argentina and Particularly of Comahue Region

Solar resource is excellent from the north to the center of west Argentina. The best wind is in Patagonia from La Pampa to Tierra del Fuego provinces (see Fig. 3). Argentina has had a solar irradiation map since the 1980s (Fig. 2) and a wind map since 2010 (Fig. 3) for the whole country. Average temperatures and rain falls in the last 20 years (Fig. 1), are shown on the next maps:

Solar irradiation maps for typical months are:

Particularly the best areas for Solar Resource are from the North West to Comahue Region (North West of Patagonia) (see Fig. 3). The wind map of the Argentine Republic was made during 2000 to 2010 by one of the Renewable Energy centers created by President Dr. Raúl Alfonsin (1986): Wind Energy Regional Center (WERC). The following map was prepared by WERC located in Rawson, capital of Chubut province (*: see Fig. 3) [3].

This map permits to locate the best wind regions of the country. Once the region is chosen, specialists in the design of wind farms carry out wind analysis of the micro-region selected for the optimal location of the wind turbines. These tasks are carried out by the Wind Engineering Group which has EFDiLa, at FENUCo.

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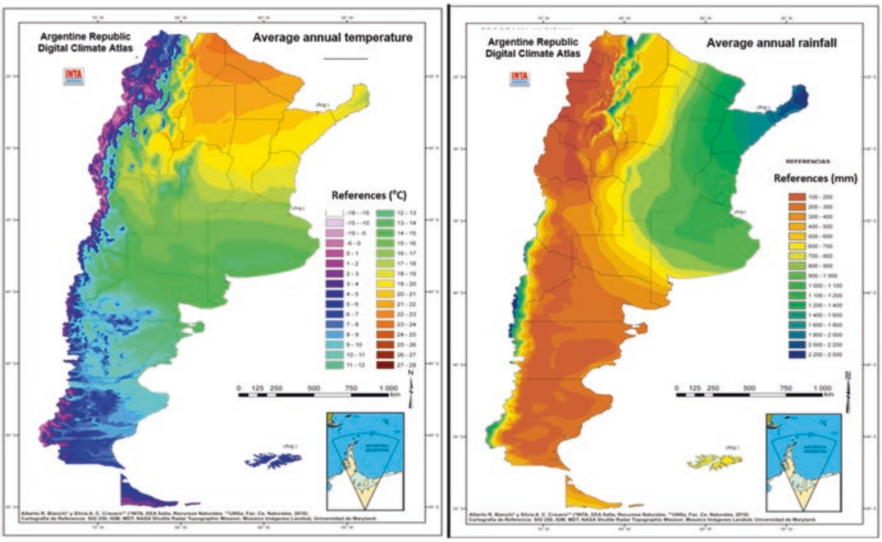


Fig. 1 Annual average temperature (left) and average annual rainfall (right) [1]

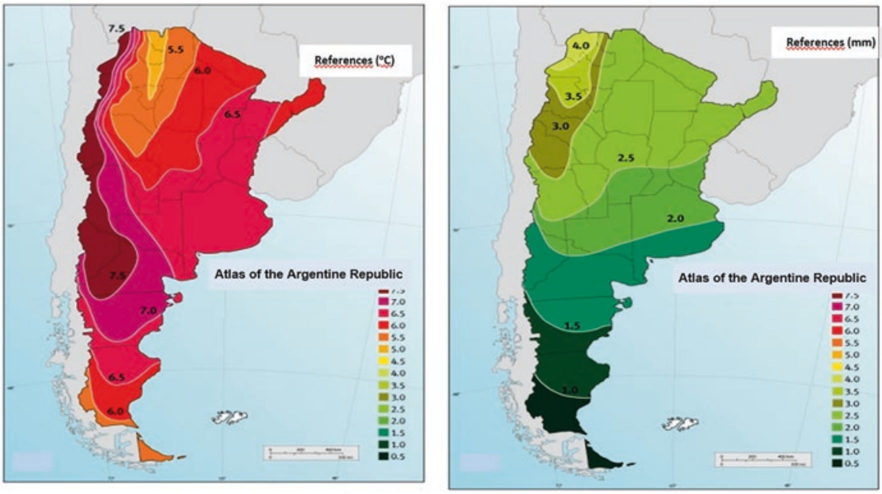


Fig. 2 Daily Global Irradiation Solar Map (kWh/m^2), January (**left**) and July (**right**) [2]

2 Environmental Considerations (2018)

Law 27,424 from December 2017 [5] permits electricity users to generate their own energy through renewable sources for self-consumption and, if there are surpluses, inject the extra energy to the grid and receive retribution from the electrical distribution company. This law creates the condition of user-generator and consequently

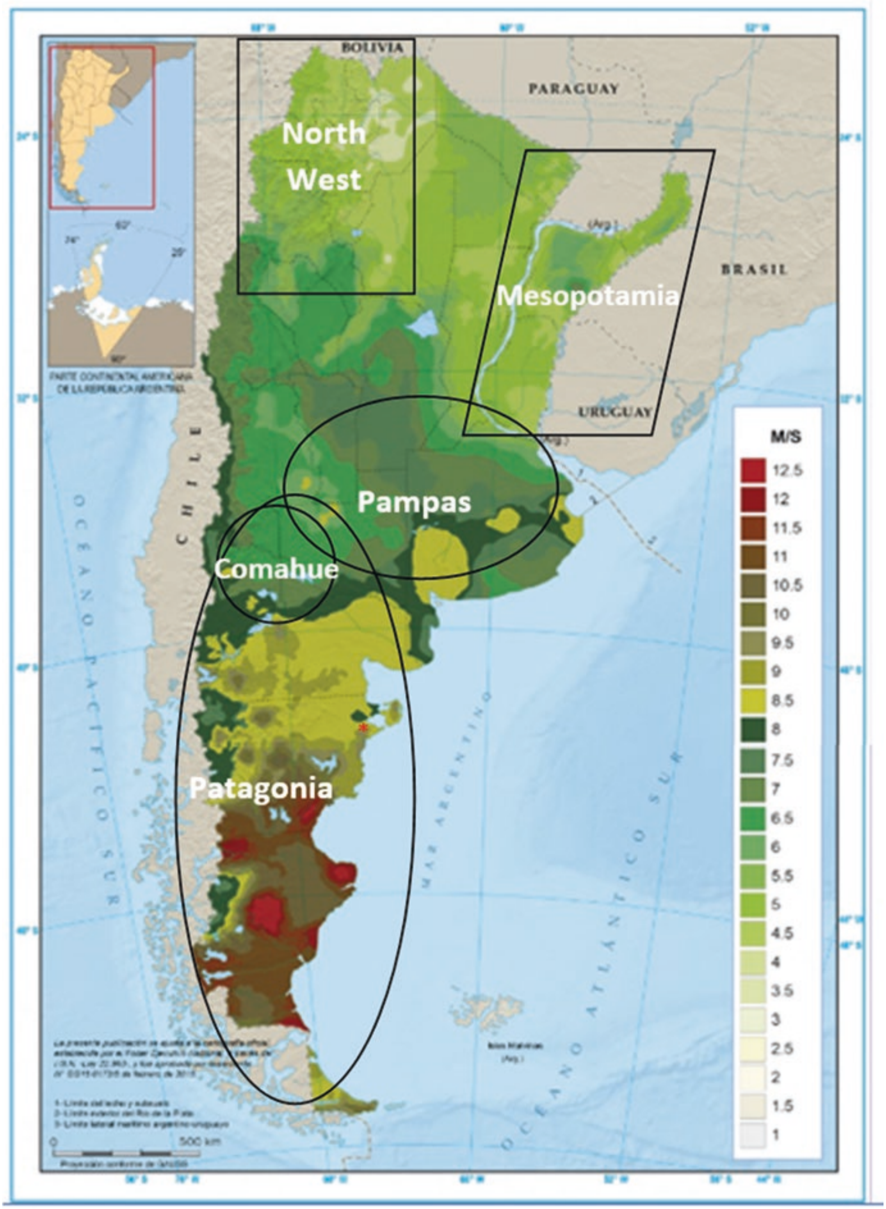


Fig. 3 Wind Map of Argentina [4]

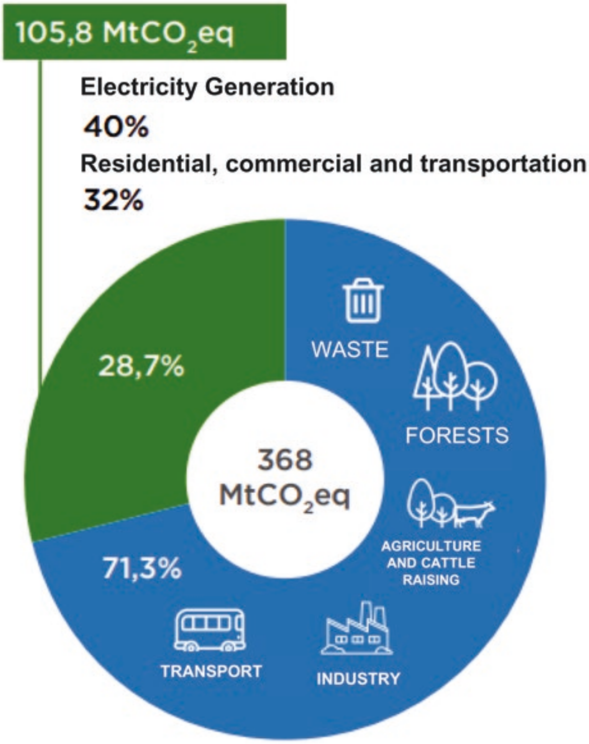


Fig. 4 CO_2 emissions in Argentina, 2018 [6]

contributes to reduce, from the user, the CO_2 emissions produced by the generation of electrical energy with conventional thermal power plants in Argentina (see Fig. 4).

3 Photovoltaic Installations in Argentina

Argentinean energy matrix shows the participation of renewable energy during 2021 (see Figs. 5 and 6):

Within REA percentage, the renewable energy sources for electricity generation are:

In the particular case of solar farms of tens of MW, the facilities increase energy production since 2019 and have a power as shown in Table 1:

Residential Solar Energy in May 2021 was 4.7 MW, in March 2022 it was 10 MW, and continues to grow due to the increase in the price of Network Residential Energy, because the National Government decides to eliminate gradually the subsidies on energy for users and electricity companies.

Is relevant to say that a photovoltaic system of 200 kW as Low Voltage smart grid is working on the city of Armstrong, province of Santa Fe since 2018.

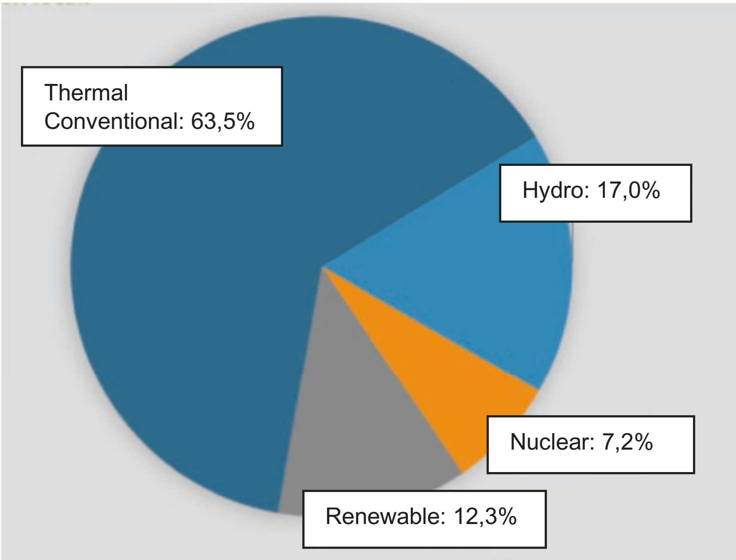
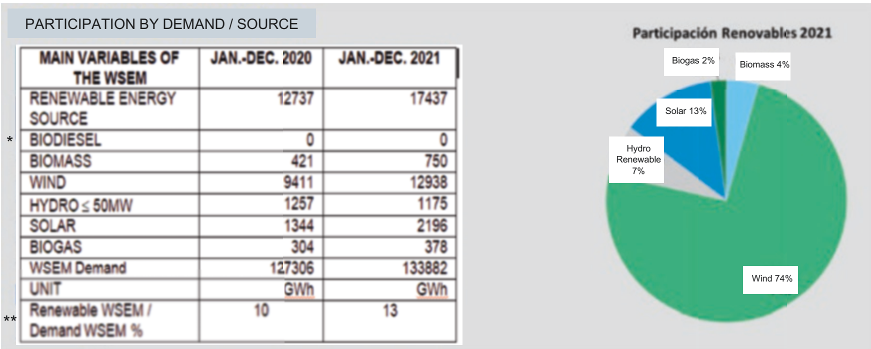


Fig. 5 Percentage of Renewable Energy in the Argentinean (REA) Energy Matrix, 2021 [7]



PARTICIPATION BY DEMAND / SOURCE

	MAIN VARIABLES OF THE WSEM	JAN.-DEC. 2020	JAN.-DEC. 2021
	RENEWABLE ENERGY SOURCE	12737	17437
*	BIODIESEL	0	0
	BIOMASS	421	750
	WIND	9411	12938
	HYDRO ≤ 50MW	1257	1175
	SOLAR	1344	2196
	BIOGAS	304	378
	WSEM Demand	127306	133882
	UNIT	GWh	GWh
**	Renewable WSEM / Demand WSEM %	10	13

Fig. 6 Different sources of Renewable Energy generation 2020–2021 [7]. *: Biodiesel: It is mixed with diesel (8%) by energy law. **: WSEM: Whole Sale Energy Market

Table 1 Summary of Power of Solar Farms per year since 2021 (g)

Year	2019	2020	2021
Power (MW)	425,06	759	1060

4 Low Voltage Residential PV Systems

Given the different types of climate in Argentina (Subtropical, Temperate, Arid, Cold), the angle of inclination of the photovoltaic panels is around the value of Latitude as an annual average angle.

For residential installations there are two alternatives: isolated network (PERMER since 1985) [3] or interconnected network (user-generator, since 2019) [5].

The generation equipment has the following components:

- Photovoltaic modules.
- Support structure for photovoltaic modules.
- Interconnection boxes among photovoltaic modules near them.
- Lead-acid battery made up of several cells of 2 V (stationary batteries).
- Charge Regulator to prevent excessive discharges or overloads of batteries.
- Cables: Sintenax®-type bipolar conductors and disconnecting elements.

The one-line diagram recommended by the National Secretariat of Energy for a residential photovoltaic installation (without batteries) consists on these elements, according to Fig. 7:

Devices connected directly to the grid	
(a) Single-phase low voltage network	
(b) Bidirectional energy meter	
(c) Thermo magnetic switch	
Left circuit	*Right circuit*
1. Thermo magnetic switch	1. Differential circuit breaker
2. Protection against atmospheric discharges (varistor)	2. Thermo magnetic switch
3. Protection against grounding	3. User charges
4. Inverter	
5. Varistor against atmos. Discharges	
6. Fuse switch	
7. Photovoltaic modules	

In case of isolated residential installations, Neuquen Provincial Energy Company (NPEC), a pioneer in photovoltaic installations in isolated sites since 1986, recommends the following two-wire scheme shown in Fig. 8:

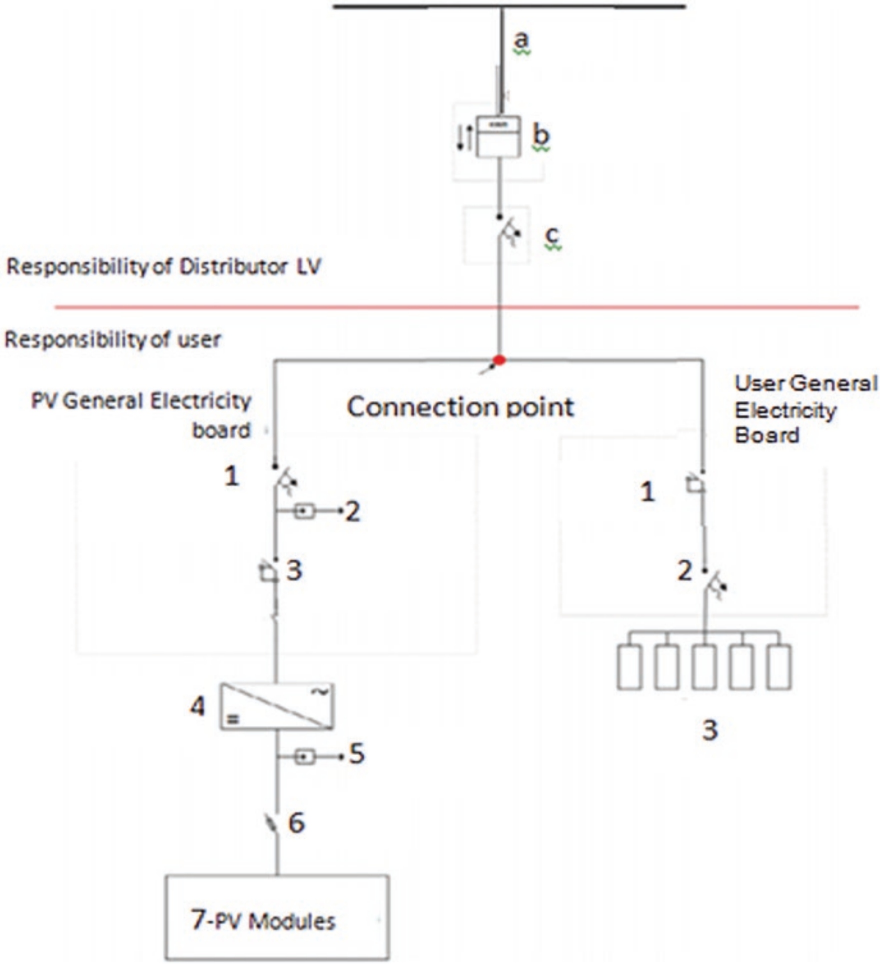


Fig. 7 One Line diagram recommended [8]

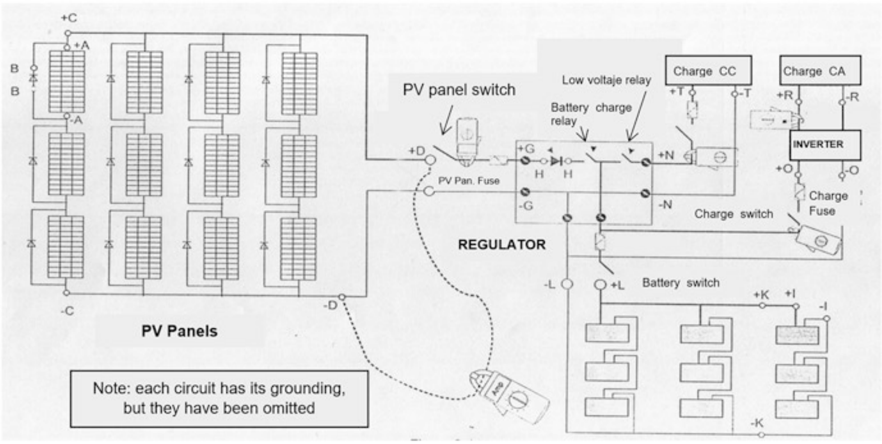


Fig. 8 Recommended two-wire scheme for isolated network installations in Neuquén [9]

5 Government Plan on Energy Market in Argentina

From 1986 to 2000, Argentina used only locally extracted gas (100%) for electrical generation and transport (taxis). From the Economic Crisis of 2001 the government neglected this great advance that return to Democracy had brought us, because they did not include promotion of gas extraction as energy political strategy [3]. In this way, Argentina became dependent on imported liquid fossil fuels (gas oil-fuel oil) and even tried to use coal of its own production. Users have been receiving a subsidized rate since 2005, paying only 20% or 30% of the cost of electrical energy production. During 2022, these subsidies begin to be restricted and the cost of Energy is increased progressively until eliminating them during 2024/2025. Also a promotion for gas extraction is working since 2016.

Higher energy cost for users produced higher demand on PV residential systems generation to provide up to 80% of their demand. Others with PV systems of more than 100% of their demand can sell the surplus to the local service company. Law 27,424 gives general recommendations for PV residential systems [5] and each province adopts a regulatory framework for taking into account particularities of provincial electrical grid. In addition, provincial or municipal entities are building state buildings including solar PV on their roofs (Bank of Neuquén, etc.).

There is an application on the web for those users of electrical energy who wishes to be users/generators in Distributed Generation, particularly with PV systems. There is a procedure to carry out the procedures via web, step by step [10].

Then a series of forms must be filled out. Power module of user-generator is reserved and the local distributor is notified for analysis of the technical feasibility of the proposal. Once with power reserved and technical feasibility are approved, the user-generator is authorized to hire an installer of the declared Photovoltaic equipment. The installer must fill out a form to be sent to the distributor. Then the user requests the bidirectional energy meter. Finally, when the installation is approved by the Local Energy Distributor with a bidirectional meter, National Secretariat of Energy issues a certificate for the applicant as User/Generator.

The equipment to be installed must be manufactured fulfilling the following standards (see Table 2):

Since 1980s, there are provinces that have been installing, maintaining and expanding Solar PV and wind turbines in rural schools, first aid rooms, border guards, oil or gas pipeline stations, meteorological stations, snow-gauge and rainfall measurement stations. Emergency phones in national roads and highways are supplied with PV panels.

Table 2 Technical standards for PV equipment

Device	Standard
PV panels	IEC 61730-IRAM 2100*-IEC 61215-IEC 61646
Equipment for connection to grid	IRAM 210013-21* – IEC 62109-IEC 62116- RD1699 – IEC 62109 – VDE 4105 – VDE-0126-1-1 VDE 4105

The use of fossil fuels is still high in Argentina in electricity generation (50–70% depending the season), in transportation (97%), and in Industry (95%) [11].

The government is trying to reduce subsidies for the use of fossil fuels, so that today the user is assuming part (60%) of real costs until end 2023 or 2024 where the user will pay 100% of them. Gradually the government will reduce the purchase of imported fossil fuels trying to reduce one of the aggravating factors of the Argentine economic crisis.

Particularly in the case of Renewable Energy (RE), since 1998 National Laws related on RE are regulated (Laws N° 27191 (e), N° 25019 [12], N° 26190 [13]), and have given to National Secretariat of Energy, not only a legal frame, but also a general technical one to instruct the Whole Sale Energy Market Company (WSEMC), who regulates the technical part and authorizes connection of power plants (on MV or HV) and user-generators (on LV) to the National Electrical System. Also those laws permit Provincial Energy companies authorize and regulate connections of energy installations in provincial electrical distribution networks.

This chapter includes an example of applications of regulations included in Law N° 27424 and all the provincial regulations for grid connection of Río Negro. This example is the Final Executive Project of a PV System from a packing shed required by First Fruit Cooperative of General Roca (FFCGR), Stefenelli, Río Negro which is ended during 2020.

6 Relevant Additional Information Relating to Generating Power by Cleaner Means

Argentina is the world's leading exporter of soy derivatives; the principal is soybean oil which is used to obtain biodiesel. Law 27,424 permits to add 8% of it to non-renewable diesel [5]. Ethanol is also produced from sugar cane and corn, and 10% alco-naphtha is added to gasoline [5]. It is remarkable that since 1986 tetraethyl lead has not been used anymore as antiknock in spark engines in Argentina [3]. One antiknock friendly with environment and persons is developed by the State Hydrocarbons Company (YPF) and actually is used since that year.

Biogas is used in bovine and pig farming area obtained from biodigesters by means of cattle dung in aqueous solution. And home solar water heaters for residential use and to take a "mate" are being used either with flat panels or with vacuum tubes.

7 Wind Tunnel Tests for BAPV Installations in Patagonia

Location of Patagonia Region and FFCGR

Comahue Region is part of Patagonia of Argentina. Patagonian surface (Lat – 36° a – 46° y Long. – 63° a – 74° Long.) (Fig. 2) is 38% of Argentinean surface, which has a coefficient plan for wind farms between 38% and 47%, because of its very good wind regime. Also during spring and summer it has solar radiation on nor-west region (5–7.5 kWh/m^2) similar to The Puna (Lat – 25° y Long. – 67°). In particular wind speed is between 4 m/s in valleys to 9 m/S on the top of platoons (measured at 10 m height). Gales are very strong during spring and summer on North West region (Neuquen and Rio Negro provinces) but cuasi-constant on center region (Chubut and Santa Cruz provinces). Turbulence index is high produced by the constant wind from the Pacific Ocean which cross The Andes Mountain Range and during spring and summer by The Zonda wind (warm wind) which come from North West of Argentina.

Since 2010, EFDiLa (Department of Mechanics, EFNUCo) is required to develop building model tests for wind and PV installations. This requirement is because on strong wind and gusts in the Patagonia region. Particularly in 2018, FFCGR required to EFDLiLa an Executive Project to reduce energy consumption from grid, particularly during the classification and packaging of fruits, from December to May of the next year, Summer and part of Autumn. In addition Energy and Environment Research Group (Electric Department, EFNUCo) made the electrical project.

This Cooperative has a classification and freezing plant of 10,000 m^2 and has two types of shed, one with parabolic roof (built 40 years ago) and other with flat one (built 8 years ago). Two models are made to make tests in wind tunnel: one for parabolic roof is built at scale 1: 40, and the other for the flat one, is built a model at scale of 1: 50. Also simulations with CFD of installation of PV panels for these two kinds of roof are made, and show detailed behavior of the wind for both cases.

8 Tests in Wind Tunnel and CFD Simulations

Since 2010, the Environmental Fluid Dynamics Laboratory (EFDLa), located in the Faculty of Engineering of the National University of Comahue, has been required to develop building model tests for wind and photovoltaic installations. This requirement is due to the strong winds and gusts in the Patagonian region. From 2018 to 2020, EFDLa research group studied a 300 kW BAPV installation that can be extended to 1.2 MW in the future, in Stefenelli Industrial Park, Río Negro (RN). These tests and projects were required by the First Fruit Cooperative of General Roca (FFCGR) to reduce the energy consumption from the network, particularly during the classification and packaging of fruits, from December to May of the next year.

FFCGR has a 10,000 m^2 classification and freezing plant and has two types of shed, one with a parabolic roof (built 40 years ago) and another with a flat gabled roof (built 8 years ago).

Two models are made to make tests in wind tunnel. Models for wind tunnel, one for parabolic roof is built at scale 1: 40 and the other, for the flat one, is built at scale 1: 50. Also simulations with CFD [14] of installation of PV panels for these two kinds of roof are made, and show detailed behavior of the wind for both cases (see Figs. 12 and 13).

9 Wind Characteristics at the Location of the Solar Panels

The prevailing strong turbulent winds at Stefenelli, with maximum gusts of 3 seconds between 48 and 50 m/s (Fig. 9), come from the West, North, and mostly from the Southwest (Fig. 10).

The place is between a type of land B (urban) and C (rural), with turbulence intensities at the roof level from nearby sheds 0.20. Therefore, both the physical and virtual wind tunnels were calibrated according to the distribution vertical velocities and turbulence intensity as indicated in Fig. 11.

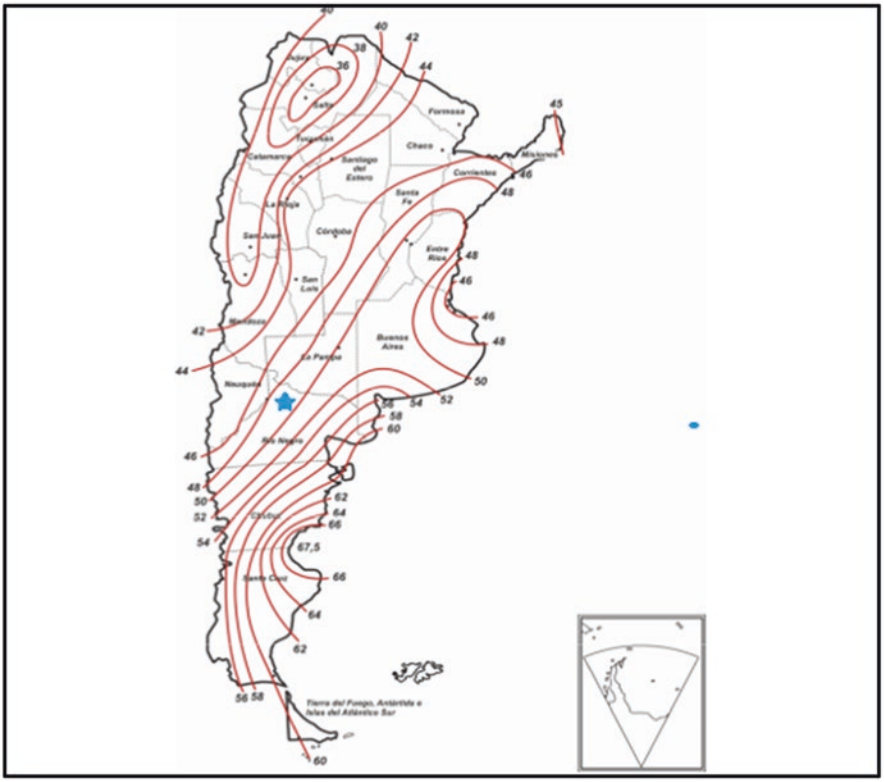


Fig. 9 Map of extreme wind speed in the Argentine Republic [15] (*): Stefenelli, R. N.

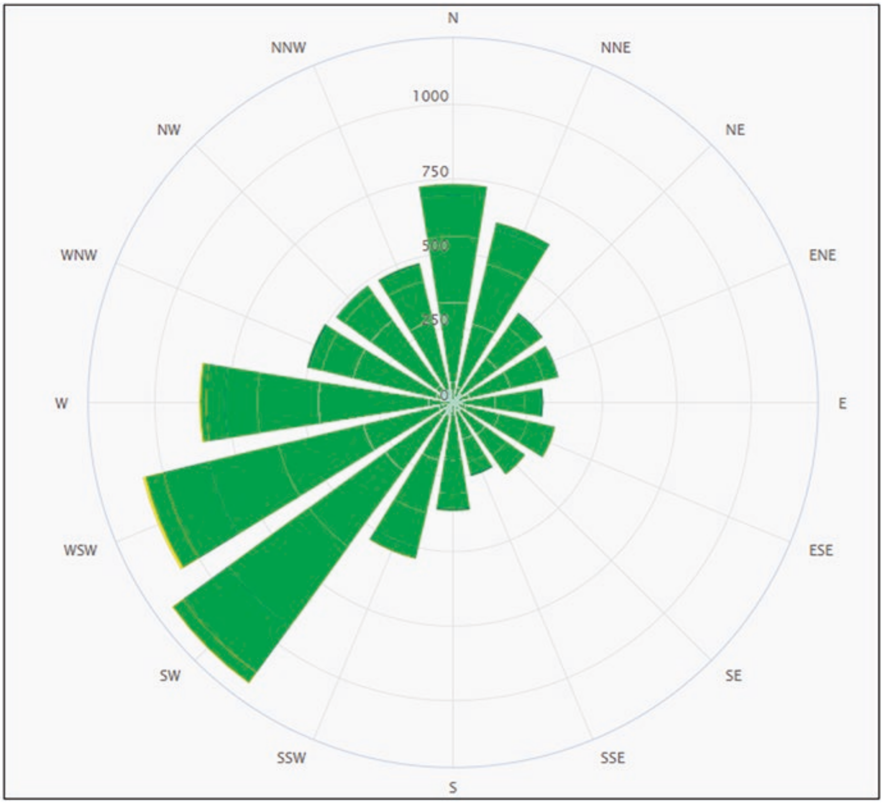


Fig. 10 Rose of the Winds in the town of Stefenelli [16]

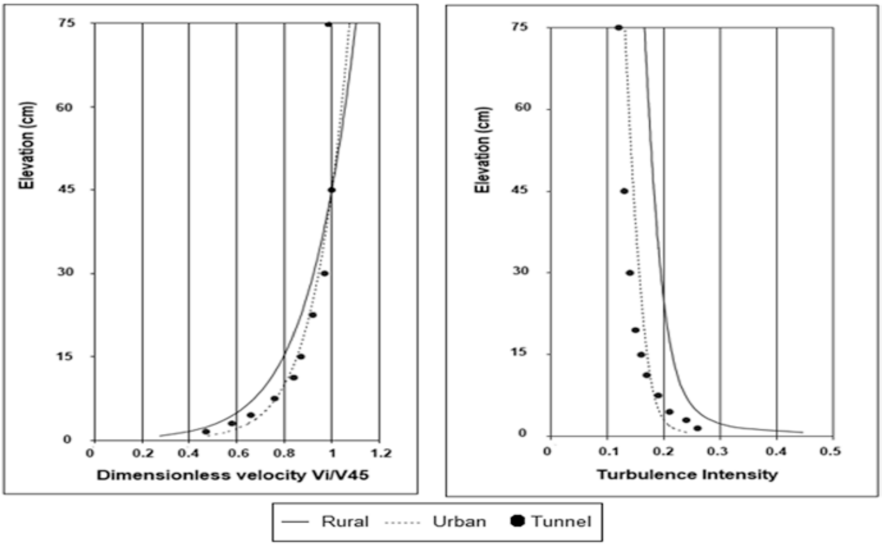


Fig. 11 (**Left**) Velocity profile simulated in the wind tunnel; (**Right**) Distribution of turbulence intensity with height [17]

10 Wind Tunnel

A wind tunnel belonging to the Environmental Fluid Dynamics Laboratory (LaDiFA) of FENUCo was used with the two models of roof. It is 7.40 m long with a test section of 0.90 × 0.90 m. It is an open one (atmospheric boundary layer type) with a 6 CV electric motor, with speed regulator and stabilizer.

The measurement of wind speed inside the tunnel was carried out with a hot wire anemometer (CEM DT-8880). Pressure measurements on the solar panels were made by static shots on the panels including small tubes. These tubes were connected to piezoelectric pressure sensors which send the measurements to a data logger that recorded them at a frequency of 1000 Hz.

11 Parabolic Roof Case

A model of a 1:40 scale was tested at three positions of the prevailing winds: North and Southwest, and also with winds from the South, because it is the rear position of the panels. The results can be observed in Fig. 12, where the suctions in the solar panels reach values between −450 and 1350 Pascal.

For the Southwest position (Fig. 12, right) it is the worst load due to the wind, because the panels suffer positive pressure loads in their lower part, and suction in the upper part.

12 Flat Roof Shed with a Slight Slope Case

The scale of this model was 1:50, because to satisfy the non-blocking conditions in the wind tunnel test section.

The results can be seen in Fig. 13, where the suction on the upper part of the solar panels varies between −280 and −640 Pascal, much lower than the case of the parabolic shed.

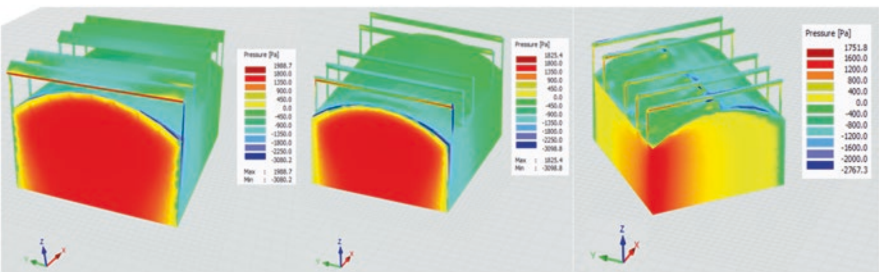


Fig. 12 Pressure distribution in the solar panels located on a parabolic roof shed: (**left**) wind from N, (**center**) wind from S, (**right**) wind from SW

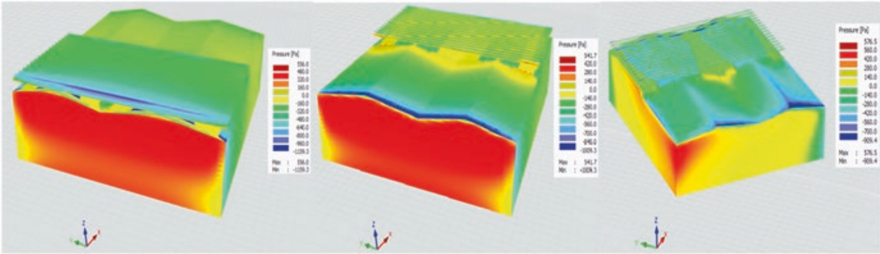


Fig. 13 Pressure distribution in solar panels located on a flat-roofed shed with a slope: (**left**) wind from N, (**center**) wind from S, (**right**) wind from S

For the Southwest direction, on upper faces of solar panels it is possible to see in Fig. 13 suction between −140 and −420 Pascal and on their lower part measurements between −10 and +10 Pascal. Therefore, these loads are lower than those of the solar panels located in the parabolic shed.

13 Conclusions

Argentina is geographically a big country, with several different climates and a wide and different kind of renewable sources. To promote RES and to accomplish COP resolutions, several electrical rules have been published and regulated since the end of 1990s, not only for Solar, but also Wind, Mini and Micro-Hydro, Biomass and Geothermal resources. Particularly the best areas for Solar Farms are from the North West to Comahue Region (North West of Patagonia). The whole country permits domestic PV installations as user-generator since Law 27424 is regulated.

In this context an application of solar BAPV is included. The existing structure under study is influenced by the strong and extreme winds of Comahue Region, North Patagonia. The micro-area wind study shows that predominant turbulent strong winds (gusts from 35 to 40 m/s) in the area of Stefenelli come from Southwest (Figs. 9 and 10). The flat roof shed is more protected from the wind, consequently the structure for supporting PV panels is easier to build and cheaper than those of parabolic roofs. In addition, parabolic roofs are older and need maintenance and stronger reinforcements on existing concrete columns.

From the fluid-dynamic point of view, the effect of PV panels installed on the two types of roofs shows that the parabolic shape has higher wind stresses on panel structure than the flat one. The conclusion of technical-economic project and wind tunnel tests is the installation of PV panels on the flat roofs.

14 Recommendations

Taking into account that parabolic roof has higher wind stresses on the panel structure than the flats, reinforcements to withstand the wind on PV support structure will be cheaper and relatively lightweight than on parabolic roof.

This project will be a first stage of BAPV installations in FCFGR changing to renewable energy use. Once installed, the PV system on the flat roof will permit to ask for additional environmental certification for their classification and packaging processes.

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Building Applied Photovoltaic Systems in Iran: Opportunities and Challenges

Majid Khazali and Abdolrazagh Kaabi Nejadian

1 Introduction

Energy consumption growth, global warming, and as a result, climate change are the main challenges facing humans [1, 2]. Looking at the history of the Earth, there have been weather changes, but after the industrial revolution, human activities have multiplied the greenhouse gases emission and consequently have made serious changes in Earth's climates [3, 4]. Based on the reports, even if the goals of greenhouse gas emission reduction are achieved, there is a high probability for the average global temperature to exceed 1.5 °C in the twenty-first century compared to eras before industrialization [5, 6]. At least, in order to keep the incremental trend below this level, it is required to considerably reduce carbon dioxide (CO_2) emissions by 2030, and should effectively be zero by 2050 [7, 8]. Therefore, there is not much time left to respond to climate change. Climate change is also felt through the frequent occurrence of severe weather events like heavy rain and high temperature in recent years [9]. Moreover, other effects of climate change, like the increase in high-temperature event frequency, very hot days, tropical nights, heavy rain in small periods, sunstroke danger, and death are increasing [10, 11]. Furthermore, there are other effects, such as infectious disease expansion due to the expansion of habitat domain of disease damage and crops quality reduction, severe disaster occurrence

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in mountainous areas due to heavy rain, effects on sea creatures due to water temperature changes, and also fishing reduction because of changes in fish types [12–14]. In order to control global warming, the system requires urgent and intensive reforms on both sides of energy supply and demand.

Greenhouse gas reduction targets can be achieved without making obstacles to economic development [15]. According to mentioned problems and due to exhaustible fossil fuel and also in order to reduce greenhouse emissions and stable energy supply, the use of renewable energy systems, besides increasing efficiency to facilitates greenhouse gas reduction [16, 17]. These energy systems specifically utilize clean and available solar and wind energies, which have the most potential to be employed [18–20]. It is worth mentioning that nuclear power plants are usually considered renewable, clean energy systems, and this option has the largest electricity production capacity [21, 22]. But numerous and big risks of this power plant have caused doubts about its future. For example, on 24 February 2022, the Russian army invaded Ukraine and, on the same day, seized the Chornobyl power plant, and sometime after that, Russia seized the Zaporizhzhia power plant [22]. Moreover, there are risks, like the occurrence of disasters like Chernobyl and Fukushima. Furthermore, nuclear power plant dependence on uranium, like Europe's dependence on Russian gas, causes some restrictions and makes energy security vulnerable. Usually, when any country achieves energy independence, the conflict factors over sources vanish, and the world is shifted toward peace. According to available and domestic renewable energy resources, the use of these sources causes energy security and stability.

Among renewable energies, solar energy is of greater importance because, in 1 hour, the sun radiates the required energy for 1 year and usually is accessible in most areas on the Earth [23, 24]. One of the most usual and effective types of equipment for utilizing this amount of energy is a photovoltaic (PV) system [25]. General components of a PV system usually include PV modules, storage batteries, DC to AC converters, controller devices, metallic structures or buildings, and connection cables; finally, the main part of this system are PV modules composed of PV cells [26]. Some significant advantages of PV systems employed in solar energy deployment include no greenhouse gas emission, low maintenance cost, lower restriction due to installation location, and lack of mechanical noise resulting from moving parts [27]. Furthermore, PV systems usually operate for several decades, and their residue rarely contains dangerous garbage [28, 29]. Moreover, in terms of life cycle water footprints, PV systems consume lower water than many systems [30]. Simple and fast fabrication and operation may be referred to as other positive features of PV systems [31, 32].

The PV module technology has been developed for more than three generations, and much research has still been continued on the fourth generation [33]. Based on employed construction technology and the light absorber materials, the photovoltaic cells can be divided into four generations, which are different in terms of performance, cost, and size. The first generation includes crystalline silicon cells (based on the wafer) that are divided into three classes monocrystalline, polycrystalline, and Passivated Emitter Rear Contact (PERC) solar PV; the latter employs an extra layer (film) for more light absorption and also to triple PV cell efficiency [34].

First-generation solar cells are produced with high efficiency, as well as increased cost. This matter causes the need for omitting unnecessary materials, especially in the active layer, and consequently leads to the idea of second-generation solar cells with thin films [35]. This generation utilizes a lower amount of materials while preserving the high efficiency of the cell. Thin film is divided into five groups, including Copper Indium (CIGS), gallium selenide, Cadmium Telluride (CdTe), amorphous Silicon (a-Si), Gallium Arsenide, and Heterojunction (HJ). The third generation of photovoltaic cells is emerging thin films, which are divided into three categories, including Copper Zinc Tin Sulfide (CZTS), dye-sensitized solar cells, and Organic Solar PVC (OSC) [36]. The technical necessity at the global level with various applications has become a key challenge, which affects the research and development toward the evolution of so-called fourth-generation technologies. So far, most efforts over photovoltaic cells' fourth generation are part of laboratory research and still are far from the industrial approach. Fourth-generation solar cells use two mechanisms, Quantum Dots (QD) and Concentrated Solar Cells (CSC) [36]. The QDs are known as nano-crystal solar cells because they are composed of the nanocrystalline spectrum from transition metals called quantum dots and are a promising technology. QDs, which are processed with solution, play a key role in high and efficient absorption of the solar spectrum, where the nanocrystals are firstly mixed in an anise bath and then coated over the Si platform [37]. There are many researches and developments that are presented in the photovoltaic cells area with the newest CSC technology. This work is based on the optics principle in which lots of solar energy is synchronized in a compressed area with helpful lens arrangement. Depending on Lens power, CSC is classified as low, medium, and high photovoltaic cells. These solar cells have many advantages lack of thermal mass, lack of quick reaction, availability in wide sizes, and finally, the experimental conversion efficiency of 40% [38]. In addition to the stated categories, it is possible to divide the PV cells based on the employed material in the structure into four classes, including Perovskite, organic, dye-sensitized, and silicon solar cells [39]. Among all these PV cells' classes and generations, Multi-Junction Concentrator Solar Cells (MJCSC) have the highest efficiency, and organic solar cells have the lowest efficiency, but the maximum cost per produced watt also pertains to MJCSC. In the meantime, cadmium telluride has the lowest cost. However, more than 90% of the installed systems use first-generation PV modules [36].

PV systems have various applications, including utilization in space equipment and on water-floating photovoltaic power plants [40]. Fortunately, due to an increase in efficiency and also economic efficiency like scale economies, the photovoltaic module costs have only decreased from 1.96 $/W to 0.38 $/W between 2010 and 2021 [41, 42]. Since it is predicted world energy consumption increases by 2035 compared to 1990 due to urbanization and rapid population growth to 50%, considering the effect of this increase on building energy consumption and electricity costs and losses, the best option to overtake the energy consumption and greenhouse gas emission rate is to use PV systems in buildings [43, 44]. Energy consumption can be divided into two types: the first case is continuous consumption of energy for equipment, which works as lighting, refrigerator, television, and others. The second case is seasonal equipment that is used for air conditioning, cooling, and heating [45]. Currently, buildings consume a little less than half of the world's energy for heating, cooling, and artificial lighting through burning fossil fuels [46]. Replacing conventional structural materials with photovoltaic systems gives more capabilities to the building both in terms of clean energy consumption and aesthetics. Building Integration (BI) and Building Connectivity/Applicability (BA) are two techniques for the inclusion of PV systems in the building [47]. Now, first and second generations of photovoltaic technologies for BIPV and BAPV are included in the form of ceilings, walls, and windows, while third-generation PVs are under serious consideration to find their potential [48].

PV Systems in Iran

Iran's share of greenhouse gas emissions in the world is 1.77% and this emission has increased since 1990 to 232% [49]. Due to such growth in emission increase, it is required to seriously follow the use of renewable energy. Despite huge hydrocarbon fuel reserves in Iran, solar energy is taken into consideration because of environmental issues, energy consumption growth, and also non-permanent fossil fuels. The construction of the module and solar cell production factory in Iran started in 1992 and then the production of electricity from sunlight is taken into consideration. So far, photovoltaic electricity production project has been exploited with two grid-independent and connected grid types. Iran's government has provided several arrangements to expand the use of PV systems which include financial support for PV systems equipment production plans, tax exemptions, providing land for the construction of the PV power plants, PV feed-in tariff (FIT) with several times the grid price and finally low-interest loans for the construction of PV power plants. Based on the official statistics of the Iran renewable energies and energy efficiency organization (SATBA) 510 megawatts of solar power plants have been constructed in Iran so far, where all of this amount is approximately directed by PV systems and is about 0.5% of electricity production in Iran.

The PV FIT model in Iran was in the form of a 20-year purchase contract for large and small-scale power plants since 2015. However, from 2021, in order to achieve 10,000 MW renewable electricity production in the country, and due to the limited financial resources, the payment is based on the amount of saved fuel for (large and medium scale) power plants. According to this model, a 7-year contract is signed between the government and renewable power plant constructor and accordingly, the power plant commits to producing electricity for 7 years, where after this period the power plant can enter into a contract with others based on new models, on the other side, the Ministry of Energy commits to pay benefits of this 7 years in a 4-year period. But for power plants with kilowatt capacity (small scale), FIT is still done with a 20-year contract subject to having electricity branching up to twice the capacity of branching at a price of 17,500 Rials per kWh, which every year, based on the inflation rate, contracts are adjusted and the purchase rate increases. Another government program for using PV systems is to build 550,000 5 kW solar systems for families covered by supportive foundations where according to it, all the cost of constructing the power plant will be provided through low-interest facilities, and part of its monthly income will be used to pay for the facilities and the rest will be used as family income.

So far, several research works have been performed on using photovoltaic systems in the form of BAPV and BIPV in Iran. Karimi et al. [50] dealt with BIPV and BAPV in three regions including Tehran, Tabriz, and Kish Island. Results of this study show that the payback period is 8 years at least, which is 3 years less than in the two other regions. Also, researchers claimed that using BAPV is a more appropriate alternative to BIPV technically and economically. Keshavarz et al. [51] investigated the construction of zero carbon envelope (ZCE) nonresidential buildings from economic and technical perspectives. Their results indicated that using PV systems as BIPV is impossible in the current condition of Iran, and correcting the energy sector subsidies can be the best solution for this problem. Korsavi et al. [52] examined a 5 KW BAPV system in the hot and arid climate of Iran. Based on their study, such a system is unaffordable regarding the energy price in Iran. In contrast to the majority of studies on BAPV and BIPV in Iran, some researchers like Farangi et al. [53] have predicted the payback period for BAPV as 3–4 years, which is affordable economically.

In addition to the important challenge of climate change, air pollution in metropolises has attracted the attention of researchers. Tehran, the capital of Iran, has the greatest population density in Iran, and more than 10% of Iran's population is in this city [54]. The household sector has the largest share of energy consumption in Iran [55, 56]. Therefore, it can be said that Tehran has the greatest energy consumption due to population density. Air pollution increasing, of which a proportion is due to electricity generation, is one of the important problems in Tehran [57]. On the other hand, the settlements of the majority of Tehran's population are multi-floor apartments with similar appearance, and metrology data in previous studies have indicated that this city has a good potential for solar energy deployment [58, 59]. According to what was mentioned above, using BAPV power plants in Tehran is a good solution to supply the consumed electricity in this city and reduce emissions [60]. Air pollution in the recent decade has become a big challenge, a major part of which can be reduced by using PV systems, such as BAPV and BIPV [60–62]. It should be noted that air pollution negatively affects the system's performance because of decreased radiation received from the sun on the earth's surface and dust deposition on the surface of PV modules [63].

Regarding the differences existing between the results of recent studies on the economic efficiency of BAPV systems in Iran, the need for a new study in this field is evident, since many economic changes, including market prices of electricity, discount rate, FIT rate, and prices of PV system components, have occurred in Iran. Moreover, due to climatic and weather changes in Iran, the need for a new study to be conducted with new data is felt more than ever. Also, in previous studies, the role of shading and associated losses in BAPV systems is less considered. In the present study, the climatic and weather conditions in Iran were first examined. As mentioned in the following, these cases are of great importance in the construction of PV power plants. Then, the historical weather data of the study area (Tehran) were prepared for establishing a BAPV power plant. These data were used in calculations and simulations of a BAPV power plant. The main goal was to evaluate the possibility of producing PV electricity in urban buildings in the study area. The area and building evaluated in this study were modeled similarly to the real-world ones as far as required. Finally, a techno-economic analysis was conducted for the BAPV system in Tehran.

2 The Climate of Iran

PV technology is highly influenced by environmental conditions, and factors, such as duration of sunshine and solar radiation intensity, ambient temperature, wind speed, precipitation, humidity, and dust level significantly affect the system efficiency so that environmental conditions have more significant effects than PV module potential on the system efficiency [26, 64]. Therefore, recognizing the study area's climate for the construction of a PV power plant is very important. It is understood that increasing the sunshine duration and solar radiation intensity positively affects the efficiency of PV systems; however, increasing the ambient temperature has a considerable negative effect on the efficiency of conventional PV modules (Silicon), whereas decreasing temperature increases the efficiency [26, 65–68]. So, this difference in efficiency may reach more than 10% [64, 69]. Regarding the relative humidity, by increasing the humidity up to a specific limit, the system efficiency is ascending, whereas for higher values, due to the light diffraction and scattering of solar beams, the system efficiency will be reduced [69, 70]. However, environmental factors, such as humidity, may have a destructive effect on the service life of PV systems [71]. Among other destructive factors for PV systems is dust, with different negative effects on the system efficiency and life depending on the type, diameter, and volume of dust particles [72]. In the meantime, the wind direction and speed and the orientation of installed PV modules affect the deposition of dust on these modules; as the wind speed increases, the dust density increases, and its density decreases in the wind direction, but using super-hydrophobic coating and other self-cleaning methods may improve the system efficiency [73]. It is worth mentioning that environmental effects are not merely for PV modules; these negative and positive effects are evident in all components of PV systems, like inverters [74].

Iran is a great country with a surface area of 1,648,000 km^2 with diverse climates [75]. Climates in Iran are generally divided into eight categories: very cold, cold, temperate rainy, semi-temperate rainy, semi-arid, hot-arid, very hot-arid, and very hot-humid [76]. The average maximum temperature in summer for these climates is 25–30, 35–40, 25–30, 30–35, 35–40, 35–45, 45–50, and 35–40 °C, respectively. The average minimum temperature in winter for these climates is −5 °C to −10 °C for very cold, −5 °C to −10 °C for cold, 0 °C to 5 °C for temperate rainy to hot-arid, 5 °C to 10 °C for very hot-arid, and 10 °C to 20 °C for very hot-humid [76]. Because of climate change, the mean temperature in Iran in the recent 30 years has increased by about 0.025 °C to 0.05 °C every year [77]. Moreover, the average annual precipitation in Iran has reached from about 350 mm to 300 mm, with a 2.1 mm reduction per year [77]. The average relative humidity in summer for these eight climates is 45–55%, 25–40%, more than 60%, more than 50%, 20–45%, 15–20%, 20–30%, and more than 60%, respectively [76]. Also, the average relative humidity in winter for these climates is 65–75%, 65–75%, more than 60%, 40–60%, 35–50%, 60–70%, and more than 60%, respectively [76]. By evaluating the changing trend of wind speed in Iran in 30 years, the average wind speed varies between 1.22 and 5.51 m/s, of which the lowest is attributed to the northwestern and northeastern parts of Iran, and the highest is related to Zabol and Manjil counties [78–80]. Also, the average win speed in 55% of the country area is between 3 and 5 m/s [81, 82].

According to 20-year studies, in 56% of Iran's area, from north to south and from east to west, the average sunshine duration increases by 16.6% per year [83, 84]. Accordingly, Iran can be divided into five regions geographically: central-eastern, northwestern-northeastern, western-southern, Caspian, and northwestern. The average sunshine duration per year in these regions is 3230, 2857, 3092, 1820, and 2475 hours, respectively. The central-eastern, western-southern, and northwestern-northeastern regions with 49.3%, 29.5%, and 14.8% coverage of Iran's area have the greatest areas, respectively [85–87]. In terms of average solar radiation intensity, Iran can be divided into four regions: northwestern, northeastern and northwestern, Caspian, central, eastern and southern, southern-central, and southern, with average solar radiation intensities of 3.8–4.5, 2.8–3.8, 4.5–5.2, and 5.2–5.4 kWh/m^2 day respectively [83, 88]. Based on reports of SATBA, it is possible to produce 232,994 GWh of electrical energy per year by using PV technology in only 10,000 km^2 of Iran's area, 0.6% of the total area [87, 89]. Also, some studies have indicated that almost all regions in Iran have a good potential to produce PV electricity [90]. Since a vast region of Iran has arid and semi-arid climates, dust storms occur in the majority of Iran's regions, of which a great proportion originated from outside of Iran's boundaries [91–93]. So, many studies have indicated that the number and intensity of dust storms in Iran in recent 20 years have increased, and only in Khuzestan province located in southwestern Iran, 1507 dust storms have been recorded in a 17-year period [94, 95]. Generally, dust storms mainly occur in western and southeastern Iran, and July and December have the maximum and minimum number of dust storm events [96, 97]. This phenomenon is one of the critical environmental challenges and an important technical challenge in using PV systems in Iran [98].

Using the Global Solar Atlas 2 belonging to Word Bank Group, SATBA has published the yearly potential map of Iran's photovoltaic power by province. This map has been prepared by considering all long-term average meteorological data, including the amount of radiation and temperature to the amount of dust, and of course without disregarding any land-use constraints [99]. The modified version of this map is shown in Fig. 1.

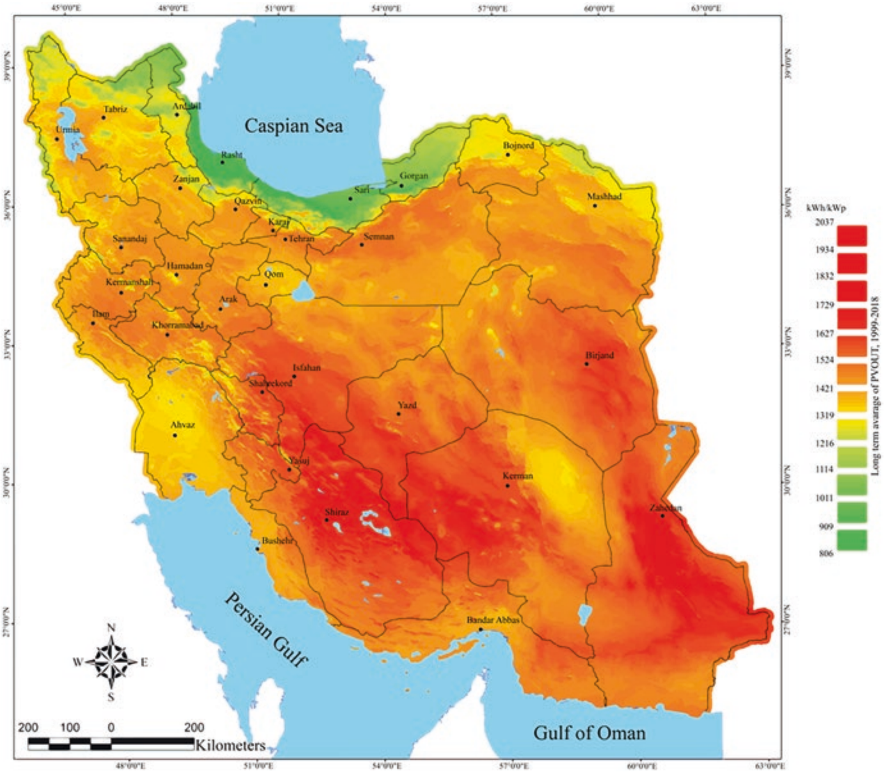

Fig. 1 Yearly PV power potential of Iran

Tehran's Climate Data

For evaluating solar power production in Tehran, new climate data are required. For this purpose, the numerical data of the Meteronorm software are used. Meteonorm is a comprehensive and credible climatology database for solar energy applications whose data accuracy is satisfactory to a desirable extent [100–102]. This software uses satellite data and data from weather stations to calculate and produce data required for various applications in meteorological, solar energy, environmental, agricultural, and forestation research fields. Average monthly data during a year for a region of Tehran with geographical coordinates of Altitude [m] = 1395, Longitude [°] = 51.322, and Latitude [°] = 35.748 are presented in Tables 1 and 2. According to these data, Tehran has a mild and semi-tropical climate, with humid winters and very arid summers.

Table 1 demonstrates the air temperature (Ta), relative humidity (RH), dew point temperature (Td), daily sunshine duration (SD), atmospheric pressure (Pa), precipitation (PRE), wind speed (WS), dominant wind direction (WD), snow depth (SnD), and Table 2 presents the cloud coverage (N), Linke turbidity factor (TL), global

Table 1 Average weather data per month for a year in Tehran

Month	T_a (°C)	RH (%)	T_d (°C)	SD (h)	P_a (hPa)	PRE (mm)	WS (m/s)	WD (°)	SnD (mm)
Jan	3.7	51.9	−5.2	170	858	32	2.3	284	1.2
Feb	6.0	45.5	−4.8	178	859	35	2.9	281	0
Mar	11.4	35.7	−3.2	208	862	30	3.5	278	0
Apr	16.6	34.6	1	228	864	38	3.4	276	0
May	22.4	27.0	2.6	278	867	10	3.8	273	0
Jun	27.8	21.2	3.7	325	869	13	3.3	254	0
Jul	30.3	21.8	6.1	321	870	12	3.2	205	0
Aug	29.2	21.6	5.1	309	870	2	2.8	191	0
Sep	25.3	24.0	3.3	278	868	2	2.7	247	0
Oct	18.6	31.7	1.5	235	865	14	2.5	279	0
Nov	10.0	46.6	−0.9	187	861	30	2.3	286	0
Dec	5.2	54.9	−3.1	170	859	30	2.1	284	0
Year	17.2	34.7	0.5	2888	864	248	2.9	263	0.1

Table 2 Average solar radiation data per month for a year in Tehran

Month	N (octal units)	TL (−)	GHI (kWh/m^2)	PAR (kWh/m^2)	DHI (kWh/m^2)	DNI (kWh/m^2)	GHI_{max} (kWh/m^2)	L_{in} (kWh/m^2)
Jan	4	3	81.2	34.5	31	123.9	121	187.2
Feb	4	3.5	97.9	41.6	41.2	114.7	136	172.5
Mar	3	4.5	142.3	60.6	56.9	147.9	197	202.3
Apr	3	5.9	174.2	74.6	69.5	160.6	229	210.7
May	2	5.8	209	90	79.4	186	265	229.8
Jun	1	5.6	223.3	96.2	73	212.8	265	230.7
Jul	2	6.1	221.6	95.9	70.2	216.5	269	249.4
Aug	1	5	209.7	90.8	65.8	213.7	246	243.5
Sep	2	4.2	174.5	75.5	44.4	217.4	214	225.1
Oct	2	4.1	131.8	57.4	42.2	170.7	168	220.1
Nov	3	3.4	91.7	39.8	31.2	137.2	125	199.3
Dec	3	3	75	32.3	25.1	125.2	109	194.2
Year	3	4.5	1832.4	788.1	629.9	2026.5	2342	2562.8

horizontal irradiance (GHI), photosynthetically active radiation (PAR), diffuse horizontal irradiance (DHI), direct normal irradiance (DNI), global radiation under the clear sky, and longwave (thermal, infrared) radiation on horizontal surface arising from the sky (upper hemisphere) (Lin).

Uncertainties for these data are as follows: 6% for GH, 11% for DNI, 0.5 °C for temperature, and 4% for the variability of GH/year. Daily data for global radiation and temperature are presented in Figs. 2 and 3, respectively.

In Fig. 3, the minimum and maximum temperatures based on the 10-year average of the study area are calculated. Also, the monthly solar radiation and temperature variation are presented in Figs. 4 and 5. Solar radiation is calculated both for global radiation and diffuse radiation.

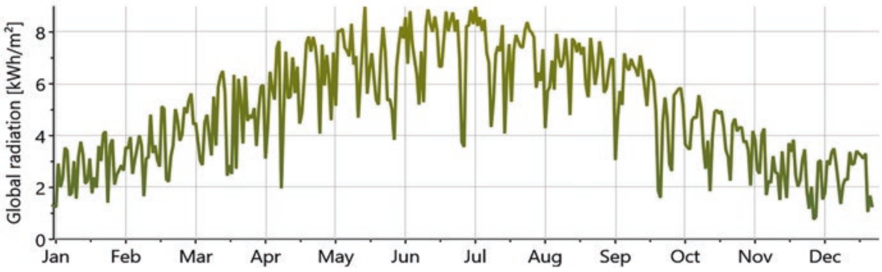

Fig. 2 Daily global radiation for the study area in Tehran

Fig. 3 Daily temperature variation for the study area in Tehran

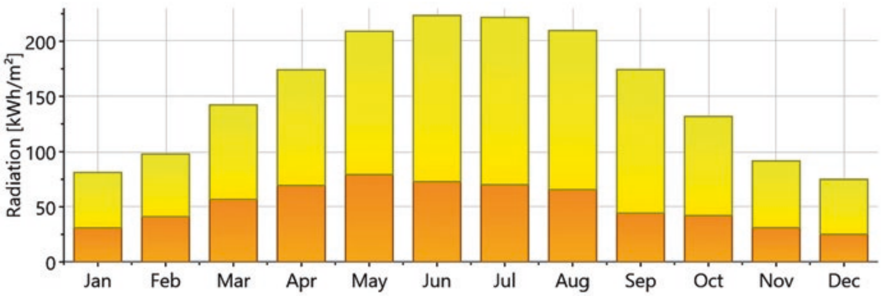

Fig. 4 Solar radiation per month for the study area in Tehran

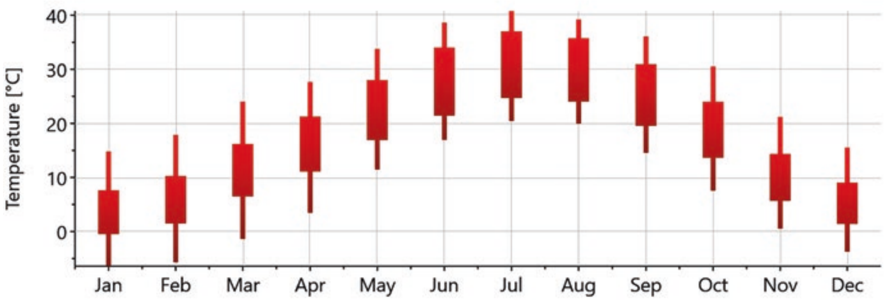

Fig. 5 Temperature variation per month for the study area in Tehran

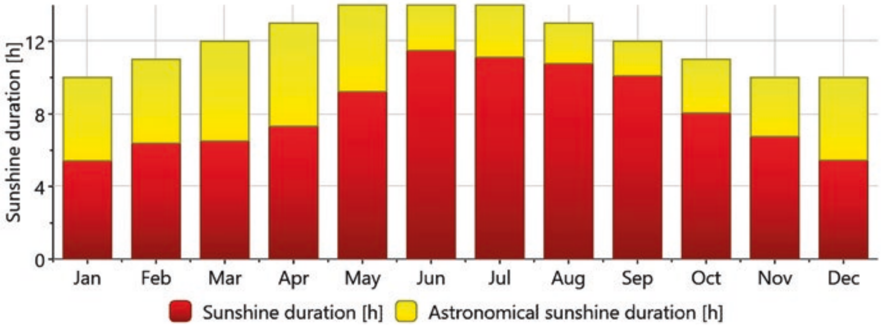

Fig. 6 Sunshine duration for the study area in Tehran

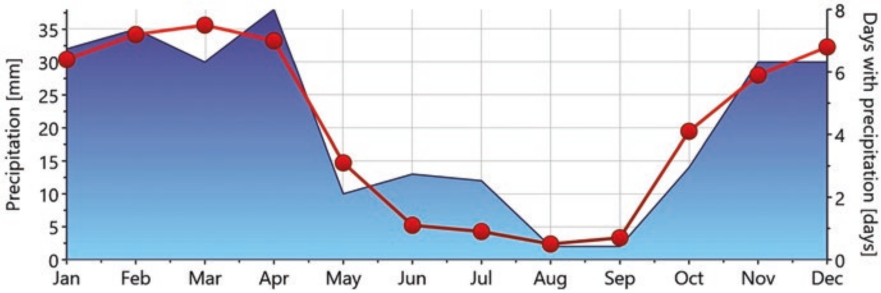

Fig. 7 Precipitation for the study area in Tehran

The sunshine duration and monthly precipitation for a year are presented in Figs. 6 and 7, respectively. Both sunshine duration and monthly precipitation are presented as the monthly average.

In Fig. 6, the sunshine duration and astronomical sunshine duration are presented. Figure 7 illustrates the precipitation level and the number of rainy days. Figure 8 demonstrates the horizon of the study area in Tehran, where the final horizon, sun path, and reflections are presented. Numbers indicated on curves show the local time.

All mentioned data are calculated based on information from the nearest weather stations and satellite evaluations based on 10-year averages. The next section first describes the theoretical calculations of BAPV, and then weather data and hourly solar radiation data per year are used to evaluate a building in a given region of Tehran economically and technically.

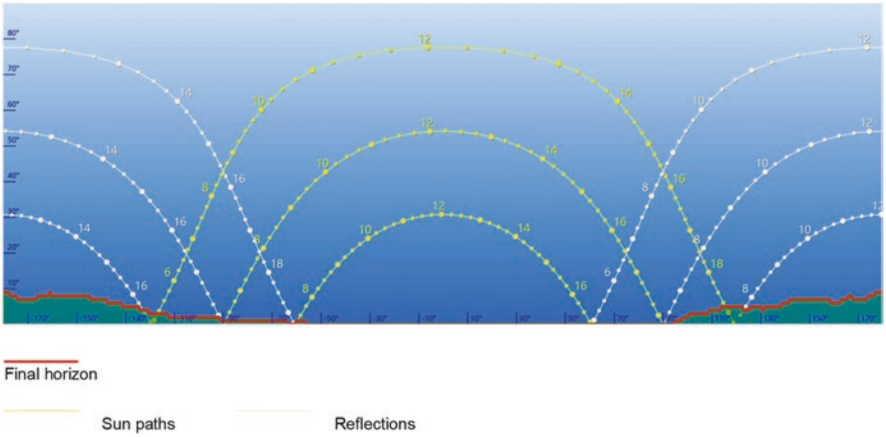

Fig. 8 Horizon of the study area in Tehran

3 Techno-economic Evaluation of PV System

Regarding policies in the energy sector of Iran, including electricity prices for consumers, FIT prices, and higher costs of off-grid PV power plant construction, this type of system is not feasible to be used where there is access to the power grid. These systems are usually used in remote areas as combined with other energy production systems, like diesel generators and wind power plants [103, 104]. Regarding the extreme increases in the exchange rate of the dollar against the Iranian Rial and decreasing value of the national currency, as most components of PV systems present in the market are not produced in Iran, the economic advantage of PV systems is reduced more than ever. Therefore, in the present study, a residential building with conventional architecture in Tehran, which is a residential complex with a flat roof, is selected for one-grid BAPV simulation and calculation. Also, due to the abundance of crystalline silicon modules in the market and the better relative performance of monocrystalline modules, this module is selected for installation [105].

In the design of the on-grid system, since there is no restrictive relationship between electricity production and consumption, the system capacity is usually determined regarding the installation place (surface) and other factors like shading. Therefore, after adequate examination of the possible surface for installation of the PV system, the system capacity is calculated, and then the entire system is designed. Here, the information on radiation rate is necessary for design, and the electricity production rate with the PV system is expressed in the following.

In this method, the system power value is the sum of the maximum nominal power of the solar module/panel and is recorded as the PV system capacity P_{AS} in kW. Also, it is necessary to consider the monthly radiation rate on the inclined surface (H_{AM}) in kWh/month. The temperature correction factor for the silicon crystalline module (K_{PT}) is assumed to be 0.85 from March to May and from September and November, 0.8 from June to August, and 0.9 from December to February. The inverter efficiency (η_{INO}) is applied based on the value reported by the manufacturer. Other losses (K''), including circuit losses, cable losses, and module surface contamination, are also considered. Therefore, the prediction of monthly electricity production (E_{PM}) in kWh/month is calculated as follows [106]:

$$E_{PM} = P_{AS} \times H_{AM} \times K_{PT} \times \eta_{INO} \times K'' \tag{1}$$

Another method for calculating the power production of a PV power plant has higher complexity, but according to performed validations, this method has an insignificant discrepancy with the method of Eq. (1) in the result [106].

Performance ratio (PR) is a determinative and universally accepted index for making decisions about and judging the performance of on-grid PV power plants [107, 108]. For calculating the PR of a BAPV power plant, the following equation is used:

$$\text{PR} = \frac{\text{PV energy AC} - \text{Standby use}}{\left(\text{GR}_\text{M} - \text{Re}_\text{M}\right) \times A_\text{M} \times \eta_\text{M}} \tag{2}$$

where GR_M is the global radiation at the module, Re_M is the reflection on the module interface, A_M is the module area, and η_M is the module efficiency. This relationship gives the ratio between the calculated and expected outputs for an operating period of the BAPV system.

In designing PV systems, the system economics, and its profitability are of great importance. The first factor used for the economic analysis of the system is the net present value (NPV). This factor expresses the sum of values of costs and incomes during the system's lifetime with respect to the interest rate at the current time. The mathematical relationship for calculating NPV is defined as follows [70]:

$$\text{NPV} = \sum_{t=0}^{n} \frac{R_t}{\left(1+i\right)^t} \tag{3}$$

where R_t is the net cash inflow-outflows during a single period t, I is the inflation rate, and t is the number of time periods. The higher the NPV, the more appropriate the project for investing in; however, zero or negative values show that the project is unacceptable for investing. If the cost/income of a year is considered, without considering any cumulative property and for a given year, Eq. (3) can calculate the value of the currency in that year for the first year of the project.

The next determinative factor is the internal rate of return (IRR). For calculating this factor, it is required to assume NPV as zero, and the equation should be solved to determine the interest rate (i) [70]. The higher the IRR, the project is proper for investing, but for values lower than the interest rate, the investment is infeasible economically. The next metric is the payback period time (PBT), which defines the division of initial system costs into the discounted net annual revenue [70]. In other words, PBT is the number of years when NPV is zero under the annual interest rate.

The main point about PBT is that its value must never be higher than the system lifetime; otherwise, the project will not achieve profitability.

For calculating the system cost for producing 1 kWh of energy, the levelized cost of energy (LCOE) equation is used [109]:

$$\mathrm{LCOE} = \frac{\mathrm{NPC}}{E_t} \tag{4}$$

where NPC is the net present costs, and E_t is the total produced energy during the project lifetime. LCOE may give a good insight for comparing BAPV with other power plants, as well as comparing the power generation cost of BAPV with the earning from selling the system [110].

Regarding the exchange rate currencies fluctuations and annual inflation in Iran, STABA uses the following equation for renewable FIT to equalize this price annually [111]:

$$\mathrm{AF}_{\mathrm{FIT}} = \left(\frac{\mathrm{RSPI}_{\mathrm{P}}}{\mathrm{RSPI}_{\mathrm{C}}}\right)^{\alpha} \times \left(\frac{\mathrm{AOERE}_{\mathrm{P}}}{\mathrm{AOERE}_{\mathrm{C}}}\right)^{1-\alpha} \tag{5}$$

where $\mathrm{AF}_{\mathrm{FIT}}$ is the adjustment factor, RSPI is the retail sales price index, and AOERE is the average official exchange rate of the euro in a one-year period. Also, subscripts P and C denote the beginning of the payment year and the beginning of the contract year, respectively. The factor α is assumed to be between 0.15 and 0.3, which is presented by the PV power plant owner when concluding a contract. The closer the α to 0.15 is, the variation of the currency component (AOERE) is higher, and the variation of the inflation component (RSPI) is lower. By selecting α close to 0.3, the latter conclusion will be reversed. The reference to declaring AOERE and RSPI is the central bank of Iran, and these values are calculated and announced in each payment period. After entering the above parameters in Eq. (5), the adjustment factor is obtained as rounded to five decimal places. As this factor is multiplied by FIT, the equivalent unit price per kilowatt-hour of production is specified in the invoice and is rounded to two decimal places. It should be noted that FIT at the time of contracting will be reduced by 30% after the tenth year.

4 Results and Discussion

As already mentioned, for the technical and economic evaluation of a BAPV system in the climate of Tehran, a residential building with conventional architecture in this city is considered. The mentioned building is modeled according to features of a real-world building, and the area topography is also considered with desirable accuracy. After modeling the building and surrounding environment, the maximum module installation capacity was considered concerning the roof floor area, which

Table 3 General characteristics of BAPV power plant

Module area	
PV modules	65 × LR6-60 HPB 300 M (v1)
Manufacturer	LONGI solar
Inclination	30°
Orientation	South 180°
Installation type	Mounted - roof
PV generator surface	109.0 m^2
AC mains	
Number of phases	3
Mains voltage (1-phase)	230 V
Displacement power factor (cos phi)	±1

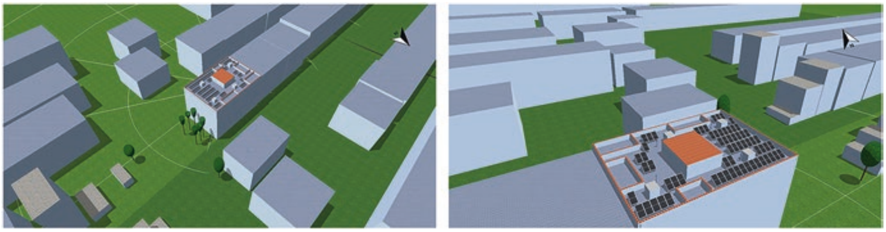

Fig. 9 Two views of the area and BAPV power plant in the present study

is about 30 kW. Then, an initial simulation is conducted for shading calculation. For simulating the BAPV system, the PVSOL software is used, which is one of the credible conventional software programs for simulating the PV system [112–114]. Previous studies have indicated that this software is the best for long-term simulation and produces reliable results that are in good agreement with experimental studies [105, 115]. After initial simulation and accurate analysis of shading, as the highest FIT is for PV power plants with a maximum capacity of 20 kW, more than 30% of modules are removed, and the capacity of the power plant reaches 19.5 kW (65,300 W modules). The general characteristics of the power plant are presented in Table 3, and its schematic is illustrated in Fig. 9.

For selecting the PV module and inverter, using the vendor list, different factors, such as efficiency, price, guarantee/warrantee, and availability in Iran, are considered. The characteristics of the selected module in the standard test condition (STC) are presented in Table 4.

In Table 4, I_{SC} is the short-circuit current, and V_{OC} is the open-circuit voltage. According to characteristics presented by the module manufacturer, the reduction in efficiency of the module is reported lower than 2% in the first 2 years of operation and 0.55% for the second to 25th year, and it is considered with exponential variation in simulations. The warranty of mentioned panel is 25 years, of which 20 years are for 90% and 25 years for 80% of the nominal power of the module. This warranty is effective in reducing annual maintenance costs. The complete

Table 4 Electrical characteristics of LR6-60 HPB 300 M module in STC conditions

Parameter	Value
Nominal output	300 W
MPP voltage	32.9 V
MPP current	9.13 A
Open circuit voltage	39.8 V
Short-circuit current	9.7 A
Fill factor	77.81%
Efficiency	17.92%
Temperature coefficient of I_{SC}	0.057%/C
Temperature coefficient of V_{OC}	−0.286%/C
Temperature coefficient of MPP power	−0.370%/C
Maximum system voltage	1000 V

characteristics of the BAPV inverter are presented in Table 5. In PV modules, there is a relationship between temperature and total resistance, causing a nonlinear efficiency. For adjusting the current and voltage to maximize the system efficiency, a maximum power point tracker (MPPT) is used. MPPT is responsible for sampling from the output of solar modules and adjusting the current and voltage of modules for transmitting maximum power in different environmental conditions [116]. Indeed, it is responsible for keeping supply and demand equal levels at every instant. MPPT elements are placed in the inverter. These converters usually engage in chancing voltage and current, filtering, and regulating for commissioning engines, charging battery banks, and transmitting to the power grid. The inverter used in the present system has two MPPTs whose characteristics are listed in Table 5. In addition to what was mentioned in Tables 4 and 5, 0.31% is assumed as cable losses.

For an economic analysis of the BAPV system, the newest rates reported by the central bank of Iran and from vendor lists are used. During the economic simulation of the system, the last exchange rate of the Rial against the Dollar was 1 to 420,000. Therefore, data from the economic model of the present BAPV system can be observed in Table 6. In this table, AF_{FIT} is calculated concerning the annual average declared by SATBA. The average annual maintenance cost is assumed equivalent to 1.5% of initial capital in dollars, and a 2% annual increase is considered due to the system deprecation. The maintenance cost is usually considered for the inverter after 10 years [117]. As the value of currency increases in Iran, the value considered for the annual increase in maintenance cost may cover further costs like the 10-year maintenance cost of the inverter. Conventional maintenance of BAPV with long-term warrantee includes regular inspection and cleaning of the module surfaces.

It is worth mentioning that as the roof of the residential building is used for a PV power plant, the land price is not considered in calculations.

In the present study, a BAPV power plant located in Tehran with a nominal capacity of 19.5 kW is analyzed technically and economically. This power plant is assumed to be on-grid with a static structure. Techno-economic analyses are conducted using hourly weather data and data included in Tables of Sect. 3. According to the simulation, the energy produced by BAPV for months of a year is illustrated in Fig. 10.

Table 5 Complete characteristics of SG20RT inverter in the BAPV system

Manufacturer	Sungrow Power Supply Co., Ltd.
Electrical data	**Value**
Quantity	1
Sizing factor	97.5%
Configuration	MPP 1: 2 × 21
	MPP 2: 1 × 23
DC nominal output	20 kW
AC power rating	20 kW
Max. DC power	30 kW
Max. AC power	22 kVA
Standby consumption	9 W
Night consumption	6 W
Min. feed-in power	30 W
Max. input current	50 A
Max. input voltage	1040 V
Nom. DC voltage	600 V
Number of phases	3
Number of DC inlets	4
With transformer	No
Change in efficiency when input voltage deviates from rated voltage	0.2%/100 V
MPP tracker	
Output range < 20% of power rating	99.9%
Output range > 20% of power rating	100%
Count of MPP trackers	2
Max. input current	25 A
Max. input power	21.2 kW
Min. MPP voltage	160 V
Max. MPP voltage	1000 V

As demonstrated in Fig. 10, the maximum produced energy is related to August. If the mean value of global radiation is merely considered, the value is higher in June. However, the simulation results indicate the effect of all weather-related factors on the PV power plant. These results can be used as predictions for future years of the BAPV power plant. Table 7 presents other technical results from simulations as annual values, including the produced energy per kilowatt of installed power, PR, energy losses due to shading, power transmitted to the network, power transmitted to the network by considering the efficiency reduction in the first year, system's power consumption (inverter) on the standby state, and CO_2 emission reduction. The CO_2 emission reduction is assumed as 600 gr per kWh of thermal power generation [118, 119].

The energy production of the power plant is suitable regarding the PR value, but despite the modifications in the initial simulation, the main contribution to produced

Table 6 Economic model data of the BAPV system

Parameter	Value
Assessment period	20 years
Discount rate = inflation rate	18%/year
Feed-in tariff	
First 10 years period FIT	
Validity	1/1/2023 – 12/31/2032
Specific feed-in / export remuneration	0.0417 $/kWh
Inflation rate for feed-in / export tariff	35%/year
Second 10 years period FIT	
Validity	1/1/2033 – 12/31/2042
Specific feed-in/export remuneration	0.0292 $/kWh
Inflation rate for feed-in/export tariff	35%/year
Costs	
Total investment costs	16,700 $
Module	13,000 $
Inverter	1200 $
Others (structures, cables, transportation, labor, feed-in meter, …)	2500 $
Maintenance	1.5% of total investment costs
Inflation rate of maintenance costs	2%/year
Specific investment costs	856.41 $/KWp

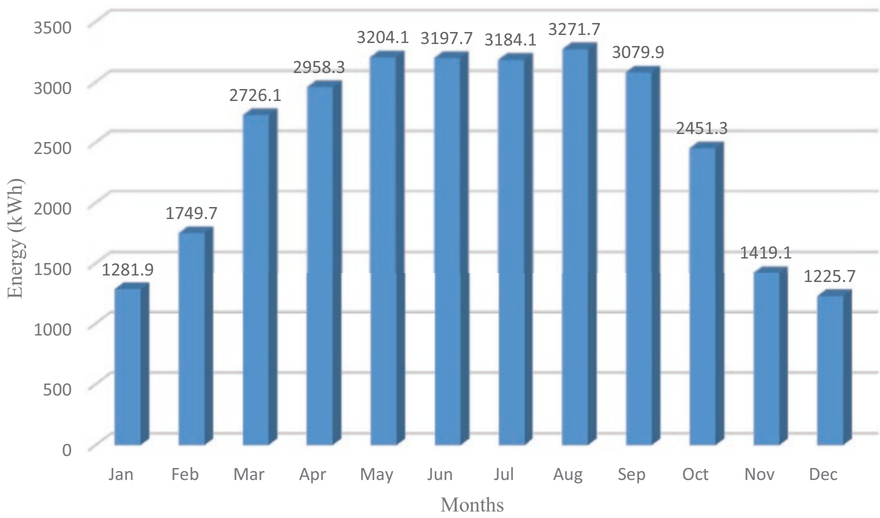

Fig. 10 Energy produced by BAPV power plant during months of a year

Table 7 Technical values from system simulation in 1 year

Parameter	Value
PV generator output	19.5 kWp
Spec. annual yield	1524.17 kWh/kWp
Performance ratio (PR)	75.6%
Yield reduction due to shading	16.2%/year
Grid feed-in	29,750 kWh/year
Grid feed-in in the first year (incl. Module degradation)	29,399 kWh/year
Standby consumption (inverter)	28 kWh/year
CO_2 emissions avoided	17,833 kg/year
PV generator surface	108.96 m^2
Global radiation at the module	2004.05 kWh/m^2
Global radiation on module without reflection	2014.21 kWh/m^2

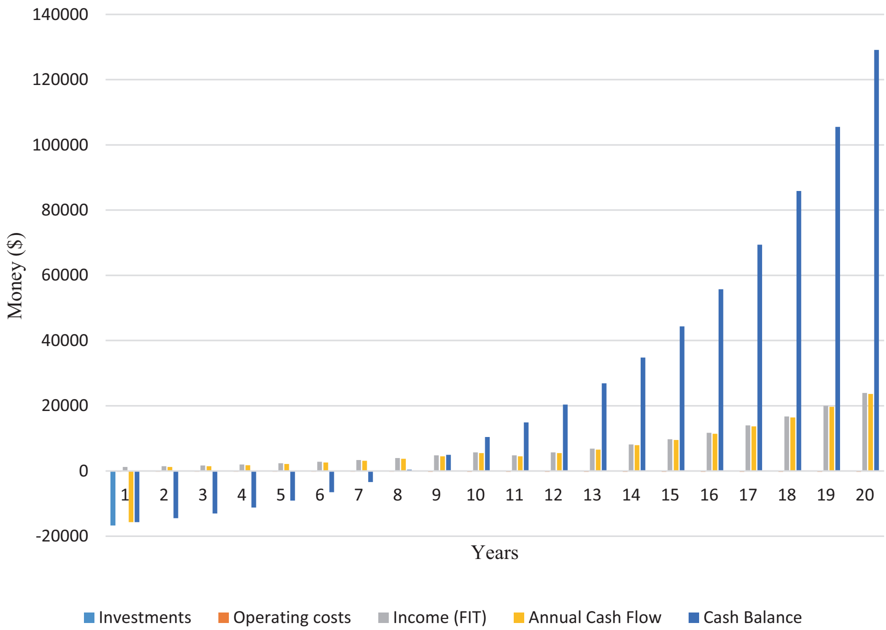

Fig. 11 Results of economic analysis of the system for 20 years

power reduction is related to shading with 66%. The saving in CO_2 emission is according to the global mean rate and studies in previous decades. However, statistics reported by some authorities in the energy sector of Iran, compared to the global average, it is 100 g/kWh higher for thermal power generation [120, 121]. Therefore, the environmental advantage of using the PV system in Iran is higher than in other countries. Results of the economic analysis are presented in Fig. 11. All costs/incomes are leveled with a discount rate of 18% based on the first year of the

Table 8 Economic factors of the BAPV system

Parameter	Value
NPV	129160.3 $
IRR	21%
PBT	7.9 (8 years)
LCOE	0.036 $/kWh

project. Cash balance indicates the accumulation of incomes and costs during 20 years, and annual cash flow is the sum of costs and incomes each year. In all calculations, the incomes are considered positive, and costs are considered negative.

The economic factors of the project are specified in Table 8. NPV is positive, and IRR is higher than the interest rate (18%). However, PBT is not interesting; it means that although the land price has not been paid and somewhat optimistic values, such as the increased rate of 35% per year for AF_{FIT} during the whole contract time and not considering the extreme fluctuations, are considered, PBT will be 8 years. Also, LCOE indicates that after the tenth year, the mean cost of power production will be higher than its price (0.0292 $/kWh).

As mentioned above, components of PV systems in Iran are highly dependent on the exchange rate. Although the global prices of PV modules and some components related to PV systems have been reduced, the cost of construction of these power plants has increased in Iran. On the other hand, notwithstanding a 50% increase in FIT (Rial) in the recent decade, its price in euro/dollar has significantly decreased. Therefore, this increase in FIT price due to the dependency of PV systems on the value of the currency is not able to offer the required economic interest for investing in this sector. These problems are because of an increase in the exchange rate and inflation by several times in Iran in recent years.

5 Conclusion

Similar to most regions on the earth, climate change, increasing energy consumption, and air pollution in cities are fundamental challenges in Iran. As renewable energy systems are clean and available, using them may be a solution to these crises. Iran has a vast area and versatile climates, and a great portion of its area has arid and semi-arid climates. Various studies have indicated that this country offers suitable potential for the construction of PV power plants. The water crisis and lower life cycle water footprint in PV power plants increase the advantage of using this system. In the present study, the general situation and weather indices of Iran's climates have been examined. Results indicate the high potential of solar power production in Iran. Then, Tehran as a metropolis was selected to study weather indices because of different reasons, such as population density, high energy consumption, air pollution, and the great potential of solar energy production. As expected, weather indices indicated that this region has a good potential to construct a PV power plant. Then, a residential building with conventional architecture in Tehran was selected and modeled to evaluate the construction of a small-scale PV power plant on its roof. Hourly weather data were used to simulate an on-grid BAPV power plant with 300-W monocrystalline modules. The number of modules was 65, and the nominal capacity of the power plant was 19.5 kW. All panels were oriented with a 30° inclination toward the south.

Technical results from simulations were satisfying; this power plant can transmit about 29,400 kWh of clean energy to the power grid, and its PR is higher than 75%. Also, by preventing the emission of at least 17,833 kg CO_2 per year, it is eco-friendly. In addition, it was found that more than half of the reduction in electricity production is related to shading losses. However, the results from the economic analysis of the system are not very promising; the PBT of the system is 8 years, and at the beginning of the second decade of the project, the mean cost of electricity production will be higher than the electricity purchasing price. Regarding some simplifications, such as constant FIT rate, not considering the unpredicted changes of prices, exchange rate increase during the project life, some risks like accidents that are not included by the warranty, and 6–8% uncertainty in weather predictions, this investment is not attractive economically. Especially since the highest FIT rate is for power plants less than 20 kWh, and in this study, a 19.5 kW power plant has been evaluated. These problems may be resolved with the stabilization of prices and exchange rates, as well as more serious supportive policies for constructing BAPV power plants. Currently, the electricity price for consumers is much lower than the FIT rate. Therefore, by gradual modification of energy subsidies and gradual and systematic realization of the rate, the motivation for BAPV construction will be increased. In addition to management and policy-making problems that cause unstable prices and improper markets for investment, foreign sanctions also affect this. By resolving these problems and regarding the high potential of Iran in the solar energy sector, a promising future can be imagined for the increased use of PV systems in Iran.

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Massive Growth of PV Capacity as a Major Cornerstone of Germany's Energy Security and Climate Policies

Rainer Hinrichs-Rahlwes

1 A Country with Low Solar Irradiation and High PV Capacity

Germany is located in Central Europe, between the 47th and the 55th northern parallel, and between the 6th and the 15th eastern meridian [1]. These are roughly the same geographical parallels as Alaska or the northern part of the United States of America. The annual sunny hours vary from north to south as well as over time. As an example, Hamburg, in the northern part of Germany, had 1500 sunny hours in 2010 and 1900 in 2022. Munich, in Bavaria, the southern part of Germany, had 2000 sunny hours in 2015 and 2500 in 2022 [2]. These data certainly do not rank Germany among the sunniest regions but rather among those with low irradiation compared to other places on our planet [3].

Despite the relatively low number of sunny hours, Germany was among the most successful pioneers of solar PV. Since 2000, with ups and downs since then, the country is actively increasing the installed solar capacity by a mix of focused legislation, policies and measures. In 2020, 59 GW_p of total installed PV capacity produced 51 TWh of electricity or 10% of the country's overall power consumption [4]. In 2021, already 10.9% of Germany's electricity demand was produced from PV, which was the seventh highest share globally – after Spain (14.2%), Greece (13.6%), Honduras (12.9%), the Netherlands (11.8%), and Chile (10.9%) [5]. At the end of 2022, Germany was also among the leading countries in terms of cumulative installed capacity, ranking 5th and being outcompeted only by China, the United

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States, Japan, and India. On a per capita basis, Germany was the global number 3 (after Australia and the Netherlands).

2 Policies for Renewables: From the Early Days to *EEG 2000*

How was all this achieved? Motivated by the ambition to mitigate climate change and at the same time phase out nuclear power, a first law to support renewable electricity production (in particular from wind, but to a certain extent also aiming at early PV installation) had already been in place since 1991.[1] After nearly a decade and technology progress over time, this law needed a thorough revision to accelerate renewable energy development in Germany. In 1998, the new government coalition of Social Democrats (SPD) and Green Party agreed to develop and enact an enabling framework to kickstart and accelerate renewable energy for Germany's power production, an objective, which was politically supported by most of the population, which again resulted in a broad support across the political spectrum, on federal level and on state level, including not only the now ruling red and green coalition, but – despite some differences in details – also the conservative and liberal opposition parties, who could always claim the merits of the 1991 feed-in law.

In May 2000, the Renewable Energy Sources Act [6, 7] – acronym EEG (Erneuerbare Energien Gesetz) – entered into force, enshrining a legally binding target of at least 20% of Germany's electricity to be sourced from renewable energy by 2020. When the law was discussed in parliament, this target sounded utopian to some and at least extremely ambitious to most legislators, including those who supported and pushed for passing the new law. Given that in 2000 only 6% of Germany's power production came from renewables with hydropower providing more than half of it, it was obvious that a strong effort was needed to achieve the 20%-target [8]. From today's perspective, these discussions prove how difficult things seem to be until they are actually done. In 2022, nearly half of Germany's electricity was produced from renewable sources, 11% from PV alone.

Why was EEG 2000 (and subsequent amendments and revisions) so successful and taken as an example for own legislation across the globe? The answer is quite obvious: It was a timely and simple piece of legislation – a landmark project when the time was mature for the next phase of the energy transformation. It allowed and incentivised virtually everybody to produce renewable energy from hydropower, wind, solar PV, biomass, and geothermal sources, by requiring grid operators to connect the installations to the grid and provide priority feed-in for electricity from renewables. And the law guaranteed fixed "feed-in tariffs" (FIT) to all producers of renewable electricity – a fixed price by kWh to be paid for 20 years. These tariffs

[1] This early legislation (*Stromeinspeisegesetz* – translating to Electricity feed-in law) already enacted fixed payments for renewable electricity producers financed by a surcharge on electricity prices. It was an early – and sometimes forgotten – prototype for EEG 2000, which could build on the basic principles of the 1991 law.

were technology-specific – calculated on a scientific basis to make sure the producers received what they needed based on low-profit expectations to implement their investment, which again provided security for banks to hand out cheap loans. And the tariffs were different for large and small installations, and for windpower even for different windspeeds. To accelerate the rapid uptake of renewables, the feed-in tariffs were reduced by 5% year on year for new installations to incentivise fast deployment instead of waiting for another year or more.

The EEG kickstarted the development of new capacities particularly in windpower (onshore, and later also offshore) and also solar photovoltaics. Solar manufacturers[2] evolved in Germany, creating a new industry with tens of thousands of new jobs across the country, including jobs for installers and including factories for PV panels, which were particularly welcome in the former eastern part of Germany, where after Germany's re-unification in 1989 (with most industries disappearing because they were technically outdated and economically unsustainable) new and future proof jobs were desperately needed.

As foreseen already in 2000, the EEG was regularly reviewed and revised, the guaranteed tariffs adapted to cost development, and – when economies of scale kicked in as they should – significantly reduced. For example, the FIT for PV was nearly 50 €-cent in EEG 2000 (99 Pfennig per kWh). It was gradually reduced to now only 5.8 €-cent/kWh for rooftop installations up to 100kW_p in 2023. For larger installations including ground-mounted installations, more exposure to the electricity market was gradually introduced, and in 2014 participation in auctions became a mandatory condition for grid-connection and guaranteed remuneration, resulting in even lower feed-in premiums (FIP – instead of a fixed FIT now as a premium on top of the spot-market price) of – so far – down to 3.8 €-cent per kWh.

3 Pushing for and Driven by European Targets and Policy Frameworks

A strong commitment by policymakers worldwide to rapidly accelerate the deployment and use of renewable energy is a mainstream narrative these days. Despite some doubts about whether all those who verbally commit to renewables actually mean it, or whether some of them are actually paying lip-services, the importance of renewable energy for supply security and for climate protection has become common sense in policy debates worldwide. This is the result of technology maturity, and of continued policy development since the early 1990s of the twentieth century. Although there had been renewable energy pioneers around the globe much earlier, particularly in Denmark, in the United States, in Spain and elsewhere, the German

[2] Wind turbine manufacturers, of course, also benefited from the law by significantly expanding their production capacities and extending their sales – in Germany and soon also beyond. But this text is about PV. Therefore, I shall only mention other renewables, where it helps to understand the political and societal context.

EEG 2000 became the final trigger to what is nowadays often branded as the global renewable energy revolution, or the next industrial revolution.

The idea behind the EEG – an ambitious mid-term target combined with technology-specific feed-in tariffs guaranteed for up to 20 years – was adapted and introduced in more than 80 countries worldwide. Policies for renewables were developed in countless constituencies in the global north as well as (and increasingly) in the global south. Looking back, the EEG and similar legislation in other countries is the origin of today's strong position of renewable energies in most parts of the world. For more than a decade, renewable energies have been the dominant sources of new power capacity additions globally, as documented i.a. by the annual Renewables Global Status Report produced by the global multi-stakeholder network REN21 [9].

Driven – among other factors – by the German government's ambition and the EEG 2000, the European Union (EU) also developed strategies and legislation to support renewable electricity. Consequently, a first Renewable Electricity Directive entered into force in 2001 [10]. It set non-binding renewable electricity targets for each member state of the EU and included elements of enabling policy frameworks. In my book *Sustainable Energy Policies for Europe* [11] I described and analysed in some detail how this directive was the starting point for the EU as a whole to embrace renewable energy as a main pillar for energy security and climate protection. In 2009, pushed by some governments, but also strongly by renewable energy (industry) associations, this process resulted in a new Renewable Energies Directive (RED) [12] setting a binding target for the EU of at least 20% by 2020 for the Renewable Energy Share in gross final energy consumption (GFEC),[3] as well as nationally binding targets for each member state. This directive was revised in 2018 [13] increasing the EU-target for Renewables in GFEC from at least 20% by 2020 to at least 32% by 2030.

When a new European Parliament (EP) was elected and a new European Commission (EC) took office in 2019, the energy transformation – now labelled as the *European Green Deal* [14] – aiming at Climate Neutrality by 2050 became a lighthouse project for the European Union. To facilitate the implementation of the broad scope of more detailed and specific objectives of the Green Deal the new EC presented a package of legislative and regulatory proposal and enabling strategies in July 2021 – labelled *Fit-for-55* [15] to highlight the EC's recommendation for a new 2030-target for the EU's Greenhouse Gas emissions reduction. The package includes – as one of more than a dozen dossiers – a proposal for an amended Renewable Energies Directive [16] aiming at increasing the EU's renewable energy target for 2030 to at least 35%. This is, however, not the place for an in-depth analysis of the EC proposal including the discussions about the necessary ambition level

[3] In difference to the Renewable Electricity Directive of 2001, the new Renewable Energy Directive of 2009 went beyond the power sector and included policies and targets for heating & cooling as well as for the transport sector. The 20% target for 2020 was an overall energy target, with the power sector only being one pillar.

and enabling policies. For more details, see my analysis as presented at WREC 2020/2021 in Lisbon [17].

Whereas several parts of the Fit-for-55 package have been successfully discussed and politically agreed between EC, EP and EU Member States, the proposed amendments to the RED are still under discussion, particularly due to a new strategic package (REPowerEU) [18] presented by the European Commission as a reaction to Russia's invasion of Ukraine. The package is aiming at increasing and accelerating Europe's energy security by diversifying resources and reducing import dependencies, particularly from Russia, and aiming at significantly accelerating the deployment of renewable energies in all end-uses across the EU. REPowerEU includes proposals for increasing the share of renewable energy in the EU's GFEC to at least 45% by 2030 (up from the 35% in the Fit-for-55 package). This shall be achieved – among various other measures – by defining renewable energy projects as being of *overriding public interest* when competing with other interests requiring legal protection. Furthermore, permitting – particularly for wind and solar installations – shall be significantly accelerated by means of defining *go-to areas*[4] for renewable energy installations with simplified environmental impact assessment requirements and by setting a maximum duration for the permitting procedures to be finalised – to a maximum of 2 years (or less) for wind onshore and a maximum of 3 months for rooftop solar and heat pumps. It is expected that the legislative process for these amendments will be finalised by mid-2023 so that the new rules can enter into force soon afterwards. Together with simplified and more open rules for admissible state aid, the integration of the REPowerEU proposals in the amended RED and other legislation and regulations can be expected to become a strong instrument to achieve – at least – 45% renewables in GFEC across all end-uses in the EU by 2030 (although several member states are still pushing for a lower target of 40% only). The renewables share in power supply will be significantly higher and dominant in most EU Member States.

A more ambitious RED with clearly defined policies to accelerate the transformation towards renewable energy in Europe will have positive repercussions in Germany – in addition to what is already highlighted in the coalition agreement [19] of the new government formed by an *Ampel-Koalition*[5] which took office after the federal elections of September 2021. The RED including future amendments and revisions will become even more relevant, since the new German government is also more proactive on EU-level, when it comes to convincing other member states to support and engage in ambitious renewable energy targets and policies.

[4] Meanwhile, these go-to-areas will probably be rebranded to *Renewable Energy Acceleration Areas*. But the purpose – to accelerate and simplify permitting and deployment remains the same.

[5] *Ampel-Koalition* translates as *Traffic Light Coalition*, derived from the signatory colours of three parties involved: the Green Party, Red for the Social Democratic Party, and Yellow for the Liberal Party (FDP).

4 New Government 2021: Relaunch of Germany's Energy Transition

Based on the success of the EEG 2000 and subsequent amendments, Germany was often considered as – and actually was – a global leader in renewable energy policies and rapid deployment of new installations – in particular wind and solar PV, but there was also significant growth of biomass and biogas production and power plants as well as continued use of hydropower, and additional tapping into geothermal potentials.

Germany's invitation to the *renewables2004* [20] conference in the former capital Bonn kicked off a series of conferences to mainstream and accelerate the energy transition globally. The conference resulted in founding the global policy network REN21 [21]. Since then, the network has published annual Renewables Global Status Reports [9] and organised biannual International Renewable Energy Conferences (IRECs),[6] the latest edition of which was held in February 2023 in Madrid, Spain.

Germany also took the initiative for creating an intergovernmental global institution to promote renewable energy, International Renewable Agency (IRENA) [22], which was eventually founded in 2009. Today, IRENA has 169 member states and is headquartered in Abu Dhabi, United Arab Emirates and it has a dependency in Bonn.

Slowdown of the Energy Transition in Germany (2013–2021)

Based on the obvious success of the EEG and also based on the global activities to promote and support renewable energy development, Germany's reputation of being a global leader in renewable energy is still strong, but the country did not always live up to this reputation. Deployment of new renewable energy capacity dropped significantly after 2012, when the government introduced changes to the EEG, which drastically reduced incentives for solar PV.

As a result of these changes, annual PV capacity additions declined (see Fig. 1) from 10.9 GW in 2011 and 10.7 GW in 2012 to only 2.6 GW in 2013 and 1.2 GW in 2014. This trend was only reversed in 2018, when 2.9 GW were installed, followed by 3.9 GW (2019), 4.8 GW (2020) and 5.0 GW (2021). First estimates for

[6] The idea was to convene conferences to discuss and promote and practically commit to the global renewable energy transition. The conferences should be held bi-annually, a scheme which was basically followed, with some exceptions and an interruption due to the Covid-19 pandemic. The follow-up conferences to *renewables2004* were held in Beijing, China (BIREC 2015), Washington, USA (WIREC 2018), Delhi, India (DIREC 2010), Abu Dhabi, UAE (ADIREC 2013), Cape Town, South Africa (SAIREC 2015), México City, México (MEXIREC 2017), Seoul, South Korea (KIREC 2019), and Madrid, Spain (SPIREC 2023). The next event is envisaged for the first half of 2024 to be held in Adelaide, Australia.

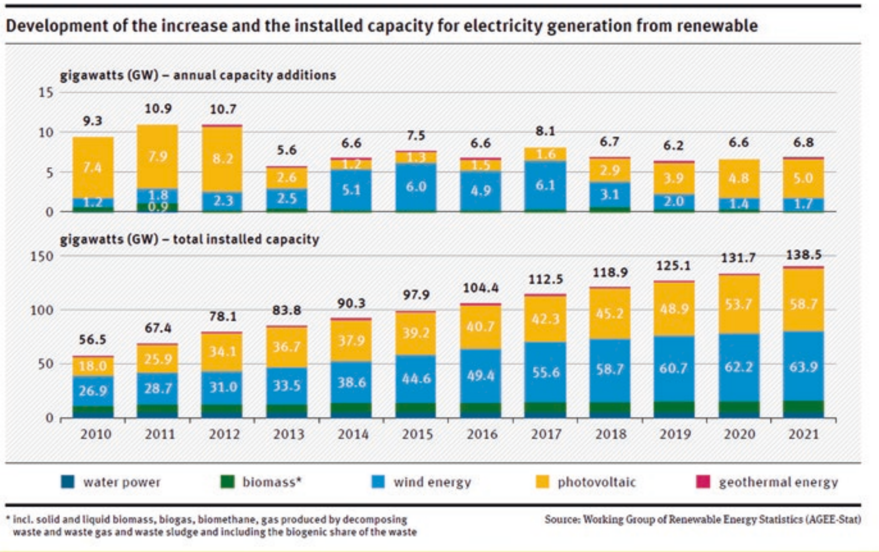

Fig. 1 Annually installed renewable energy capacity [23]

2022 assume nearly 7.2 GW of new PV capacity [24], which may be taken as an indicator that some recovery is taking place.

Annual new windpower capacity grew up to 6.1 GW in 2017, before policy changes put an end to this level of expansion to a second major technology. Shifting from fixed feed-in tariffs to auctions and market premiums as the main support scheme in addition to growing administrative barriers led to less than 2 GW annual wind power capacity additions since then. A turning point for onshore wind power is not yet in sight, but the *Ampel-Koalition* vowed to reverse the negative trends and massively increase renewable energy deployment by setting up enabling legislation, aiming at higher targets and particularly at simplified and shorter permitting procedures for new installations in order to stay on track for reaching the objectives of the Paris Climate Agreement. This renewed ambition includes the objective of climate neutrality for Germany by 2045 the latest, and for complete coal phase out which shall "ideally be achieved by 2030".

New Objectives and New Policies

The new government coalition agreed – and had already introduced several packages of proposals for enabling legislation, when this text was written in early 2023 – on a share of at least 80% renewables in the power sector by 2030, to be achieved by higher auction volumes for onshore and offshore wind as well as larger PV installations, and by supporting and facilitating more distributed and community-owned renewable installations and renewable energy communities, the latter being particularly favourable for PV with and without battery storage, including with (partial) self-consumption. The agreed objective is a PV capacity of 200 GW by 2030 (up from 59 GW in 2021). All suitable roofs shall be used for solar energy, which will become mandatory – in a first step – for commercial buildings, potentially to be followed by similar mandates for private homes and residential buildings. The coalition also agreed to increase the support for electromobility by focused incentives for buying electric vehicles as well as by facilitating faster roll-out of charging stations, including by mandates for public buildings and places.

Russia's invasion and ongoing war in Ukraine resulted in even further increased ambition to reduce energy import dependencies. Huge efforts were made to diversify (fossil) gas supply by contracting new suppliers and by building new terminals for LNG (liquified gas). Although contracting new fossil gas supplies is obviously contradicting the need for more – particularly distributed and domestic – renewable energy capacities which is important for the overarching objective of decarbonisation according to the Paris Agreement, it seems that accelerating renewable energies deployment is actually a major element of all emergency strategies when it comes to mitigating the negative impacts of Russia's war on supply security and energy costs for private as well as commercial consumers. We are told that diversification of fossil gas suppliers will only be relevant for a transition period and will soon be transformed into green gas and green hydrogen. Doubts remain how fast this transformation will actually be implemented. But it is still true that the war led to faster implementation of new acceleration measures for renewable energy deployment, particularly for wind and solar power and for heat-pumps to electrify the heating and cooling supply.

Legislation for Higher Ambition and Accelerated Deployment

The higher ambition and a number of the envisaged measures were transposed in legislative proposals, some of which were already agreed in parliament and had entered into force, when this text was written. A few months after the newly elected government took office, they introduced a comprehensive legislative proposal in early 2022, the "Easter Package", followed by a "Summer Package", which consisted of draft amendments to the EEG, and other energy-related laws and regulations. The packages [25] were aiming to legally enshrine the agreed objective of at least 80% renewable power by 2030, and to accelerate and simplify permitting procedures for new renewable energy installations.

The amended law, the EEG 2023 [26], is a key element of the government's ambition to "triple the speed of renewable energy expansion". As a major improvement to earlier legislation the EEG 2023 (paragraph 2) defines an important legal priority by enacting the principle that the "erecting and operating of renewable energy installations and related auxiliary installations is of overriding public interest and a service to public security".[7] According to the EEG 2023, this principle is set to apply until Germany is basically climate neutral.

The EEG 2023 also defines new dates and higher volumes for planned auctions for the different renewable energy technologies and sources. An annually increasing capacity will be auctioned for hydrogen-based power storage capacities (paragraph 28d: from 400 MW in 2023 to 1000 MW in 2028), and for installations for the production of green hydrogen (paragraph 28e: 800 MW in 2023 to 1400 MW in 2026). Paragraph 4 sets the envisaged capacity of onshore wind turbines to grow to 69 GW in 2024, 115 GW in 2030 and 160 GW in 2040. PV capacity shall grow to 88 GW in 2024, 2015 GW in 2030 and 400 GW in 2040. Biomass is set to an installed capacity of 8400 MW in 2030. All renewable energy sources as defined in the law are expected to produce 287 TWh of electricity in 2023, growing to 600 TWh in 2030 (paragraph 4a). To achieve these objectives, annual auction volumes are defined in paragraphs 28a-e. In addition, the *Wind Energy at Sea Act* [27, 28] sets the objective of at least 30 GW of offshore wind by 2030, 40 GW by 2035, and 70 GW by 2045.

The annual auction volumes for ground-mounted PV installations and all PV installations that are not part of a building, or a noise protection wall are set to 5850 MW in 2023, 8100 in 2024 and 9900 MW each year from 2025 to 2029 plus 650 MW in 2023, 900 MW in 2024 and 1100 MW annually from 2025 to 2029 for installations that are integrated or attached to buildings (BIPV, BAPV) including noise protection walls.

Most new renewable energy installations need to qualify for guaranteed grid connection and remuneration through these auctions, which are held on pre-defined dates several times a year. For all different types and sizes of renewable energy installations, which are subject to bidding in these auctions, strike prices or the methodology for their calculation and adaption are defined in EEG 2023. For BAPV and BIPV, the strike price is generally set to 7 cent/kWh. For installations of up to 10 kW_p it is set to 8.6 cent/kWh, and for installations of up to 40 kW_p it is 7.5 cent/kWh. For installations of up to 1 MW_p it amounts to 6.2 cent/kWh. These values are increased by 4.8 cent/kWh (installations of up to 10 kW_p) respectively 1.9 cent/kWh (for larger installations) for feeding all the produced electricity into the grid – an incentive not to opt for self-consumption. Starting in February 2024, the strike prices for new solar PV installations are reduced by 1%, and again after every 6 months.

According to paragraph 22, small installations of up to 1 MW (or 18 MW for wind) and in particular installations owned by *renewable energy communities* as defined in paragraph 22b are exempt from auctions and qualify for direct remuneration, which is meant to particularly support and incentivise their uptake.

In addition to the rules and principles set out in EEG 2023, the government is striving for shorter and simplified permitting procedures, particularly for wind

[7] The translation of this paragraph as well as other parts of EEG 2023 quoted here were done by the author of this text and therefore cannot qualify as official or legally binding translations.

onshore and for ground mounted as well as building-related PV. For rooftop solar and *balcony solar* levies and fees to be paid by the owners were removed or reduced. Major advantages for solar PV were introduced in taxation [29]. New solar panels can now be sold at lower prices because they are no longer subject to VAT (19%), inter alia if they are installed on residential buildings, or if their rated capacity is below 30 kW_p. Another useful decision is waiving the income tax on feed-in payments. Until the end of 2022, these payments were subject to income taxation. This is being waived as of January 2023, including retroactively for 2022, automatically for up to 10 kW_p, on application for installations of up to 30 kW_p and for up to 100 kW_p per taxpayer.

5 Challenges Ahead

Building on the described enabling measures for faster renewables deployment, particularly for the PV sector, more will have to be enacted and implemented in the next few months and certainly before the next federal elections in autumn 2025. Particularly for wind onshore, permitting bottlenecks will have to be removed so that more projects will actually be ready to place bids in the upcoming auction rounds or to be directly implemented, if they are exempt from auctioning. To a lesser extent, accelerated permitting will also be necessary for larger PV installations, particularly those which are subject to auctioning. For BIPV, rooftop and other building-related PV installations, further alleviation of remaining administrative barriers needs to be addressed and solved, among others by facilitating electronic procedures instead of paperwork, and by further reducing bureaucratic burdens for small installations such as *balcony solar* [30], small modules of up to 600 or 800 W_p, which can directly be connected to standard power plugs in every household. Furthermore, it would be necessary to remove disincentives which prevent higher shares of self-consumed electricity particularly from PV installations on private and commercial buildings, inter alia by accelerating smart meter deployment and by facilitating and supporting battery storage in private, residential, or commercial buildings and encouraging more behind-the-meter production and consumption of renewables, and in particular PV.

Another important aspect to be addressed in the near future is the question of resource availability – in terms of sustainability as well as in terms of availability in a world with growing political tensions and potentially related resource shortages. Given that about 80% of all production stages of PV modules are produced in China, and given that a similar share of necessary raw materials for PV modules is also depending on imports from a few countries, it is obvious that there is a need for more diversified suppliers of resources, as well as for innovative materials.

Finally, and certainly not least, the high level of import dependency for solar modules requires timely and strong efforts to maintain and restore localised manufacturing capacities across the globe – and from a German (and European) perspective this translates into the need for an effective strategy to (re)develop increasing production capacities for solar modules across Europe, triggered and supported by enabling policy decisions including financial support to attract investors and thus to set up localised value chains. It needs to be mentioned that the wind industry is facing similar challenges – with a stronger focus, however, on safeguarding and securing existing manufacturing capacities instead of developing new ones as in the PV sector, where most of the capacities created in the first decade of this century were closed or transferred to other parts of the world with more favourable frameworks. But the challenges for wind and solar are basically the same – to develop and maintain globally distributed instead of widely centralised production capacities and resource availabilities in a few countries or regions.

6 Instead of Conclusions: Outlook for Germany and Europe

With little more than a year in office, the new German government coalition has already implemented important policy decisions and successfully passed legislation to relaunch and accelerate Germany's energy transition. After years of decreasing growth rates and low annual capacity additions a clear political will is perceived to relaunch the energy transition and to bring Germany back on track to fulfil the commitments of the Paris Agreement – enhanced by the widely shared objective of reducing supply disruptions and cost increases by accelerating the shift to renewable energy, which is abundantly and widely domestically available. Despite some questionable decisions for new fossil gas suppliers and related negative impact on greenhouse gas emissions reduction, the strong resolution to successfully overcome the fossil-induced supply and cost crisis by speeding up renewables, has also revitalised the political commitment to achieving climate neutrality by 2045. Public perception is growing that drastically increasing renewable energy capacities in all end-uses is a win-win option: securing energy supply security goes hand-in-hand with revived expectations that Germany will eventually be back as key player in the global renewable energy transformation.

And this is not only true for Germany as a country, but it also applies from a European perspective, where Germany is one of the major drivers. Defining renewable energy projects as being of overriding public interest and in the interest of public security is not only part of the German EEG 2023 but will also be enshrined in the amended EU Renewable Energy Directive.[8] An increased 2030 target of at least 45% renewables in the EU's GFEC is part of the final negotiations about the amended directive, and also significant simplification and acceleration of permitting procedures for wind and solar projects, just as a solar rooftop initiative is part of

[8] The Revision of this directive is in the final phase of political negotiations when this text is written. The 45% target as well as other elements described in this paragraph are not yet officially agreed between the European Council (representing the 27 Member States) and the majority of the European Parliament, which will both have to agree, before the amended version can actually enter into force. The results mentioned here are the likely outcome according to the information available at this point in time.

REPowerEU, which aims at establishing solar rooftop obligations for new – and later also for existing – commercial and private buildings. It also includes the target of annual installations of at least 45 GW_p of new PV capacity in the EU in this decade.

Triggered by the Inflation Reduction Act (IRA) [31] of the Biden Administration in the US, which provides strong financial support to renewable energy industry and renewable energy projects, the European Commission is now developing a *Green Deal Industrial Plan* [32] including a *Net-Zero Industry Act* which aims at Europe to be a global leader of the *clean tech revolution* by "turning skills into quality jobs and innovation into mass production, thanks to a simpler and faster framework. Better access to finance will allow our key clean tech industries to scale up quickly". The initiative will also include a *Critical Raw Materials Act* and will be combined with a reform of the EU electricity market design.

The transformation towards a renewables-driven energy system is in full swing, globally and in Germany and in Europe. Global scenarios foresee a huge share for solar PV in energy systems dominated by renewables. Bringing back and securing major parts of the value chain in Europe will provide millions of new and future proof jobs, in manufacturing, and even more distributed in operation and maintenance, and for architects and installers, as well as in mining and recycling. Solar PV is a major part of this expected and necessary transformation.

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Building Integrated Photovoltaic–Thermal System (BIPVT) Performance Under the Tropical Climate Conditions

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1 Major Geographical and Climatic Regions of Malaysia

Malaysia is situated in Southeast Asia that is separated by the South China Sea into two geographical areas, Peninsular Malaysia and East Malaysia, with latitude and longitude between 1° to 7°N and 100° to 119°E, respectively, as shown in Fig. 1. Both peninsular and East Malaysia are affected by similar airstream and have coastal plains and mountains that are often densely forested [1].

Malaysia has a tropical climate with uniform temperature, randomly variable sunny-to-cloudy skies, frequent rainfall, and high relative humidity, characterized by southwest and northeast monsoon regimes. The patterns of climate variables vary in different regions due to the influence of monsoon regimes [2, 3]. A climatic year has four seasons: The northeast monsoon that starts from November or December to March, first inter-monsoon period from March to April or May, the Southwest monsoon from May or June to September or early October, and the second inter-monsoon period from October to November [4].

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Fig. 1 Map of Peninsular and East Malaysia [5]

Wind Speed

Typically, Malaysia experiences gentle and non-uniform wind speeds between 0.6 and 4.5 m/s in different regions and seasons; some regions experience stronger winds during certain periods of the year. As shown in Fig. 2a, the wind speed in the Northeast monsoon season at the beginning and end of the year is higher than in the Southwest monsoon season, and it blows faster on the east coast of Peninsular Malaysia.

Precipitation

The main rainy season that often causes large floods in Malaysia is in the northeast monsoon regime, particularly to the states on the east coast of Peninsular Malaysia, west of Sarawak, and east of Sabah. In contrast, in the relatively drier southwest monsoon regime, most states experience minimal monthly precipitation except for Sabah in East Malaysia. In the inter-monsoon phase, the formation of storms leads to the maximum monthly average precipitation for both monsoon transition seasons. Figure 2b shows Peninsular and East Malaysia‘s monthly and annual average daily precipitation.

Ambient Temperature

Malaysia always has a high ambient temperature due to its location in the tropical region. As shown in Fig. 2c, the annual and monthly mean daily ambient temperature is in the range of 23–29 °C. Analysis of the diurnal pattern of climatic elements throughout the year shows that wind is inversely related to precipitation and ambient temperature.

Relative Humidity

Regarding heavy rains related to tropical regions and high ambient temperatures, Malaysia always has a high relative humidity. As shown in Fig. 2d, Malaysia‘s annual and monthly mean daily relative humidity is 73–94%. Analysis of the diurnal pattern of climatic elements throughout the year displays that rising precipitation and ambient temperature increase and decrease relative humidity, respectively, while wind speed does not influence relative humidity.

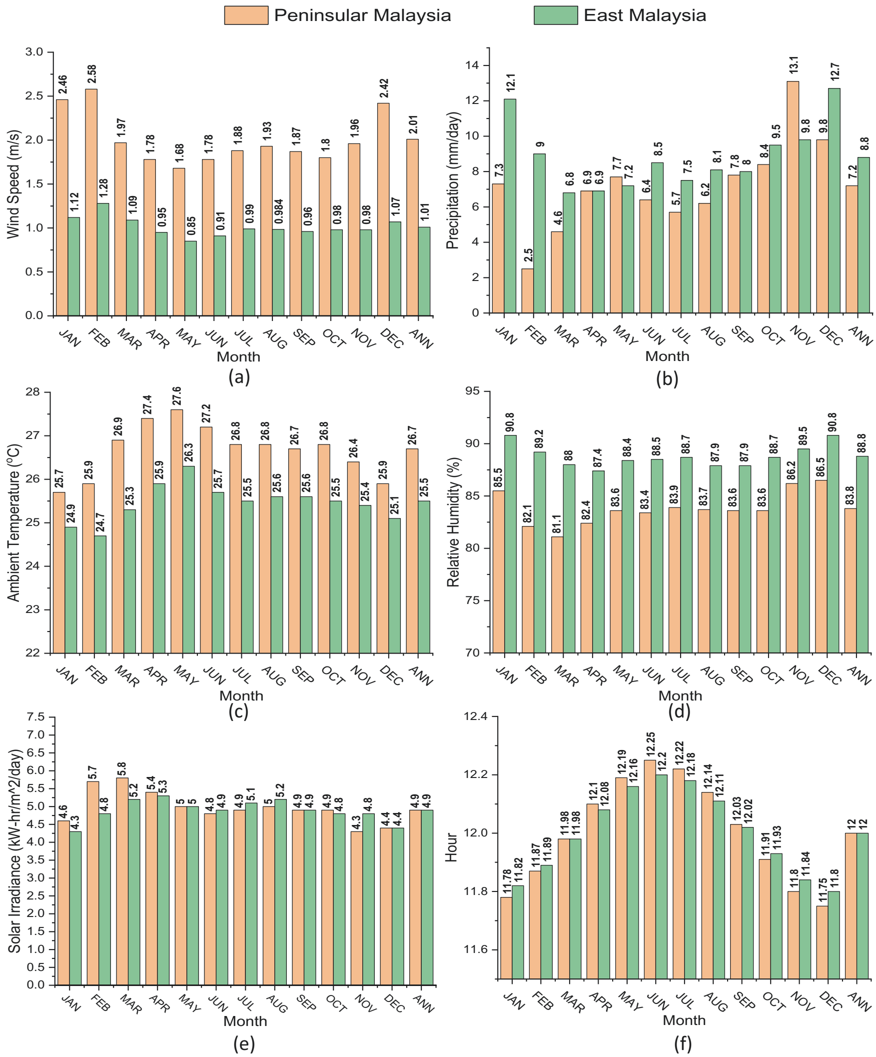

Fig. 2 Monthly and annual average daily (**a**) precipitation, (**b**) ambient temperature, (**c**) relative humidity, (**d**) wind speed, (**e**) solar irradiance, and (**f**) daylight hours of Peninsular Malaysia and East Malaysia [6, 7]

Solar Radiation

Given its proximity to the equator, Malaysia has plenty of solar radiation with a significant level of diffuse radiation and an average of 12 h of daylight for the entire year. Figure 2e, f display monthly and annual average daily irradiance and daylight hours of Peninsular and East Malaysia.

2 Malaysia Energy Statistics

In recent decades, Malaysia has moved toward as a developed country, and the rapid urbanization, population growth, and climate conditions have dramatically increased energy consumption. Over 20 years, from 1998 to 2018, energy consumption has more than doubled, increasing the overall supply of primary energy to meet energy demand [8]. Despite having abundant raw and crude primary energy resources such as oil and gas, Malaysia implemented the fuel diversification strategy by adding RE and imported coal and coke to ensure energy security, accelerate economic and financial development, and reduce greenhouse gas emissions [9].

Table 1 presents the primary energy sources and their consumption pattern from 1998 to 2018. The data in Table 1 shows that the total primary energy supply has increased by 59% over 20 years to meet energy demand. In contrast, the energy landscape in Malaysia encountered transformations such as the growth of natural gas consumption, the increase of RE, the Paris climate agreement, new technologies, and the emphasis on energy efficiency, which led to a 5.5% decrease in fossil fuels supply, a 17% decrease in crude oil supply and a 4% increase in renewables [8].

The energy supply in Malaysia greatly depends on energy transformation, local consumption, imported and exported primary and secondary energy sources, RE sources, air pollution, incidents and events, economy, regional and global policies, and most particularly over the last few years, epidemics.

Malaysia has the ability to supply domestic energy demands and export to other countries, regarding abundant energy resources such as oil and gas and facilities to transform raw and crude primary energy sources into usable secondary energy sources. In general, there are three types of facilities to transform raw and crude primary energy sources into secondary energy sources in Malaysia, as follows:

- Oil refineries transform crude oil into diesel, fuel oil, petrol, ATF, AVGAS, LPG, kerosene, and non-energy. Meanwhile, 36.8% of the crude oil is imported. Table 2 shows the input fuel to the oil refineries and the output usable secondary energy sources.

Table 1 Total primary energy supply by fuel type

	1998	2018
Fuel Type	Primary energy supply	Primary energy supply
Natural gas	19,104	40,948
Crude oil	19,063	29,463
Hydropower	1722	22,272
Coal & coke	1107	6192
Biodiesel	0	399
Biomass	0	200
Solar	0	200
Biogas	0	200
Total primary energy supply	40,996 ktoe	99,873 ktoe

Table 2 Oil refineries input and output

Input	Primary energy source	Output	Secondary energy source
LNG	31,105	LNG	25,920
GPP-LPG	2154	LPG	2075
MDS	1103	Diesel	125
		Kerosene	53
		Non-energy	323
Total	34,362 ktoe	Total	28,496 ktoe

Table 3 Gas plants input and output

Input	Primary energy source	Output	Secondary energy source
Crude oil	25,553 ktoe	Diesel	9665
		Petrol	5524
		ATF & AVGAS	3451
		Non-energy	2550
		Fuel oil	2432
		LPG	900
		Refinery gas	130
		Kerosene	18
Total	25,553 ktoe	Total	24,670 ktoe

Table 4 Power plants input and output

Input	Primary energy source	Output	Secondary energy source
Coal & Coke	20,485	Thermal	11,674
Natural gas	11,540	Hydro	2265
Hydropower	6235	Co-gen	616
Diesel	194		
Solar	155		
Biogas	77		
Biomass	39		
Fuel oil	0		
Total	38,724 ktoe	Total	14,555 ktoe

- Gas plants transform natural gas into LNG, LPG, diesel, kerosene, and non-energy. Table 3 indicates the input fuel to the gas plants and the output utilizable secondary energy sources in 2018.
- Power plants transform natural gas, fuel oil, coal and coke, diesel, hydropower, biomass, solar, and biogas into electricity. Table 4 displays the input fuel to the power plants and the output exploitable secondary energy sources in 2018, while 100% of the Coal & Coke is imported.

Secondary energy sources derived from primary energy transformation are the most consumed in the transportation and industrial sectors, followed by residential and

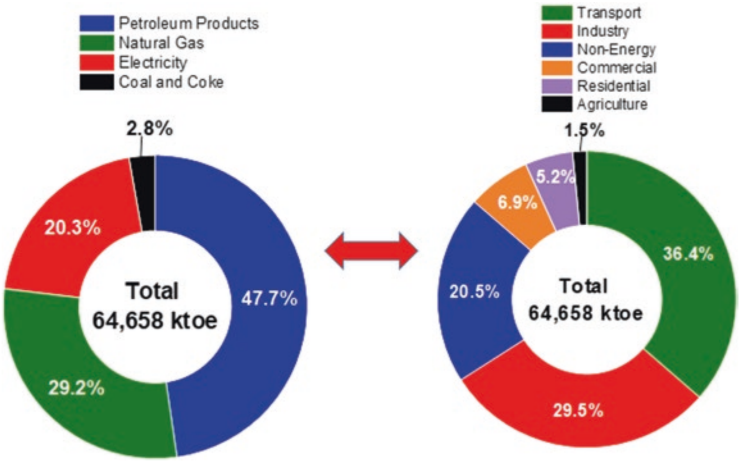

Fig. 3 Final energy consumption by sectors

commercial sectors. At the same time, agriculture is the sector with the least energy consumption, as shown in Fig. 3. An analysis of Malaysia's national energy between 1998 and 2018 demonstrates that energy consumption in transportation, industrial, and residential and commercial sectors declined by 23%, 8.1%, and 7.7%, respectively. In contrast, Non-Energy Use and agriculture sectors grew by 159.5% and 33.3%, respectively [8]. Additionally, Fig. 3 shows that petroleum products and natural gas were significantly more consumed than other sources in these sectors, followed by electricity as the most consumed energy source. Eventually, coal and coke was Malaysia's least consumed energy source.

Regarding the energy consumption pattern, the Malaysia government has prioritized the environmental impact assessment of all energy development projects and the use of renewables to minimize the negative effects of energy production, transportation, transformation, and consumption on the environment for achieving the goals of the Paris Agreement in response to global climate change.

3 Malaysia's Renewable Energy

Forasmuch as a large proportion of Malaysia's energy demands are met by fossil fuels, the Malaysian government intensified the development of RE by regulating the fuel diversification policy and considering RE as the fifth fuel since 1999 in order to provide a portion of the energy required, ensure energy security, and become a carbon-free country in the early 2050s [9]. Therefore, the following initiatives, programs, and strategies have since been implemented for the growth of RE technologies [10]:

8th Malaysia Plan (2001–2005)

- Small RE Power (SREP) Program for the connection of small power generation plants to the national grid.
- Small-scale Biomass Power Generation and Cogen Full Scale Model Demonstration (BIOGEN) Project by using oil palm waste.

9th Malaysia Plan (2006–2010)

- Development of rooftop solar through the Malaysian Building Integrated Photovoltaic (MBIPV) program.

10th Malaysia Plan (2011–2015)

- Adoption of the RE Act 2011 (Act 725) and the Sustainable Energy Development Authority Act 2011 (Act 726).
- Establishment of the Sustainable Energy Development Authority (SEDA) Malaysia as the designated authority for RE development in Malaysia.
- Implementation of a Feed-in-Tariff (FiT) scheme to accelerate the growth of grid-connected RE.

11th Malaysia Plan (2016–2020)

- Providing the Large-Scale Solar (LSS) competitive bidding program in order to develop solar photovoltaic power plants.
- Introducing the mechanism of Net Energy Metering (NEM).
- Introduction of Self-Consumption (SELCO) Program.
- Adopting sustainable energy development strategies by providing 1000 MW of large-scale solar projects, 500 MW of rooftop solar projects, and 188 MW of non-solar projects in order to enhance economic growth and investment opportunities to address the COVID-19 epidemic.

Although the fuel diversification policy has failed several times as a result of certain problems such as low electricity tariffs, high financial costs, and regional financial crises, the government has partially overcome these problems by forming the Sustainable Energy Development Authority (SEDA) and implementing the RE Act 2011. In addition, the Malaysian government, through the adoption of low-carbon and green policies, supportive policies, and initiatives such as Net Energy Metering (NEM), Smart Automation Grants (SAG), Green Technology Financing Scheme (GTFS), Green Investment Tax Allowance (GITA), Green Income Tax Exemption (GITE), and approval of the law to pay taxes based on the volume or weight of greenhouse gas emissions for companies using fossil fuels, have fueled the growth of the clean energy in Malaysia.

Renewable Energy Potential in Malaysia

Renewables in Malaysia include a wide range of natural energy resources, from hydropower and solar energy to biomass and geothermal, exploitable for power plants, transportation, and industrial sectors, while geothermal energy potential has

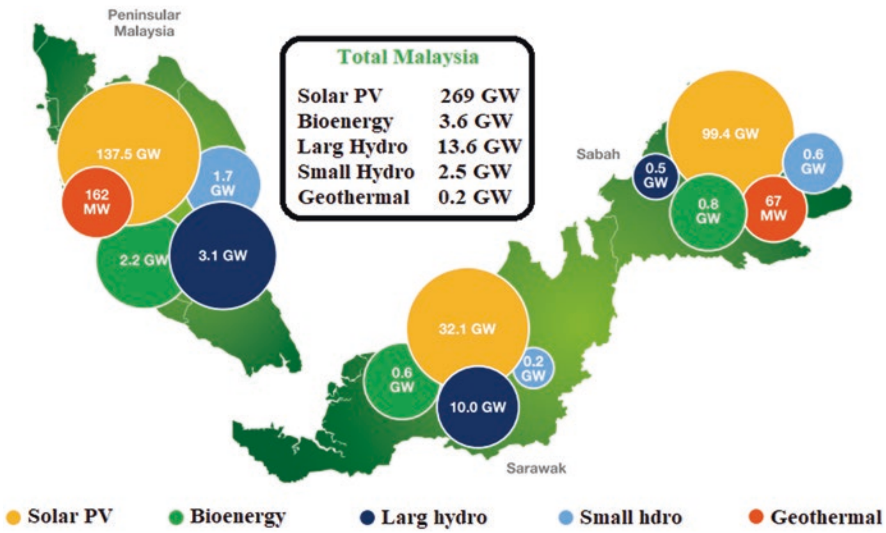

Fig. 4 Summary of RE resource potential in Malaysia [10]

remained untapped. Figure 4 shows the potential of RE resources in Malaysia as follows [10]:

- Solar photovoltaic: 269 GW including ground-mounted configurations (210 GW), rooftop PV system (42 GW), and floating configurations (17 GW).
- Large hydropower: 13.6 GW including 3.1 GW in Peninsular Malaysia, 493 MW in Sabah, and 10 GW in Sarawak.
- Small hydro: 2.5 GW.
- Bioenergy: 3.6 GW including biomass (2.3 GW), biogas (736 MW), municipal solid waste (516 MW).
- Geothermal: 229 MW.

Solar

Given its location near the equator, Malaysia is blessed with abundant potential for solar energy systems regarding the relatively high solar irradiation. Solar energy systems, with the ability of being used in residential and commercial buildings as well as the possibility of integration into the industrial sectors, have attracted the greatest attention of the Malaysian government among renewables concerning the energy crisis of the future, greenhouse gas emissions, and ozone depletion [11]. The solar PV system is the preferred technology by RE in Malaysia with respect to relatively high solar irradiation and photovoltaic electricity potential in Malaysian regions, as shown in Fig. 5.

According to the land utilization data, 1.2% of Malaysia's total area, equivalent to 4085 km^2, is available for ground-mounted solar PV systems with a potential of

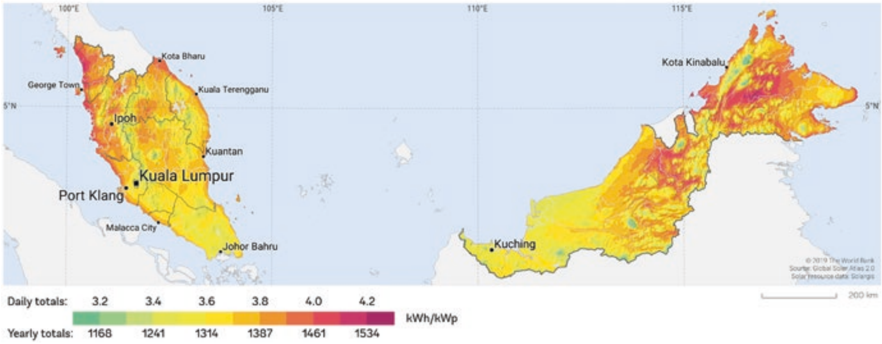

Fig. 5 Photovoltaic electricity potential in Malaysia [12]

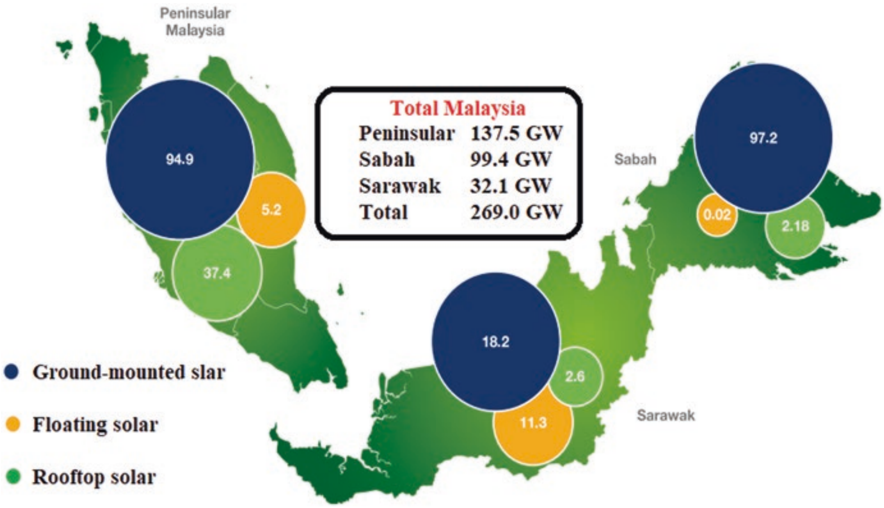

Fig. 6 Solar photovoltaic resource availability by installation and region [10]

210 GW. At the same time, there are 17 hydroelectric power plants and 62 reservoir dams with an area of 2944 km^2 of the total water surface area to install floating solar photovoltaic systems with a potential of about 17 GW. In addition, the potential for rooftop solar PV in Malaysia is approximately 42 GW due to the availability of 4.6 million buildings, including 3.9 million residential buildings, 520,000 commercial buildings, 115,000 industrial buildings, and 10,500 public buildings with a power generation capacity of 22.7, 9.9, 5.2, and 4.4 GW, respectively [10]. Figure 6 indicates solar PV resource availability by installation and by region. Regarding the potential of solar photovoltaic systems, the Malaysian government has presented several solar photovoltaic projects, including Large-Scale Solar (LSS) and Building Integrated Photovoltaic (BIPV).

LSS competitive bidding program including ground-mounted solar PV installations and floating solar PV installations on water bodies has been launched since 2011, in order to develop solar photovoltaic power plants, supply country's energy needs through renewable energies, and reduce the cost of energy.

Moreover, the Malaysian government has offered MBIPV project by providing leasing program with zero capital cost, tax incentives, design services, commissioning, operation, and solar power purchase agreements (SPPA), in order to increase the participation of the private sectors and develop building integrated photovoltaic System (BIPVT).

Hydropower

Hydroelectric power plants present proper efficiency among RE sources, and hydroelectric power plant projects can significantly contribute to industrial growth, improve energy security, and reduce greenhouse gas emissions, meanwhile, the creation of roads for the transportation can develop economic and tourism.

Malaysia has a high hydropower potential, and with respect to the high rainfall throughout the year, this energy source can be fully utilized for a long period in Malaysia. Hence, in recent years, small hydropower plants have been developed in Malaysia with privilege granted by the government to private firms through the feed-in tariff (FIT) mechanism and with regards to the lower initial investment, shorter payback period regarding the proper efficiency, long life of the equipment and low costs of repairs and maintenance of systems and equipment, and lower greenhouse gases emitted compared to larger hydropower plants.

In keeping with the existence of 189 river basins in Malaysia, the potential of small hydroelectric plants is approximately 2.5 GW, whereas Peninsular Malaysia has the highest potential with 1736 MW, followed by Sabah and Sarawak with 591 and 188 MW, respectively. Furthermore, the potential of large hydro resources in Malaysia is 13.6 GW with an existing capacity of 5.7 GW, whereas Sarawak has the highest potential with 10 GW, followed by Peninsular Malaysia and Sabah with 3.1 GW and 493 MW, respectively. Figure 7 shows hydropower resource availability by installation and by region.

Bioenergy

Malaysia has a huge potential for RE resources in bioenergy, including resources from palm oil waste, rice husk, coconut trunk fibers, cocoa waste, rubber waste, sugar cane waste, municipal waste, and forest waste [13].

Bioenergy in Malaysia has a potential of 3.6 GW including 2.3 GW of biomass, 736 MW of biogas, and 516 MW of municipal solid waste, with a minimum biomass production of 168 million tons/annum, while Peninsular Malaysia with 2.2 GW. It has the highest potential, followed by Sarawak and Sabah with 800 and 600 MW [10, 14]. Figure 8 displays bioenergy resource availability by installation and by region.

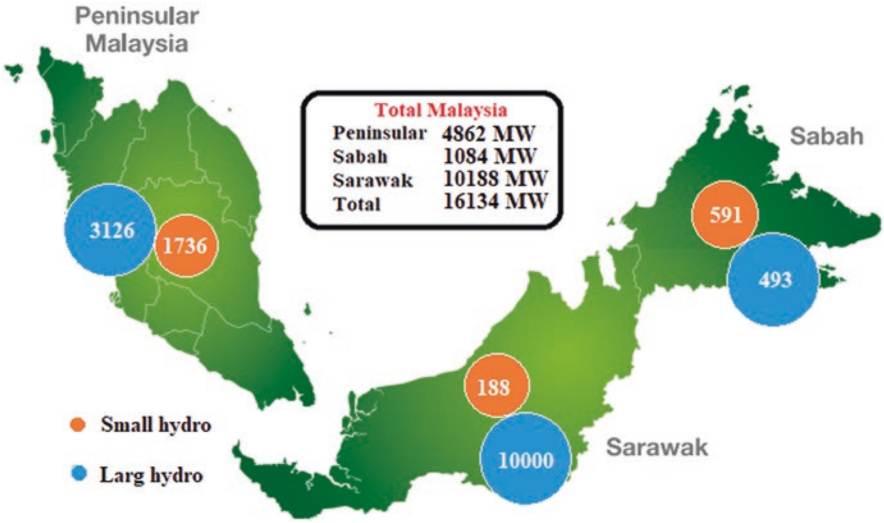

Fig. 7 Hydropower resource availability by installation and region [10]

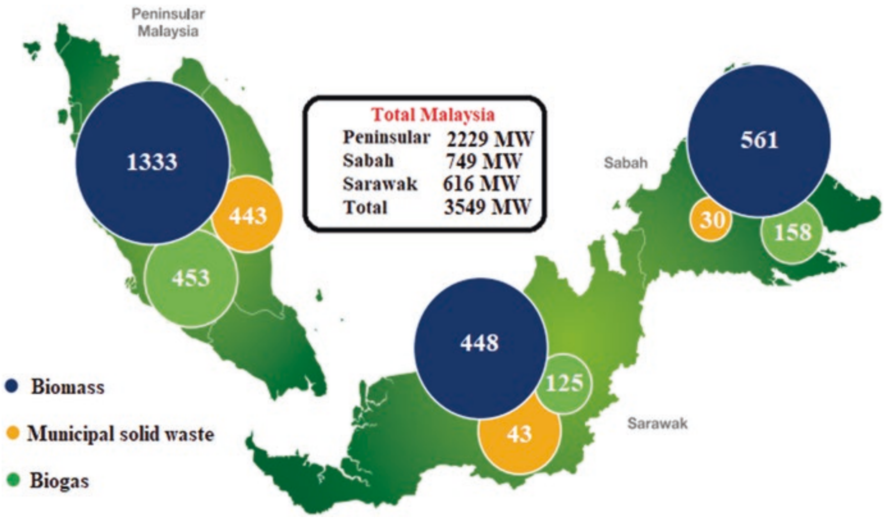

Fig. 8 Bioenergy resource availability by installation and region [10]

The use of (i) low price of biomass pallets to generate inexpensive electricity, (ii) biodiesel as a fuel replacement in the industry and transportation sectors, and (iii) municipal solid waste and palm oil mill effluent in the production of biogas needed by power plants, apart from reducing fossil fuels consumption in Malaysia, it also has reduced the emission of carbon dioxide (CO_2), sulfur oxides (SOx) and nitrogen oxides (NOx) [15–17]. However, bioenergy has been slowly growing in Malaysia due to the existence of barriers and restrictions such as carbon tax and pricings, the lack of scientific and technical expertise, the absence of advanced domestic technologies, and the high production costs and maintenance of equipment [15].

Geothermal

Geothermal investigation in Malaysia was conducted from 2009 to 2016 in collaboration with the collaboration of SEDA Malaysia and the Department of Mineral & Geoscience, and two regions, Tawau, Sabah, and Ulu Slim, Perak, were identified with a geothermal energy potential of 162 and 67 MW, respectively [10, 18]. Figure 9 indicates geothermal resource availability by installation and region.

Given the abundance of RE in Malaysia as well as drawbacks of geothermal power such as side effects on the environment caused by the sulfur dioxide and silica emission during digging, earthquake hazard as a result of digging, high initial investment, and high cost of geothermal generation with regard to current technology, this RE resource remains untapped, while it is expected to grow to 273 megawatts in the early 2030s [18, 19].

Installed Renewable Energy Capacity in Malaysia

Malaysia's total installed RE capacity was 8450 MW by 2021, representing 23% of Malaysia's total installed capacity mix. As shown in Fig. 10, large hydro resources have the largest installed capacity of 5692 MW, while solar photovoltaic and

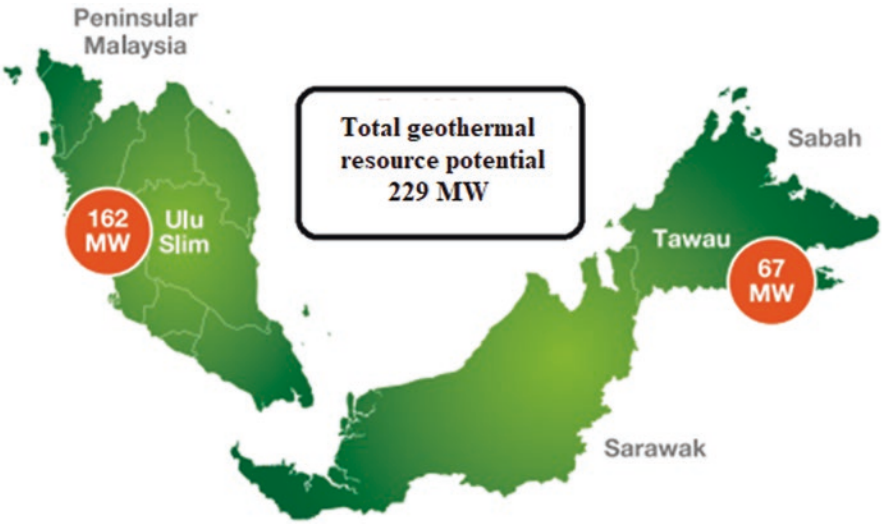

Fig. 9 Geothermal resource availability by installation and region [10]

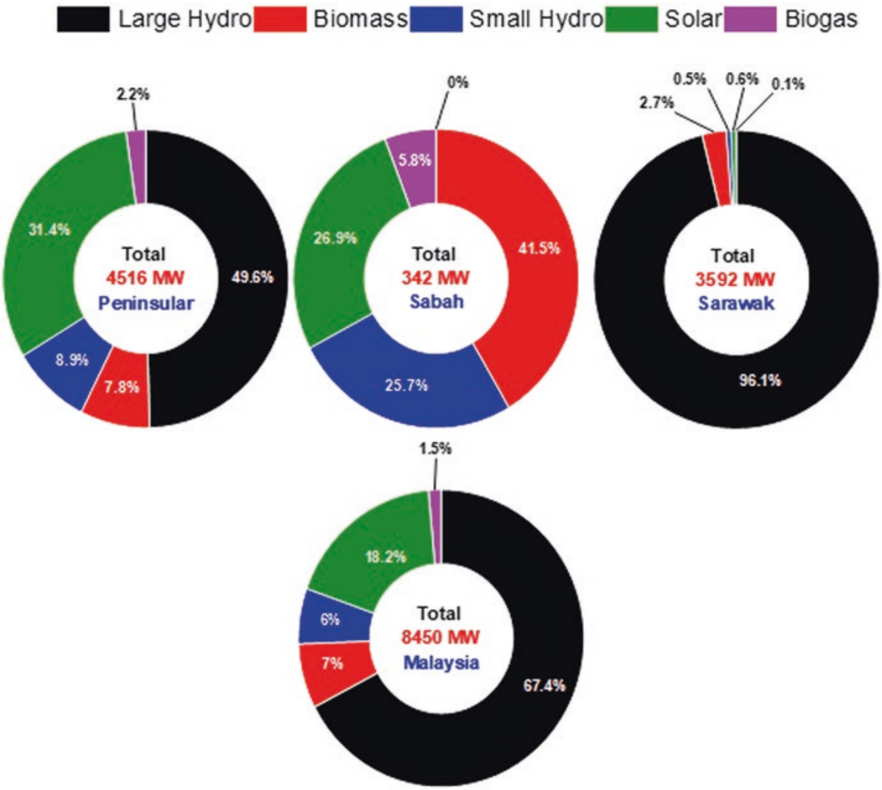

Fig. 10 Installed RE capacity in Malaysia

biomass are 1534 and 594 MW, respectively [10]. Peninsular Malaysia has the highest RE installed capacity at 4516 MW, followed by Sabah and Sarawak, with an installed capacity of 342 MW and 3592 MW, respectively.

Malaysia Renewable Energy Roadmap

Malaysia RE Roadmap (MyRER) is the strategic framework to attain 12.9 GW representing 31% and 18.0 GW representing 40% of the national capacity mix by 2025 and 2035, respectively, to meet Malaysia's commitment under the Paris Agreement led by the United Nations Framework Convention on Climate Change (UNFCCC). Figure 11 displays RE Capacity Mix to achieve the target in 2025 and 2035 [10].

Table 5 describes the reduction in the intensity of greenhouse gas emissions per GDP in 2030 and 2035, which is 40 and 60% compared to 2005 levels. For Peninsular Malaysia, CO_2 emission intensity will be reduced by 26% compared to

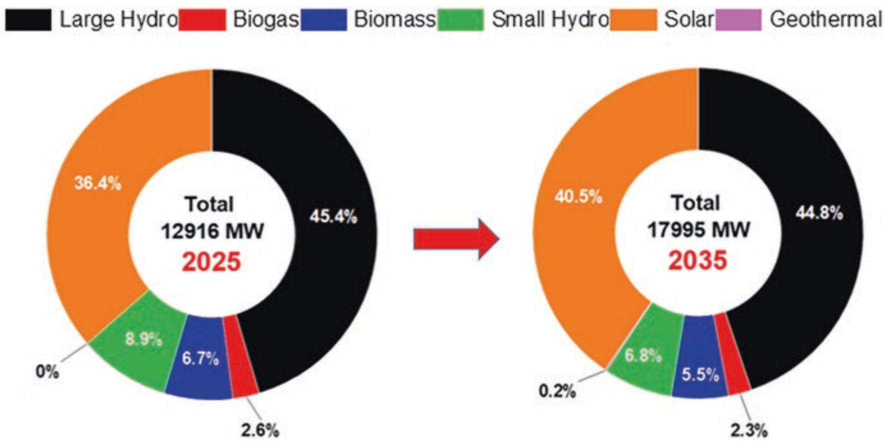

Fig. 11 RE Capacity Mix to achieve the target in 2025 and 2035

Table 5 Summary of impact on carbon emissions in the MyRER

Impact of carbon emissions	Peninsular		Sabah		Sarawak	
	2025	2035	2025	2035	2025	2035
CO_2 emission (millions of tons)	94.2	78.35	3.53	3.1	11.38	7.76
CO_2 intensity (tons/MWh)	0.7	0.5	0.43	0.31	0.32	0.19
CO_2 intensity (kgCO2 /GDP)	0.071	0.039	0.04	0.028	0.062	0.028

2005, with a CO_2 emission intensity of 0.096 kgCO2/GDP, reaching 0.071 kgCO2/GDP in 2025 and a further reduction to 0.039 kgCO2/GDP in 2035. For Sabah, CO_2 emission intensity will be reduced by 23% compared to 2005, with a CO_2 emission intensity of 0.052 kgCO2/GDP, reaching 0.040 kgCO2/GDP in 2025 and a further reduction to 0.028 kgCO2/GDP in 2035. For Sarawak, a significant reduction in carbon intensity has been achieved with the commissioning of the Bakun and Murom hydroelectric power plants since 2011, reaching 0.062 kgCO2/GDP in 2025 and a further reduction to 0.028 kgCO2/GDP in 2035 [10].

The MyRER strategic framework for achieving a low-carbon energy system requires: (i) accelerating the launch of solar energy projects, (ii) employing the maximum potential of bio-energy and hydroelectric energy, and (iii) application of new technologies and methods of RE development, which requires the adoption of policies and enabling initiatives including Revising existing electricity regulations and market practices to increase private sector participation and provide more options to the customer to choose the type of RE to supply the required electricity, enhance private sector participation, further access to financing, shape human capital and infrastructure, and increasing system flexibility.

4 Building Integrated Photovoltaic–Thermal System (BIPVT)

Recently, BIPVT systems have been developed with the combined advantages of photovoltaic cells and solar thermal collectors for achieving net zero carbon buildings, and their performance depends on system design, environmental conditions, and regional climate [20, 21]. BIPVT systems can be used in various structural compositions such as walls, roofs, windows, and shading devices [22].

This section presents the BIPVT system in Kuala Lumpur at latitude 3.13°N and longitude 101.7°E to supply electricity and hot water for a residential building. In this system, water-based PVT collectors have been used with the capability to integrate into other heating and cooling systems, comprising a polycrystalline silicon PV module, a spiral flow absorber in the form of continuous coil made of stainless steel hollow rectangular tubes placed beneath the PV module, and a thermal insulation which is packed underneath the absorber to prevent More heat escapes and provides a more uniform temperature throughout the system. The coil has a water inlet and outlet as a coolant, whereas the circulation of water in the coil eliminates heat from the PV module, and the outlet water flows from the coil to the heat storage tanks with a higher temperature than the inlet water [23]. This project was carried out to investigate the variation in the outlet water temperature and power generation in 2014 at the National University of Malaysia (UKM).

According to the excellent agreement of the calculated and measured data, a techno-economic analysis has been carried out to assess the performance of the larger-scale rooftop BIPVT system to supply electricity and hot-water in a residential building in Kuala Lumpur with respect to the latest climate change in Malaysia. Figure 12 indicates the schematic diagram of the BIPVT system, which comprises three main parts: (i) building, (ii) power grid, and (iii) solar PVT collectors.

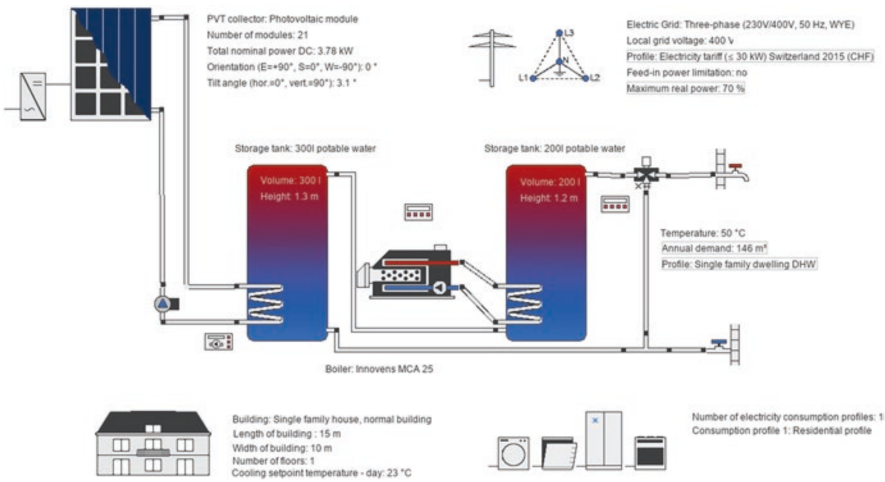

Fig. 12 Domestic hot water and preheating by BIPVT system

Table 6 Specifications of BIPVT system

Description	Value	Unit
Collector aperture area	1.28	m^2
Collector tilt angle	3.1	°
Collector orientation	0	°
PV module type	Polycrystalline	–
Nominal DC power STC	180	W
Number of inverters	3	–
Coolant	Water	–
Absorber	Spiral flow	
Pump flow rate	1075	L/h
Primary tank volume	300	L
Secondary tank volume	200	L
Boiler power	25	kW

The building's specifications, including the design, dimensions, orientation, temperature, and energy consumption, are extremely effective in designing a solar energy system to meet energy demand. The building's annual heat and power demand with an area of 150 square meters is 2619 and 3500 kWh, respectively, regarding the ASHRAE handbook and ASHRAE/IES Standard 90.1-2010 for building heating and cooling load calculation. The BIPVT system comprises 21 water-based PVT collectors to meet the building's energy demand. Table 6 describes the specifications of the PVT collector.

In a BIPVT system, domestic hot water is provided through a thermal sector of solar collector and combination boiler in two stages, preheating and backup heating. In the preheating process, solar PVT collectors deliver the heat energy through a single hot water loop. Initially, the cooling water flows into collectors by circulating pump to remove the heat from PV modules, reduce the operating temperature of PV modules, and improve the efficiency of PV modules. Afterward, the hot water is stored in the primary storage tank, while a differential temperature controller switches on the pump according to the specified temperature difference between the collector and the tank. In the backup heating process, hot water in the top layers of the primary storage tank at a temperature above that of the bottom layers drains to the bottom of the secondary storage tank at a lower temperature than the above layers to enhance the secondary storage tank temperature. Moreover, if the tank temperature falls below the set-point temperature, the combination boiler operates to supply the heat energy required to achieve the desired hot water temperature. Eventually, the water at the bottom of the primary storage tank with the lowest temperature flows to meet the cold water demand or mixes with the outgoing hot water of the secondary storage tank to achieve the desired water temperature.

Figure 13a shows the monthly heat energy required to deliver domestic hot water at 50 °C. As shown in Fig. 13b, solar energy converted into heat by PVT collectors cannot meet energy demand, and consequently, the auxiliary heater operates to provide the heat energy required. Figure 13c indicates the auxiliary heater's monthly energy consumption to provide the required heat energy, and Fig. 13d shows an

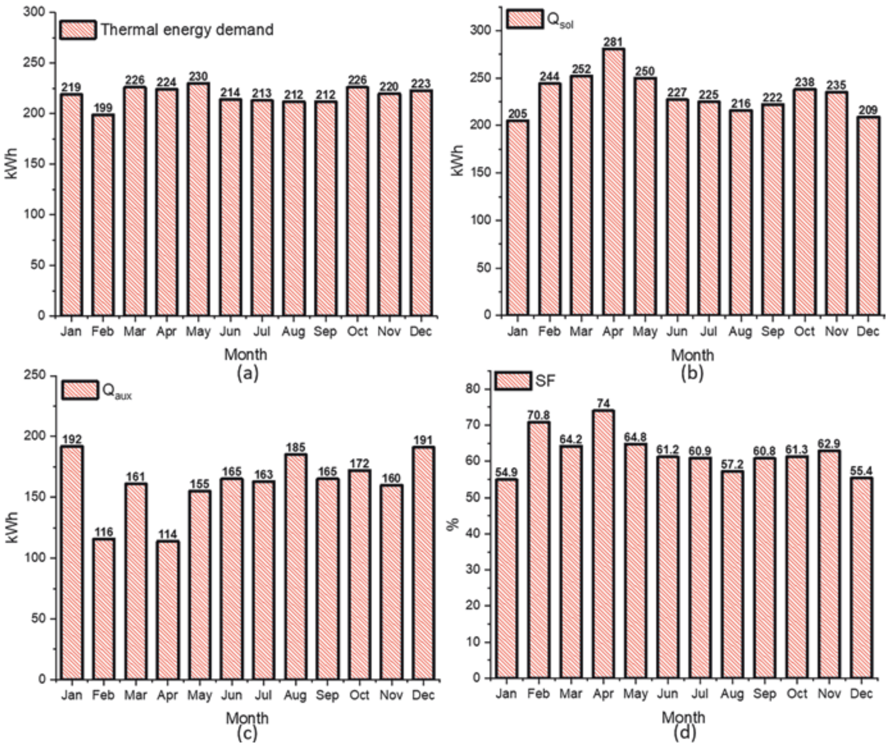

Fig. 13 (**a**) Thermal energy demand, (**b**) solar energy converted to heat by the BIPVT system, (**c**) auxiliary heater energy to the system, and (**d**) solar fraction

average solar fraction (SF) of a system to specify the contribution of solar energy to the provision of domestic hot water.

In addition, the electricity generated by the on-grid BIPVT system with a total nominal power of 3.78 KW, including 21 180 W PV modules and inverters, may supply the building's electricity requirements or be transferred to the electrical grid. Figure 14a shows the monthly building's electricity requirement, and Fig. 14b indicates the monthly DC yield of the BIPVT system. As shown in Fig. 14c shows that the AC yield of the BIPVT can meet the building's electrical energy demand, while Fig. 14d displays the excess electricity transferred to the electrical grid on a monthly basis.

Figure 15 shows the energy flow diagram, including heat and electrical energy generated by the BIPVT system on the left side, and energy distribution, including demands and losses on the right side of the diagram [24]. Additionally, the annual thermal and electrical performance of the BIPVT system is detailed in Tables 7 and 8. The results show that the efficiency of the BIPVT is about 18.2%, whereas the contribution of this system's thermal and electrical sectors is 6.3% and 11.9%, respectively.

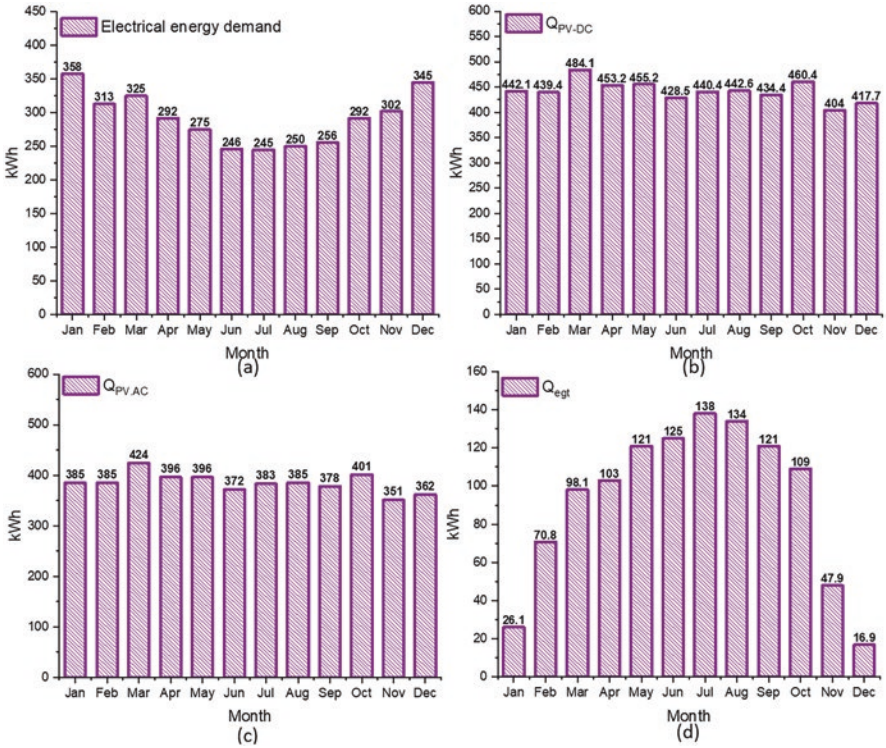

Fig. 14 (**a**) Electrical energy demand and (**b**) DC-yield of the BIPVT system, (**c**) AC-yield of the BIPVT system, and (**d**) excess electricity transfer to the grid

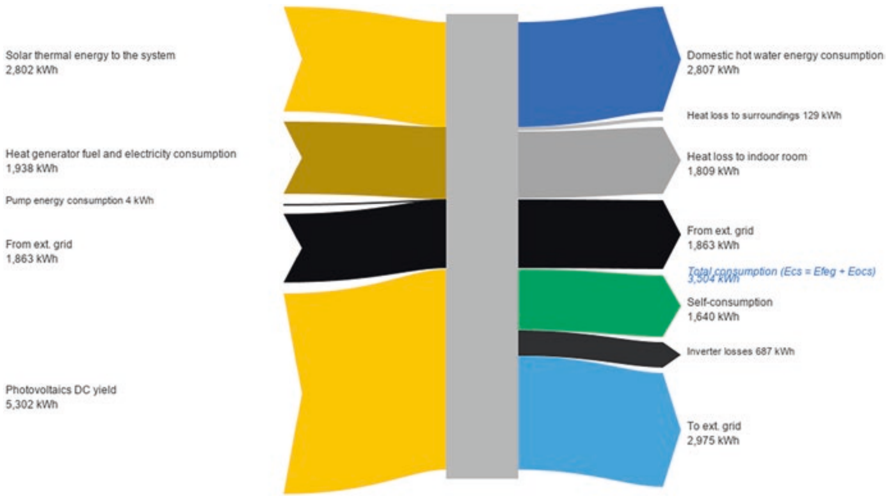

Fig. 15 Energy flow diagram (annual balance)

Table 7 Thermal sector performance

Description	Symptom	Value	Unit
Irradiation onto collector area	G_{sol}	44,477	kWh
Solar fraction: fraction of solar energy to tank	SF_T	60.9	%
Solar energy to tanks	S_{sol}	2610	kWh
Energy from the heat generator to the tank	S_{aux}	1675	kWh
Heat removed from tank	S_{out}	3278	kWh
Solar fraction: fraction of solar energy to system	SF_n	62.3	%
Solar thermal energy to the system	Q_{sol}	2802	kWh
Heat generator gas consumption	$Q_{aux.con}$	1938	kWh
Heat generator energy to the system	$Q_{aux.sys}$	1694	kWh
Total energy consumption	$Q_{use\text{-}th}$	2807	kWh
Heat loss to indoor room (including heat generator losses)	Q_{int}	1809	kWh
Heat loss to surroundings (without collector losses)	Q_{ext}	76.6	kWh
Boiler exhaust fumes losses	Q_{ex}	52.3	kWh
Electricity consumption of pumps	E_{par}	3.8	kWh
Pump heat loss	Q_{par}	1.7	kWh

Table 8 Electrical sector performance

Description	Symptom	Value	Unit
Radiation onto module area	G_{sol}	44,477	kWh
Yield Photovoltaics DC	$Q_{PV\text{-}DC}$	5302	kWh
Yield Photovoltaics AC	$Q_{PV\text{-}AC}$	4615	kWh
Total electricity consumption	$Q_{use\text{-}el}$	3504	kWh
Specific energy annual yield	SE_{PV}	1221	kWh/kWp
Soiling losses	Q_{soil}	113.3	kWh
Mismatching losses	Q_{mism}	220.9	kWh
Degradation losses	Q_{degr}	27.8	kWh
Cable losses	Q_{cbl}	0.5	kWh
Direct consumption (self-consumption)	Q_{dcs}	1640	kWh
External grid transfer	Q_{teg}	2975	kWh
From external grid	Q_{feg}	1863	kWh

The environmental impact assessment of the BIPVT system shows that this system reduces natural gas consumption by 769 m^3/annum, whereas the contribution of this system's thermal and electrical sectors is 266 and 503 m^3/annum, respectively. Furthermore, the BIPVT system reduces greenhouse gases emission by 3143 kg/annum, while the contribution of the thermal and electrical sectors of this system is 667 and 2476 kg/annum. Figure 16 shows the monthly fuel savings and decarbonization of the BIPVT system.

Table 9 shows the techno-economic analysis of the BIPVT, demonstrates that regarding the lifespan of 25 years, the payback period of this system is

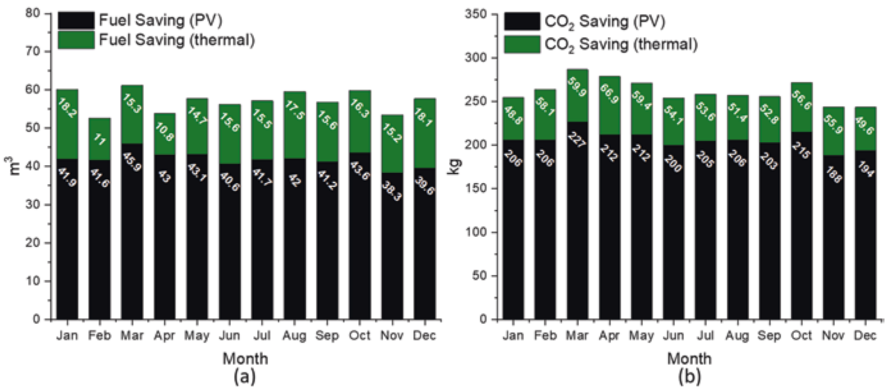

Fig. 16 Monthly (**a**) fuel saving and (**b**) CO_2 saving by the BIPVT system

Table 9 Profitability calculation annual values

Description	Value	Unit
Net present value	4032	MYR
Payback period	17	a
Absolute profit	8388	MYR
Energy production costs	0.17	MYR/kWh
Receipts from the sale of energy	27,935	MYR
Costs of fuel and district heat	780	MYR
Electricity costs	11,123	MYR
Energy supply costs	11,903	MYR
Annuity	161.3	MYR/a
Annuity factor	4	%
Loss of energetic yield due to degradation (PV only)	7194	kWh
Loss of financial yield due to degradation (PV only)	1922	MYR
Internal rate of return	2.68	%
Cost savings through PV	43,002	MYR
Cost savings through solar thermal	6080	MYR

approximately 17 years with an internal rate of return of 2.68%, a net present value of 4032, and an absolute profit of 8388.

In addition, Figs. 17 and 18 show that the downward trend of net present value and profitability of the system is due to the loss of energetic yield and, thus, financial yield as a consequence of PV modules degradation over time.

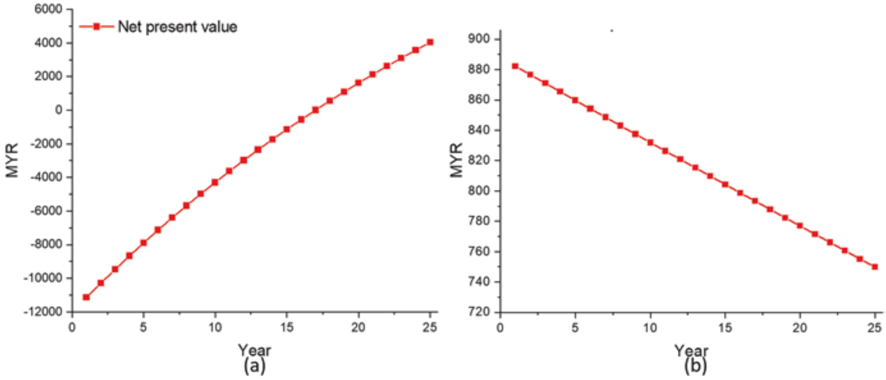

Fig. 17 Net present value and absolute profit trend over 25 years

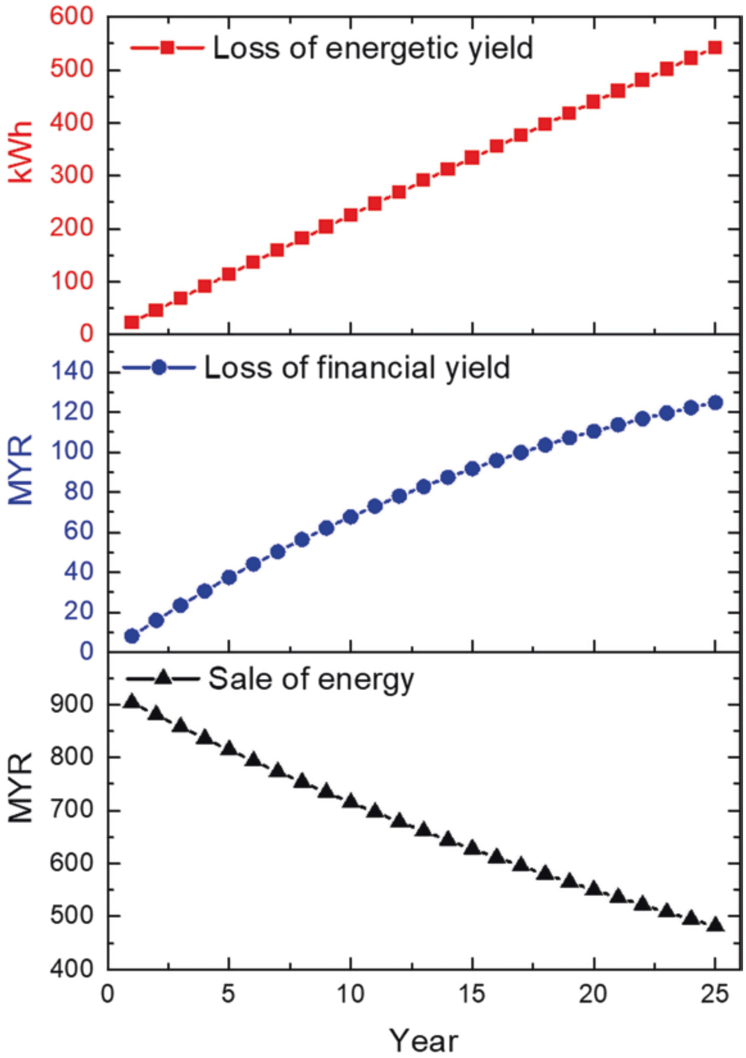

Fig. 18 Net present value and absolute profit trend over 25 years

5 Conclusions

A comprehensive analysis of Malaysia‘s tropical climate, national energy, and renewable energy (RE) was performed. Moreover, the techno-economic potential of building an integrated photovoltaic–thermal system (BIPVT) and its environmental impact were investigated concerning the Malaysian tropical climate.

Malaysia has a tropical climate with uniform ambient temperature, frequent precipitation, and sunny to overcast skies. Malaysia is moving toward becoming a developed country, while rapid urbanization, population growth, and the tropical climate have dramatically increased energy consumption in Malaysia.

Given its location near the equator, Malaysia is blessed with abundant RE consisting of a wide range of natural energy sources, from hydropower plants (16.1 GW) and solar energy (269 GW) to biological energy (3.6 GW) and geothermal (229 MW). Hence, despite having abundant oil and gas resources, the Malaysian government implemented the fuel diversification strategy by adding RE as the fifth fuel to ensure energy security. to ensure energy security, reduce greenhouse gas emissions, and economic and financial development. Although the Malaysian government intensified the development of RE by adopting supportive policies and initiatives, allocating funds, and implementing the 8th to 11th Malaysia programs, the total installed RE capacity in Malaysia was only 8450 MW by 2021, which represents 23% of the total installed capacity in Malaysia, due to several failures in the implementation of the fuel diversification strategy. However, the Malaysian government aims to achieve 18.0 GW, equivalent to a 40% share of RE in the national capacity mix by 2035, and to reduce greenhouse gas emission intensity per unit of GDP by 60% compared to 2005.

Among RE, solar energy systems are the preferred technology of Malaysian national energy due to the abundance of sunlight, the system with facility for use in residential and commercial buildings, and the opportunity for integration into industrial processes. Building an integrated photovoltaic–thermal system (BIPVT) has recently been developed for net zero carbon buildings. The technical-economic analysis of this system shows that using the BIPVT system in a residential building under the tropical climate of Malaysia can reduce natural gas energy consumption and greenhouse gas emission by 769 m^3/year and 3143 kg/year, respectively, with approximately 18.2% effectiveness. Regarding to the average lifespan of 25 years for the system components, the system’s payback period is approximately 17 years with an internal rate of return of 2.68%, a net present value (NPV) of 4032 MYR and an absolute profit of 8388 MYR.

Despite many active industries and residential and commercial buildings in Malaysia, more supportive policies and initiatives can increase private sector participation and, therefore, the use of solar systems in Malaysia.

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Design Considerations for BIPV Systems in Oman

Hussein A. Kazem, Ali H. A. Al-Waeli, Miqdam T. Chaichan, and K. Sopian

1 Introduction

The increase of renewable energy investments and interest in sustainable development worldwide is a clear indication for the shift toward sustainable sources of energy and the global commitment to establish resilient energy sources [1]. However, many of these resources require further research and development to become reliable and effective [2]. There are two main premises for adopting renewable energy technologies, the first being the necessity to depend on a stable source of energy, and the second is to avoid the climate side-effects of utilizing the existing traditional energy sources as such fossil fuels [3]. Although the extent of the pollution and environmental damage might be a changing number, and a point of debate, the occurrence of such pollution has not been debated. Among these renewable energy resources is solar energy, which has gained popularity due to its many features such as portability, ease of installation, and minimal maintenance requirements, in

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addition to requiring no mechanical movement or producing no noise or pollution to the surrounding environment [4]. However, it is noteworthy to point out that solar potential varies from one location to another. Some countries or cities have higher levels of solar irradiation than others. The suitability of a particular local for solar energy utilization is an important aspect to study [5].

In modern times, electricity is extremely important to improve quality of life and is considered a primary human need. However, it is considered difficult and costly to supply electricity to remote areas; it is expensive to extend the electricity grid to remote areas where small electrical power is required. Moreover, sometimes it is not physically possible due to the terrain and other geological hindrances [6]. Therefore, many rural communities rely on diesel generators, which is still not a sustainable option.

Photovoltaic (PV) solar modules are the most common type of solar energy systems, particularly crystalline-type PV cells. These PV modules exhibit energy efficiency that reaches up to 18% [7], and is reported to reach even higher than that value [8]. However, in most cases, the efficiency mentioned is only achieved in standard test conditions (STC) which is when they are subjected to a solar irradiance of 1 kW/m^2, a solar cell temperature of 25 °C, and an air mass of 1.5 [9]. However, when operated in outdoor environment, much reduction in efficiency occurs due to various factors such as the increase of cell temperature, shading, dust, and other environment-related factors. Therefore, it is important to provide effective standards and practices to maximize the gains from such investment and ensure its sustainability [10]. Global solutions to such problems do exist, such as providing means for cooling the PV module, avoiding shading, minimizing dust, and choosing the angle of installation, to name a few. However, these global recommendations may not provide the most accurate techniques or methods to improve such systems. Therefore, it is crucial to create local practices that are compatible with the socioeconomic setting, weather conditions, and overall local parameters. In doing so, the user, designer, engineer, and investor can benefit by having a clearer path to effectively utilize solar energy technology. Therefore, in this chapter, we provide an analysis of designing building-integrated PV systems in the Sultanate of Oman.

Most commercial photovoltaic modules are either polycrystalline or monocrystalline [11]. PV modules are composed of many PV cells that are connected in series and parallel to produce higher voltages and currents. PV modules may be connected in series to form a string and strings can be connected in parallel to form an array [12]. The PV system is a system that typically consists of a PV module, charge controller, inverter, and battery for storage. PV systems can be used as grid-connected, GCPV, or off-grid, standalone.

The GCPV configuration requires policy that allows for selling the electricity produced back to the grid [13]. In some countries, Feed-in-Tariff is implemented temporarily to encourage investment in solar energy [14]. In other countries, Net metering could be used, where the meter is reversed when the electricity is fed to the grid [15]. PV systems can be installed almost everywhere on earth and even in space [16]. Building-integrated photovoltaics (BIPV) are commonly pitched for residential purposes, but are also used in the industry [17]. Some companies install PV

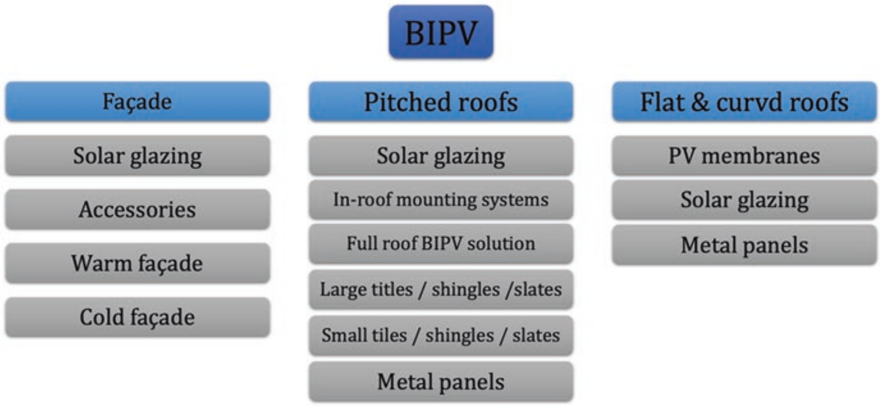

Fig. 1 Classification of building-integrated PV systems

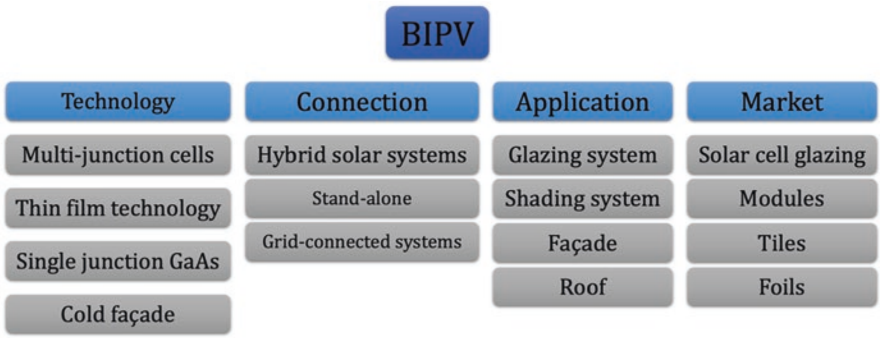

Fig. 2 Broader classification of Building-integrated PV systems

farms or power plants on premises, parking lots, and even off-premise [18]. Building-integrated PV systems require various considerations to be implemented correctly such as: (i) building structure, (ii) orientation, (iii) load-support capabilities, (iv) roof type, and many others. Figure 1 shows a classification of BIPV systems. A broader classification that includes the applications, technology type, connection, and market is shown in Fig. 2. It is important to note that there is a clear definition for BIPV systems. A system is considered to be "building-integration PV" if it can meet two criteria: (i) convert sunlight into electricity or be formally defined as a photovoltaic module/cell, and (ii) it serves as a component of the building. Therefore, it is critical not to mix between building-integrated PV systems and roof-mounted PV systems. In that sense, for BIPV systems the solar photovoltaic cell or module or array is built to replace building facades or existing windows, "The reviewed current standards agree in requiring a PV module or system to have (at least) dual functionality as an electricity generator and a building component to qualify as building-integrated photovoltaics" [19].

Although much research has showcased the potential of BIPV systems, some researchers also found the disadvantages on an economic level. Bojic and Blagojevic [20] investigated a BIPV system of a two-floor house in Serbia and analyzed its electricity revenue. The results indicated that PV integration into building facades as an alternative source of energy in urban buildings is not economically viable. Hence, optimization analysis is necessary to improve the cost-effectiveness of this technology.

In this chapter, various considerations for designing and testing BIPV systems are presented, specifically for installation in the Sultanate of Oman. Therefore, meteorological data are presented and analyzed, in addition to a discussion on the state of solar technology in Oman from economic and policy perspectives.

2 BIPV Systems in Oman

The Sultanate of Oman (also referred to as Oman) is located north of the equator. Oman consists of 11 governorates, and is divided into 51 s-level administrative divisions which are referred to as “Wilayats”, with its capital Muscat which is located in Muscat governorate. The country is part of the Gulf Cooperation Council (GCC) and has a GDP of 85.97 billion USD in 2021 [21]. Oman consists of many biomes such as desert, mountains, valleys, and marine which makes it a country with diverse natural resources. The map of Oman is shown in Fig. 3 which provides further details regarding its geographical distribution. The power system in Oman consists of (i) Main interconnected system (MIS), (ii) Musandam power system, (iii) AD Duqm power system, and (iv) Dhofar power system. As of 2020, Oman’s estimated population reached around 5,175,047 [22]. According to OPWP report, it is expected that the electricity demand will reach 8960 MW in 2023. This increase in demand would require a support infrastructure to increase the generation, and expand transmission and distribution networks across the country. These added costs along with the impact of fossil fuel price fluctuations will impact the country’s budget. The rising energy demands and the persistent efforts within the Gulf Cooperation Council (GCC) to promote renewable energy sources have made investments in various renewables a central focus in the countries’ energy sector development and their pursuit of environmental sustainability.

Moreover, the country is subjected to relatively high solar radiation levels, ranging between 6.47 and 6.85 kWh/m^2/day in some locations [24], making solar energy a highly favorable option to be implemented in the country. Figure 4a shows the global horizontal radiation distribution throughout Oman, while Fig. 4b shows the photovoltaic potential of Oman according to solar atlas [25].

Solar technology is generally classified into photovoltaic (PV) modules, solar heaters, and hybrid photovoltaic thermal (PVT) systems. The first two have been implemented in Oman at an industrial level, but more emphasis has been made toward photovoltaics. A PV module converts sunlight into DC electricity which can either be inverted and fed to a load or to the gird, or it can be stored in batteries for

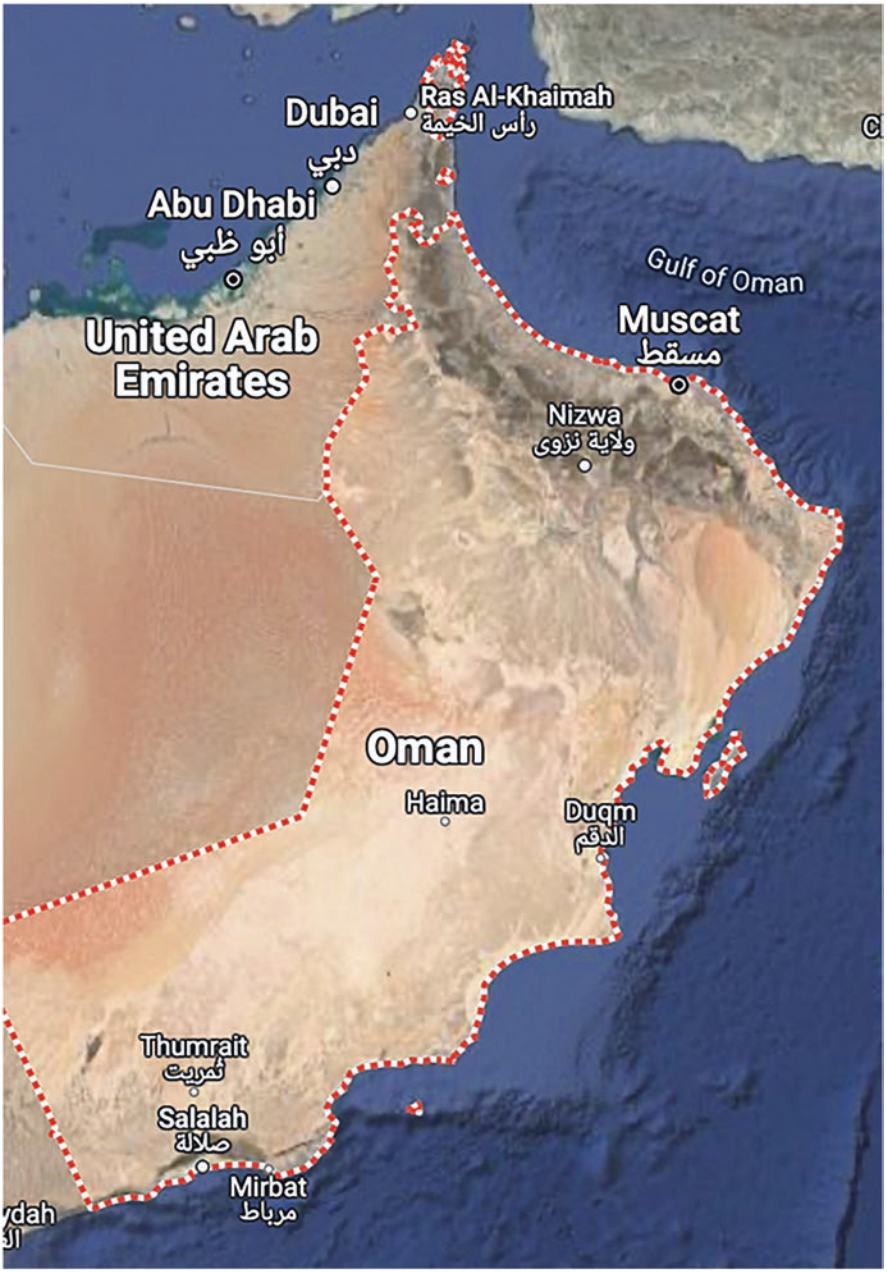

Fig. 3 Map of Sultanate of Oman [23]

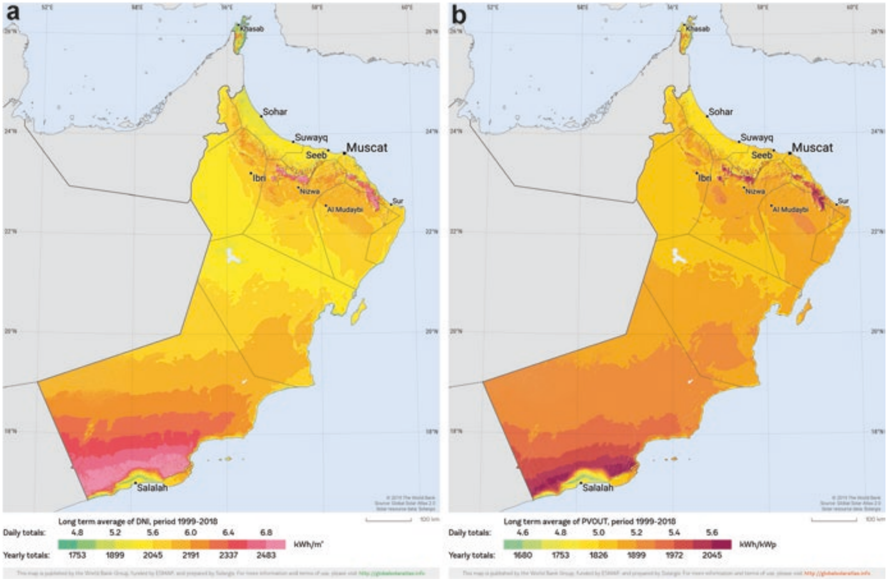

Fig. 4 Oman's map with (**a**) global horizontal irradiation and (**b**) potential of photovoltaic (PV) electricity. (Source: © 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis [25])

later usage. Various PV power plants have been initiated in Oman for the past two decades. The first being Almazyounah which holds a capacity of 303 kW. Other planned projects such as Ibri-2 Independent Power Producer (IPP) which is planned for a capacity of 500 MW which at peak capacity could supply 33,000 homes with electricity. Also, the 100 MW Amin Photovoltaic Power Plant which is planned by the Petroleum Development Company of Oman (PDO). Moreover, efforts to optimize energy generation for buildings utilizing PV systems have been made locally in the level of research [26].

The volume of solar energy combined capacity in Oman reached 8 gigawatts in 2018 [27]. Solar accounted for 73% of the renewable energy capacity in Oman in 2019. In terms of electricity generation, solar produced up to 211 GWh in 2020 [28]. Oman continues to grow its solar energy, and renewable energy, capacity. As the total energy supply (TES) of renewables for 2018–2019 increased by 59%. However, in 2020, fossil fuels still dominate electricity generation in Oman, as it accounts for 99% of the electricity generation. This chapter presents an analysis of BIPV systems and their design considerations.

Meteorological Data

The impact of the local weather on the PV array's electricity production is very significant which makes planning and sizing of BIPV systems highly dependent on it [29]. The influence of local weather on PV systems in Oman has been well studied in the past decade [30–33]. The main factor that is typically considered is solar irradiation, but also other factor carries significant effects on these systems during operation such as air temperature, wind regime, dust, humidity, and rainfall patterns [34]. These factors have been the subject of many investigations and the impact of each factor was quantified in the literature, worldwide. Hence, it is crucial to acquire weather data for the location intended for a PV investment. The types of weather data vary but are generally classified into three: (i) meteorological, (ii) satellite-based, and (iii) hybrid data utilizing the other two types. In this chapter, the meteorological data used is daily averaged global radiation (mWh/sq.cm), daily sunshine hours (h), daily averaged air temperature (°C), daily total rainfall (mm), and daily averaged wind speed (knots), which is shown in Table 1.

Table 1 shows the range of yearly averaged metrological data which helps to establish the following assumptions: (i) 9.6 daily sunshine hours, (ii) daily average air temperature of 28.8 °C, (iii) average global solar radiation of 0.582 kWh/m^2, (iv) 0.2 mm daily averaged total rainfall, and (v) daily averaged wind speed of 6.1 knots (3.1 m/s). However, the maximum and minimum values are also important for the design; low solar radiation values will impact the number of days of autonomy and subsequently impact the number of batteries required and BIPV system capacity (within the constraints of available area in the building). Table 2 showcases the maximum and minimum values for the metrological data.

The table displays the extremes for averaged data such as the highest daily solar radiation recorded which was in 2020, reaching as high as 8364.0 mWh/sq.cm. Moreover, the highest recorded average daily air temperature which was around 41.3 °C. Knowing the extremes helps in preparing for the worst-case scenario or improving the system's robustness. For instance, in 2022, the maximum recorded daily rainfall reached 14.9 mm which is substantially larger than that of previous years. And so, knowing the average of the years may help in providing a better estimate for the number of autonomous days; to design a more suitable energy storage

Table 1 Yearly averaged metrological data for Oman from 2017 to 2020

Indicator ⇒ Year ⇓	Daily sunshine hours (h)	Average daily air temperature (°C)	Daily global solar radiation (mWh/sq.cm)	Daily total rainfall (mm)	Average daily wind speed (knots)
2017	9.6	29	5902.2	0.1	6.3
2018	9.6	29	5706.9	0.0	5.9
2019	9.7	28.6	5654.4	0.2	6.0
2020	9.6	28.9	6017.9	0.5	6.3

Note: Data taken at latitude of 23.6086 N and longitude of 56.2614 E and at an elevation of 2.0 meters. Moreover, trace of rainfall less than 0.05 mm

Table 2 Maximum and minimum averaged metrological data for Oman from 2017 to 2020

Year ⇒ Indicator ⇓	2017	2018	2019	2020
Maximum daily sunshine duration (h)	11.8	11.8	12.1	11.8
Minimum daily sunshine duration (h)	0.9	0.4	1.2	0.1
Maximum averaged daily air temperature (°C)	40.4	41.3	38.9	39.6
Minimum averaged daily air temperature (°C)	16.8	19.6	19.3	15.6
Maximum daily global solar radiation (mWh/sq.cm)	8304.0	8188.0	8310.0	8364.0
Minimum daily global solar radiation (mWh/sq.cm)	902.0	880.0	923.0	360.0
Maximum daily total rainfall (mm)	11.4	13.8	15.4	43.2
Minimum daily total rainfall (mm)	0	0	0	0
Maximum average daily wind speed (knots)	14.2	16.4	15.0	14.9
Minimum average daily wind speed (knots)	2.8	3.5	2.3	2.1

Note: Data taken at latitude of 23.6086 N and longitude of 56.2614 E and at an elevation of 2.0 meters. Moreover, trace of rainfall less than 0.05 mm. If the solar irradiance 'sunshine' is below the threshold, it is not counted as a sunshine hour

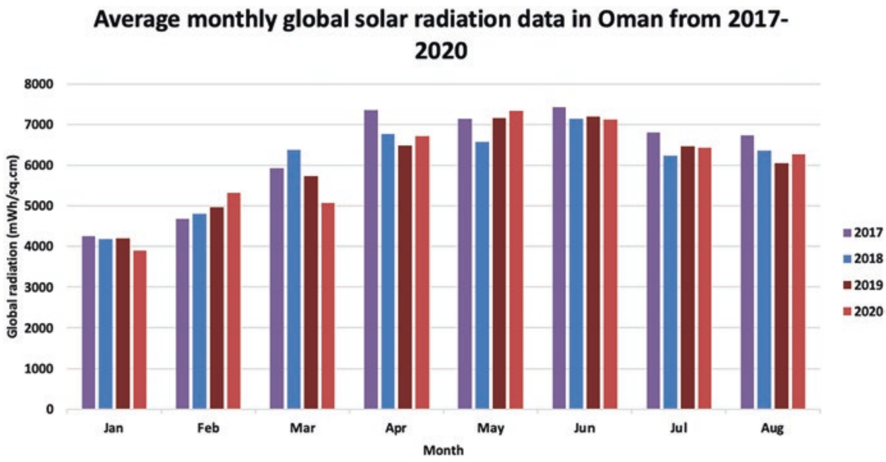

Fig. 5 Average global solar radiation data in Oman from January to August for the years 2017–2020

system for the PV system. The average monthly variation of solar radiation from January to August for the years 2017–2020 is provided in Fig. 5.

BIPV System Performance

The performance of the system is evaluated in essence based on the energy produced but it must be with reference to a certain criterion. In some cases, the performance is evaluated comparatively in some cases, by offering different scenarios and comparing the outcome. In other cases, the evaluation is based on the performance ratio of the integrated PV system. Roofs are often compared to façades and different directions are also considered. Some authors are interested in the efficiency of the system itself, as the efficiency can be significantly impacted by the design of the BIPV and the selected material. It is also crucial to view the thermal performance of the system and perform spectral measurements for BIPV windows if utilized. Another important design aspect is the elements, their capacity, and the overall system configuration. For the case of grid-connected BIPV systems, studies examined both electrical DC and AC output energies from the system, in addition to other metrics to evaluate the analyze the power quality of the system such as total harmonic distortion and harmonic components.

Nicoletti et al. [35] proposed a simple evaluation method for solar photovoltaic blinds (SPB) in BIPV systems. The approach aims to evaluate slat mutual shading with consideration for view factors, geometries and orientation. The annual yield and its relation to geometric factors were also assessed. The model also considers the lamellas. The authors found that reciprocal shading conditions impact the incident direct radiation, while the diffuse radiation is dependent on sky view factor. The slat distance to width ratio was also found to be a major factor for maximizing annual electricity produced by the system. The study also shows that the annual production is minimally affected by the reflectivity of the back of the slats. Other studies viewed the annual performance ratio (PR) of the system, as done by Kumar et al. [36] who investigated the performance of a BIPV array using thin-film cadmium telluride (CdTe) for the roof and façade of a building, considering the tropical climate conditions of Malaysia. The study showcases the importance of selecting the appropriate surface and orientation to integrate a PV system within; considered cases included flat roof, east façade, west façade, north façade, and south facing façade. The results indicated a higher average monthly energy production for the PV-integrated flat roof than the east, west, and north façades. This is mainly because more area is available for the PV, and it is closer to the optimum tilt angle. Moreover, according to the findings, the study concludes that north-oriented façades exhibit a poorer performance compared to the roof or other façades.

In terms of climatic conditions, the performance of the PV is influenced by solar irradiance, ambient temperature, wind speed, humidity, and dust. Among the main causes of drop in the performance of the system is the increase of cell temperature which negatively impacts its energy conversion efficiency. Therefore, some researchers studied different techniques to provide active or passive cooling to the process [37–40]. Figure 6 shows a classification of the thermal management methods for BIPV systems.

Ho et al. [41] investigated using water-saturated microencapsulated phase change material (MEPCM) for the thermal management of the BIPV system. The proposed technique is classified as passive and no active elements were required. The system was modeled and analyzed analytically using computational fluid dynamics (CFD). In the analysis, the study examined different MEPCM melting points and layer thicknesses and viewed their impact on the thermal and electrical performance of the system. The results favored the use of MEPCM for BIPV systems over

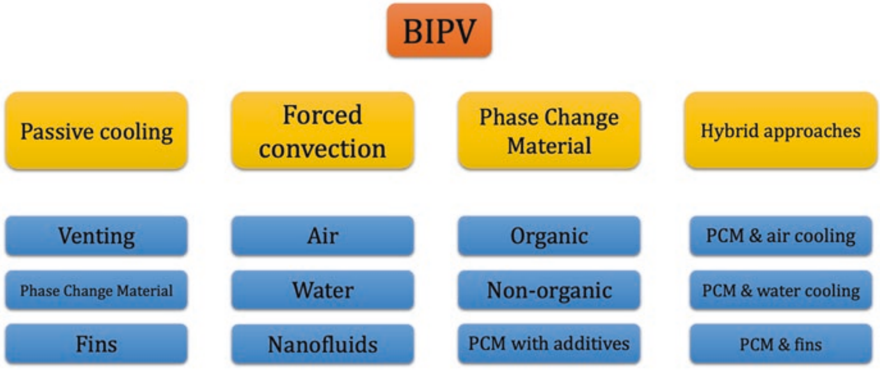

Fig. 6 Classification of BIPV thermal management methods

traditional PV systems and recommended a 3 cm layer tick MEPCM with a melting point of 30 °C during local summer climatic conditions of Taiwan. Huang and Hewitt [42] numerically and experimentally investigated using two PCMs for thermal regulation. Although it is useful to use PCMs, the main issue was identified to be its low thermal conductivity. Hence, the authors examined using PCMs with different phase change temperatures to improve the heat regulation of the system and increase the thermal regulation time. The PCMs involved in the study included RT21, RT27, RT31, and RT60. Therefore, five different cases (combinations of PCMs) were examined. The results indicated that the thermal mass and conductivity of the PCMs significantly impact the performance of the PV/PCM system. And that during daily operation, the highest achieved temperature reduction was found for the RT27-RT21 case.

Alrashidi et al. [43] performed indoor and outdoor characterization tests on a semi-transparent cadmium telluride (CdTe)-based BIPV to be utilized in the United Kingdom. For the indoor tests, spectral measurements were performed on the BIPV window to obtain its average transmission (visible and solar transmissions). The average solar and visible transmission were found to be 12% and 25%, respectively. Moreover, the thermal performance was evaluated as well using a solar simulator as a source of energy. The outdoor testing was performed to obtain the glazing thermal factor (U-value) and the thermal performance. The results indicated a maximum solar heat gain of 20%.

Aristiza'bal and Gordillo [44] introduced a grid-connected BIPV system in Colombia, which is claimed to be the first in the country. The system was monitored for 2 years by measuring its AC and DC power, system efficiency, inverter efficiency, PV array-generated energy and BIPV-generated AC energy. Furthermore, other metrics were found such as total harmonic distortion, frequency, harmonic components, flickers, power factor, etc. The system consisted of 12 crystalline silicon PV modules forming an array, an inverter, and meters for energy measurements, in addition to solar irradiance sensor, temperature sensor, and DC and AC current sensors. The findings showed that the AC energy output is at its highest in January and December, while it is low around April and May.

Martín-Chivelet [45] presented a building retrofit case study by integrating PV modules into a ventilated façade. The PV was made of crystalline silicon solar cells and utilized a standard structure consisting of glass, ethylene-vinyl acetate (EVA), PV cells, EVA, and polyvinyl fluoride (PVF). Moreover, the material selection for the façade was made based on the selected PV modules in terms of dimensions, and visual appearance. Finally, the PV self-sufficiency index of the BIPV was expected to be around 6.6% after the renewal of all lighting and windows. Moreover, the results showcase the impact of partial shading from nearby buildings or trees on the performance of the BIPV, which led to a poor performance ratio, below 60% throughout the year, for the east façade.

Zomer et al. [46] analyzed the performance of both BIPV and building-applied PV (BAPV) for airports in Brazil. To achieve the maximum annual output, the study proposes optimum orientation and tilt angles for the PV modules. While, BIPV modules were designed to accommodate the building's architecture in the airport. The analysis was carried out in two Brazilian airports to compare BAPV and BIPV. The results showed that BIPV exhibits higher installed peak power (100%) and energy generation density (87%), while the annual energy yield was 7% higher for the BAPV. The study emphasizes the compromise needed to establish a design that can better fit the requirements. Although less energy is produced when the optimum tilt angle is not selected, the building's aesthetics are more positively affected because the PV is installed based on the building's existing design. Table 3 provides a summary of the studies reviewed on BIPV systems in the literature.

Table 3 Summary of studies on building-integrated photovoltaic system performance

References	Type of study	Location	Year	System type	Performance metrics
Nicoletti et al. [35]		Italy	2023	Solar photovoltaic blinds (SPB)	Electrical energy production
Ho et al. [41]	Numerical	Taiwan	2012	BIPV with water-saturated MEPCM	PV temperature, daily PV efficiency
Huang and Hewitt [42]	Experimental & numerical	Ireland	2009	BIPV with two types of PCMs	PV front surface temperature
Alrashidi et al. [43]	Experimental	United Kingdom	2020	Semitransparent CdTe BIPV window	Test cell temperature, clearness index, internal glazing surface temperature, and solar heat gain coefficient
Aristiza'bal and Gordillo [44]	Experimental	Colombia	2008	Grid-connected BIPV	DC and AC output energies, PV array efficiency, performance ratio, total harmonic distortion
Martín-Chivelet [45]	Experimental	Spain	2018	BIPV-ventilated façade	Active power, final yield per month, performance ratio, and PV module temperature
Zomer et al. [46]	Experimental	Brazil	2012	BIPV and BAPV	Annual energy yield, peak power and energy generation density

Local Energy Policies

The Sultanate of Oman has implemented several regulations and incentives related to building-integrated photovoltaic (BIPV) systems to encourage the adoption of renewable energy. For instance, renewable energy laws, or Oman‘s Renewable Energy Law (Royal Decree No. 114/2014) which aimed to promote the use of renewable energy in the country. It established a framework for the development of renewable energy projects, including BIPV systems, and provides for the creation of a Renewable Energy Project Development Fund to support such projects. Another policy was net metering. Oman‘s net metering policy allows homeowners and businesses to generate electricity using renewable energy sources, such as BIPV systems, and sell excess energy back to the grid. This helps offset the cost of the BIPV system and provides a financial return on investment. Feed-in tariffs were also introduced, guaranteeing a set price for electricity generated by renewable energy sources, including BIPV systems. The tariffs are set by the Oman Power and Water Procurement Company (OPWP) and are designed to encourage the adoption of renewable energy technologies. Moreover, grants and subsidies were offered by the Omani government to support the development of renewable energy projects, including BIPV systems. These may include financial support for the installation and maintenance of BIPV systems, as well as technical assistance and training.

In April of 2010, the authority for public services regulation made a pilot project initiative by inviting developers to propose projects for rural locations supplied by Rural Areas Electricity Company (RAEC). The authority declared receiving 35 proposals for projects that included wind, Concentrated Solar Power (CSP), and solar PV. Moreover, it issued a regulatory statement that six renewable energy pilot projects were short-listed. In February of 2013, the authority confirmed including a rural areas policy, requiring a renewable energy component into article 87. In essence, RAEC applications must include a renewable energy technology component in each project. Without including a renewable energy component, RAEC must explain the reasoning and supporting analysis for the technology being not economically viable or technically feasible [47].

In January of 2016, the authority announced that renewable energy projects supporting policies were expected to be approved from the Council of Ministers including the economic gas pricing, for economically and technically feasible renewable energy projects, compared to the international price of gas, to be immediately implemented. Moreover, a study, for the national energy strategy to 2040, recommended that 10% of Oman’s generation should be from renewable energy sources. And in January of 2017, the authority revised existing regulatory frameworks for adopting rooftop PV systems in Oman. Those revisions included establishing the minimum technical standard for those systems, allowing net metering for compensating the energy generated by those systems, and allowing distribution companies to act as agents for Oman Power and Water Procurement Company (OPWP) to purchase rooftop generated electricity from the consumers [47].

In 2018, the residential PV initiative in Oman proposed a phased installation of 2–4 kWp PV systems at the premises of 10–30% of residential customers. The funding of the initial phase comprises an advance of future gas-saving benefits and reduction on subsidies along with customer contributions, in addition to proposing an accelerated subsidy adjustment [48].

As for the environmental aspect, in 2017, a ministerial decree for environmental permits (Ministerial Decision No.48/2017 issuing the Regulations for Organizing Environmental Permitting) was issued. The regulation consisted of 13 articles and 3 annexes. The purpose was to regulate environmental permit issues by authority at the Ministry of Environment and Climate Affairs [49].

Intuitive PV System Sizing

The simplest method to estimate the performance of photovoltaic systems is the intuitive method [50].

$$N_{PV} = \frac{E_L}{\eta_s \eta_{\text{inv}} PSH} S_f$$

where (N) is the number of PV modules required to supply the daily energy consumption demand (E_L) and (Sf) is the safety factor which is used to compensate power losses due to temperature and resistive losses. The efficiency of the system components and inverter is represented by η_s and η_{inv}, respectively.

In terms of storage, the battery capacity can be calculated by considering the number of autonomous days and the permissible depth of discharge rate of a cell, *DOD*, [51], as follows:

$$C_{Wh} = \frac{E_L \times \text{number of autonomous days}}{DOD \times \eta_c \times V_B}$$

where *DOD* is multiplied by the voltage (V_B) and the efficiency (η_c) of the battery block. Moreover, the daily PV module/array output (E_{PV}) can be obtained considering its array (A_{PV}), efficiency (η_{PV}), daily solar irradiation incident on it (E_{sun}), the inverter's efficiency (η_{inv}), and the efficiency of the wires (η_{wire}) [52]:

$$E_{PV} = A_{PV} \times E_{\text{sun}} \times \eta_{PV} \times \eta_{\text{inv}} \times \eta_{\text{wire}}$$

Energy can be calculated at the front end of a PV system or considering the load side by subtracting the load energy demand (E_L) from the daily PV energy output as follows:

$$\text{Energy difference} = \sum_{i=1}^{366} \left(E_{PV} - E_L \right)$$

If the energy difference is a positive value, then there is excess energy produced (EE), and if it is negative, then it is considered an energy deficit (ED). EE can be stored in the battery storage system, while ED defines the system's inability to supply the demand at certain times.

While the energy that is needed to be stored in the batteries annually (*EB*) is calculated considering the battery's charging efficiency (η_{charge}) as follows:

$$E_B = \left(\sum \text{Energy excess} - \sum \text{Energy deficit} \right) . \eta_{\text{charge}}$$

And hence, the expected daily storage capacity of the batteries (C_B) is:

$$C_B = \frac{E_B}{366}$$

Meanwhile, another important consideration is the availability of the power supply, where 100% availability refers to the supply meeting the demand year-round without interruptions: making it a reliable system. While 0% means the demand cannot be met by the PV modules throughout the year. However, a system with 100% availability requires high initial costs and may not be possible given the constraints related to the building's available area. The availability is typically expressed with loss of load probability (LLP) which is a statistical value that describes the ratio of annual energy deficits to annual load demand, and is calculated as follows:

$$LLP = \frac{\sum_{i=1}^{366} \text{energy deficit}_i}{\sum_{j=1}^{366} \text{energy demand}_i}$$

LLP can be utilized to obtain the battery capacity at load demand (C_B) and PV array capacity at load demand (C_{PV}), which can also help to obtain the parameters (C_A) and (C_S) which represent the ratio of PV array capacity to load demand and ratio of battery capacity to load demand, respectively [52, 53].

$$C_A = \frac{C_{PV}}{L}$$

$$C_s = \frac{C_B}{L}$$

where the battery and PV array capacity at load demand are denoted with C_B and C_{PV}, respectively, while L stands for the load demand.

If the system is installed in a grid-independent configuration, it can be used to eliminate or reduce electricity bills. To analyze the viability of such configuration, the net present value (NPV) is calculated for the economic analysis of the system [54–56].

$$NPV = \sum_{n=0}^{N} \frac{Cost_{total,n} - Benefit_{total,n}}{(1+r)^n}$$

where (r) is the discount rate and (N) is the PV system lifetime in years, while $Cost_{total,\,n}$ and $Benefit_{total,\,n}$ are the total costs and benefits for (n) year.

In addition, such investment is assessed through pay-back period (PBP) which is essential how long it takes to recover the investment costs. Another parameter to assess the system is the internal rate of return (IRR) which accounts for the time value of money and determines the rate of interest for which NPV is zero [57–59].

3 Design Considerations

The interest in this technology coupled with the variability of parameters associated with its utilization makes it critical to be aware of all design aspects and to account for any influencing parameter. In essence, such technologies require to be positioned in a favorable design scheme. The dependency of BIPV on the type of building and on the weather makes it necessary to have specific case studies and to be customized in a way that fits the environment and market of the installation site/location. Therefore, this section provides the considerations for designing BIPV system.

Prior to the design stage, two forms of assessment are critical: (i) an evaluation of environmental conditions and (ii) assessment of the building itself. The first evaluation must account for orientation, surrounding buildings, terrain, average sunshine hours, and incident solar irradiance. It should also consider the surrounding vegetation and the alterations it undergoes across different seasons. The second evaluation prior to design is that of the building's envelope, surfaces, size, design, dimensions, auxiliary structures, and other characteristics. In essence, the design has to consider the components or sections to be integrated before beginning to design the system.

Also, the designer must assess the solar potential on all surfaces of interest, which is essentially a combination of both assessments. Then the most effective surfaces are identified. The design phase begins by employing different procedures or methodologies for the different parts of the envelope. For instance, the aesthetics and technical requirements of a BIPV façade are more expensive and complex than those of a BIPV roof [60].

Options and Strategies

Initial considerations must be placed toward the options for designing BIPV systems and the strategies for its implementation. Starting with climatic conditions and intended location, in addition to orientation. Other design aspects are needed to integrate PV systems into buildings such as architectural, engineering, and energetic designs. All of which will impact the project requirements and its design criteria.

The integration of a PV system into the building helps in reducing building material and their associated costs, allows for on-site daytime electricity generation, adds to the architectural elegance of the building, and provides a support structure. Furthermore, the envelop of the building is likely to be waterproof, which creates a separation between the outer and inner climates of the building. Other advantages would be regulation and control of energy, safety, privacy, ventilation, and daylight.

It is crucial to optimize the integration process to maximize energy generation and minimize material or installation costs [61].

Electric Load Minimization

The premise of minimizing electrical loads is that PV systems have energy generation limitations and to achieve a zero net energy building it would be very helpful to minimize the electrical energy requirements of the building. This can be achieved through the implementation of energy-efficient appliances, minimizing thermal loads, or any other energy-consuming case. For instance, in Oman, the summer season requires continuous operation of air-conditioning systems to ensure comfort living inside buildings. However, in some residential and even commercial settings, these systems have low coefficient of performance (COP). Some buildings are designed without much consideration to improve its ventilation. Hence, the techniques that could be considered include improving the building's envelop, implementing natural ventilation or passive cooling techniques or applications, and daylighting techniques as well. In doing so, it becomes easier for the designer to choose an appropriate BIPV system that can provide electricity to the loads, store or sell excess electricity. Moreover, the analysis will include the potential energy cost savings for the desired building [62].

Energy Yield Optimization

The process of achieving an efficient BIPV system that is cost-effective and reliable requires two main steps: (1) reducing the demand or electrical load, (2) maximizing the electricity generated by the solar panels or arrays. To maximize the energy yield it is necessary to design the system to achieve the highest possible energy output throughout the time of operation. And to avoid any unnecessary energy loss. For instance, to consider the variation in tilt angle across the different seasons and hence to select the best tilt angle. Also, to provide a cooling mechanism for the PV to improve or maintain its energy conversion efficiency. The appropriate selection of component such as the inverter with a high efficiency. Finally, avoiding any possible shading scenario due to the building itself or surrounding buildings, structures, or environment such as trees and hills.

Sizing

The selected BIPV capacity is often determined through design constraints. In some cases, the electrical load may not be fully met by the BIPV system due to limited area, weight, and other constraints. Hence, many buildings with PV systems installed still require to import energy from the grid or other sources. In some cases, on an industrial and commercial level, the BIPV system is only designed to feed a certain load such as parking lights, indoor illumination, water heating requirements, etc. [63].

Tilt

The consideration for optimum tilt angle is important because it allows for maximum PV exposure to sunlight at various times of the day, or seasons throughout the year. A general rule of thumb is to use the latitude angle and subtract 15° from it in the summer and add 15 during the winter. However, in a house or a building, the situation is different due to fixed nature of the panel when integrated in a roof and the roof pitch itself. Most middle eastern buildings are designed with flat roofs which has its own advantages and disadvantages. For PV integration into such buildings, the PV could be laid horizontally on the roof, but that would be hard given the load requirements. The tilt angle is another example of how the building design may constrict the PV system design.

Orientation

Orientation is another critical factor to ensure maximum sunlight exposure for the BIPV module on a daily and yearly basis. Typical BIPV systems that are south-oriented exhibit perform better than west- and east-facing facades. Moreover, horizontal BIPV systems are usually facing south, while vertically installed systems are facing west.

4 Case Studies in Oman

This section describes the factors to help design, install, and test BIPV systems in Oman and to further examine the potential of BIPV systems in Oman, particularly for a roof-integrated type BIPV installed in the city of Muscat, which is located in northern Oman. This section will demonstrate the design consideration, performance estimation, and analysis of feasibility for such system, to help in exploring Oman's potential for BIPV systems. In this section, the aim is to highlight the performance of roof-installed PV systems and reflect based on those values onto BIPV systems.

There are several factors to consider when installing building-integrated photovoltaic (BIPV) systems in Oman:

1. Solar resource: Oman has high levels of solar radiation, which have been established in this chapter, making it a good location for solar energy generation. The solar resource will vary depending on the specific location in Oman, so it is important to assess the solar irradiance at the site before installing a BIPV system. Metrological, satellite, or hybrid data sources can be used. Metrological data is collected from ground-based instruments, such as weather stations, whereas satellite data is collected from satellites orbiting the Earth. Metrological data is typically collected at a limited number of locations and may not be available in all areas, whereas satellite data is collected from a global perspective and provides more comprehensive coverage of the Earth's surface.
2. Regulations and incentives: It is important to understand the regulations and incentives related to solar energy in Oman before installing a BIPV system. The Omani government has implemented several policies and incentives to encourage the adoption of renewable energy, including feed-in tariffs for solar energy. However, rules are always changing, and it is crucial to acquire proper consultation prior to inverting in BIPV technology. Moreover, it is important to consider them for design and cost analysis.
3. System design: The design of the BIPV system should consider the specific needs and characteristics of the building, as well as the solar resource at the site. This may include considerations such as the orientation and slope of the building's roof, the shading conditions, and the electrical load of the building.
4. System components: It is important to select high-quality components for the BIPV system, including the photovoltaic modules, inverters, batteries, and other balance of system components. It is also important to consider the warranty and maintenance requirements of the system components.
5. System installation: The installation of the BIPV system should be carried out by qualified professionals who have experience with solar energy systems. It is also important to ensure that the system is installed according to local codes and standards, and that the necessary permits and inspections are obtained.
6. System cooling: Since the aim is to maximize the gains from the system and minimize the losses, and because of the high operating temperatures in Muscat, then there is a likelihood of significant drops in energy during peak sun hours or around peak solar irradiance, which is why it is recommended to use passive cooling strategies for these systems.

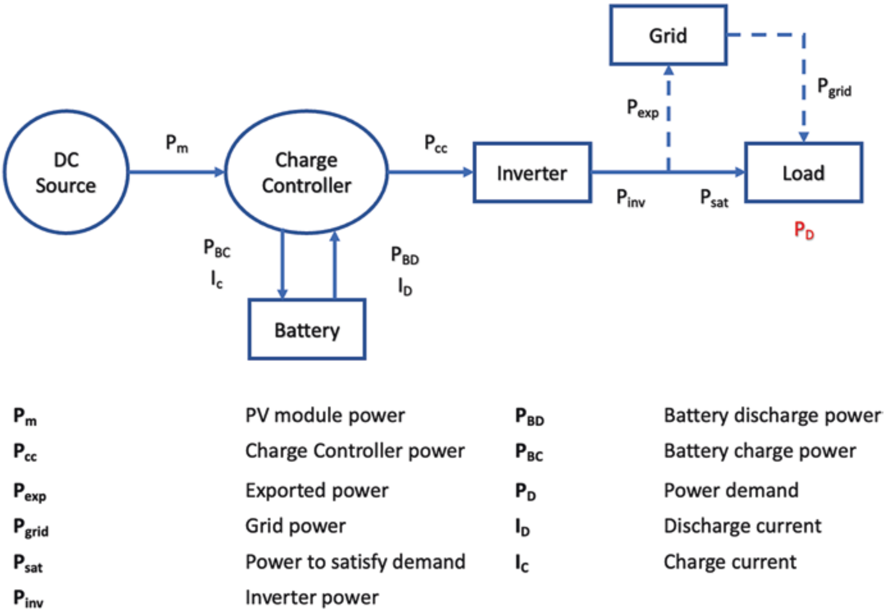

Fig. 7 Schematic drawing of the grid-independent PV system [64]

Al-Saqlawi et al. [64] developed a novel approach of assessing roof-top solar PV/battery technology, which operate without a recourse to the electricity grid, as a case study in Muscat, Oman. The system was defined as a grid-independent system, which is described in Fig. 7. Such system stores the excess energy in batteries as opposed to exporting them to the grid which can be advantageous such as avoiding reverse power flows which occur when connecting the system to the grid. The authors developed a model in gPROMS and performed the study for Muscat, Oman. The developed model included a physical sizing of the system. Moreover, the study investigated the system economically with considerations for economic targets for residential roof-top PV system. The appropriate tilt angle (β) for each month in Muscat and the input weather data are shown in Fig. 8. The hourly real-time data was matched to real demand data and the simulation period was set to 20 years.

In the study, Al-Saqlawi et al. [64] use the nominal operating cell temperature model (NOCT) to calculate the cell temperature as follows:

$$T_C = T_A + \frac{\text{NOCT} - 20}{800} \text{GSI}_T$$

where T_C and T_A are the cell and ambient temperatures. While GSIT is the incident solar radiation, which is determined by the tilt angle (β) of the *PV* and orientation toward the sun. The orientation is dependent on latitude (ϕ), elevation angle (α), and declination angle (δ). The last, (δ), depending on the day of the year is calculated as follows [65]:

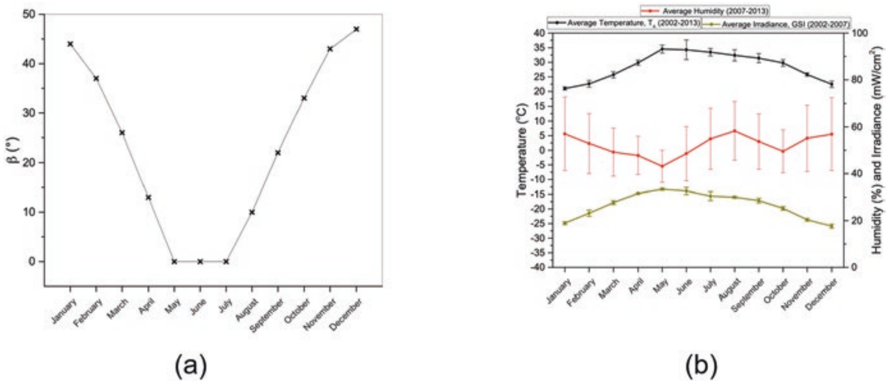

Fig. 8 Monthly (**a**) optimum roof-top PV tilt angle (β) in the city of muscat, (**b**) weather variation in Muscat [64]

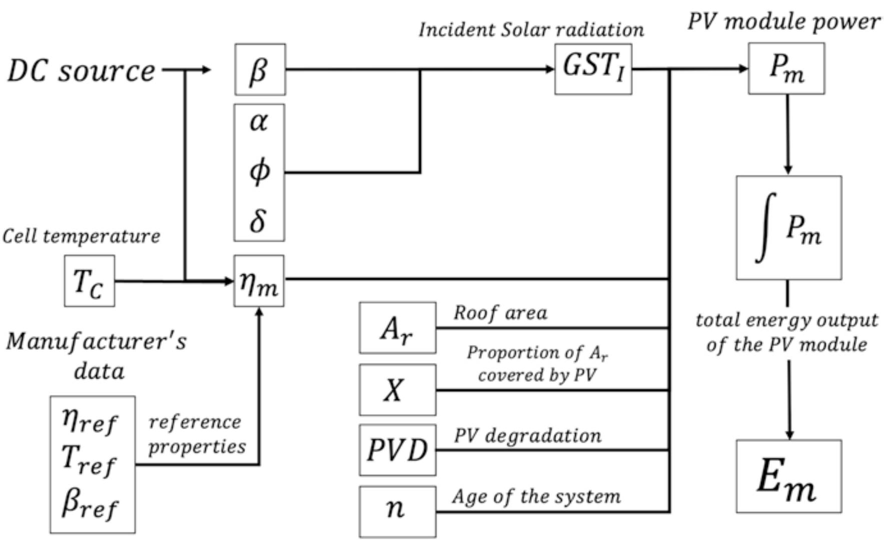

Fig. 9 Method of obtaining the total energy from the PV module (Em) using the integral of the PV module power (Pm)

$$\delta = \sin^{-1}\left(\sin\left(23.45^\circ\right)\sin\left(\frac{360}{365}\left(d-81\right)\right)\right)$$

The method of obtaining the total energy output from the PV module is illustrated in Fig. 9.

However, based on the assumptions made for the selected system, such configuration was found not feasible. The system can only be feasible if there were higher electricity prices and battery costs were reduced significantly, with reductions above 90% [66].

In 2022, Al Busaidi et al. [67] carried out a performance analysis of a 22.8 kW PV system utilized for an Eco-house in Muscat, Oman. Figure 10 shows a photograph of the eco-house with the PV system and its system configuration. The research used data collected from September 2017 to October 2018. Figure 11 shows the average monthly temperature and solar energy generated by the system.

The average monthly energy exported and imported by the grid-connected solar system at the higher college of technology HCT eco-house was calculated. The results showed that the net exported and imported energy saved approximately 1500 kWh during the same period. This research examined the impact of high ambient temperature on solar energy production by a photovoltaic system. According to the analysis of recorded solar energy data, the highest solar energy production occurred in June due to the highest solar radiation and longer production hours during the day. However, the effect of higher temperature on energy production in June was limited.

Figure 12 shows the monthly average efficiency and net energy from the PV system. Moreover, the average monthly wind speed for a period of 12 months was calculated, and the impact of wind speed on solar energy production in Muscat was found to be minimal. However, the presence of wind may have a positive effect on the performance of solar photovoltaic systems, as it can increase the efficiency of solar panels by reducing the temperature on their surface.

5 Conclusion and Recommendations

In this chapter, a board overview and introduction to building-integrated photovoltaic (BIPV) systems was provided. A BIPV is a type of renewable energy system that generates electricity from solar panels that are integrated into the building's structure, such as the roof or walls. However, such system is dynamic and requires much preparation and design to ensure the right implementation and to attain a good return on investment. Feasibility, building structure, aesthetics, electrical demands, financing, and maintenance are among the aspects to be considered prior to installing a BIPV system. Moreover, metrological data was provided for a better implementation of such systems in Oman. The main conclusions of this chapter are:

1. Feasibility: The first step is to determine whether a BIPV system is feasible for your building. This will depend on factors such as the size and orientation of the building, the availability of suitable surfaces for mounting the panels, and local regulations.
2. Building structure: BIPV systems add weight to the building, so it is important to ensure that the structure can support the additional load.
3. Electricity demand: It is important to carefully assess your electricity demand and ensure that the BIPV system will be able to meet your needs.

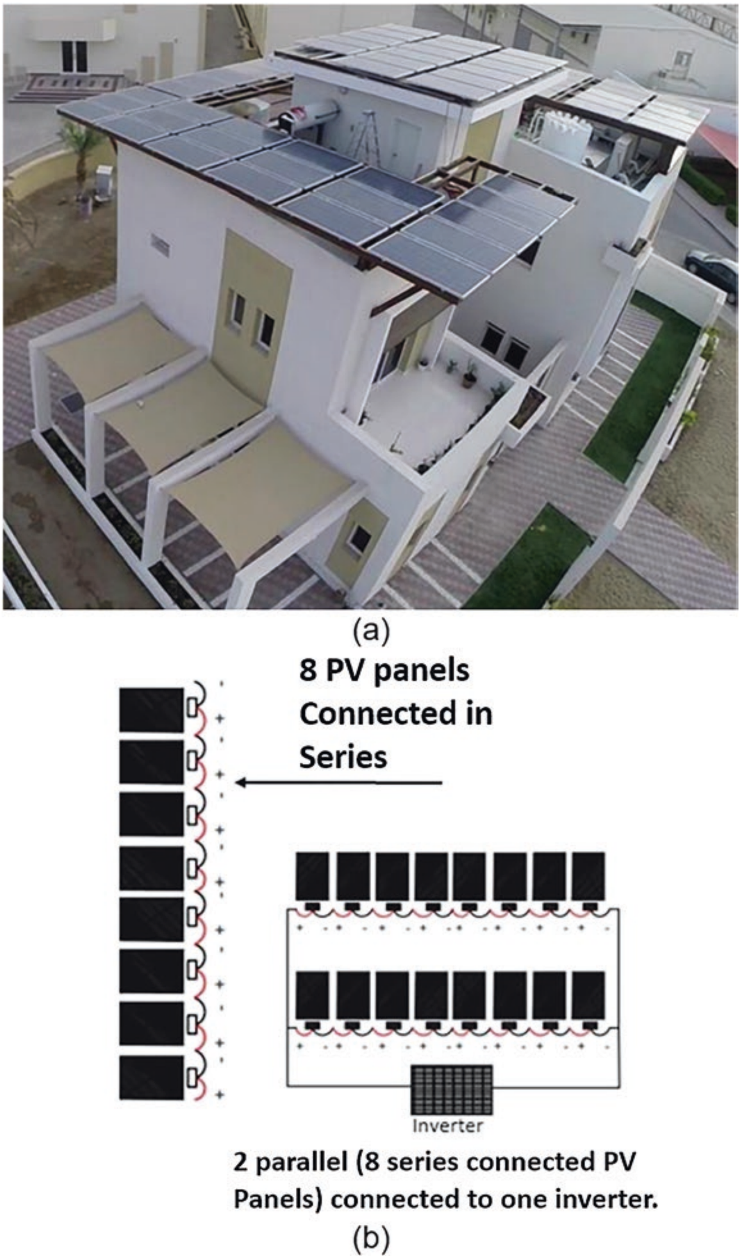

Fig. 10 PV system for an eco-house (**a**) ariel view photograph of the eco-house, (**b**) schematic diagram of the PV system connections [66]

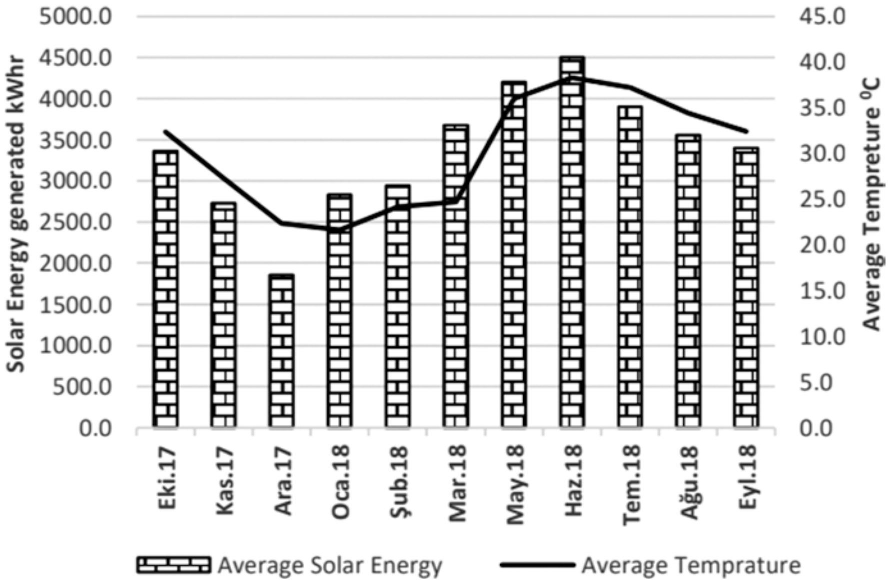

Fig. 11 Average monthly temperature and solar energy [66]

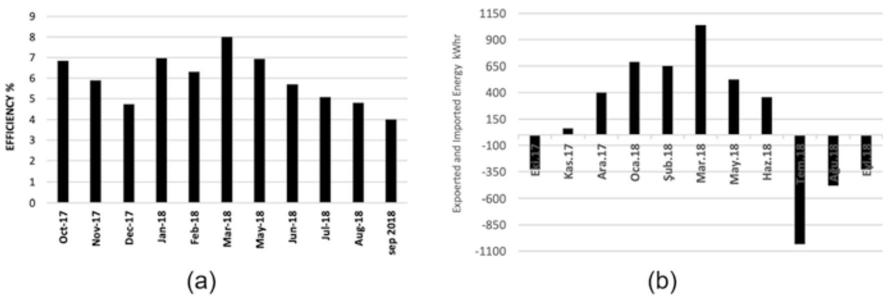

Fig. 12 Monthly (**a**) average efficiency of the PV system, (**b**) net energy from the PV system [66]

4. Financing: BIPV systems can be expensive to install, so you will need to consider the costs and determine whether you have the necessary budget or whether you will need to secure financing.
5. Maintenance: BIPV systems require regular maintenance to ensure that they are operating at their best. You will need to consider the ongoing costs of maintaining the system.
6. Aesthetics: BIPV systems can be integrated into the building in a way that is visually appealing, but it is important to ensure that the panels blend in with the overall design of the building.

Moreover, the challenges that face BIPV systems' utilization in Oman mainly include high temperatures, dust and sand, shading, grid connectivity related to regulations, and requirements for grid connectivity and maintenance. The findings from the literature are provided as follows:

1. South-facing BIPV roof exhibits a higher solar potential compared to south-facing BIPV curtain wall.
2. The technical requirements and aesthetics for roof BIPV are typically less demanding than BIPV façade.
3. The designer must distinguish between BIPV-specific and commercial PV modules.
4. Passive cooling methods are effective in improving the overall energy yield of the system.
5. Energy analysis and exergy assessment of BIPV systems are highly dependent on the daily solar radiation.

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Renewable Energy Options and Built Environment in the Gulf Cooperation Countries Adapting to Combat Climate Change

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1 Introduction

Currently, with devastating weather disasters witnessed worldwide; in Asia (flooding of Pakistan and China), Europe (drought of rivers, wildfires, flooding, massive ice stones), North America and South America (drought of rivers, wildfires, flooding), scientists are obliged to conduct more advanced research in climatology, modeling, forecasting the future using Big Data analytics [1].

Long-term weather parameters (climate change) and the Built Environment nexus were classified into categories. These categories include building structure, which is affected by several factors (floods, landslides, storms, and snow loads), building constructions (influenced by fastening systems and water supply), building materials (impacted by frost resistance, ultraviolet resistance, and insulation properties) and the indoor climate (affected by humidity and temperature) [2]. There is a strong tie and Nexus between Weather (Climate), Prediction & Projection and Built Environment; the latter is defined as human-made environment that provides proper setting of houses, buildings, zoning, streets, open spaces transportation options, and

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more. According to the Environmental Protection Agency [3] the built environment touches all aspects of our lives, including the buildings and city habitats, the distribution systems that provide us with water and electricity, roads, bridges, and transportation systems used. It is the man-made or modified structures that facilitate the living, working, and recreational spaces.

Furthermore, there is a strong relation between Built Environment and Health. The built environment influences our level of physical activity; for instance, the inaccessibility or nonexistence of sidewalks and bicycle or walking paths contributes to sedentary habits, leading to poor health outcomes such as obesity, cardiovascular disease, diabetes, and some types of cancer [4]. Additionally, there is a strong relationship between the built environment and weather parameters, and hence climate change has been characterized in order to propose systemic changes to improve the adaptation of cities to climate change [5].

Among the useful research in using long-term meteorological data to create awareness and contribute to a growing body of climate change that is necessary for the development of effective mitigation and adaptation strategies is the recent published work [6]. Forty years of air temperature changeover was utilized and the polynomial fitting scheme was used – to both monthly and annual air temperature data – to detect trends and classify them into linear and nonlinear (quadratic and cubic) categories. Applying similar approach of utilizing long-term data is the study on a new globally reconstructed sea surface temperature analysis dataset since 1900 developed by the China Meteorological Administration [7].

Furthermore, building environment management systems should allow for minimizing the possible future negative impact of natural hazards caused by the behavior of long-term weather parameters. This can be achieved by looking into the correlation coefficients between these parameters with the passing and forthcoming years [8]. Proper planning and configuring built environment disaster, economic, social, energy, water, and comforting risk from monitoring and studying correlation between various weather parameters throughout the years, i.e., modeling, will lead to great reduction and comfort in urban life [9–11].

To have a sustainable building, one needs reliable information on the long-term performance and, more specifically, the expected service life of building materials, components, assemblies, and most importantly anticipated effects of climate change on the built environment [12].

Al-Humaiqani and Al-Ghamdi [13] listed important indicators that play a crucial role in marking a resilient quality to build environment planning, analysis, and design, where among them is weather modeling.

The variation of long-term meteorological parameters, past and future projections, is anticipated to have a significant impact on the built environment, especially, whereby the world faces climate change as one of the biggest environmental challenges ever [14–18]. In 2015, the estimated climate change cost to private businesses was about USD 43 trillion during the twenty-first century [19]. This explains why researchers do modeling and correlations to their weather data [20–22].

As early as 2012, a useful report was published alerting Arab countries, in particular, to strive toward adaptation to a changing climate; a case for adaptation governance and leadership in building climate resilience [23]. It contains eight chapters and most important is Implement Policy Responses to Increase Climate Resilience. In 2018, another alerting report for the Arab region was published by GEF, UNDP [24] under the title “Climate Change Adaptation in the Arab States: Best Practices and Lessons Learned”. The reason for focusing on the Arab world is because the region is home to rising levels of conflict and the world’s largest population of refugees and displaced people, it is the planet’s most water-scarce and food-import-dependent region, and the only region where malnutrition rates have been rising. The impacts of climate change are exacerbating the existing challenges of sustainably managing limited natural resources across the Arab region where climate change-related desertification has expanded, greatly increasing the vulnerability of the local population. Among important topics in this report is “Country actions to build climate resilience” which lists 18 case studies conducted as projects and the project related to this work is Enhancing Climate Change Adaptation in the North Coast and Nile Delta Regions in Egypt. The main parameters that may affect the Arab region is Temperature, Precipitation, Sea Level Rise, Natural Hazards and it will impact Economy, Food security, Water security, Displacements, and Human health. Recently, the London School of Economics and Political Science (LSE) had published a useful blog on Climate Adaptation and Kuwait’s Built Environment [25]. It focuses on the relationship between Kuwait’s built environment and its changing climate and plea to it leaders to examine this relation carefully to understand how climate adaptation can improve the status quo and ensure reduced future negative impacts (Kuwait is a member state of Gulf Cooperation Council, GCC)). Furthermore, researchers from UAE [26], which is also a member state of GCC countries, had Modeled Current and Future Climate Change in the UAE using Various GCMs in MarksimGCM. They found a strong correlation between the present T_{max} vs T_{max} 2020, Tmax $_{2040}$, Tmax $_{2060}$, Tmax $_{2080}$, and $_{Tmax}$ 2095 for both RCP4.5 and RCP8.5. In their work, the precipitation projections show greater variation than temperature. This means that maximum temperatures are going to increase in the coming years based on the predictions according to the different scenarios using MarksimGCMR; GCMs are numerical models predicting atmospheric physical processes, ocean dynamics, and land surface processes, while presenting the most advanced predictive tools available to simulate the impact of increased greenhouse gas levels on the global climate system. It has to be noted that there are four emission scenarios, RCP 2.6 is based on low emission, RCP 4.5 and RCP 6 are based on intermediate emissions, and RCP 8.5 is based on high emissions, with each assuming different radiative forcing and primary energy use levels [27]. In a thoughtful move, UK government had issued “Built Environment Climate Change Adaptation Action Plan 2022–2026” [28]. The UK government realized very well that homes and buildings, heritage places, energy systems, public parks, and sports fields are part of our built environment and should be made more resilient to climate impacts like bushfires, heatwaves, floods, and coastal inundation. Their plan will ensure that Victoria is well placed to consider climate change impacts in decisions about how they plan for and build communities. Resilience and recovery are critical for highly exposed regional cities and towns and adapting the built environment to climate change is an investment in saving lives, reducing trauma and minimizing economic damage from disasters and the associated recovery costs. The plan of UK government is to strengthen and extend existing climate change responses; build adaptation capacity across stakeholders and establish regulatory and other frameworks needed for long-term transformative action.

The purpose of using the long-term (67 years) recorded weather data parameters in Bahrain and the published result of the forecasted weather data in the GCC countries by the World Bank and IPCC in 2100 is to explore the degree of climate change in the GCC countries and what renewable energy and building design and built environment is more suitable compared to other options. This is a novel study which aims to alert policy makers, architects, engineers, and environmentalists to project the temperature, humidity, precipitation, etc., in 2050 to allow for actions, mitigations, and adaptation to climate change and be resilient toward it.

2 Methodology

Recorded data from 1955 to 2022 were made by Bahrain Meteorological Directorate, Ministry of Transportation & Telecommunications, Kingdom of Bahrain. The station is well calibrated and regularly updated. It has data since 1902 but the most reliable data are those from 1955. The station is located at Bahrain International Airport, Muharraq town.

The data is measured continuously and distributed at 10 min intervals, then at hour interval and per day to per month to per year. The station records various meteorological parameters; however, for this research we have selected the most important parameters for built environment. Although solar and ultraviolet radiation data are both important, they were only recorded accurately and systemically by the meteorological directorate in Bahrain since 2014. Therefore, they were presented but not used for forecasting. However, the recorded temperature (minimum, average, and maximum) can be considered to represent the solar radiation; it's a result of absorbing and emitting solar energy. The recorded weather parameters (average and anomalies) are average temperature, maximum temperature, minimum temperature, humidity, wind speed, dust, and precipitation. These data may represent the entire island because the area of the main island is about 604 km^2 (length about 51 km and width 18 km) with latitude 26.03°N and longitude 50.55°E (refer to Fig. 1).

The Kingdom of Bahrain consists of 30 small islands, and it is a family member of the Gulf Cooperation Council Countries (GCCC) which was established on May 25, 1981 in the Abu Dhabi – Capital of United Arab Emirates. GCC is a regional, intergovernmental, political, and economic union comprising Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. The Headquarters of GCC is in Riyadh, Kingdom of Saudi Arabia.

In order to produce regression equations for each meteorological parameter (y) versus year (x), we used several regression fits [29] such as:

Fig. 1 Bahrain Map (left) showing the location of the official weather station in Muharraq City, where Bahrain International Airport is located. The GCC Countries map (right) lies at latitude from 23°N to 30° N and longitude from 48°E to 56°E

1. Linear regression: $y = ax + b$.
2. Quadratic regression: $y = ax^2 + bx + c$.
3. Cubic regression: $y = ax^3 + bx^2 + cx + d$.
4. Power regression: $y = a\,x^b$.
5. ab-Exponential regression: $y = a{\cdot}b^x$,
6. Logarithmic regression: $y = a + b\ln(x)$.
7. Hyperbolic regression: $y = a - b/x$.
8. Exponential regression: $y = e^{a + bx}$.

We had reported earlier [30] that the exponential (cubic) regression is the most accurate correlation (among 8 correlation coefficients) to predict all the recorded long-term (65 years) weather parameters in Bahrain; there are no multi-correlations between different parameters. For Bahrain, we had used the exponential (cubic) regression since it was found to have the highest correlation coefficient for such data, both Average and Anomalies data; the highest is for humidity versus year ($r = 0.900$, strong relation), and the least is for precipitation ($r = 0.1647$, poor relation) for Average data. As for the Anomalies data, the highest is for humidity versus year ($r = 0.9019$) and the least is for precipitation versus ($r = 0.1647$, no relation). Therefore, herein, we used the exponential cube regression fit, for both Average data and Anomalies. These regressions can be used to plan for future built environment and to predict or foresee a particular meteorological parameter due to concentration of greenhouse gases (GHG), led by carbon dioxide (CO_2), in our atmosphere, along with all negative man-made destruction to the environment which has resulted in climate change and subsequently to the evolution or creation of extremities.

We also utilized the data and analysis reported in the IPCC WGI Interactive Atlas for some weather data in GCC countries to allow for comparison. IPCC WGI is a novel tool for flexible spatial and temporal analyses of much of the observed and projected climate change information underpinning the Working Group I contribution to the Sixth Assessment Report, including regional synthesis for Climatic Impact-Drivers (CIDs) [31]. We also used the portal of Climate Change Knowledge

Portal (CCKP) by the World Bank [32] which is the hub for climate-related information, data, and tools for the World Bank Group (WBG). The Portal provides an online platform from which to access and analyze comprehensive data related to climate change and development. The climate data aggregations are offered at national, sub-national, and watershed scales.

3 Results

Table 1 summarizes the correlation coefficients (*r*) for the average data of the long-term meteorological parameters: average temperature, maximum temperature, minimum temperature, average humidity, average wind speed, dust, and precipitation. It clearly shows that the highest correlation coefficient (R^2) for a weather parameter is average relative humidity ($R^2 = 0.8262$) followed by annual mean minimum temperature ($R^2 = 0.7382$). The least correlation coefficient was for annual total number

Table 1 Summary of the correlation coefficients (*r*) for the different quantities fitted to the different forms for Average Data

1	Annual mean temperature $y = 2 \times 10^{-5} x^3 - 0.0011 x^2 + 0.018x + 26.341$	$R^2 = 0.5955$
2	Annual mean maximum temperature $y = -7 \times 10^{-7} x^3 + 0.0004 x^2 + 0.02 x + 29.4$	$R^2 = 0.6498$
3	Annual mean minimum temperature $y = 2 \times 10^{-5} x^3 - 0.0003 x^2 - 0.027 x + 23.447$	$R^2 = 0.7382$
4	Annual total precipitation $y = -0.0016 x^3 + 0.1482 x^2 - 3.5275 x + 94.927$	$R^2 = 0.0422$
5	Annual mean relative humidity $y = 6 \times 10^{-5} x^3 - 0.00091 x^2 + 0.1762 x + 66.411$	$R^2 = 0.8261$
6	Annual mean wind speed $y = -7 \times 10^{-7} x^3 + 0.0003 x^2 - 0.0444 x + 10.244$	$R^2 = 0.4615$
7	Annual total number of days with dust, dust storm or sandstorm $y = 10^{-5}x^3 - 0.0002x^2 - 0.0668 x + 6.662$	$R^2 = 0.029$
8	Annual mean temperature anomalies $y = 2 \times 10^{-5} x^3 - 0.0011 x^2 + 0.0186 x + 0.0005$	$R^2 = 0.5955$
9	Annual mean maximum temperature anomalies $y = -7 \times 10^{-7} x^3 + 0.0004 x^2 + 0.02 x - 0.7095$	$R^2 = 0.6498$
10	Annual mean minimum temperature anomalies $y = 2 \times 10^{-5} x^3 - 0.0003 x^2 - 0.0297 x + 0.6172$	$R^2 = 0.7382$
11	Annual total precipitation anomalies $y = - 0.0016 x^3 + 0.148 x^2 - 3.5275 x + 23.927$	$R^2 = 0.0422$
12	Annual mean relative humidity anomalies $y = 6 \times 10^{-5} x^3 - 0.0091 x^2 + 0.1762 x + 0.4109$	$R^2 = 0.8261$
13	Annual mean wind speed anomalies $y = -7 \times 10^{-7} x^3 + 0.0003 x^2 - 0.0444 x + 0.7442$	$R^2 = 0.4615$
14	Annual total number of days with dust, dust storm or sandstorm anomalies $y = 10^{-5} x^3 - 0.0002 x^2 - 0.0668 x + 0.662$	$R^2 = 0.029$

of days with dust, dust storm or sandstorm ($R^2 = 0.029$). We used in the text both R and R^2; R is the correlation between the predictor variable, x, and the response variable, y, while R^2 is the proportion of the variance in the response variable that can be explained by the predictor variable in the regression model [33].

4 Discussion

Figure 2 shows the annual variation of the recorded average long-term temperature throughout the years from 1955 to 2022. The figure shows that the temperature is expected to increase exponentially in Bahrain. It might reach an average of 36.0 °C by 2050. Considering the temperature, the built environment should undergo substantial changes. It seems that taking into account the house walls' thickness and the use of shade forecasting on the houses is not enough. It is notable, too, that some serious consideration should also be given to the exposure of the roofs or facades to sunlight in order to harvest solar electricity to avoid CO_2 emission. It is indeed a big challenge to architects, developers, and environmentalists.

Figure 3 shows the annual variation of the recorded maximum long-term temperature throughout the years from 1955 to 2020. The figure shows that the temperature is expected to increase exponentially in Bahrain. It might reach an average of 33.7 °C by 2050. This seems to be an unusual result as it should be higher than the expected average temperature in 2050 (36.0 °C).

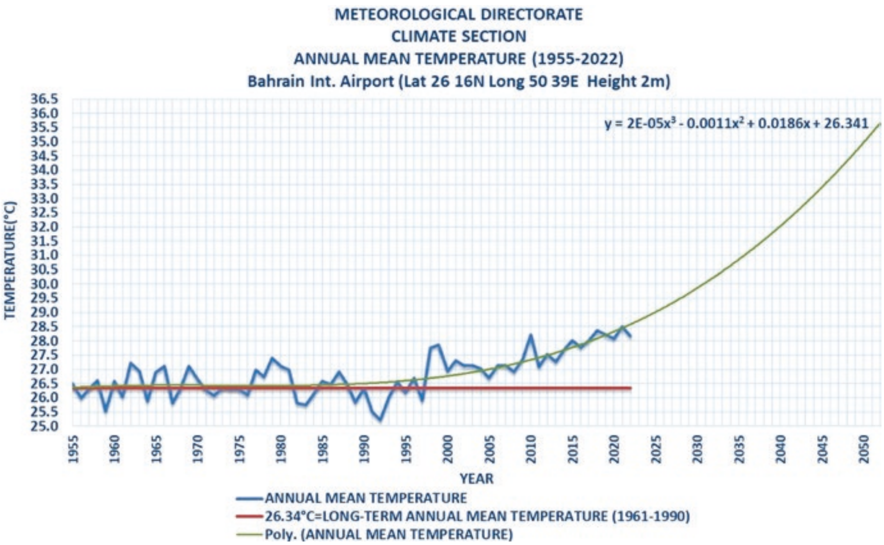

Fig. 2 The annual variation of the recorded average long-term temperature throughout the years from 1955 up to 2022. The curve is represented by the following equation: $y = 2 \times 10^{-5} x^3 - 0.0011 x^2 + 0.018x + 26.341$, r = 0.772

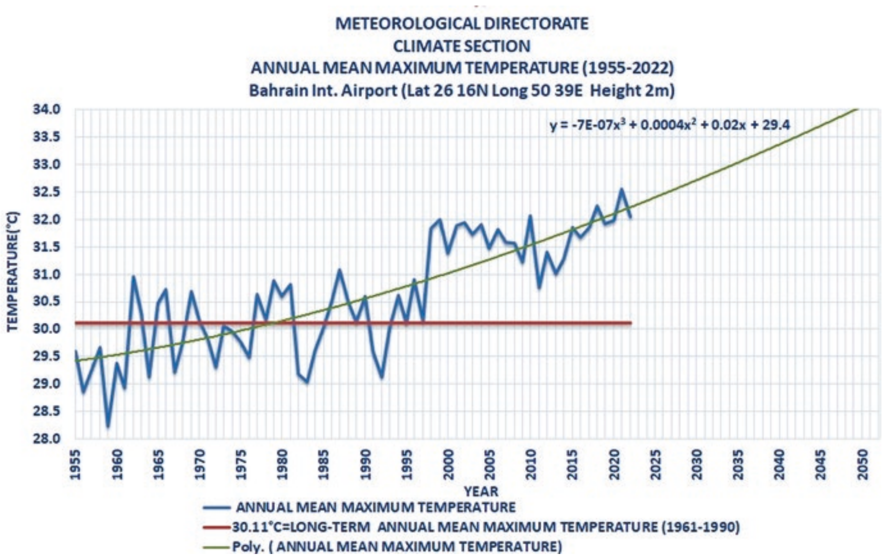

Fig. 3 The annual variation of the recorded average long-term maximum temperature throughout the years from 1955 up to 2022. The curve is represented by the following equation: $y = -7 \times 10^{-7} x^3 + 0.0004\, x^2 + 0.02\, x + 29.4$, r = 0.806

Figure 4 shows the annual variation of the recorded minimum long-term minimum temperature throughout the years from 1955 to 2022. The figure shows that the temperature is expected to increase exponentially in Bahrain. It might reach an average of 35.0 °C by 2050. This result is consistent with the expected average temperature in 2050 (36.0 °C), where both are subjected to nearly a "worrying" exponential increase. The result means that no significant winter is expected in the future. Accordingly, the built environment should be thought of very well.

Figure 5 shows the annual variation of the long-term average temperature anomalies of the years from 1955 up to 2022. The curve (exponential cube regression fit) shows that the temperature in 2050 will be larger by 9.5 °C than the long-term average temperature (which was normalized to 0 °C). This is a substantial increase for a span of 30 years.

The annual variation of the long-term maximum temperature anomalies of the years from 1955 up to 2022 (Fig. 6) shows that by 2050, the rise of the maximum temperature will be 9.5 °C compared to long-term maximum average (65 years) which is alerting especially because the correlation coefficient r is relatively high (0.7879). However, the situation seems to be worse when looking at the annual variation of the long-term minimum temperature anomalies of the years from 1955 to 2022 (Fig. 7). It shows that in about 30 years the increase in the long-term average minimum temperature will be 12 °C, given the fact that the correlation coefficient r is relatively high (0.8424).

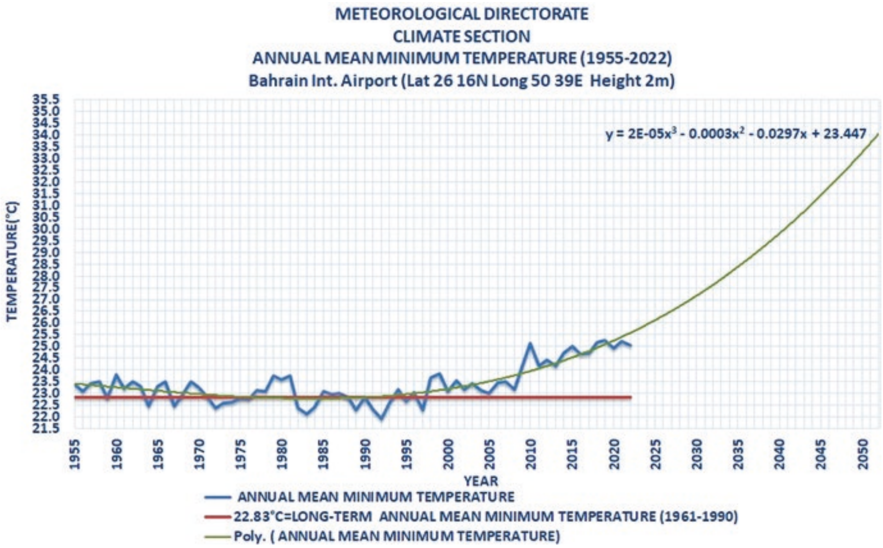

Fig. 4 The annual variation of the recorded average long-term minimum temperature throughout the years from 1955 up to 2022. The curve is represented by the following equation: $y = 2 \times 10^{-5} x^3 - 0.0003\, x^2 - 0.027\, x + 23.447$, r = 0.859

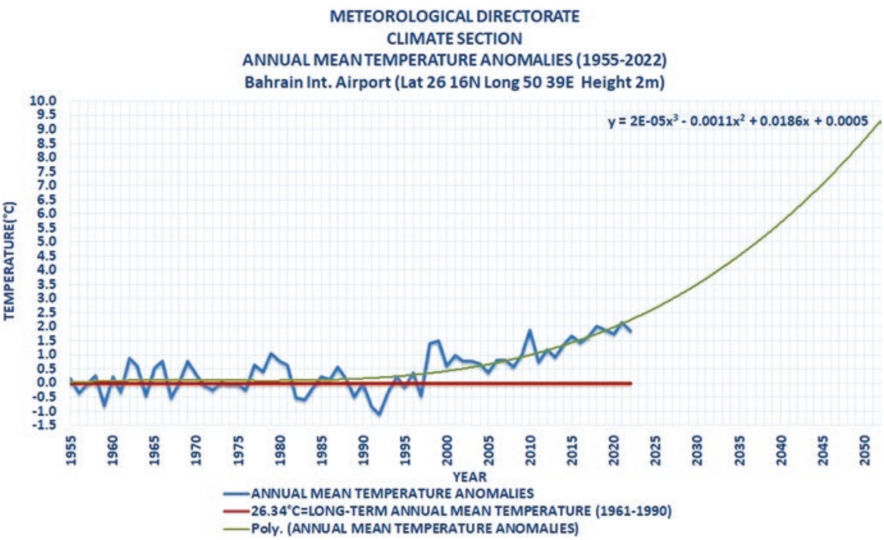

Fig. 5 The annual variation of the long-term average temperature anomalies of the years from 1955 up to 2022. The curve is represented by the following equation: $y = 2 \times 10^{-5} x^3 - 0.0011\, x^2 + 0.0186\, x + 0.0005$, r = 0.772

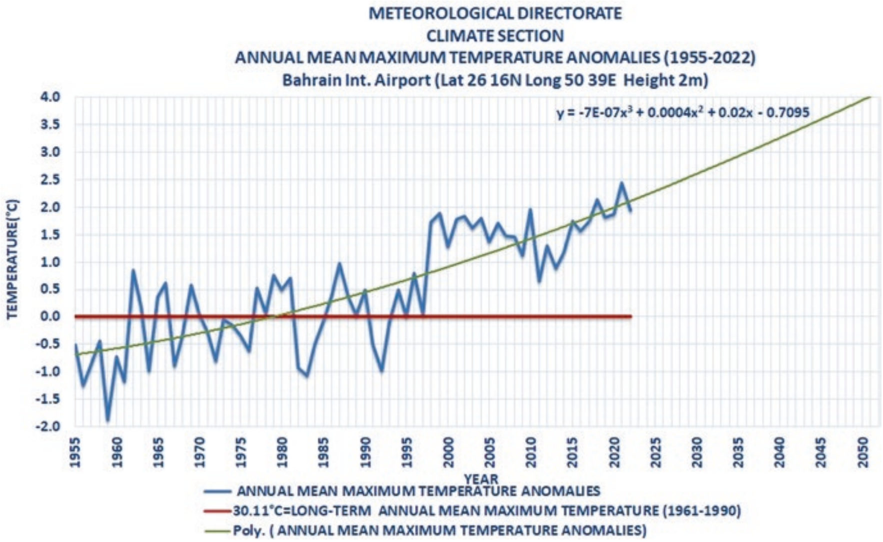

Fig. 6 The annual variation of the long-term average maximum temperature anomalies of the years from 1955 up to 2022. The curve is represented by the following equation: $y = -7 \times 10^{-7} x^3 + 0.0004 x^2 + 0.02 x - 0.7095$, r = 0.806

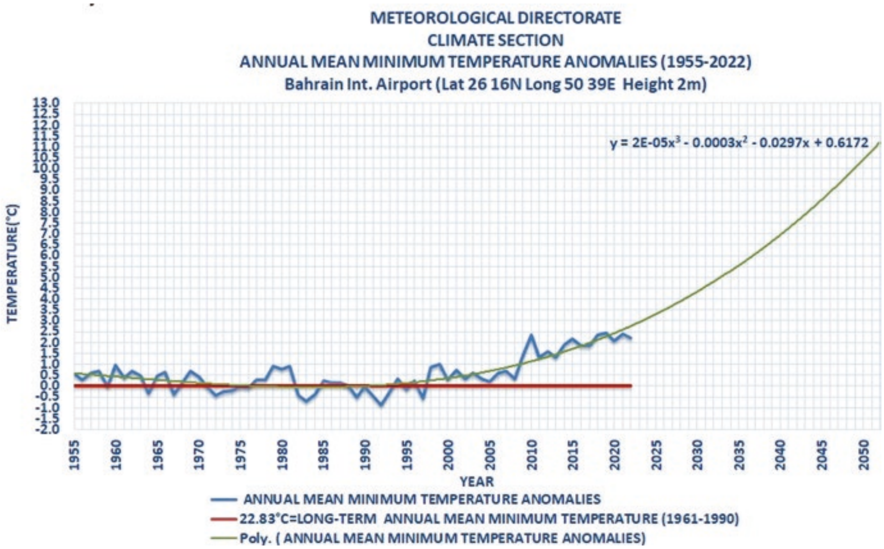

Fig. 7 The annual variation of the long-term average minimum temperature anomalies of the years from 1955 up to 2022. The curve is represented by the following equation: $y = 2 \times 10^{-5} x^3 - 0.0003 x^2 - 0.0297 x + 0.6172$, r = 0.859

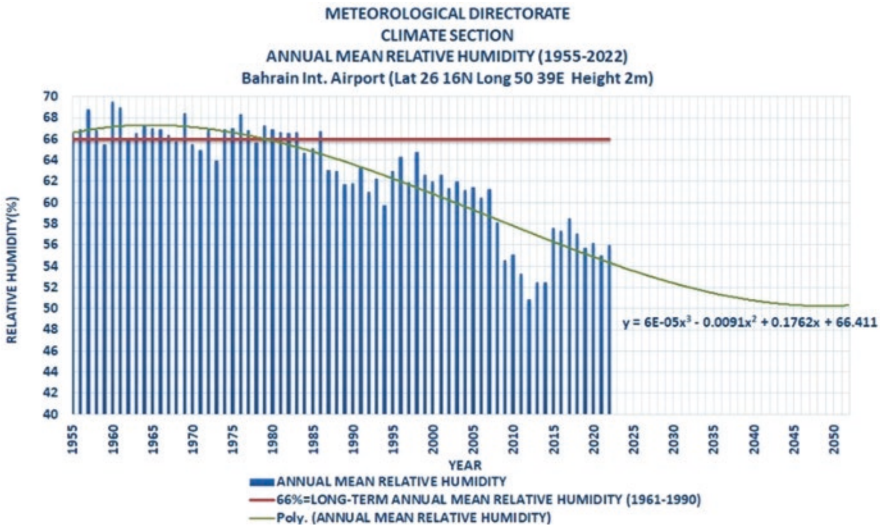

Fig. 8 The annual variation of the long-term average relative humidity of the years from 1955 up to 2022. The curve is represented by the following equation: $y = 6 \times 10^{-5} x^3 - 0.00091 x^2 + 0.1762 x + 66.411$, r = 0.909

The most surprising result is the variation of annual mean relative humidity from 1955 to 2020, which shows that humidity is expected to decrease from 66% (the long-term average) to 46% by 2050 (Fig. 8). This is an advantage for people living on islands as the cooling system may perform better, particularly for air conditioners working in water due to the evaporation mechanism.

The highest correlation coefficient, among all the examined meteorological parameters, belongs to humidity (r = 0.9000). The same observation is applied to the annual variation of relative humidity anomalies (Fig. 9). The relative humidity will be less than the long-term average humidity by 22 unit percentage. This is the highest correlation coefficient calculated in this study (r = 0.9019).

Figure 10 illustrates the long-term average annual wind speed variation (from 1955 to 2022). The results indicate that the wind speed has a tendency to reduce annually reaching an average wind speed of 8.2 knots (4.1 m/s) by 2050 compared to the long-term annual average (9.5 knots = 4.75 m/s), i.e., decrease by about 13%. This means that the potential of using wind energy for city and homes electrification is less fortunate unless microturbines are used; where they have a low cut-in speed value (1 m/s). It is interesting to note that the correlation coefficient is not high (r = 0.6754). For the annual variation of the wind speed anomalies, the result shows that the wind speed drops by 1.4 knots (0.7 m/s) by 2050 compared to the long-term average (Fig. 11).

Figure 12 illustrates the long-term average annual variation from 1955 to 2022, taking into consideration the annual total number of days with dust, dust storms or sandstorms (visibility 1000 meters or less). It seems that there is a tendency that storm or sandstorm events will increase to 15 by 2050 (Fig. 12). For the annual

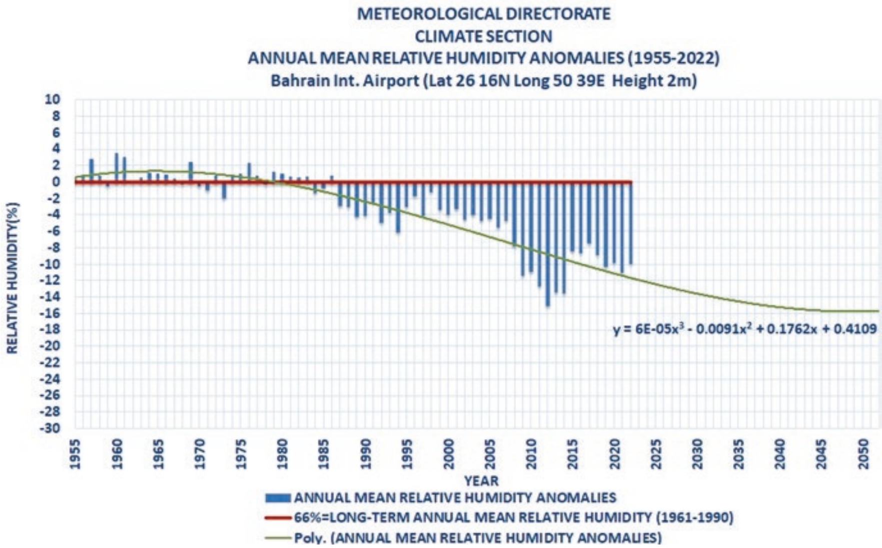

Fig. 9 The annual variation of the long-term average anomalies relative humidity of the years from 1955 up to 2022. The curve is represented by the following equation: $y = 6 \times 10^{-5}\, x^3 - 0.0091\, x^2 + 0.1762\, x + 0.4109$, r = 0.909

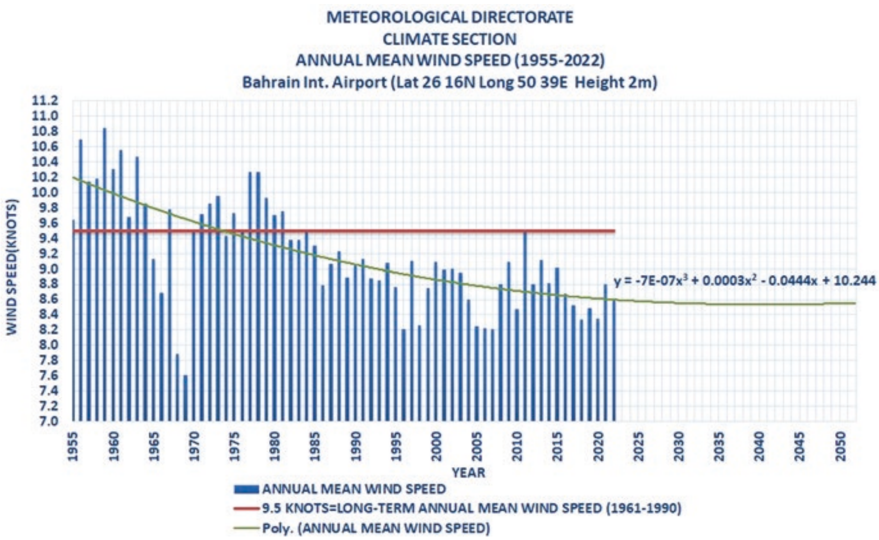

Fig. 10 The annual variation of the long-term average wind of the years from 1955 up to 2022. The curve is represented by the following equation: $y = -7 \times 10^{-7}\, x^3 + 0.0003\, x^2 - 0.0444\, x + 10.244$, r = 0.679

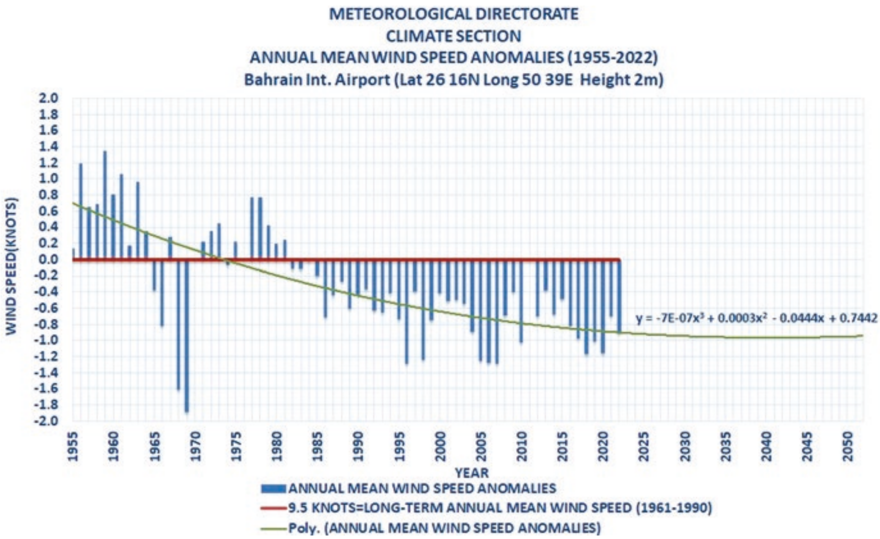

Fig. 11 The annual variation of the long-term average wind anomalies of the years from 1955 up to 2022. The curve is represented by the following equation: $y = -7 \times 10^{-7} x^3 + 0.0003 x^2 - 0.0444 x + 0.7442$, r = 0.679

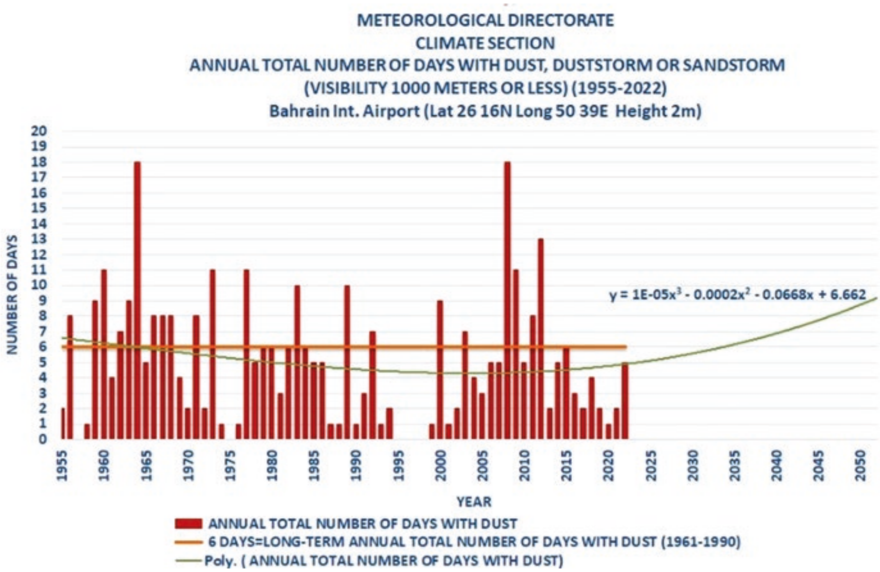

Fig. 12 The annual variation of the long-term average annual total number of days with dust, dust storm or sandstorm (visibility 1000 meters or less) from 1955 up to 2022. The curve is represented by the following equation: $y = 10^{-5}x^3 - 0.0002x^2 - 0.0668\, x + 6.662$, r = 0.171

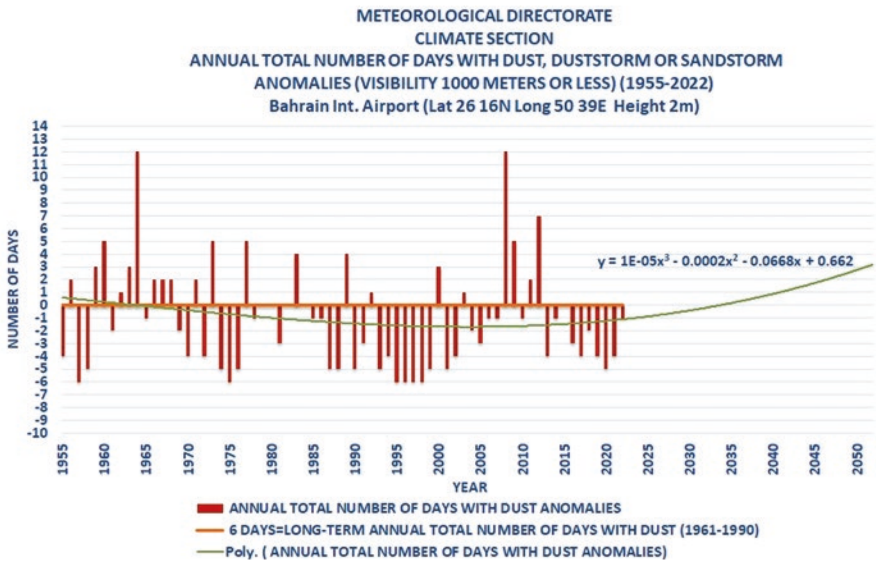

Fig. 13 The annual variation of the long-term average annual total number of days with dust, dust storm or sandstorm anomalies (visibility 1000 meters or less) from 1955 up to 2022. The curve is represented by the following equation: $y = 10^{-5} x^3 - 0.0002 x^2 - 0.0668 x + 0.662$, r = 0.170

variation of dust, dust storm or sandstorm anomalies, the result shows that 9 more dust storms or sandstorms will occur by 2050 compared to the long-term average (Fig. 13). Fortunately, the correlation coefficient between dust events (both average and anomalies) are low, i.e., r = 0.1733 and 0.1733, respectively.

This means that the performance of PV panels and, to a larger degree, the solar concentrators parabolic (CSP) will be hugely affected as they are very sensitive to sand and dust. If this is the trend, then future renewable energy option for the built environment should exclude CSP, otherwise, the consumption of water will be high which will offset the advantage of solar benefit.

Figure 14 shows the results for the long-term average annual precipitation variation from 1955 to 2022. The results indicate that there is a great tendency to reduce annually reaching deficit value (− 270 mm) by 2050 (Fig. 14), while for the anomalies, the annual precipitation is less than the long-term average (71 mm) by 340 mm (huge deficit) by 2050 compared to the long- term average (Fig. 15). Due to the very low correlation coefficient between precipitation versus year – which is 0.1647 for both average and anomalies data, no consideration is given for this analysis.

In order to mitigate the impacts of random, short-term fluctuations on the weather over a specified time frame, the moving average was calculated and illustrated for the annual mean temperature average (Fig. 16) and annual mean temperature anomalies average (Fig. 17).

This moving average offers an analysis of average temperature data points by creating a series of averages of different subsets of the full data set, herein, every 5 years. We had selected the temperature (both average and anomalies) because of its

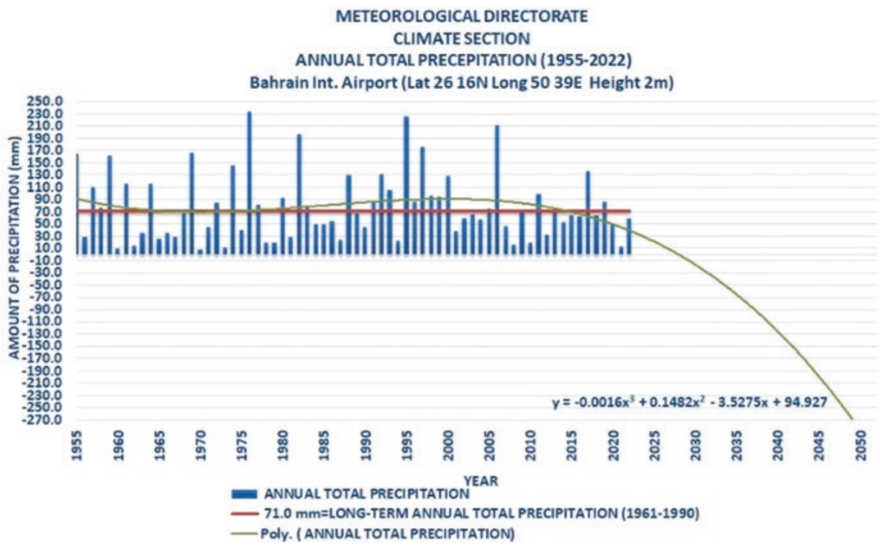

Fig. 14 The annual variation of the long-term average annual precipitation from 1955 up to 2022. The curve is represented by the following equation: $y = -0.0016\,x^3 + 0.1482\,x^2 - 3.5275\,x + 94.927$, r = 0.205

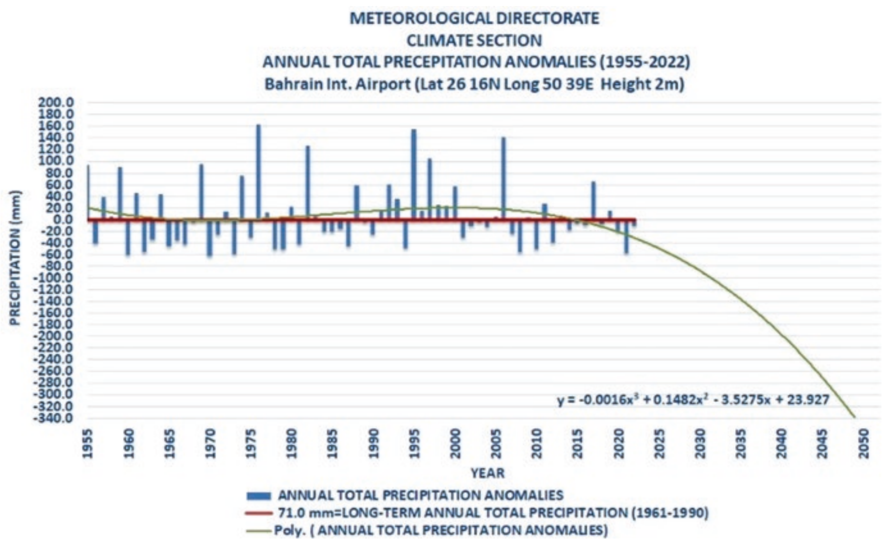

Fig. 15 The annual variation of the long-term average annual precipitation anomalies from 1955 up to 2022. The curve is represented by the following equation: $y = -0.0016\,x^3 + 0.148\,x^2 - 3.5275\,x + 23.927$, r = 0.206

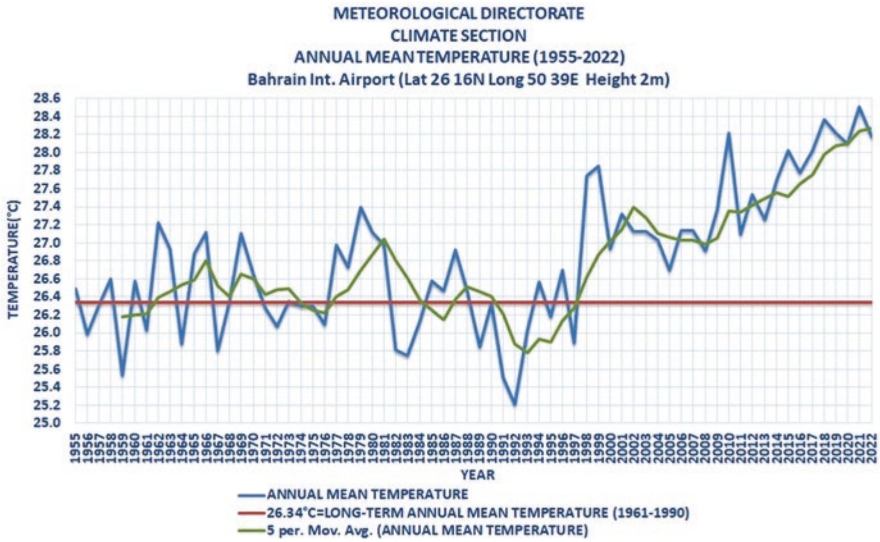

Fig. 16 The annual variation of the recorded average long-term temperature, along with using moving average per 5 years subset, throughout the years from 1955 up to 2022

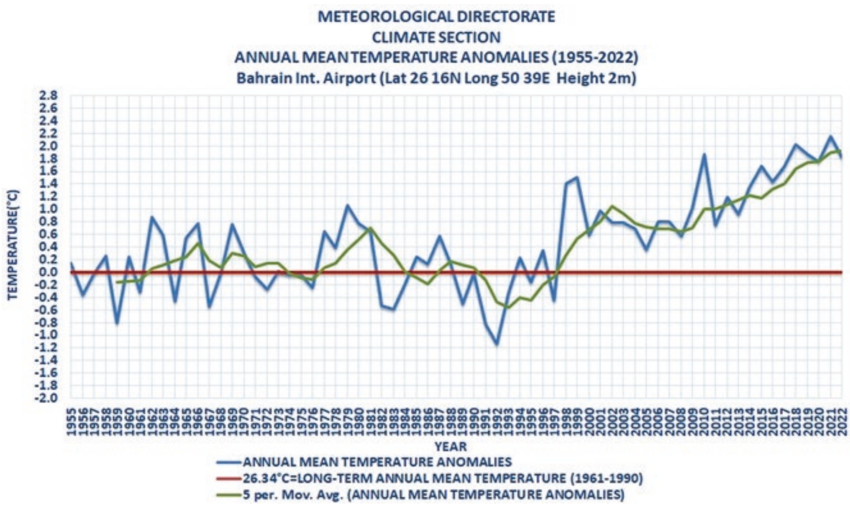

Fig. 17 The annual variation of the recorded mean long-term temperature anomalies, along with using moving average per 5 years subset, throughout the years from 1955 up to 2022

significance in built environment and both have relatively high correlation coefficient (r = 0.73922495, R^2 = 0.54645353 and r = 0.73922495, R^2 = 0.54645353, respectively) as this weather parameter is significant in the building design, either to minimize heat input (in high solar radiation countries), or maximize heat input (in low radiation countries) [34, 35]. Figures 16 and 17 ascertained that the temperature

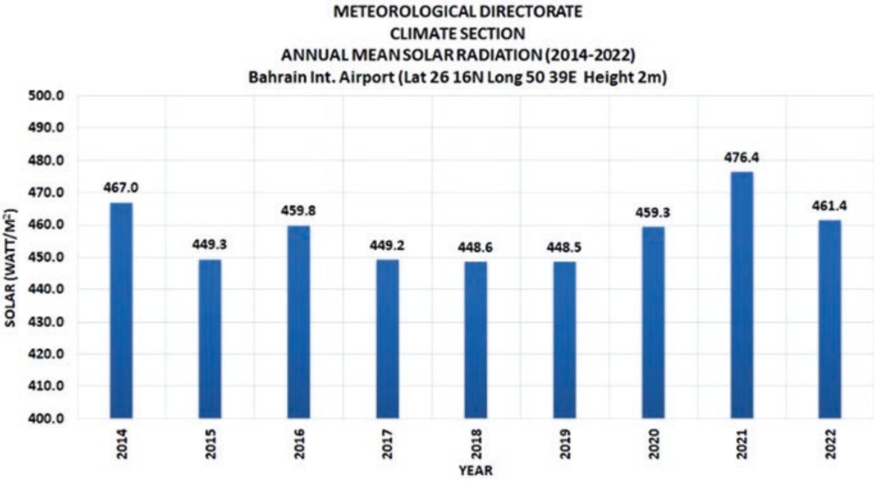

Fig. 18 The actually measured annual solar radiation on a horizontal surface measured at Bahrain International Airport, Muharraq, Kingdom of Bahrain

increase is expected to be substantial and a lot of mitigation should be made to offset such an expected increase.

Figure 18 shows the average solar radiation on a horizontal surface measured at Bahrain International Airport, Muharraq, Kingdom of Bahrain. The annual solar radiation is fluctuation and does not show a tendency to increase. The, relatively, low solar radiation values in 2017 to 2019 are strange as the temperature was high during these years.

Figure 19 shows the actually measured average ultraviolet solar radiation (UVC) on a horizontal surface measured at Bahrain International Airport, Muharraq, Kingdom of Bahrain. The annual UVC radiation is fluctuation and does not show a tendency to increase. The, relatively, low UVC radiation in 2022 is extremely strange, as the temperature was high in this year. The devices were calibrated and the software were checked properly. We compared these UVC radiations with other recorded data (in 2022) at different locations (5 locations) – distributed across Bahrain – but found all UVC instruments give low UV radiation level (Table 2), i.e. 18.3, 17.3, 18.4, and 18.6 W/m^2 while at Bahrain International airport at Muharraq it was 17.3 W/m^2. This may indicate a large Ozone concentration in the atmosphere or nitrogen oxide concentration which are emitted from the cars and interact with UV radiation and produces Ozone.

The long-term (1985–1990) average solar UV radiation in Bahrain was found [36] to be equal to 215 Wh/m^2 (about 21 W/m^2). For comparison, the measured daily and monthly average (60 months) in Riyadh, KSA) [37] shows that maximum UV radiation occurs in July (16.6 Wm^{-2}) and the minimum values occur in December (8.3 Wm^{-2}). In Kuwait [38], the highest and lowest intensity monthly-daily recorded values for ultraviolet was 445 (about 37 W/m^2) and 31 Wh/m^2 (about 3.5 W/m^2), respectively.

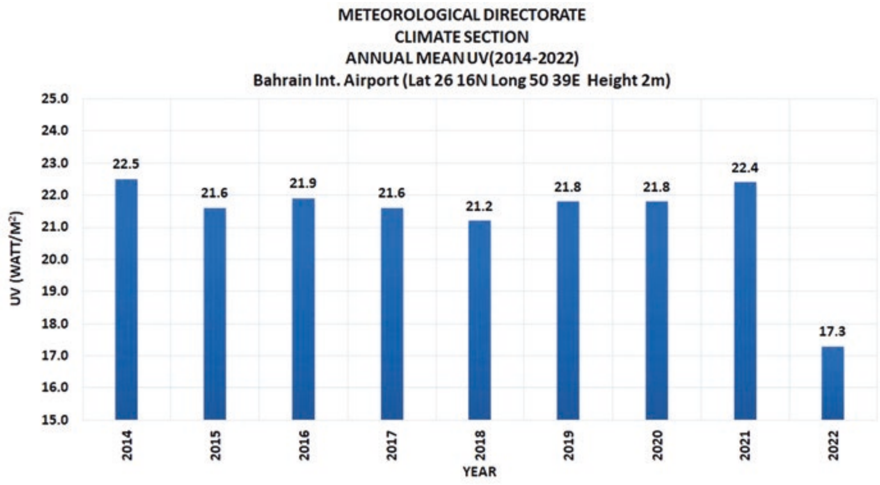

Fig. 19 The actually measured average ultraviolet solar radiation (UVC) on a horizontal surface measured at Bahrain International Airport, Muharraq, Kingdom of Bahrain

Table 2 The actually measured UVC radiation in 2022 at different locations (5 locations) – distributed across the Kingdom of Bahrain

METEOROLOGICAL DIRECTORATE
CLIMATE SECTION
Monthly Mean UV (WATT/M^2)

	Bahrain International Airport	King Fahad causeway	Durrat AlBahrain	Bahrain International Circuit	University of Bahrain
Jan-22	14.5	13.6	14.0	15.1	15.4
Feb-22	17.5	17.9	17.3	18.9	19.5
Mar-22	17.8	17.9	17.9	18.9	19.2
Apr-22	16.6	18.5	17.5	18.8	17.3
May-22	17.8	18.8	17.9	20.0	19.0
Jun-22	21.1	22.1	20.5	22.7	21.0
Jul-22	18.7	18.7	17.1	19.0	17.3
Aug-22	20.3	21.7	20.0	21.0	23.0
Sep-22	20.5	22.0	19.0	19.9	22.2
Oct-22	16.2	19.1	17.9	16.4	19.1
Nov-22	13.9	15.5	15.5	15.9	16.1
Dec-22	12.4	14.1	13.0	13.9	14.1
Annual Mean UV (WATT/M^2)	17.3	18.3	17.3	18.4	18.6

The forecasted high temperature in Bahrain by 2050 is relatively very high; it is about 10 °C more than the average (26 °C). This is very suspicious, we therefore have to consult and compare with other international forecasting centers. Therefore, we referred to the climate knowledge portal established by the World Bank [32] which allows forecasting temperature, perception and relative humidity, besides displaying the sea level rise in any worldwide country, including the GCC countries. The result shows that certain models (SSP5) using the Coupled Model Intercomparison Projects (CMIP6) indicate an increase of nearly 6 ° C compared to year 1995. Their projection is based on data from 1995 to 2014. It has to be noted that CMIP6 includes scenarios with high and very high GHG emissions (SSP3-7.0 and SSP5-8.5) and CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively, scenarios with intermediate GHG emissions (SSP2-4.5) and CO_2 emissions remaining around current levels until the middle of the century, and scenarios with very low and low GHG emissions and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions (SSP1-1.9 and SSP1-2.6). There are 5 Scenarios for forecasting based on input modeling. These are:

1. *1.5 °C objective of the Paris Agreement.*
   This is the most optimistic scenario. Global CO_2 emissions fall to zero by 2050. Societies adopt more environmentally friendly practices, with the focus shifting from economic growth to general well-being. Investments in education and health increase and inequality decreases. Severe weather events are more frequent, but the world has avoided the worst consequences of climate change.
   Challenges for adaptation: low
   Challenges for mitigation: low
2. *SSP1-2.6: Sustainable development scenario*
   Global CO_2 emissions are strongly reduced but less rapidly. The objective of zero emissions is reached after 2050. This scenario presents the same socio-economic trends toward sustainable development as in the first scenario, but the temperature increase stabilizes at around 1.8 °C by the end of the century.
   Challenges for adaptation: moderate
   Challenges for mitigation: moderate.
3. *SSP2-4.5: Middle of the road scenario*
   CO_2 emissions hover around current levels before beginning to decline by mid-century. Socio-economic factors follow their historical trends, with no significant change. Progress toward sustainability is slow, with disparate development and income growth. Under this scenario, temperatures rise by 2.7 °C by the end of the century.
   Challenges for adaptation: high
   Challenges for mitigation: high.
4. *SSP3-7.0: Regional rivalry scenario*
   Greenhouse gas emissions and temperatures keep regularly increasing, with CO_2 emissions almost doubling from current levels by 2100. Countries become more competitive with each other, prioritizing issues of national and food security. By the end of the century, average temperatures have risen by 3.6 °C.
   Challenges for adaptation: high
   Challenges for mitigation: low.
5. *SSP5-8.5: Fossil fuel-driven development scenario*
   This is the "worst case scenario". Current levels of CO_2 emissions are almost doubled by 2050. The world economy grows rapidly, but this growth is driven by fossil fuel exploitation and very energy-intensive lifestyles. By 2100, the average temperature of the planet will have risen by a catastrophic 4.4 °C.
   Challenges for adaptation: low
   Challenges for mitigation: high.

Figures 20 and 21 show the projection of average temperature and average maximum temperature change in Bahrain using the World Bank data portal (based on data from 1995 to 2014) using five scenarios. Their models show an increase in the average temperature in Bahrain by 3 °C by 2050 and 7 °C by 2100 (Scenario SSP5-8.5, i.e., worst case scenario). The uncertainty in this scenario (purple shadow)

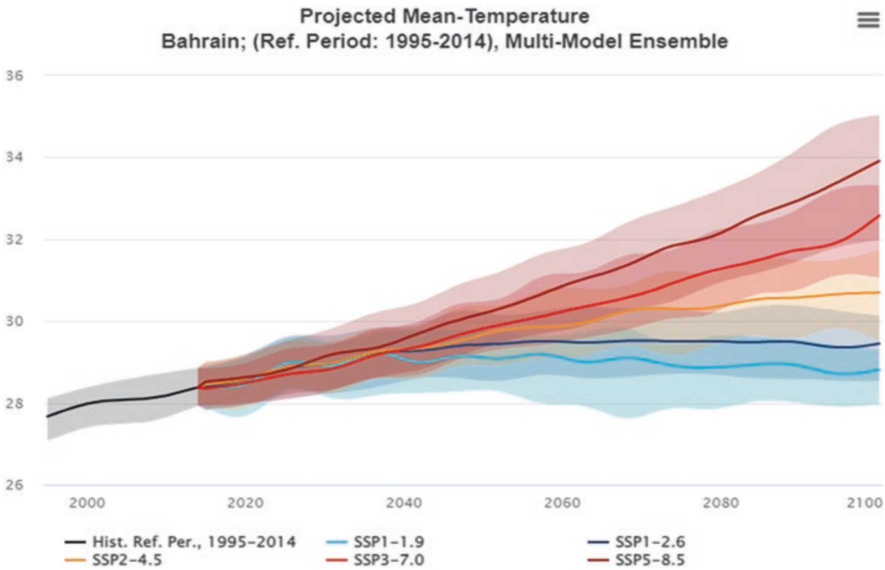

Fig. 20 Projections of average temperature change in Bahrain using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

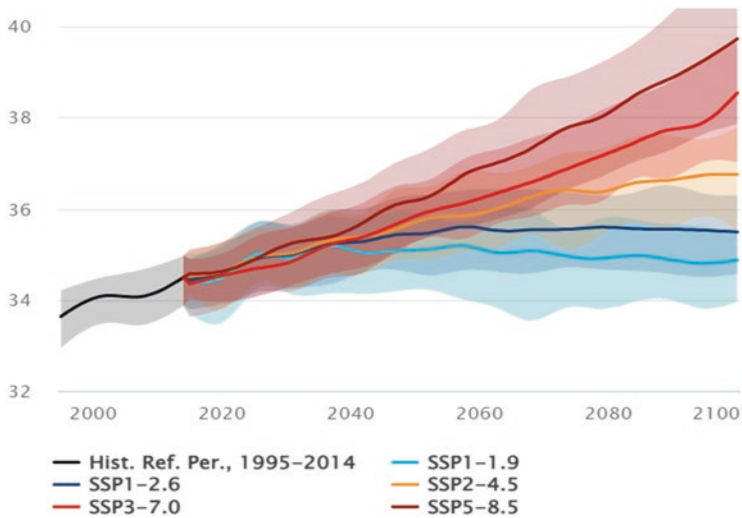

Fig. 21 Projections of the maximum temperature change in Bahrain using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

shows the increase in the average temperature in Bahrain by 4 °C by 2050 and by 8 °C by 2100.

Figure 22 shows projections of the average precipitation change in Bahrain using the World Bank data portal (based on data from 1995 to 2014) using five scenarios. It shows a tendency in increasing the Precipitation in Bahrain from 50 mm in 1995 to about 60 mm (20%) by 2050 and to about 70 mm (increase by 40%). In our model, the precipitation tends to decrease very substantially by 2050; the result can be rejected since the correlation coefficient is very low (r ≈ 0.2). Meanwhile, the relative humidity is expected to decrease in 2050 to 61%, compared to 60% in 1995, i.e. a decrease by about 3%, while it remains the same in 2100 (Fig. 23). In our model, the relative humidity is expected to decrease from 66% to 51% by 2050, i.e., reduction by nearly 20% (r = 0.909).

Figure 24 shows the historical sea level for coastal Bahrain (1993–2015). The observed animalities are related to the mean of 1993–2012. It is clear from the curve that the average annual anomaly sea level in Bahrain had increased substantially in 2015 (by 100% compared to year 1993) and is continuing to increase.

Figures 25, 26, 27, and 28 are related to the projected temperature, precipitation, relative humidity as well as the recorded coastal sea level in the Kingdom of Saudi Arabia. It shows a substantial increase in the average temperature from 25 °C in 1995 to 32 ° C in 2100 (an increase of 7 °C), increase in precipitation from 40 mm in 1995 to about 60 mm (33% increase), and decrease by 10% in the relative humidity. The sea level is exhibiting an increase by 70% from year 1993 to year 2015.

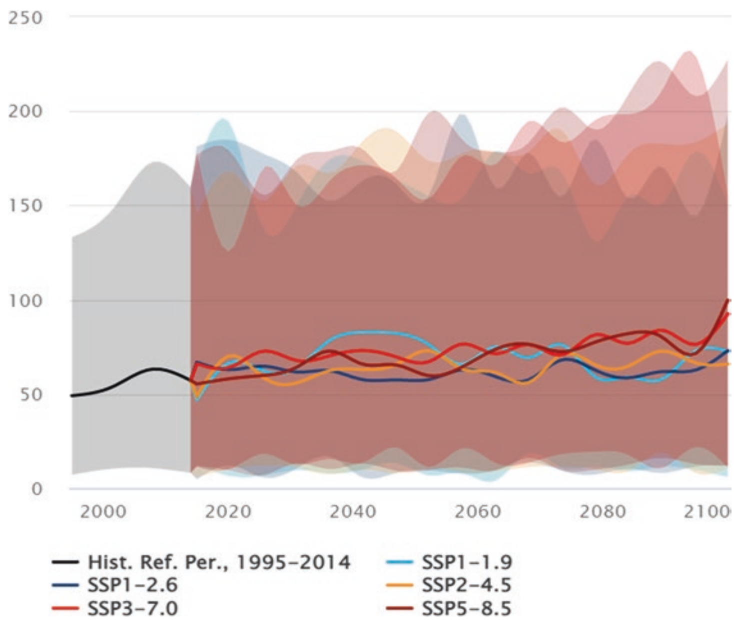

Fig. 22 Projections of the average precipitation change in Bahrain using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

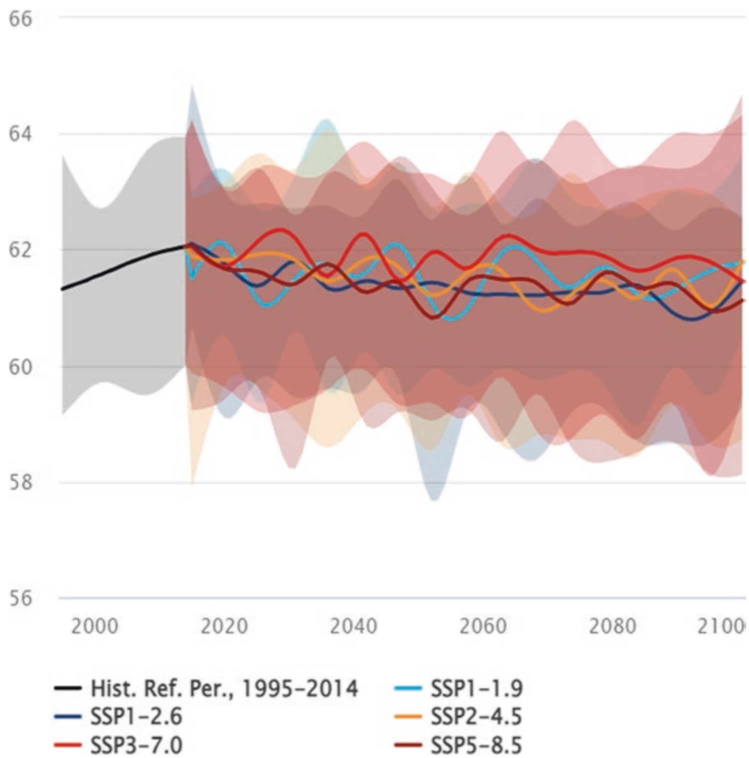

Fig. 23 Projections of the average relative humidity change in Bahrain using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

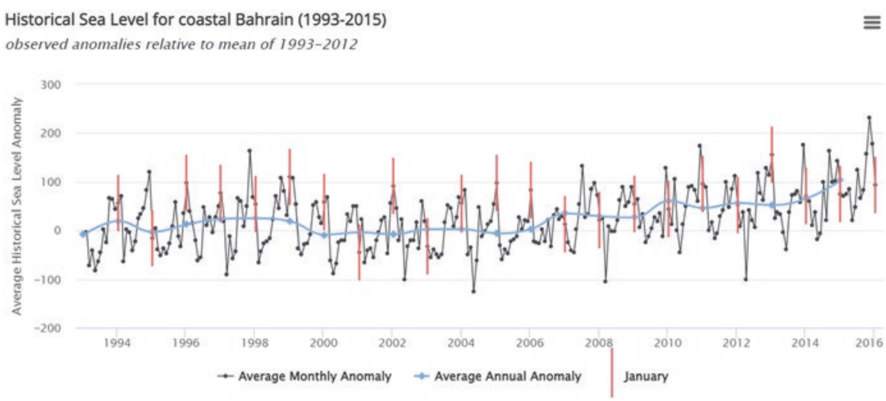

Fig. 24 The historical sea level for coastal Bahrain (1993-2015) using the World Bank data portal. The observed animalities are related to the mean of 1993–2012

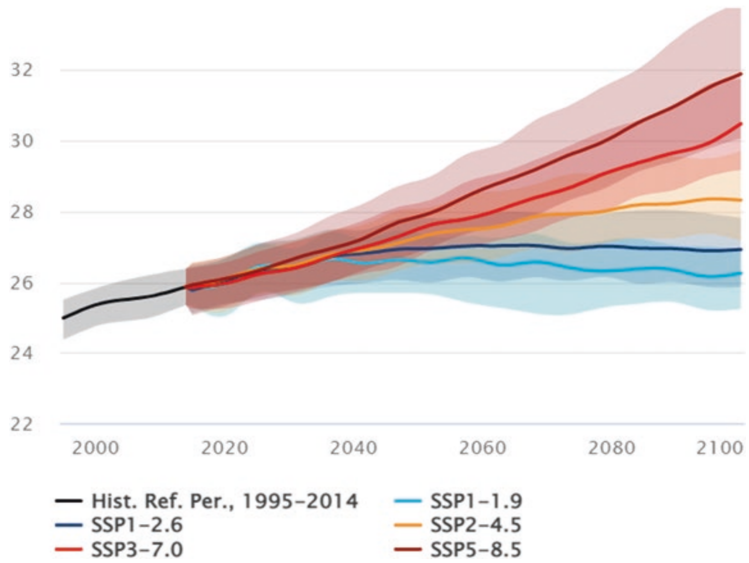

Fig. 25 Projections of average temperature change in Saudi Arabia using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

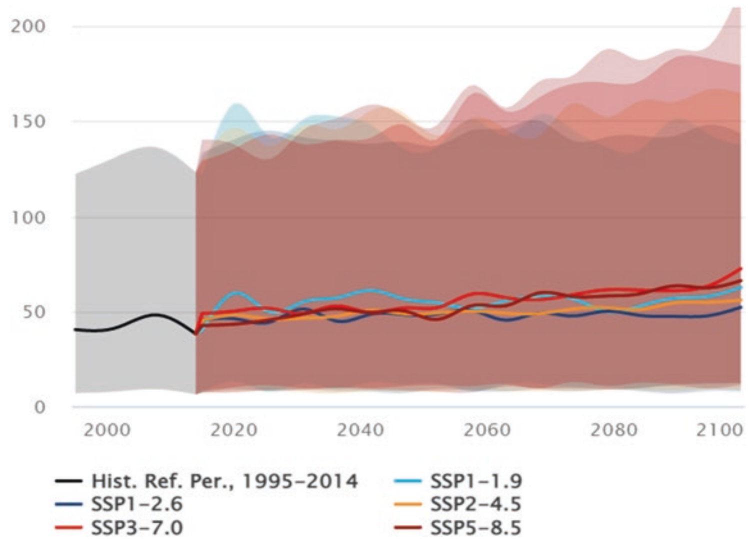

Fig. 26 Projections of the average precipitation change in Saudi Arabia using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

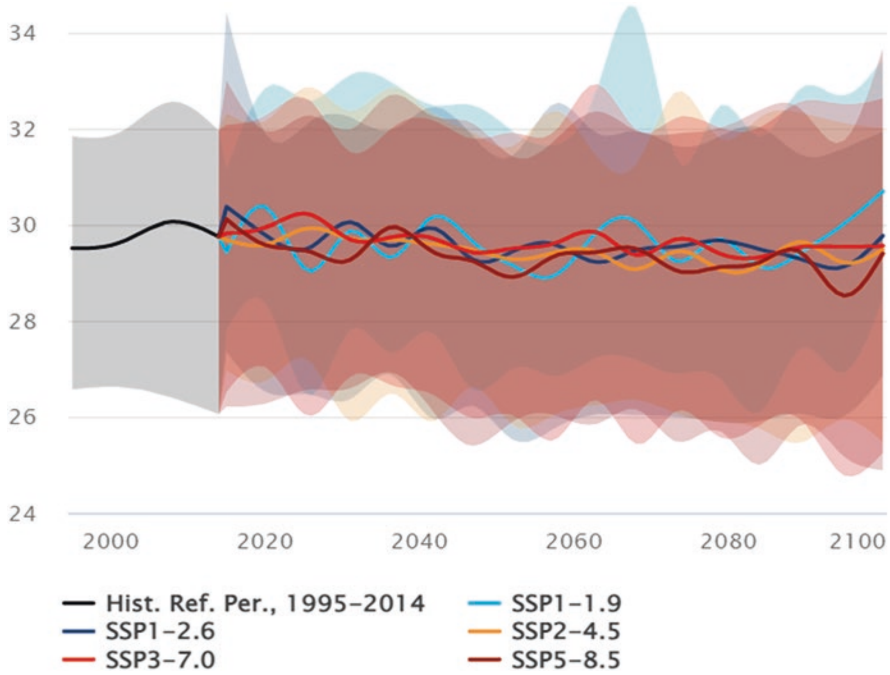

Fig. 27 Projections of the average relative humidity change in Saudi Arabia using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

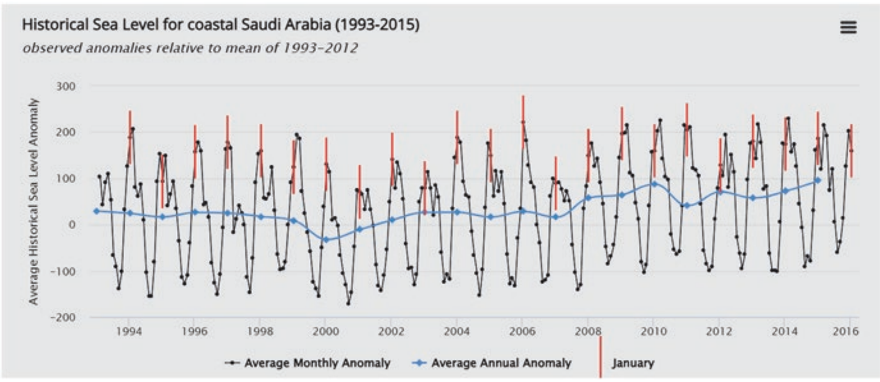

Fig. 28 The historical sea level for coastal Saudi Arabia (1993–2015) using the World Bank data portal. The observed animalities are related to the mean of 1993–2012

Figures 29, 30, 31 and 32 are related to the projected temperature, precipitation, relative humidity as well as the recorded coastal sea level in the Kingdom of Saudi Arabia. It shows a substantial increase in the average temperature from 27 °C in 1995 to 34 °C in 2100 (an increase of 7 °C), increase in precipitation from 40 mm

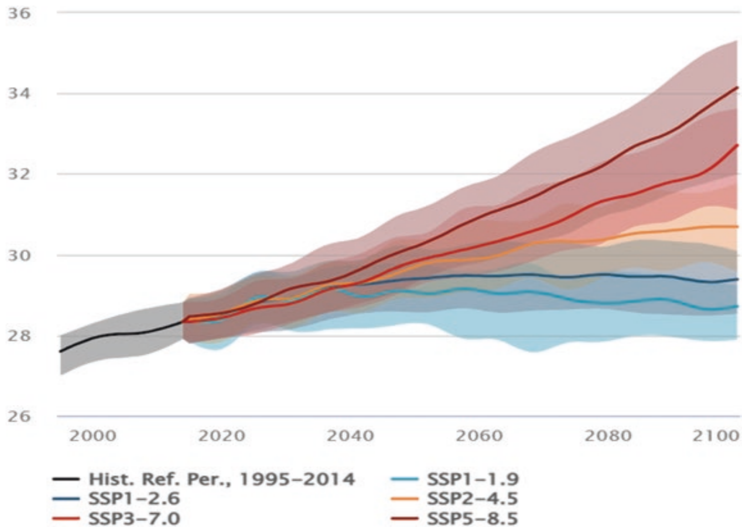

Fig. 29 Projections of average temperature change in Qatar using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

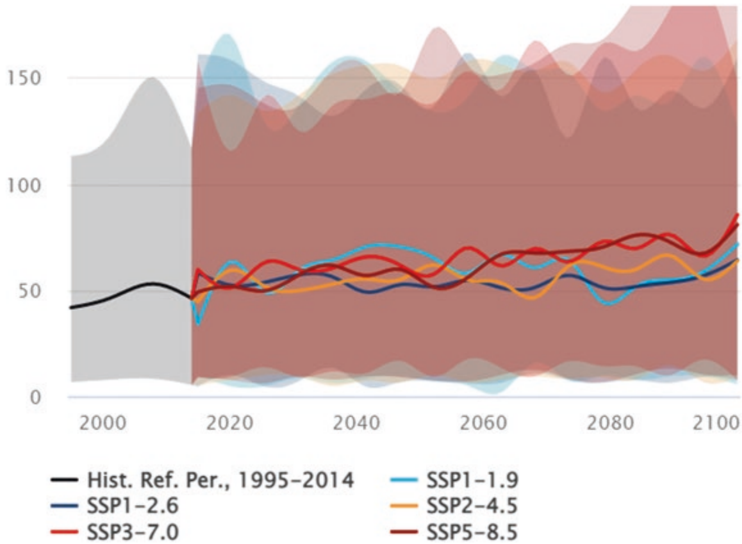

Fig. 30 Projections of the average precipitation change in Qatar using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

in 1995 to about 70 mm (43% increase), and decrease by 2% in the relative humidity. The sea level is exhibiting an increase by 100% from year 1993 to year 2015.

Figures 33, 34, 35 and 36 are related to the projected temperature, precipitation, relative humidity as well as the recorded coastal sea level in Kuwait. It shows a

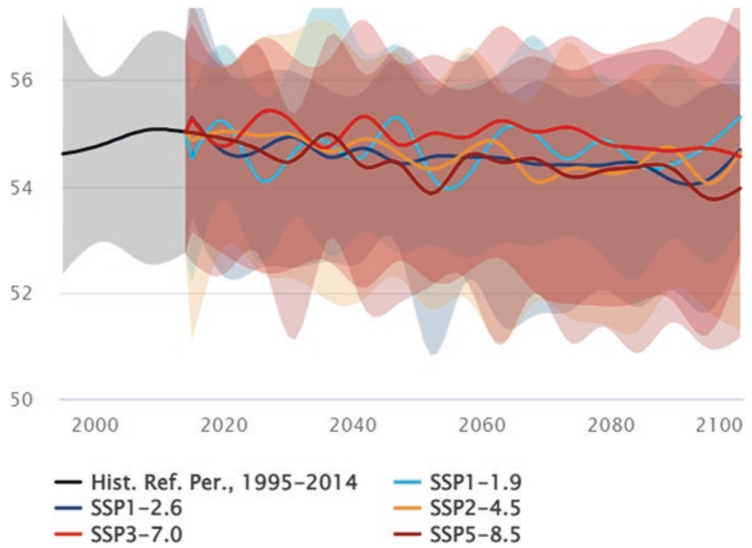

Fig. 31 Projections of the average relative humidity change in Qatar using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

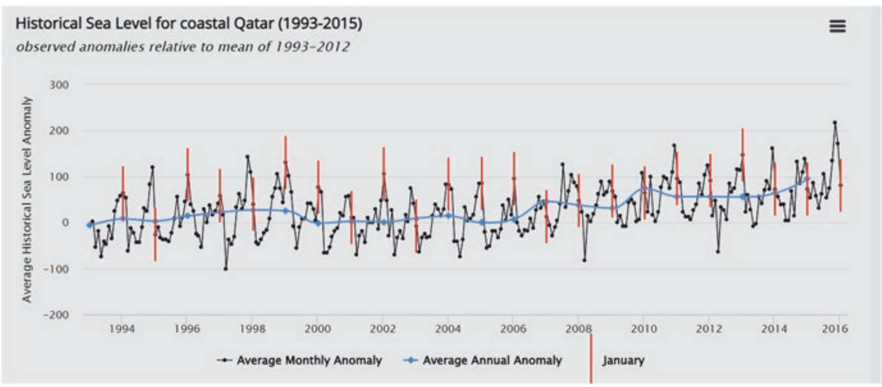

Fig. 32 The historical sea level for coastal Qatar (1993–2015) using the World Bank data portal. The observed animalities are related to the mean of 1993–2012

substantial increase in the average temperature from 25 °C in 1995 to 33 °C in 2100 (an increase of 8 °C), increase in precipitation from 70 mm in 1995 to about 85 mm (21% increase), and decrease by 6% in the relative humidity. The sea level is exhibiting an increase by 100% from year 1993 to year 2015.

It has to be noted herein that the national Action plan for Kuwait 2019–2030 [39] reported an increase in temperature by 3.0–4.8 °C in the period 2071–2100 under RCP 8.5 and a decrease in annual mean precipitation by 5–15% to 25–30% for the same period.

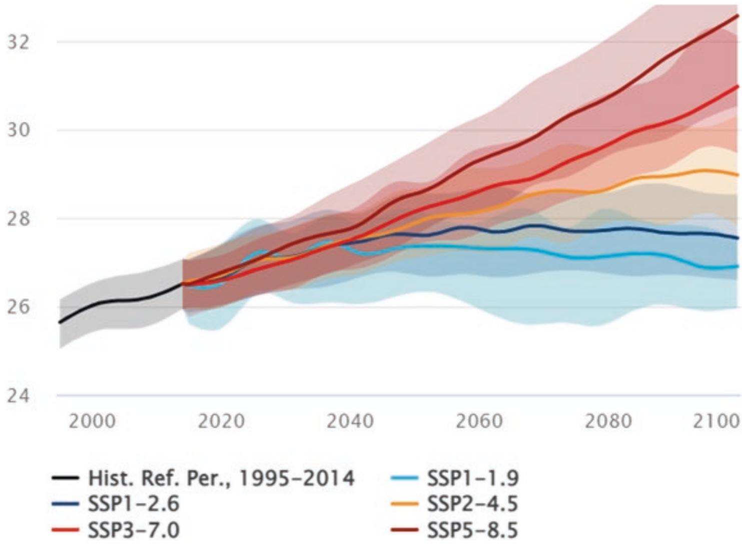

Fig. 33 Projections of average temperature change in Kuwait using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

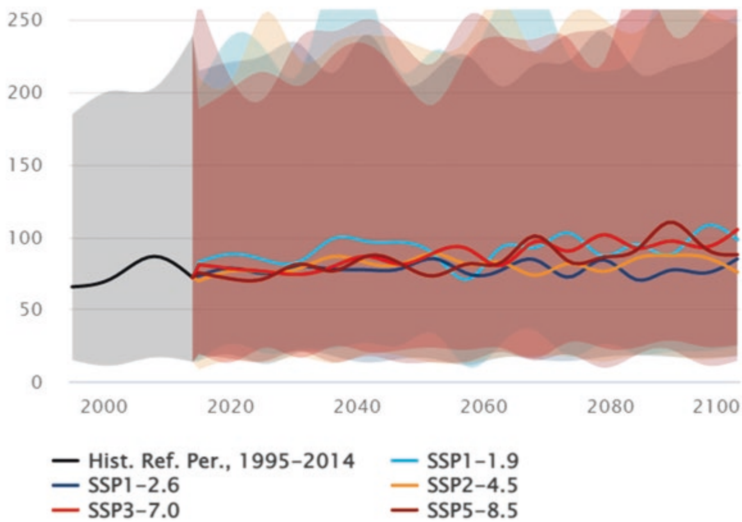

Fig. 34 Projections of the average precipitation change in Kuwait using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

Figures 37, 38, 39, and 40 are related to the projected temperature, precipitation, relative humidity as well as the recorded coastal sea level in the UAE. It shows a substantial increase in the average temperature from 27 °C in 1995 to 34 °C in 2100 (an increase of 7 °C), increase in precipitation from 30 mm in 1995 to about 50 mm

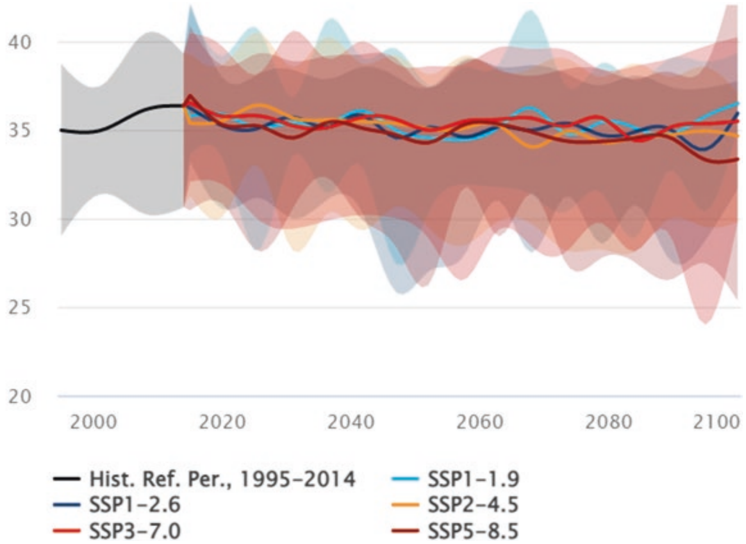

Fig. 35 Projections of the average relative humidity change in Kuwait using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

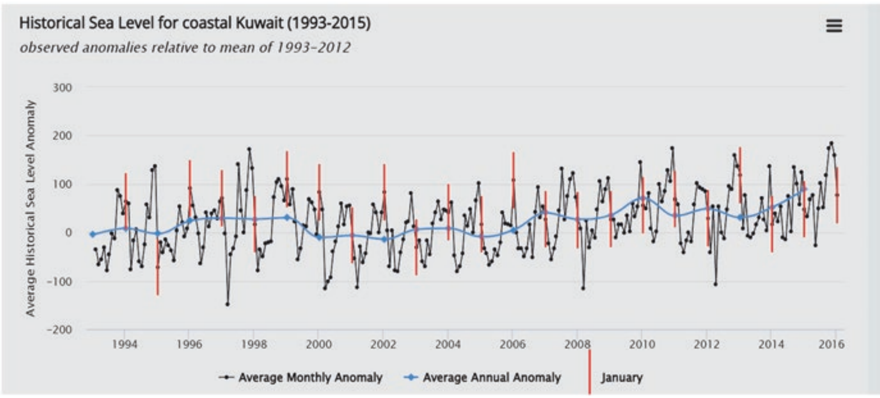

Fig. 36 The historical sea level for coastal Kuwait (1993-2015) using the World Bank data portal. The observed animalities are related to the mean of 1993–2012

(40% increase), and decrease by 6% in the relative humidity. The sea level is exhibiting an increase by 90% from year 1993 to year 2015.

Al Balooshi et al. [26] in studying the forecasted temperature change in UAE, in using MarksimGCMR predictions, reported that Al-Ain (one of the seven Emirates) will experience the highest temperatures in 2095. The maximum temperature will reach 47.4 °C in Abu Dhabi (one of the seven Emirates and the capital of UAE), and will reach 46.9 °C in Sharjah (one of the seven Emirates) and will reach 45.64 °C in Al-Ain (one of the seven Emirates); this means that the increase in maximum

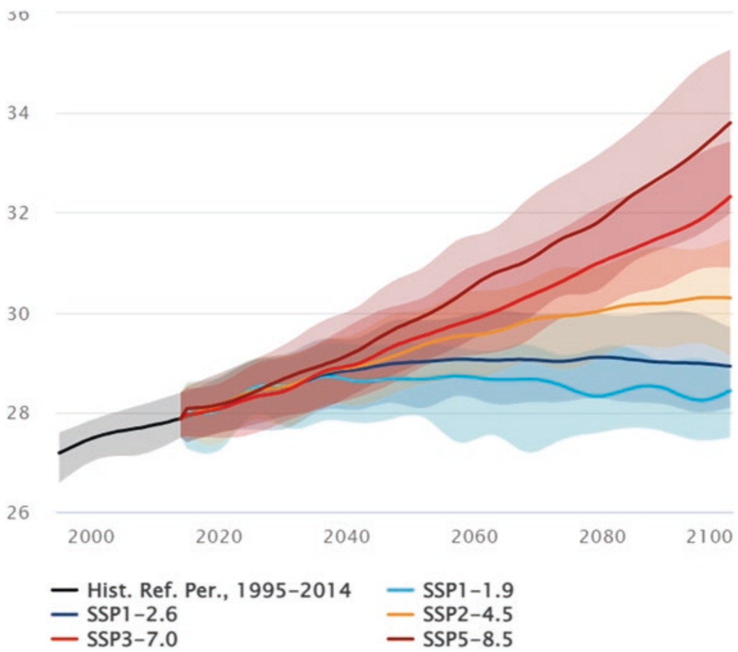

Fig. 37 Projections of average temperature change in the United Arab Emirates using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

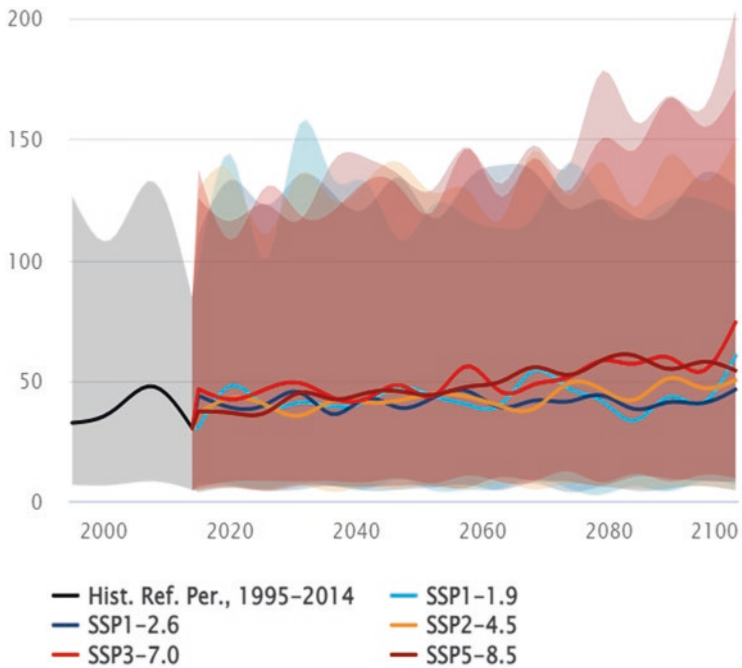

Fig. 38 Projections of average precipitation change in United Arab Emirates using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

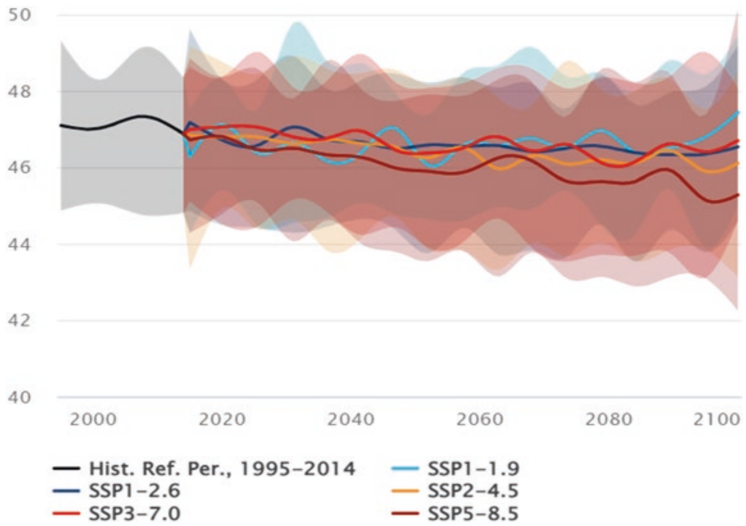

Fig. 39 Projections of average relative humidity change in the United Arab Emirates using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

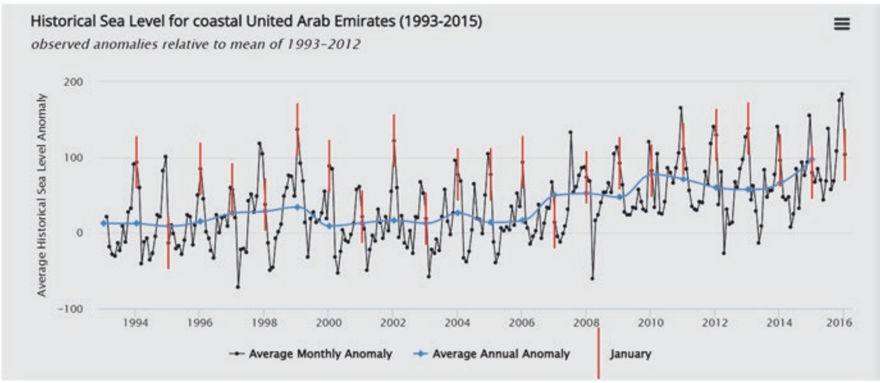

Fig. 40 The historical sea level for coastal Bahrain (1993–2015) using the World Bank data portal. The observed animalities are related to the mean of 1993–2012

temperatures in Abu Dhabi, Al-Ain and Sharjah is 4.56, 4.74, 5.34 °C, respectively, and Sharjah will have the largest temperature increase by the end of the century.

For RCP4.5, Al-Ain will have the largest increase (3.48 °C), Abu Dhabi will have (2.44 °C) and Sharjah will have (3.38 °C); the temperature rise will range between 2.44 °C and 4.56 °C for RCP4.5 and RCP8.5 in Abu-Dhabi, 3.84 °C and 4.74 °C in Al-Ain and 3.38 °C and 5.35 °C in Sharjah [26]. This increase in temperature is less than our projected temperature in Bahrain by 2050.

Figures 41, 42, 43 and 44 are related to the projected temperature, precipitation, relative humidity as well as the recorded coastal sea level in the Sultanate of Oman. It shows a substantial increase in the average temperature from 25 °C in 1995 to 31 °C in 2100 (an increase of 6 °C), increase in precipitation from 25 mm in 1995 to about 45 mm (80% increase), and slight increase in relative humidity by 2% in the relative humidity. The sea level is exhibiting an increase by 100% from year 1993 to year 2015.

In our model, the wind speed in Bahrain is expected to decrease from 9.5 knot (4.75 m/s) to 8.8 knot (4.4 m/s), i.e., reduction by nearly 8%. Unfortunately, the climate knowledge portal by the World Bank [32] did not make future projection for wind speed, therefore, we had used the model made by the IPCC [40] to compare the result of our model compared to international centers like the climate knowledge portal. Figure 45 shows the Surface wind Change % – at four warming levels 1.5, 2.0, 3.0, and 4 °C scenario SSP5-8.5 (related to 1850-1900), with annual (using 31 models) for the Arabian Peninsula [40] – where Bahrain is located. The results show a slight increase (about 2%) – which does not agree with our model but it has to be pair in mind that this is for regional rather than local.

As we have seen, our model gives higher forecasted values compared to the international research center in forecasting the climate change. ESCWA had made forecasting for Bahrain [41] using Scenario RCP8.5 – Fossil Fuel Development SSP5 – which consists of six models – one of the models

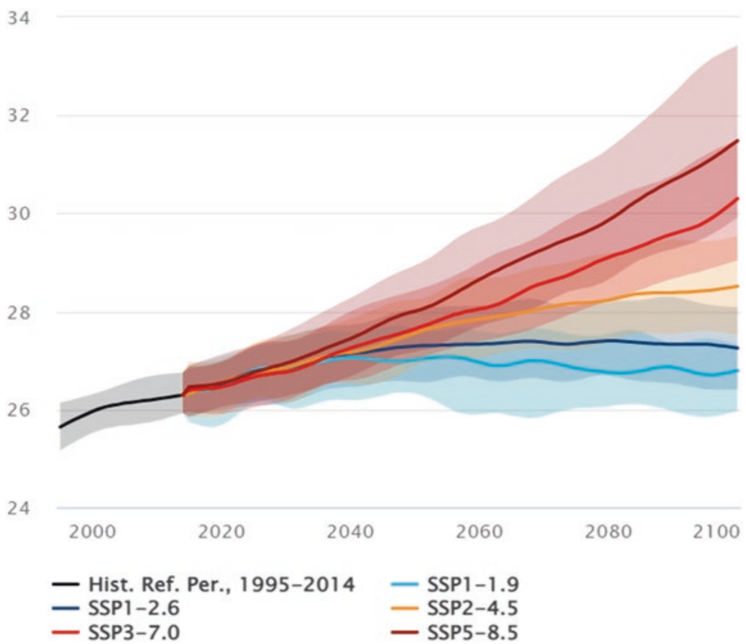

Fig. 41 Projections of average temperature change in Oman using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

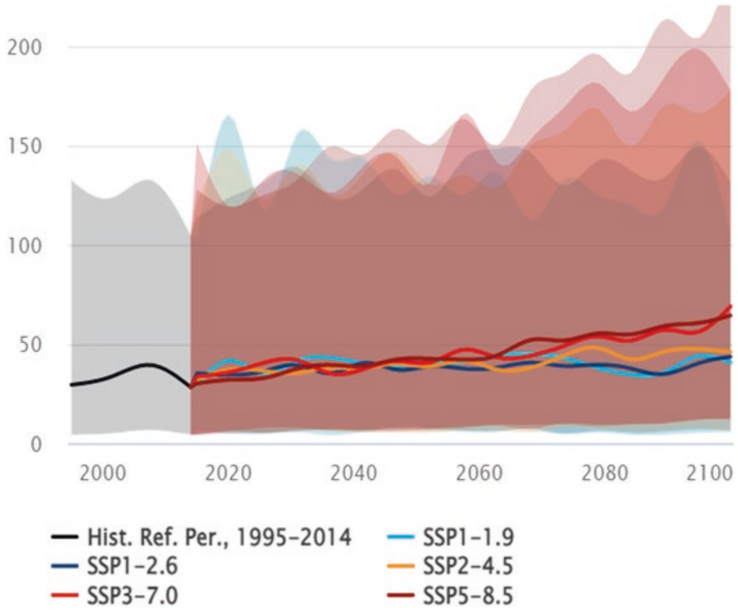

Fig. 42 Projections of average precipitation change in Oman using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

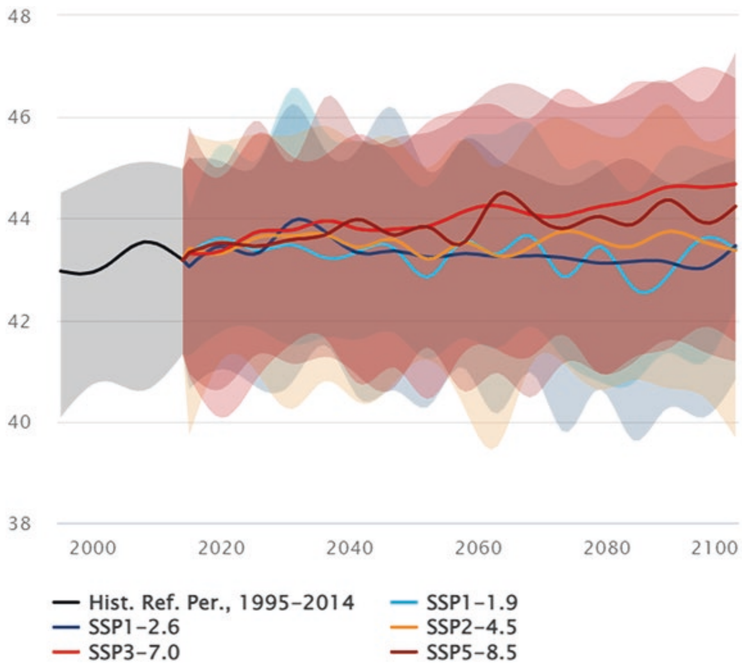

Fig. 43 Projections of average relative humidity change in Oman using the World Bank data portal (based on data from 1995 to 2014) using five scenarios

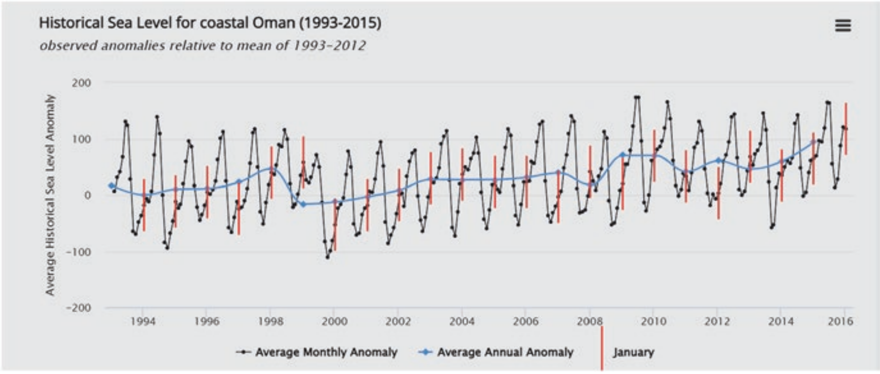

Fig. 44 The historical sea level for coastal Oman (1993–2015) using the World Bank data portal. The observed animalities are related to the mean of 1993–2012

(CMCC-CM-SR5) – shows an increase in the average temperature of 29.7 °C by 2035 which is close to our model (31 °C by 2035) – refer to Figs. 2 and 46. However, the mean line of all models in ESCWA model gives an increase of temperature by 2035 to be 28.8 °C. Each degree Celsius increase in the average temperature has an impact in the water consumption for municipal use in Bahrain which is equal to 700 L/year/capita [41] – refer to Fig. 47.

It is worth mentioning that the occurrence of construction disasters in Poland, during a period of 12 years, was due to random extreme weather events (73%) such as strong wind or strong wind with heavy precipitation causing floods and landslides [5]. Therefore, studying correlation between time scale (years) and different weather parameters is significant and could save lives, economy, safety, and security.

The Government of Bahrain had made an initiative to support financially ten households to install 7.8 kW – PV system on the rooftop of their houses (domestic building) in different areas of Bahrain in 2017. The purpose was to see the performance of these PV systems and explore technical, social, financial, and environmental outcomes. This is a step toward setting legislation for houses that adapt and to resilience to future climate change. It is also a step toward encouraging the use of solar energy in domestic houses to generate solar electricity to fulfill Bahrain's target to have 5% Renewable Energy share of the total conventional energy by 2025, with a 10% target by 2035 which was modified and announced in COP-26 to be 20% by 2035 [42]. It is also a step to put new code for future built environment.

Herein, we have assessed the technological, economic, and environmental of installing a PV rooftop system on a domestic house in the kingdom of Bahrain from 20th March 2018 until 31st March 2020 (Fig. 48). The maximum solar electricity generated from this first domestic building in Bahrain in a month was 1228.9 kWh (August 2018) and the least was 728.16 kWh (December 2019).

The maximum Specific Yield (SY) obtained, in a particular day, in 2 years, was 6.12 kWh/kW$_p$ (on 14 April 2019). The annual average of Specific Yield for this domestic building is 4.13 kWh/kW$_p$/day. The average Performance Ratio (PR) of

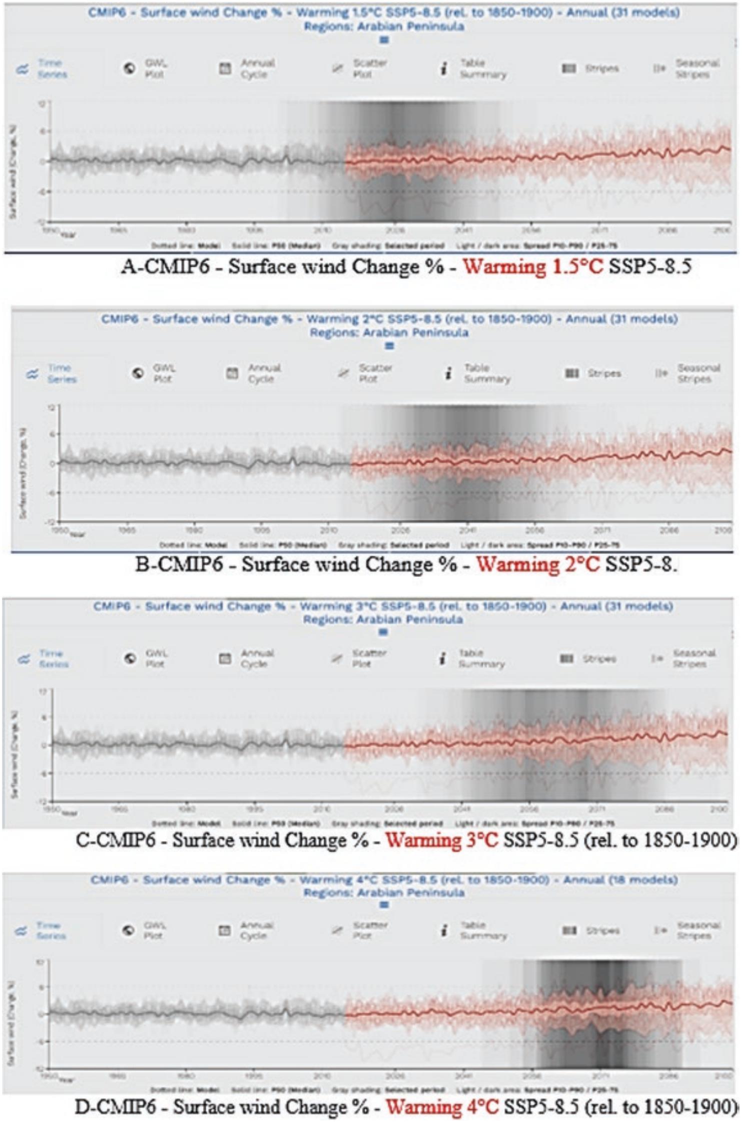

Fig. 45 CMIP6 – Surface wind Change % – at four warming levels 1.5, 2.0, 3.0 and 4 °C scenario SSP5-8.5 (rel. to 1850–1900) – Annual (31 models) Regions: Arabian Peninsula [40]. CMIP6 stands for The Coupled Model Intercomparison Project, which began in 1995 under the auspices of the World Climate Research Programme (WCRP), which is now in its sixth phase (CMIP6)

the PV system in 2019 was 73.0%. The Self Sufficiency (SS) for this installation was found to vary from 15.3% to 50.7%. The average SS value for this house in 2018 was 22.8% while in 2019 was 28.6%. It is found, herein, that installing such PV system in a domestic house will cut, annually, about 39.0% of CO_2 which is

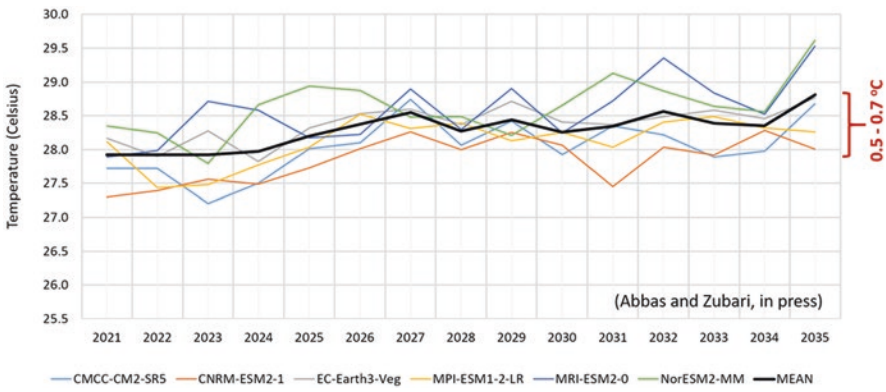

Fig. 46 Forecasted average temperature variation in Bahrain using ESCWA East Asia using worst scenario (RCP8.5) based on six mathematical models [41]

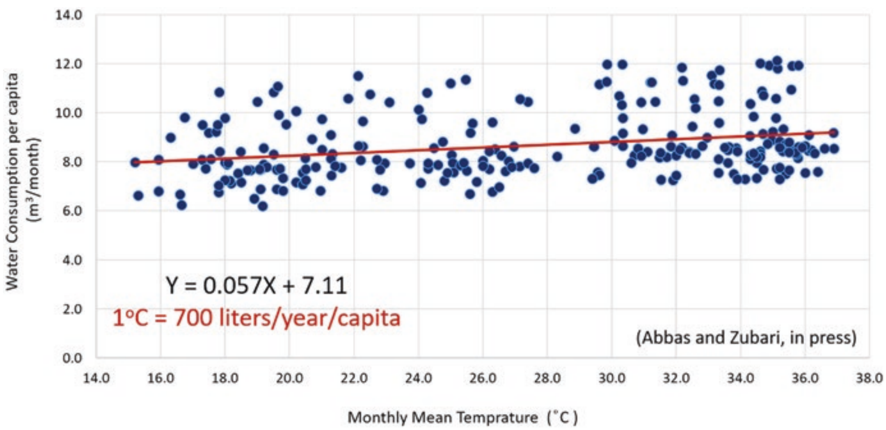

Fig. 47 The relation between temperature rise and water consumption for municipal use in Bahrain. Results are based on monthly electricity consumption and temperature of 22 years (2000–2022) [41]

equal to 4.637 tons and hence saves 38,567 ft^3 of natural gas. This initiative in Bahrain is a step toward retrofitting the built environment to combat climate change.

Finally, the outcome of this study can be tested by doing similar investigation on other weather data sets in the Gulf Cooperation Countries (GCC) and worldwide to explore whether still the Exponential (cubic) regression will have the highest correlation coefficient or other may find other regression from the eight regression coefficients tested in this study. This is important because most of these data set of weather parameter is used for estimating the potential of renewable energy [43–47] as well as in built environment & sustainable cities [48, 49] and sustainability & Sustainable Development Goals (SDGs) [50].

Fig. 48 The layout of the PV panels of the first 7.8 kW PV domestic building (House 4 #108) in Bahrain. Top of PV panels (top right), below the PV panels (top left), during the official inauguration of the project (bottom right) and view of the roof PV from ground (bottom left)

According to Alsaad [25] Kuwait is already experiencing the impacts of climate change, as temperatures within the past 5 years have reached unprecedented highs and are expected to increase in the future. This will affect the habitability of the country severely, causing mental and physical stress to the health of residents as exposure to high temperatures causes exhaustion, heat strokes and intensifies existing respiratory, cerebral, and cardiovascular diseases. Furthermore, an increase in temperature increases seawater temperature causing a large-scale migration of fish species to nearby areas. Also, the increase in temperature means use of indoor cooling which means more energy demands, and more energy demands translate to more CO_2 emissions. They concluded that relationship between Kuwait's built environment and its changing climate must be examined to understand how climate adaptation can improve the status quo and ensure reduced future negative impacts.

The Built Environment system comprises our cities, towns, suburbs, and regional areas, along with supporting infrastructure and services. GCC countries should set out a plan similar to Victorian Government's proposed actions [28] but for the next 30 years to respond to climate change risks to their built environment as their climate is already changing, which will reduce current and future risks, build social and economic resilience, and protect the well-being. An average global temperature rises of 1.5 °C could be reached in the early 2030s and 2 °C would be exceeded by around 2050, under all emissions scenarios. Therefore, with a successful built environment plan, climate change will not threat the integrity of the built environment's assets and its ability to provide reliable services.

The state of Kuwait had issued National Adaptation Plan (NAP), 2018–2030 [39] is to provide an integrated development plan and subsequent programs targeting local communities and environmental components in areas under the threat of climate change. The NAP is prepared in accordance with the UNFCCC directives and articles and includes a detailed survey of the environment and the most affected areas and sectors in climate change, detailed analysis pertaining to climate change vulnerability, and gaps in each sector to adapt to climate change. Subsequently, programs and projects are to be initiated in the short term and in the long term to adapt to climate change in the country. Unfortunately, the plan did not tackle the renewable energy and built environment actions.

The Built Environment system must strengthen and extend existing climate change responses; build adaptation capacity across government, private sector, and the community; and establish regulatory & other frameworks needed for long-term transformative action. The interconnection of built environment and climate change is illustrated in Fig. 49. The Built Environment system incorporates services, infrastructure, and processes, including where people live and how they build, how people respond to emergencies and climate change, community services, utilities and infrastructure, natural systems and environmental management, finance and insurance risk services [28].

An overview of the different definitions and indicators in which resilience qualities (RQs) have been applied to built environment planning, analysis, and design, emphasizing the various dimensions and relevant capacities [51]. Their study concluded that integrated resilience indicators, planning, and design methodology are crucial for incorporating RQs into the framework that influences the built environment. The built environment RQs demonstrated by this study include reflectivity (Rf), robustness (Rb), redundancy (Rd), flexibility (Fx), resourcefulness (Rs), rapidity (Rp), inclusivity (Ic), and integration (It).

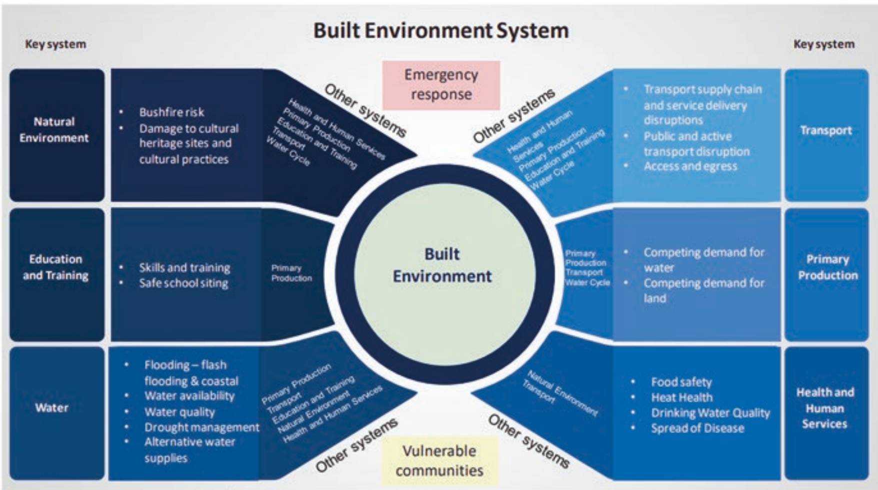

Fig. 49 The interconnection of built environment and climate change [28]

LEVEL, the authority on sustainable building, in New Zealand [52] had suggested useful hents for building design to cope with climate change. According to them, the impact of climate change will vary from region to region and building designers will need to consider the following:

(a) Incorporating passive solar design features to reduce the need for heating in winter and air-conditioning in summer.
(b) Designing buildings with more shading in response to increased solar radiation.
(c) Increasing structural design to deal with increased wind guest loading and flooding.
(d) Designing buildings to make more use of natural ventilation.
(e) Designing the roof, roof drainage, and stormwater run-off to cope with higher and more intense rainfall.
(f) Incorporating water-saving features in homes to reduce pressure on urban water supplies (see Water).
(g) Potential flood risk in low-lying areas.
(h) Limiting building in flood-prone areas or coastal regions that are likely to experience increased erosion in the future.

Engineers and architects are now reevaluating the design of buildings, increasing their stability against climate change [53]; they have created green construction methods, protecting structures from changing elements while decreasing their production of greenhouse gas emissions. Also, using protective features, effective materials, low-emission designs, and smart technology can successfully enhance a building's sustainability and strength.

Furthermore, a review of building life cycle carbon emission assessment methodologies for integrating climate change impact in new building design process was published recently [54]. The following topics have been studied in this review:

(a) Identified the challenges of using Life-Cycle Carbon Emission Assessment (LCOO2A) for the early building design stage or informing policy-making.
(b) Proposed several solution methods to improve the consistency and accuracy of Building LCOO2A.
(c) Summarized the computer-aided tools considering their ability to provide "full picture" of total life cycle carbon emissions.
(d) Proposed recommendations to LCA tool developers, researchers, and policy makers for future directions of building LCOO2A practice.

Finally, it has to be noted that, currently, artificial intelligence techniques can be used to monitor weather parameters and then make the prediction simultaneously [55–58].

5 Conclusion

The exponential (cubic) regression, which is the most accurate correlation (among 8 correlation coefficients) [30] has been utilized to forecast the Climate Change in Bahrain based on long-term (67 years) recorded weather parameters. This model was compared with other well recognized and respected international models made by Climate Change Knowledge Portal (CCKP) by the World Bank, IPCC, and ESCWA. The temperature in Bahrain and other GCC countries will increase substantially (from 6 to 8 °C) by 2100. The forecasted precipitation in GCC countries tends to slightly increase by 10–20% while humidity tends to decrease slightly by 5–10%. The sea level rise is not inevitable by 2050 as it had already increased by 100% for the period from 1993 to 2015 (span of 22 years). The frequency of dust storms in all GCC countries may increase, although the correlation coefficient is very modest. These observations urge the policy makers to relay on solar PV and PV thermal and integrate the PV with building and make houses and buildings to have special design to fit with climate change (more heat, more rain, more dust storms, and drier weather or less relative humidity) to minimize damage due to heavy or extreme rain, floods, and sea wave surges. Renewable energy devices should have specification that maintain their efficiencies and performance. Building should be to integrate easily with renewable energy devices and can withstand larger number of micro-wind turbine as wind speed is expected to decline by about 10–20% in Bahrain and to less extent in some of GCC countries. A successful GCC Build Environment plan, or for each GCC country, is needed and should be made soon.

This study is a milestone in modeling the variation of meteorological parameters to improve the built environment resilience qualities and probably help in setting mitigation and resilience strategies based on the projection of future weather parameters. However, further research to develop plans and policies for effective and timely responses to climate change effects is also required.

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Solar Energy Scenario in India

J. Vijayalaxmi, Chandu Sai Tarun, and Neha Shremitha

1 Introduction

India is endowed with vast solar energy potential, which can be harnessed effectively through solar photovoltaic installation. A total of 60,813.93 MW of solar energy has been harnessed to date by India according to the Ministry of New and Renewable Energy [9].

Solar energy potential in the nation is the highest of all the renewable energy sources. 250–300 days a year experience clear, sunny weather throughout the most parts in India. Its yearly radiation, which ranges from 1600 to 2200 kWh/m^2, is comparable to that experienced in tropical and subtropical areas. The annual energy potential is around 6000 million GWh [9].

2 Indian Energy Scenario

Challenges

India's energy sector faces a number of challenges. The following are some of the biggest challenges India may encounter in satisfying its energy needs [4]:

- The demand for primary energy is anticipated to triple over the next 20 years, rising from the present 601 Mtoe (million tonnes of oil equivalent) to 1859 Mtoe in 2032.

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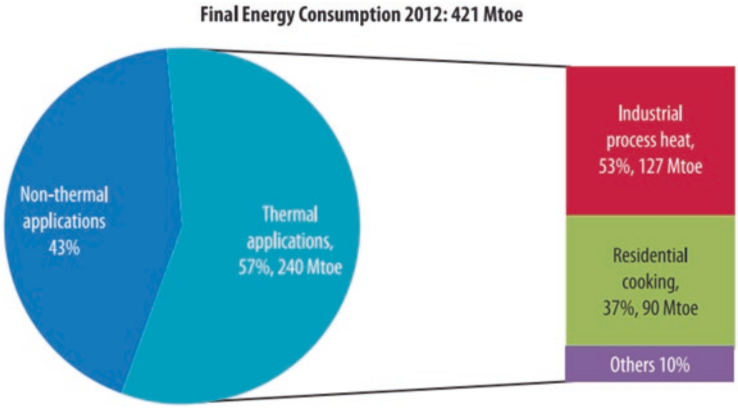

Fig. 1 Share of thermal energy in final energy consumption. (Source: Maithel et al. [4])

- At the moment, 31% of primary energy and 77% of oil are imported. By 2032, 93% of oil will need to be imported, while a sharp rise in coal imports will make up about 70% of the major energy needs.
- Since coal makes up a significant portion of India's energy supply, CO_2 emissions are predicted to increase by threefold.

Utilising local renewable energy sources becomes crucial in light of these challenges. According to an analysis of India's energy consumption patterns, thermal applications account for 57% (240 Mtoe) of total energy consumption (Fig. 1). The main thermal applications, which account for more than 90% of the need for thermal energy, are water heating, cooking in homes, and industrial process heat. The majority of this thermal energy demand is currently satisfied by fuels such as coal, biomass, and petroleum.

National Solar Potential

The solar energy industry in India is growing significantly. The country's installed solar capacity was 61.625 GW_{AC} as of October 31, 2022. India ranks fourth globally in terms of solar energy utilisation in 2021 [9].

India has a vast potential for solar energy. Approximately 5000 trillion kWh of incident energy is received by India's land surface each year, with the bulk of areas receiving 4–7 kWh per square metre each day. As a result, both technology paths for converting solar radiation into heat and power, namely solar thermal and solar photovoltaics, may be successfully exploited, offering enormous scalability for solar in India. Additionally, solar energy allows for easy capacity growth with short lead times and the option of distributed power generation. Considering the electrification of remote areas, off-grid decentralised and low-temperature solutions will be beneficial and satisfy other energy requirements for power, heating, and cooling in both rural and urban locations. Due to its vast accessibility, solar is the most reliable energy source in terms of supply security. If all incident solar energy were to be captured effectively, it could hypothetically be used to create enough electricity to power the entire country [9].

It is also obvious that every effort must be taken to utilise the country's comparatively substantial energy resources given the high percentage of the poor and energy-unserved population. While domestic coal-based power generation is now the cheapest source of electricity, future possibilities indicate that this may change [9].

In India total RE installed capacity was 128.2 GW in 2019, up from 52.3 GW in 2010, thereby recording an AAGR of 10.6%. Out of this total installed capacity for solar was recorded at 35.1 GW in 2019, up from just 0.1 GW in 2010, with an AAGR of 148%. In India's own RE installed capacity, solar's share increased from 0.1% in 2010 to 27.3% in 2019 [8] (Figs. 2, 3, 4, 5, and 6).

The following climatic charts are generated from Meteonorm software v.8.1 (1996–2015).

Experimental results showed that wind flow can improve heat convection on the surface of the PV panel. Hence, an operating temperature decrease; especially during the peak sun hour, will increase PV productivity. Therefore, when the operating temperature of the PV panel decreases, the voltage generated will increase with the output power [7]. With monthly average wind speeds ranging from 1 to 3 m/s there is a good advantage.

Even a place like Bangalore with moderate temperatures year-round, high wind speeds, and availability of 280 days of good sunlight combine to make it an excellent place for using solar power. Hence, it is one of the ideal cities in India to go solar in [7].

Covid-19 Impact

India is anticipated to contribute the most to the growth in renewable energy in 2021, with additions there each year nearly doubling from 2020. After delays brought on not just by Covid-19 but also by contract discussions and difficulties with land acquisition, a significant number of projects for solar PV and wind energy that were auctioned are anticipated to go online [3].

Additionally, the National Action Plan on Climate Change notes: "India is a tropical country, where sunshine is available for longer hours per day and in great intensity. Solar energy, therefore, has great potential as a future energy source. It also has the advantage of permitting the decentralised distribution of energy, thereby empowering people at the grassroots level" [9].

As per IEA report in 2018, India was expected to install one-third less solar PV capacity in 2020 than in 2019. New PV capacity installations in the first half of 2020 were 70% lower than the first-half growth average for the previous 3 years (Fig. 7).

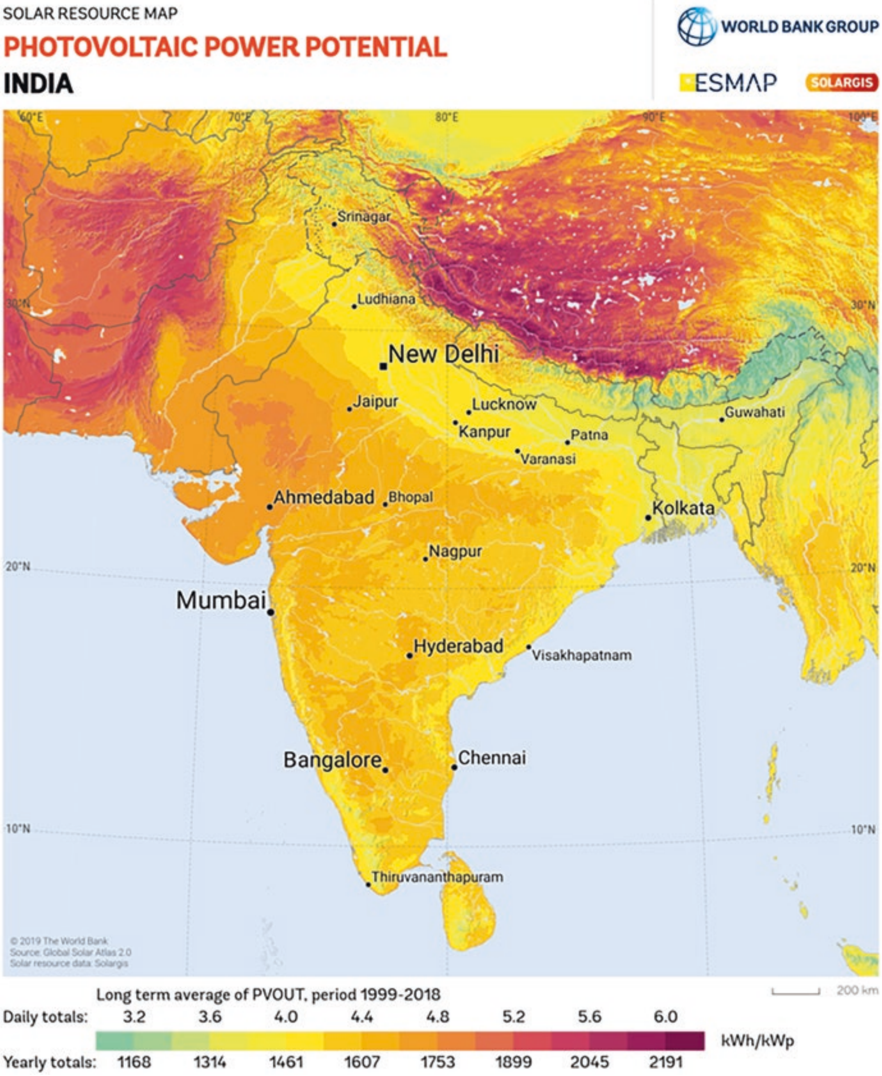

Fig. 2 Photovoltaic power potential in India. (Source: World Bang Group)

This decline was brought on by a confluence of Covid-19-related supply chain breakdowns, construction slowdowns, and elevated macroeconomic concerns.

As a result, this prediction predicted 19% fewer additions in 2020 as compared to a previous update in May. It is anticipated that PV deployment would pick up in 2021 and 2022, exceeding the 2019 level as delayed and new projects go online.

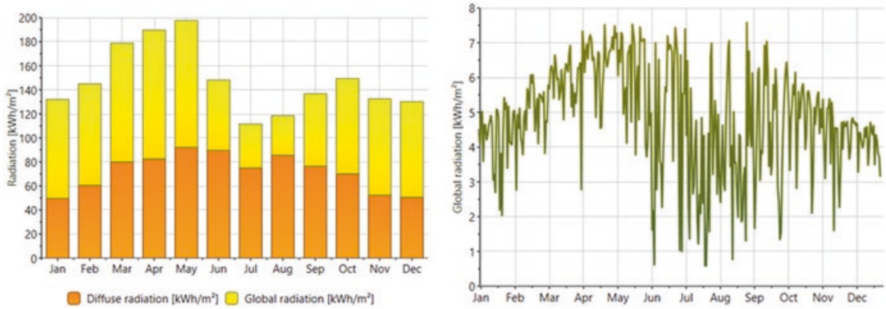

Fig. 3 (**a**) Solar radiation and (**b**) daily global radiation. (Source: Meteonorm)

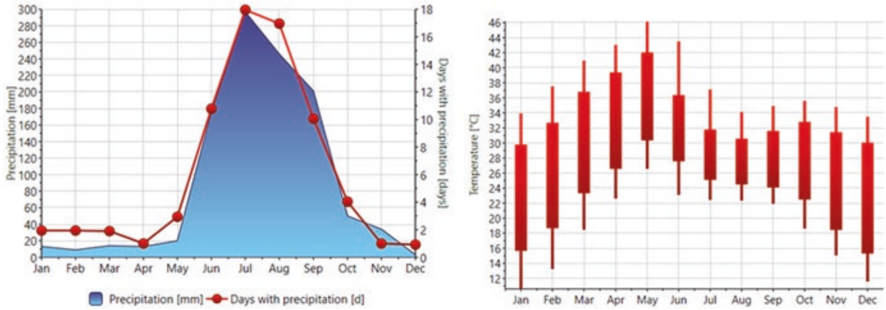

Fig. 4 (**a**) Precipitation and (**b**) temperature. (Source: Meteonorm)

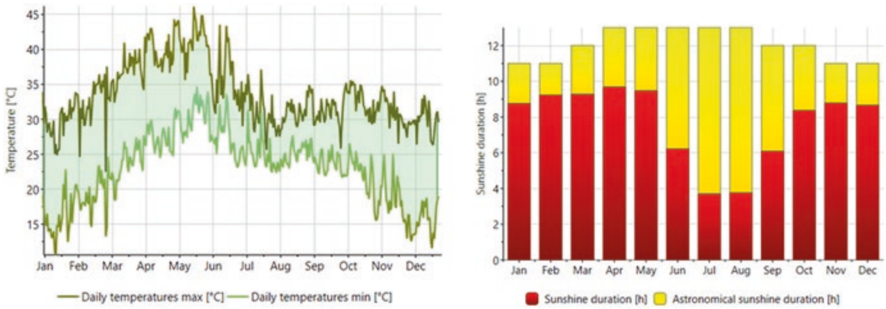

Fig. 5 (**a**) Daily temperature and (**b**) sunshine duration. (Source: Meteonorm)

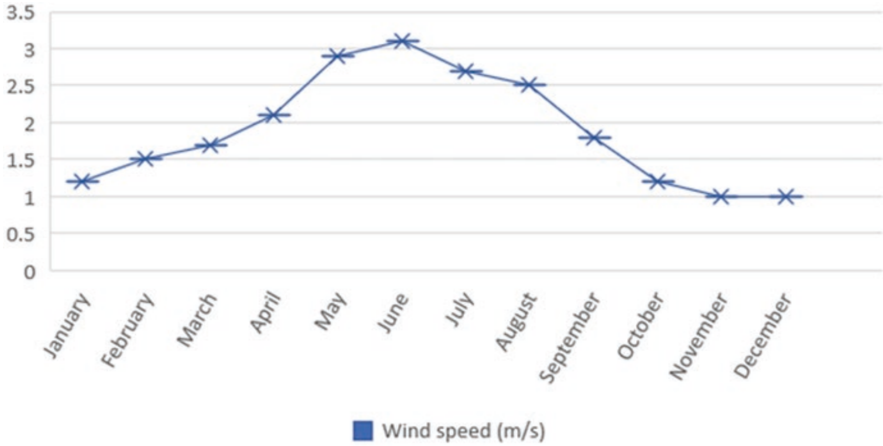

Fig. 6 Wind speed. (Source: Meteonorm)

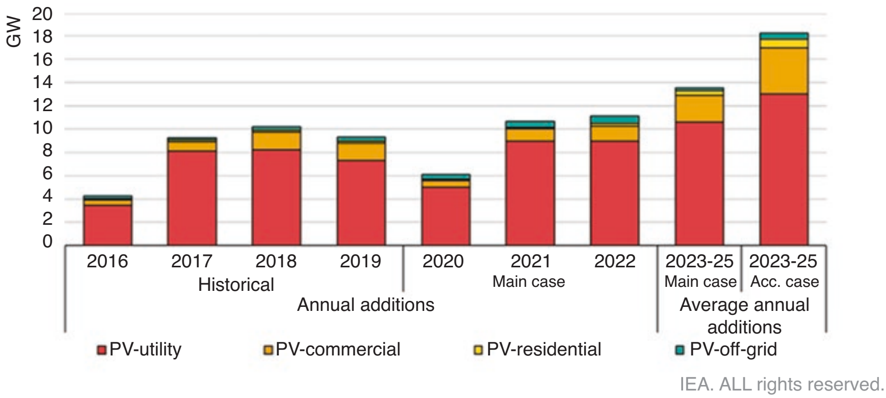

Fig. 7 India PV capacity additions 2016–2022, and average annual additions 2023–2025. (Source: IEA [3])

3 Solar Energy Applications

The two main types of solar energy technologies are (a) solar photovoltaic (PV) technologies, which generate electricity, and (b) solar thermal technologies, which give heat.

Solar Photovoltaic Technologies

With the use of solar photovoltaic (PV) technology, sunlight can be directly converted into power. Electricity is produced using photovoltaic cells, also referred to as solar cells or photovoltaics. The market now offers three different solar cell technologies: mono-crystalline, poly-crystalline, and thin films. Depending on the solar cell type, the solar PV system‘s output varies. Thin film cells are often less efficient than mono- and poly-crystalline cells, which also require less roof space to produce the same amount of power [4].

A solar PV system can be installed as building-integrated photovoltaics in addition to rooftop systems (BIPV). BIPV involves the replacement of building envelope components like the wall, roof, skylights, or facades with photovoltaic material. These can be used to obtain a larger RE share in the overall building energy consumption and can be incorporated into the construction of new buildings as well as retrofitted to existing buildings. However, BIPV currently costs more than rooftop solar PV systems since it saves money primarily by reducing mounting structures and offsetting traditional construction materials [4].

Rooftop Solar PV

According to estimates, rooftop solar has a 124 GW market potential. The projected goal is to attain 40 GW by 2022. However, currently, rooftop solar generates close to 6 GW of energy. Of the 6 GW of installed solar power currently available, only 13% comes from residential rooftop systems. Due to COVID-19 disruptions, a decline in distributed PV deployment is noticed [1].

Rooftop solar PV systems have a higher capital cost per megawatt than large-scale PV systems. Smaller components, higher installation costs, a smaller base upon which to distribute fixed expenses, and fewer economies of scale are all to blame for this. In addition, leasing rooftops has higher costs than installing large-scale PV, including developmental fees and the opportunity cost in the case of self-owned rooftops in urban areas. According to the Central Power Authority (CEA), transmission and distribution (T&D) losses account for around 22% of every unit of electricity generated, placing an undue financial strain on distribution companies [5].

In 2018, rooftop solar generated 2.1 GW, of which 70% was used for industrial or commercial purposes (Fig. 8). India is developing off-grid solar power in addition to its extensive grid-connected solar photovoltaic (PV) effort to meet local energy needs. By the end of 2015, slightly under one million solar lanterns had been sold in the nation, reducing the demand for kerosene. Solar products have become more and more helpful in addressing rural requirements. A countrywide initiative that year saw the installation of 1,18,700 solar house lighting systems, 46,655 solar street lighting installations, and the distribution of little over 14 lakh (1.4 million) solar cookers in India [9].

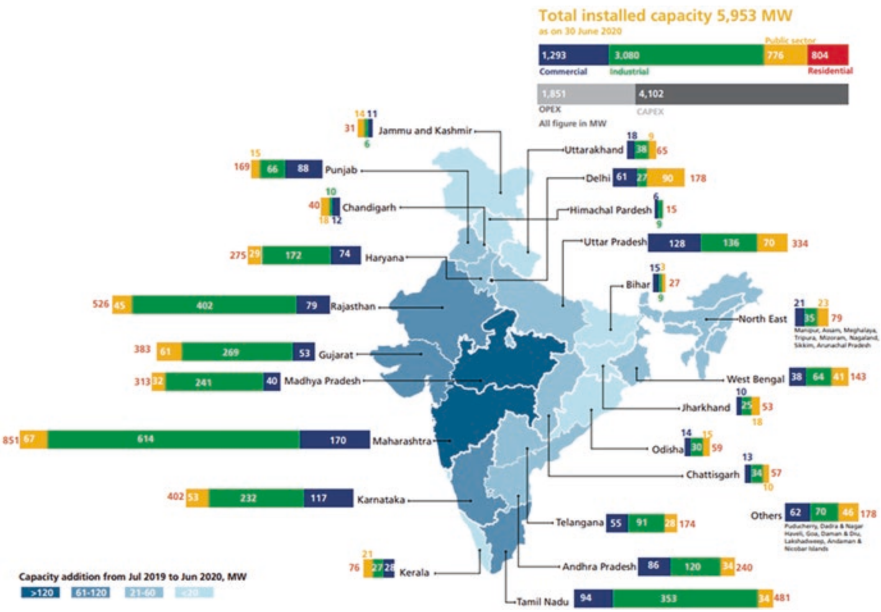

Fig. 8 India solar rooftop map. (Source: Bridge to India [6])

To meet its overall 40GW rooftop solar installation goal by 2022, India has published a "tentative" year-by-year breakdown of each state targets [9].

Among the states with the highest goals are: Maharashtra (4700 MW), Uttar Pradesh (4300 MW), Tamil Nadu (3500 MW), Gujarat (3200 MW), Karnataka (2300 MW), Rajasthan (2300 MW), Madhya Pradesh (2200 MW), and West Bengal (2100 MW).

The operational rules for the implementation of Phase II of the Grid Connected Rooftop Solar and Small Power Plant Programme were released by the Ministry of New and Renewable Energy (MNRE) in August 2019. The MNRE has set a goal of adding 4000 MW of RTS capacity in the residential sector and another 18,000 MW in the non-residential sector in order to reach the target of 40 GW of grid interactive rooftop solar by 2022 (commercial, industrial, government, and institutional consumers) [2].

Incentives to DISCOMS MNRE will offer performance-linked incentives to discoms to cover expenditures like the extra people needed to run the RTS cells, capacity building, developing new infrastructure, etc. in order to hasten the deployment of RTS. The incentive will be determined as follows: A 5% incentive will be given to discoms for installed RTS capacity that is added that is between 10% and 15% above the base capacity. Discoms will earn 10% of the RTS benchmark cost for installed capacity that is above 15% of the base capacity after receiving 5% of the RTS benchmark cost for the first 5–15% [2].

Incentives for Residential Consumers To encourage the adoption of RTS, MNRE offers capital incentives to residential consumers, including individual households and housing communities. The benchmark cost of RTS systems as announced by the MNRE, or the rate determined through transparent bidding by the discom, is used to determine central financial assistance (CFA) [2].

Individual households: For RTS systems up to 3 kW in capacity, MNRE has changed the CFA to increase it to up to 40%. For RTS systems with a capacity of 3–10 kW, 20% CFA at the benchmark cost will be supplied for the first 3 kW and 40% for the remaining 7 kW. System capacities up to 10 kW are the only ones eligible for the capital incentive [2].

CFA will be capped at 20% for group housing societies (GHS) and residential welfare associations (RWAs) installing RTS plants that supply power to shared amenities. The maximum capacity that can be used for CFA will be 500 kW overall and 10 kW per dwelling, including any existing installations on individual houses within that society or association [2].

Solar Thermal Technologies

Solar thermal technologies transform solar energy into heat for applications such as space conditioning (heating, cooling), residential and commercial cooking, agricultural and industrial drying, water desalination, low- and medium-temperature industrial process heat, and water heating. In comparison to solar PV technology-based conversion to electricity, the efficiency of solar energy conversion into thermal energy is significantly higher. Therefore, converting to thermal energy has a larger useful energy yield per unit of land area than converting to electricity [4].

India can take advantage of the potential provided by decentralised solar thermal technologies to achieve the objectives of reducing reliance on imported fuels, improving energy security, increasing access to energy, reducing electricity demand, improving environmental quality, and fostering socioeconomic development [4].

Various benefits are provided by solar thermal technology, some of which are described below.

- When converting solar energy into thermal energy instead of electricity utilising solar PV technology, the efficiency is significantly higher. For instance, commercially available crystalline solar PV panels have an efficiency of 10–15%, whereas a flat plate collector or solar concentrator typically varies from 35% to 70%. Therefore, converting to thermal energy has a larger useful energy yield per unit of land area than converting to electricity.
- Unlike solar PV systems that are connected to the grid, where the electricity generated is sent through the grid, the thermal energy produced using solar energy is consumed locally, minimising energy transmission loss.
- Local manufacturing and employment prospects are provided by the employment market which has boomed with the deployment of renewable-energy tech-

nology. Renewable-energy technology applications have created more than 12 million jobs worldwide. The solar PV application came as the pioneer, which created more than 3 million jobs. Solar thermal applications (solar heating and cooling) have created more than 819,000 jobs.

However, there are difficulties in using solar energy to produce heat. A few of these are:

- Solar energy is a low energy density source that requires a large shadow-free area when the energy requirements are high.
- Solar thermal systems' energy output is variable due to diurnal and seasonal changes in solar radiation; as a result, they need adequate storage systems and successful hybridisation with other energy sources to fulfil the thermal energy demand.
- Because solar radiation is only available during the day and varies seasonally, solar systems' capacity utilisation factor (CUF) is low [4].

As of March 2014, it was estimated that India had 5.8 GW installed across all solar thermal technologies (Fig. 9). Estimates place the yearly solar thermal energy production at 0.6 Mtoe. Only 0.6 Mtoe (0.25%) of the 240 Mtoe total thermal needs is currently satisfied by solar thermal technologies [4].

Sector	Solar thermal technology	Installed capacity		Energy delivered (GWh/year)
		Collector area/no.	GW_{th}[12]	
Residential	Solar water heaters[13]	6.5 million m^2	4.600	5,562
	Solar cookers[14, 15]	0.64 million (nos)	0.134	32
Commercial and institutional	Solar water heaters[16]	1.1 million m^2	0.800	941
	Solar concentrators[17]	19,000 m^2	0.013	14
Industrial	Solar water heater[18]	0.35 million m^2	0.240	299
	Solar concentrators[19]	10,000 m^2	0.007	9
	Solar air heater[20]	10,000 m^2	0.007	9
Agriculture	Solar dryer[21]	3,200 m^2	0.002	3
Total			5.803	6,869 (0.59 Mtoe)

Fig. 9 Total installed capacity and energy delivered from installed solar thermal technologies. (Source: [4])

4 GoI Actions and Targets

What Are the Government Plans to Increase the Solar Implementation in Buildings in India?

Owing to India's National Action Plan on Climate Change (NAPCC), India has encompassed several measures towards eight missions. India is a tropical country with sufficient sun radiation available for longer hours per day and has great potential for power generation. To harness the sun's potential for power generation, India has launched the "National Solar mission" under the brand name "Solar India". The aim of the mission is to establish India as a global leader in solar energy through policy conditions using the 3-phase approach.

This mission focuses on collaborating with state governments, regulators power utilities, and local self-government bodies to frame policies to initiate the Solar India mission which is as follows:

1. Solar Purchase Obligation for power utilities with a specific solar component.
2. Solarising domestic and industrial applications.
3. Mandating solar heaters through building bye-laws and NBC (National Building Code).
4. Availing of soft loans for upgrading solar technology or manufacturing capacity.
5. Decentralising solar power lines for off-grid applications with incentives under MNRE's Village electrification program.
6. Setting up stand-alone power plants in remote areas such as Lakshadweep, Andaman, and Nicobar Islands.
7. The National Tariff Policy 2006 mandates the State Electricity Regulatory Commissions (SERC) of the state government to fix a minimum purchase (3%) of solar energy through off-grid.
8. Encouraging rooftop solar PV and other small plant installations with government tariffs.
9. The National Centre of Excellence (NCE) is established to improve efficiency in solar applications.

National Target

The initial goal of 20 GW capacity for 2022 set by the Indian government was attained 4 years earlier than expected. The goal was increased in 2015 to 100 GW of solar power by 2022, with 40 GW coming from rooftop solar, with a goal of US$100 billion in investment. To make land available to those who are promoting solar plants, India has developed roughly 42 solar parks [9]. Nearly 20.7 billion US dollars in foreign money was invested in solar power projects in India between 2010 and 2019.

The National Solar Mission was established by the Government of India in order to position the country as a leader in solar energy by establishing the political framework for its rapid national adoption.

In January 2011, the National Tariff Policy was changed to ensure that the minimum solar-specific RPO climb from 0.25% in 2012 to 3% by 2022. For the purpose of boosting solar energy, CERC and SERCs have released a number of rules, such as solar RPOs, REC frameworks, tariffs, grid connectivity, forecasting, etc. Numerous States have developed their own solar policies [9].

Karnataka is the highest solar energy production states in India (Fig. 10). Karnataka receives an average insolation of 5.55 kWh/m^2/day annually. Insolation varies from 4.5 to 7 kWh/m^2/day throughout the year. All districts of the state receive average insolation of 5.5–6.5 kWh/m^2/day annually. This highlights that solar energy-based electricity generation would help in meeting the growing energy demand in this state.

The state also has introduced many policies like:

1. Grid-connected ground-mounted utility-scale projects.
2. Grid-connected rooftop projects.
3. Distributed generation (1–3 MW).
4. Off-grid projects.
5. Minimum targets proposed for a policy period.

Table 1 showcases the data of state-wise installed capacity of various renewable power sectors in India. Solar power is the highest contributor to power production among all the alternatives with 60,813.93 MW of installed capacity with the next best being wind power at 41,666.08 MW [9].

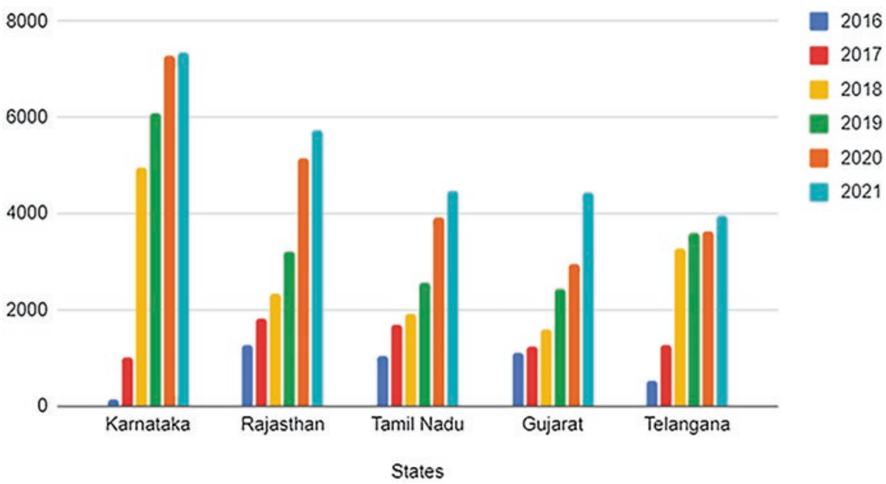

Fig. 10 Top 5 highest Solar Energy production states in India. (Source: [9]

Table 1 State-wise installed capacity of renewable Power as on 30.09.2022

P&C Division														
State-wise installed capacity of Renewable Power as on 30.09.2022.														
S. No.	STATES / Uts	Small Hydro Power	Wind Power	Bio-Power					Solar Power					Total Capacity
				BM Power/Bagasse Cogen.	BM Cogen. (Non-Bagasse)	Waste to Energy	Waste to Energy (Off-grid)	Bio Power Total	Ground Mounted Solar	Rooftop	Solar Component in Hybrid	Off Grid Solar	Solar Power Total	
		(MW)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)
1	Andhra Pradesh	162.11	4096.65	378.10	105.57	53.16	29.21	566.04	4257.39	160.93	0.00	88.34	4506.66	9331.46
2	Arunachal Pradesh	133.11						0.00	1.27	4.34	0.00	5.62	11.23	144.34
3	Assam	34.11			2.00			2.00	105.00	33.48	0.00	9.44	147.92	184.03
4	Bihar	70.70		112.50	12.20		1.32	126.02	138.93	30.55	0.00	21.28	190.76	387.48
5	Chhatisgarh	76.00		272.09	2.50		0.41	275.00	364.46	47.15	0.00	386.73	798.34	1149.34
6	Goa	0.05				0.34		0.34	0.95	25.33	0.00	0.12	26.40	26.79
7	Gujarat	89.39	9798.52	65.30	12.00	7.50	25.93	110.73	6045.11	1957.38	0.00	43.09	8045.58	18044.22
8	Haryana	73.50		151.40	89.26	11.20	7.02	258.88	265.80	398.70	0.00	290.15	954.65	1287.03
9	Himachal Pradesh	960.71			9.20		1.00	10.20	38.10	19.31	0.00	29.94	87.35	1058.26
10	Jammu & Kashmir	144.68						0.00	2.49	22.00	0.00	24.07	48.56	193.24
11	Jharkhand	4.05			4.30			4.30	19.05	35.21	0.00	39.32	93.58	101.93
12	Karnataka	1280.73	5268.15	1867.10	20.20	1.00	13.85	1902.15	7446.96	382.11	0.00	30.31	7859.38	16310.41
13	Kerala	266.52	62.50		2.27		0.23	2.50	286.48	346.73	0.00	20.76	653.97	985.49
14	Ladakh	39.64						0.00	6.00	1.80	0.00	0.00	7.80	47.44
15	Madhya Pradesh	99.71	2844.29	92.50	14.85	15.40	9.00	131.75	2459.02	221.47	0.00	81.65	2762.14	5837.89
16	Maharashtra	381.08	5012.83	2568.00	16.40	12.59	39.43	2636.42	2089.10	1202.44	0.00	100.09	3391.63	11421.96
17	Manipur	5.45						0.00	0.00	6.36	0.00	5.92	12.28	17.73
18	Meghalaya	32.53			13.80			13.80	0.00	0.21	0.00	3.94	4.15	50.48
19	Mizoram	41.47						0.00	0.10	1.56	0.00	6.35	8.01	49.48
20	Nagaland	31.67						0.00	0.00	1.00	0.00	2.04	3.04	34.71
21	Odisha	115.63		50.40	8.82			59.22	403.56	21.66	0.00	27.45	452.67	627.52
22	Punjab	176.10		299.50	173.95	10.75	14.74	498.94	828.58	222.75	0.00	75.74	1127.07	1802.11
23	Rajasthan	23.85	4576.82	119.25	2.00		3.83	125.08	12590.27	835.00	1380.40	477.99	15283.66	20009.41
24	Sikkim	55.11						0.00	0.00	2.76	0.00	1.92	4.68	59.79
25	Tamil Nadu	123.05	9873.92	969.10	43.55	6.40	23.65	1042.70	5804.93	368.50	0.00	59.93	6233.36	17273.03
26	Telangana	90.87	128.10	158.10	2.00	45.80	13.84	219.74	4360.49	268.19	0.00	8.71	4637.39	5076.10
27	Tripura	16.01						0.00	5.00	4.41	0.00	6.85	16.26	32.27
28	Uttar Pradesh	49.10		1957.50	159.76		75.63	2192.89	1871.50	258.78	0.00	134.50	2264.78	4506.77
29	Uttarakhand	218.82		72.72	57.50		9.22	139.44	298.40	262.71	0.00	14.34	575.45	933.71
30	West Bengal	98.50		300.00	19.92		3.78	323.70	110.00	53.04	0.00	12.99	176.03	598.23
31	Andaman & Nicobar	5.25						0.00	25.05	4.59	0.00	0.27	29.91	35.16
32	Chandigarh							0.00	6.34	50.69	0.00	0.81	57.84	57.84
33	Dadar & Nagar Haveli							0.00	2.49	2.97	0.00	0.00	5.46	5.46
34	Daman & Diu							0.00	10.15	30.86	0.00	0.00	41.01	41.01
35	Delhi					59.00		59.00	8.96	200.70	0.00	1.46	211.12	270.12
36	Lakshwadeep							0.00	0.75	0.00	0.00	2.52	3.27	3.27
37	Pondicherry							0.00	0.80	34.55	0.00	0.18	35.53	35.53
38	Others		4.30					0.00	0.00	0.00	0.00	45.01	45.01	49.31
	Total (MW)	**4899.50**	**41666.08**	**9433.56**	**772.05**	**223.14**	**272.09**	**10700.84**	**49853.48**	**7520.22**	**1380.40**	**2059.83**	**60813.93**	**118080.35**
	MW = Megawatt													

Source: [9]

5 Case Studies

Case Study on Solar PV Cells in MSSRF (MS Swaminathan Research Foundation)

MSSRF was founded in 1988 by Dr. M. S. Swaminathan, who is chairman of the foundation. It is a non-profit NGO trust based in Chennai, India. The Foundation aims to accelerate the use of modern science for sustainable agricultural and rural development.

The Research Foundation had installed building-integrated photovoltaics systems (BAPV) for harnessing solar power. Earlier during the year 2000, Charge Coupled Devices (CCD) are installed in the terrace of Ecotechnology block, which is a charge-coupled device and later in 2018, solar photovoltaics (PV) are installed on the terrace of the main block of MSSRF (Fig. 11).

(a) *Charge Coupled Device (CCD)*: A charge-coupled device (CCD) is a light-sensitive integrated circuit that captures images by converting photons to electrons. A CCD sensor breaks the image elements into pixels. Each pixel is converted into an electrical charge whose intensity is related to the intensity of

Fig. 11 Rooftop view of MS Swaminathan Research Foundation. (Source: Google maps)

Fig. 12 CDD installation on the terrace

light captured by that pixel. Solar CCD system requires battery support to store the excess electricity generated by solar panels, as only afternoon hours direct sunlight is used for the electricity generation.

Total of 96 panels, each of the size 550 mm*1750 mm of power 445 Wattage, are used to generate 10 kV of electricity. These solar panels are inclined at an angle of 35° facing the southwest direction. This Solar CDD system is not used anymore for electricity generation (Fig. 12).

(b) *Solar Photovoltaic (PV)*: These PV panels are installed in the year 2018, by IIT Madras. A total of 176 panels, each of size 450 mm*1038 mm with 445.0 Wattage power are used to generate 160 kV of electricity. These PV panels are used to run the air conditioners in the library of the main block and the excess

Fig. 13 Solar PV installation on the terrace

electricity is fed into the grid. There is approximately 20% reduction in electricity bill amount (Fig. 13).

6 Conclusion

India has a huge potential in terms of harvesting solar energy. The incident solar radiation can successfully be utilised in generating electricity through photovoltaics as well as generating heat through solar thermal applications. The weather conditions throughout the year comparable with any other tropical countries and can yield a good harvest of solar potential. India experiences average daily global radiation of around 4–7 kWh and the average monthly wind speeds are above 1 m/s which support the productivity. Even temperate climate zones like Bangalore experience a good amount of 280 sunny days. Discoms under various state governments are giving incentives to both residential and industrial users. With an area and potential only next to China, India can become a global leader in Solar energy production with appropriate awareness and user-friendly policies and subsidies promoting the use of renewable energy. India is expected to be the first country to be affected by heat stress impacting the work efficiency, energy efficiency at the building level is a key aspect to reducing the heat stress. Renewable energy sector predominantly solar power can play a major role in adding clean energy to the Indian construction and industrial sectors as well as in reducing the carbon footprint as a lot of India's domestic and commercial power consumption is dependent on fossil fuels. The goal was increased in 2015 to 100 GW of solar power by 2022, with 40 GW coming from rooftop solar, with a goal of US$100 billion in investment. India is expected to touch the 200 GW mark in utility PV and distributed PV put together, policies under National solar mission are under place to encourage the rural electrification, encourage the installation of rooftop solar PVs in residences. Solar thermal applications like water heating and cooking in homes and off-grid applications like street lights, solar lanterns, and solar pumps are a boon to the rural population where grid connectivity and 24 h power supply is still a dream to many.

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A Review of Policies, Energy Resources Towards a More Sustainable Economy: A Study on Renewable Energy in India

J. Vijayalaxmi and Dhananjay Manthanwar

1 Introduction

Economy globally has grown rapidly in recent past, the global GDP increased from $24 trillion in 1990 to about $31 trillion in 2000 and expected to reach $94 trillion by 2021. Such massive development necessitates enormous amounts of energy for production, transportation, and human life maintenance (including air conditioning, heating, and lighting), and as illustrated in Fig. 1, these social and economic activities have resulted in constant greenhouse gas (GHG) emissions into the atmosphere, producing climate change and its accompanying detrimental impacts. Since 1992, the United Nations has organized numerous international meetings to stabilize GHG at safe levels in order to avoid harmful effects on the environment. The Paris Climate Conference in December 2015, where 195 countries committed to tackling climate change by lowering GHG emissions, was likely one of the most successful conferences. According to that Agreement, each party would take independent activities and review its unique climate plans (i.e., the Nationally Determined Contributions) every 5 years. The effects of these policies on the structure of their economies, energy resources, market shares of energy sectors, and other aspects of their resources and economies are still unclear. Individual economies had long since taken appropriate steps to reduce emission levels and transition to a greener and more sustainable economies. In order to better comprehend the potential effects of policies and help each nation move toward sustainable and cleaner growth, it is crucial to understand the energy market and pertinent policies in that country.

India is a developing economy in South Asia with sizable energy markets. India has a wealth of natural resources that may help with the transition to a low-carbon

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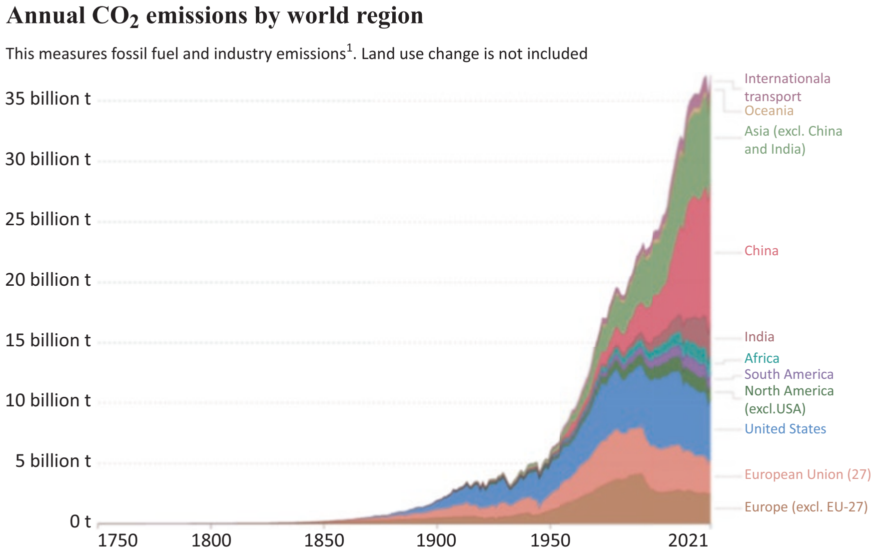

Fig. 1 Annual CO_2 emissions from fossils fuels in the world. (Source – Global Carbon Project)

and cleaner economy, from terrestrial to marine resources, but the activities appear to be taking their time.

India has a large economy in terms of GDP [1], energy policy decisions focusing on renewables, cleaner, and greener sources are lacking. According to research data, India still lacks complete electrification and LPG supply because the policies and decision-making have not been developed properly; in recent years there has been focus on renewables and importance of clean energy.

There aren't many studies on energy issues in India, and there aren't any thorough reviews and critical analyses of research on energy resources, pertinent policies, or scientific empirical research studies to provide the proper links between these elements and identify challenges so that the nation can quickly transition to a low-carbon and cleaner economy. Several decades ago, the nation's peer-reviewed energy-related research articles covered topics like energy resources and development, analysis of household energy use, discussion of the potential of renewable energy sources and how they might be used to address energy and environmental issues, and more.

The infrastructure and facilities in India are relatively underdeveloped, and the technology and study techniques used to estimate the potentials of energy resources, as well as the perspectives of economic development and energy demand, are relatively simple. During these times, studies are crucial to support policy-making decisions.

With a growing population, rising energy demand has become a major issue. We will run out of energy sources such as fossil fuels, gasoline, and others extracted from nature within the next few years or decade. The disposal of their residue is also a significant issue. The extraction of these energy sources consumes a significant amount of energy, labor, and other resources which requires huge capital. The requirement of renewable here comes in picture, renewable energy is an energy that initially requires capital but proves to be economical and efficient over the period of time.

According to a view on literature, the key distinctions in current and previous studies are primarily the topic's scope and study methods. An examination of energy sources, regulations, and research projects with a view to developing a cleaner and more sustainable economy in Vietnam [2] – Renewable and Sustainable Energy Reviews by Duy Nong and others discussed the following, the Researchers discussed about the energy models available in Vietnam, the attempt to fulfill Vietnam's energy requirements using the renewable energy and the policies framed by the government in achieving the goals. They also suggested the better and efficient policy-making in order to achieve the power targets at much lower cost. They also discussed the capacity of the country and the market, the difficulties in growing economy and production capacity of the country in the renewable sector.

In order to do so, they conducted a thorough examination of all of Vietnam's energy resources and potentials under present circumstances. Previous studies' research gaps, scope, methodologies, and sources are investigated. They discussed the connections between energy resources, legislation, technology, empirical research, and economic situations as well as the implications for Vietnam's sustainable development in light of these connections between energy potential, technology, global contexts, and current socioeconomic conditions. The same study can be carried out in India, using the Indian Subcontinent as a base for a review of energy resources and their optimal use. This study also aims to provide a review of energy systems, with a focus on hydropower and solar energy, as well as discussions about other non-renewable sources of energy.

M.A. Hasan in Acceptability of transport emissions reduction policies: A multicriteria analysis [3] looked into the mitigation potential of various transportation policies, taking into account their costs, benefits, and ethical implications. The author also discusses Multicriteria analysis (MCA) and various techniques involved in MCA such as AHP. They applied Simple Additive Weighting (SAW) to 26 policies and 25 experts from various organizations. They plotted the expert reviews on a scale ranging from 0 to 9.

A thorough analysis of all energy potentials and resources in India pertaining to the below listed items is carried out.

1. Conduct an analysis of all energy policies and components.
2. Investigate scope.
3. Talk about the connections between energy resources, policy, and the state of the economy.

The parts that follow have been structured to give such information and discussions: Sect. 2 – Overview of India and its energy resources/potentials. Section 3 – Energy policy and studies in India. Section 4 – Discussion on policy implication and suggestions for future research. Section 5 – Concluding remarks. Section 6 – Executive summary.

2 Overview of India and Its Energy Resources/Potentials

India is located above the Indian Ocean sharing borders with China, Pakistan, Bangladesh, Nepal, and having area 3.287 million square kilometers and 7517 km coastal area has a huge scope of energy generation in all forms. India experiences tropical monsoon climate (tropical wet and dry climate). India has rich networks of system consisting of majorly 8 rivers and 400 rivers in total which creates enormous scope for hydro power generation. Having about 12 hours of sunshine available at most all days in every part of country, still agriculture sector is not powered fully, the data shows that agriculture sector is still powered only 52% as shown in (Fig. 2), that is where improvements shall be done, being a primarily agriculture-based country.

It has the world's sixth biggest economy in terms of nominal GDP. Since the start of the twenty-first century, annual average GDP growth has hovered between 6% and 7%, and from 2013 to 2018, India overtook China as the main economy with the quickest rate of development. The young population and low dependency ratio, high rates of savings and investment, growing globalization in India, and integration into the global economy all contribute to the Indian economy's long-term development prospects being favorable. The industrial and agricultural sectors employ the majority of the workforce, while the service sector, which makes up half of GDP, is the one that is growing the quickest [1].

Coal Resources and Coal-fired Power Plants

Here are some major thermal power plants as shown in Table 1.

More than 65% of India's energy capacity comes from thermal power plants, with coal accounting for 80–85% of the nation's thermal power output. We must lessen our reliance on coal, as the world's coal reserves total 352125.97 million tons [4]. According to [5], India has enough coal reserves to last for about 111 years, but at the most recent Conference of Parties (CoP-26) of the UNFCCC, which was held

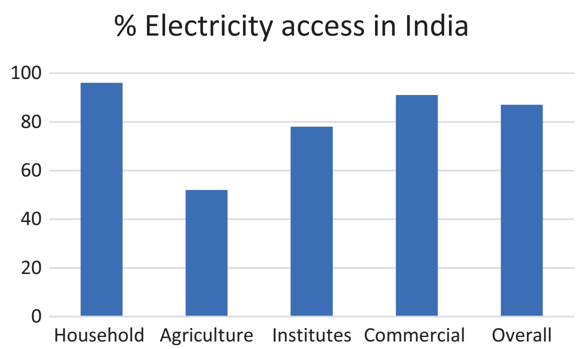

Fig. 2 Electricity access to various sectors

Table 1 Top 3 thermal power plants in India

Name	Operator	Location	Configuration
Vindhyachal Thermal Power Station	NTPC	Madhya Pradesh	4760 MW
Mundra Thermal Power Station	Adani Power	Gujrat	4620 MW
Sasan Ultra Mega power plant	Reliance Power	Madhya Pradesh	3960 MW

Table 2 Top 3 hydro power plants in India

Name	Operator	Location	Configuration
Tehri Dam (3 Stages)	THDC Limited, Uttarakhand	Uttarakhand	2400 MW
Koyna Hydroelectric Project (4 Stages)	MAHAGENCO, Maharashtra State Power Generation Co Ltd.	Maharashtra	1960 MW
Srisailam	APGENCO	Andhra Pradesh	1670 MW

in Glasgow in November 2021, many of India's allies are reluctant to commit to specific action plans to keep global warming below the 1.5 °C threshold. India is the third-largest emitter of carbon dioxide, behind China and the United States, at 2.44 billion tons annually.

Water Resources and Hydropower Plants [6]

India's abundant water resources enable the nation to increase the construction of hydroelectric plants. India has committed to using non-fossil fuels to generate 40% of its installed capacity by 2030, with renewable energy targets of 175 GW by 2022 and 450 GW by 2030 [7]. Hydropower is therefore essential for integrating renewable energy into the system and solving balance issues. India's renewable energy targets for electricity generation depend heavily on hydropower. However, problems with contracts, environmental challenges, and financial constraints all cause chaos (Table 2).

India's hydroelectric potential, measured in terms of installed capacity, is estimated to be 148,700 MW, of which 42,783 MW (28.77%) have been built thus far, and 13,616 MW (9.2%) are in the development stage.

Project Status

In India, a number of hydropower projects (HEPs) have been put on hold due to contract disputes, environmental challenges, local unrest, financial issues, and wary customers. In the past 10 years, only around 10,000 MW of hydropower could be installed. In March 2019, the Indian government designated large HEPs as renewable energy (RE), making new HEPs eligible for subsidies and green funds for RE projects. Hydropower Purchase Obligations (HPO) might become a reality soon according to the Draft Electricity (Amendment) Bill 2020. However, it is preferable to re-engineer the power market to take hydropower into account as a peaking and grid-balancing source and prorately distribute its higher tariff across overall energy demand.

The north and north-eastern regions have the greatest hydroelectric potential. The most untapped hydropower potential is in Uttarakhand (47 GW), followed by Arunachal Pradesh (12 GW). Construction of HEPs is periodically postponed due to conflicts between riparian States since water and water power are state issues; the Subansiri HEP is a classic example of this. The most untapped potential is found in the Indus, Ganges, and Brahmaputra rivers. India's river systems are involved in a number of global issues. In order to have a coherent strategy and method for quicker growth, hydropower should be added to the concurrent list along with electricity.

Clearance Issues

HEPs still require environmental approval. Due to environmental concerns, some HEPs had their operations discontinued or had their capacity and design changed. It is now quite obvious what constitutes an e-flow, a free-flow stretch, an eco-sensitive zone, and an influence on untamed flora and fauna. Therefore, the hydropower potential, particularly pumped storage hydropower, should be reevaluated in light of contemporary technology and environmental concerns. HEPs must have TEC approval from the Central Electricity Authority (CEA), while thermal projects that do not must not receive TEC approval. Additionally, permission must be granted for any site alterations needed for construction. Clearance is granted following extensive discussion with the CWC and a lengthy period of time. Processes must be assessed in order to shorten the TEC's time requirement.

Wide-ranging social and environmental effects result from hydropower developments. Geological surprises during construction are typical for HEPs. The long land purchase process includes a Gram Sabha vote, a public hearing, and other steps. Forest clearing takes time. Concerns about resettlement and rehabilitation (R&R) are not only expensive but also delicate. At the approval stage, it has been seen that projects do not sufficiently budget for these components. Consequent arrangements lead to cost and time overruns. The project budget should include for adequate R&R expenses. The project management team should have experts in social science, the environment, and communication. Unnecessary delays and cost overruns may be prevented if HEPs could be issued upon the receipt of the relevant licenses, as with Ultra Mega Power Projects.

Financial Aspects

HEPs are situated in difficult-to-reach areas. In order to complete the project, they need to build roads and bridges. Opportunities for expansion in surrounding places are improved by roads and bridges. The Indian government has chosen to help them financially as a consequence. However, the process for providing financial aid has to be sped up. Large HEPs also reduce flooding, but they are not funded until the Ministry of Water Resources designates them as a national project. The Ministry of Power has now decided to support flood risk reduction. The cost of power would most likely decrease as a result of these advances.

The debt-to-equity ratio for HEPs is 70:30, and its tariff is set up so that debt is repaid in the first 12 years. Hydroelectricity is unprofitable as a result of this front-loading of tariffs. Now that the debt payback duration and project life have been extended to 18 and 40 years, respectively, the government has also implemented a rising charge of 2% per year to lower the starting rate.

Tariff regulations must be adjusted in order for them to work. Although the tariff can be rationalized, the problems with costs and time overruns might not be resolved. Unexpected events that are not foreseen in building contracts are brought on by geological surprises, R&R concerns, and environmental issues, which leads to unnecessary arbitration, litigation, and implementation delays. Payment delays or postponements put contractors in a difficult financial situation. As a result, in order to speed up the implementation of HEP, a sound and reliable procedure for prompt settlement of contractual difficulties must be developed.

Policy (According to MNRE) [8]

Concurrent themes include power and electricity generated by hydroelectric plants. Because water is a state issue, the actual execution of SHP projects is overseen by state policies. The State Government makes the choice to establish or allocate SHP projects. The State Government is seeking expressions of interest/proposals/bids from private developers. Each state has its own policies and procedures for growing the industry and allocating projects. The relevant State Government provides Techno-Economic Clearances (TEC)/approvals for SHP projects. The Ministry, as the nodal Ministry for the development of the country's small hydro industry, provides a comprehensive framework by way of promoting sector growth using several ways These include assistance with assessing SHP potential, including micro siting, developing testing and standardization, and training facilities, survey and investigation support, Detailed Project Report (DPR) preparation, capital subsidy for projects, and support for renovation and modernization, among other things. Small hydropower projects do not often face the deforestation and displacement issues that major hydropower projects do. The projects have the ability to address the energy needs of rural and isolated places. Because of these reasons, tiny hydel is one of the most appealing renewable methods of grid-quality electricity generation. 24 states in the nation have policies in place to encourage private sector engagement in the development of SHP projects.

Nuclear Power Plants [9] (Table 3)

Some of the nuclear power plant projects which are under construction are listed below (Table 4):

Some of the nuclear power projects which are planned up for the future are as follows (Table 5):

The total nuclear power generated currently is around 4560 MW through 19 units from 6 Nuclear power stations. Some major nuclear power plant includes Tarapur Maharashtra having 1400 MW and Rawatbhata at Rajasthan having 1180 MV. Nuclear power plant projects under construction are about 2720 MW and the major of them is Kudankulam Tamil Nadu having 2 units of 1000 MW each. The

Table 3 Nuclear power plants in India

Power station	State	Type	Operator	Units	Total capacity (MW)
Kaiga	Karnataka	PHWR	NPCIL	220 × 3	660
Kalpakkam	Tamil Nadu	PHWR	NPCIL	220 × 2	440
Kakrapar	Gujarat	PHWR	NPCIL	220 × 2	440
Rawatbhata	Rajasthan	PHWR	NPCIL	100 × 1200 × 1220 × 4	1180
Tarapur	Maharashtra	BWR (PHWR)	NPCIL	160 × 2540 × 2	1400
Narora	Uttar Pradesh	PHWR	NPCIL	220 × 2	440
Total				**19**	**4560**

Table 4 Nuclear power plants in India under construction

Power station	State	Type	Operator	Units	Total capacity (MW)
Kudankulam	Tamil Nadu	VVER-1000	NPCIL	1000 × 2	2000
Kaiga	Karnataka	PHWR	NPCIL	220 × 1	220
Kalpakkam	Tamil Nadu	PFBR	NPCIL	500 × 1	500
Total				**4**	**2720**

Table 5 Nuclear power plants in India (upcoming)

Power station	Operator	State	Type	Units	Total capacity (MW)
Rawatbhata	NPCIL	Rajasthan	PHWR	640 × 2	1280
Kakrapar	NPCIL	Gujarat	PHWR	640 × 2	1280
Jaitapur	NPCIL	Maharashtra	EPR	1600 × 4	6400
Kudankulam	NPCIL	Tamil Nadu	VVER	1200 × 2	2400
Kaiga	NPCIL	Karnataka	PWR	1000 × 1, 1500 × 1	2500
	NPCIL		AHWR	300	300
	NPCIL		PHWR	640 × 4	2560
	NTPC		PWR	1000 × 2	2000
Total				**10**	**20,600**

future of nuclear is a lot bright in India, 10 plants about 20,600 MW is under planning stage which majorly takes up at Jaitapur Maharashtra having 6400 MW,

Solar Energy [8]

India has a large solar energy potential. Every year, around 5000 trillion kWh of energy are incident over India's geographical area, with the majority of locations receiving 4–7 kWh per square meter per day. Solar photovoltaic electricity may be successfully harvested, allowing for considerable scalability in India. It also allows for distributed power generation as well as quick capacity growth with short lead periods. Off-grid, decentralized, and low-temperature applications will improve rural electrification while also meeting other energy demands for electricity, heating, and cooling in both rural and urban locations. Solar energy is the most secure of all energy sources due to its abundance. In principle, harnessing a tiny portion of total incident solar energy can provide enough electricity to power the entire country.

Millions of Indian communities have benefited from decentralized and distributed solar energy-based applications that satisfy their cooking, lighting, and other energy needs while being ecologically friendly. Among the social and economic benefits are reduced drudgery among rural women and girls engaged in long-distance fuel wood collection and cooking in smoky kitchens, reduced risks of contracting lung and eye ailments, job creation at the village level, and, ultimately, an improvement in the standard of living and the creation of opportunities for economic activities at the village level. Furthermore, throughout the years, India's solar energy sector has emerged as a major participant in grid-connected power generation capacity. It contributes to the government's long-term growth strategy while emerging as a critical component of the solution.

According to the National Institute of Solar Energy, the country's solar potential is roughly 748 GW, assuming that solar PV modules cover 3% of the wasteland area. Solar energy has been highlighted in India's National Action Plan on Climate Change, with one of the key aims being the National Solar Mission. The National Solar Mission (NSM) was launched on January 11, 2010. The National Sustainable Development Mission (NSM) is a significant program of the Government of India that promotes environmentally sustainable growth while addressing India's energy security concerns.

To achieve the aforementioned goal, the Government of India has launched a number of schemes to encourage the generation of solar power in the country, including the Solar Park Scheme, VGF Schemes, CPSU Schemes, Defense Scheme, Canal Bank & Canal Top Scheme, Bundling Scheme, Grid Connected Solar Rooftop Scheme, and so on.

Among the policy measures implemented are the establishment of a trajectory for Renewable Purchase Obligation (RPO), which included Solar, Waiver of interstate transmission system (ISTS) costs and losses for interstate sales of solar and wind power for projects to be completed by March 2022, Must-run status, Guidelines for solar power procurement through a tariff-based competitive bidding procedure, Solar photovoltaic system and device deployment standards, Rooftop solar installation and smart city development guidelines, Building bylaw amendments to require rooftop solar for new development or greater Floor Area Ratios, Infrastructure status for solar projects, Raising tax-free solar bonds, obtaining long-term financing from multilateral organizations, and so on.

India just surpassed Italy to take the fifth worldwide position in solar power installations. Solar power capacity has more than doubled in the previous 5 years, rising from 2.6 GW in March 2014 to 30 GW in July 2019. Solar tariffs in India are now highly competitive and have reached grid parity.

3 Energy Policies and Studies in India [6]

In a rapidly changing technical environment, it is critical to have a clear vision of goals and required activities in order to fully realize the benefits of energy storage and aid in the acceleration of the implementation of renewable energy technology. India plans to boost its wind and solar power generating capacity to 160 GW by 2022, with the goal of increasing non-fossil-based energy consumption to 40% by 2030. According to the Central Electricity Authority (CEA), the percentage contribution of installed generating capacity (by sector) is as follows (Table 6, Fig. 3).

Installed generation capacity (fuel-wise) is as follows (Table 7).

4 Policy Implications and Future Research Proposals

Increasing Demand

With an installed power capacity of 395.07 GW as of January 2022, India is the world's third-largest producer and second-largest user of energy.

Growing population, increased electrification, and per-capita demand will give further impetus. In 2022, power consumption is expected to reach 1894.7 TWh.

Attractive Opportunities

The government declared the issuing of sovereign green bonds in the Union Budget 2022–23, as well as the designation of energy storage technologies, including grid-scale battery systems, as infrastructure.

A PLI plan to stimulate the manufacture of high-efficiency solar modules was granted Rs. 19,500 crore (US$ 2.57 billion) in the same budget.

Policy Assistance

The electricity industry has seen an increase in FDI inflows as 100% FDI is permitted.

Table 6 Sector-wise contribution of installed generating capacity in (%)

Sectors	MW	% of total
Central sector	99,005	24.6%
State sector	1,04,855	26.2%
Private sector	1,95,637	49.0%
Total	**3,99,497**	**100.0%**

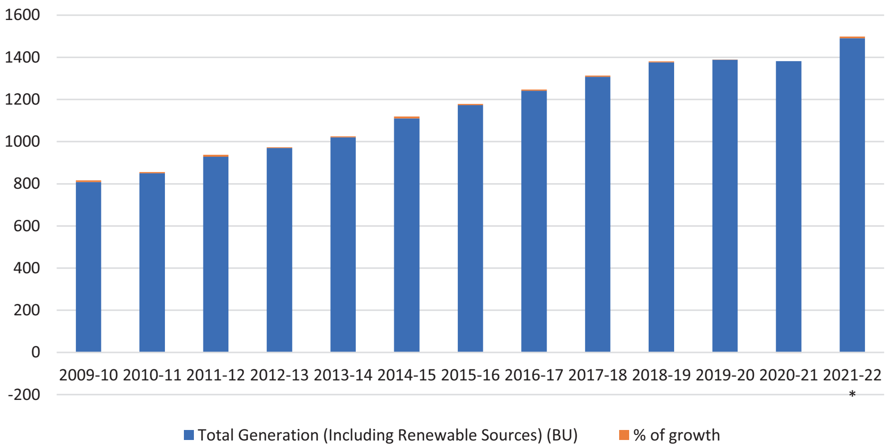

Fig. 3 Total generation and growth over previous year in the country during 2009–2022*

Table 7 Installed generation capacity (fuel wise)

Category	Installed generation capacity (MW)	% share in total
Fossil fuel		
Coal	2,04,081	51.1%
Lignite	6621	1.7%
Gas	24,910	6.3%
Diesel	520	0.1%
Total fossil fuel	**2,36,131**	**59.1%**
Non-fossil fuel		
RES (Incl. Hydro)	**1,56,610**	39.2%
Hydro	**46,725**	**11.7%**
Wind, solar & other RE	1,09,890	27.5%
Wind	40,360	10.1%
Solar	54,000	13.5%
BM power/Cogen	10,210	2.6%
Waste to energy	480	0.1%
Small hydro power	4850	1.2%
Nuclear	6782	1.7%
Total non-fossil fuel	**1,63,412**	40.9%
Total installed capacity (fossil fuel & non-fossil fuel)	**3,99,543**	**100%**

Electrification across the country is projected to be boosted by schemes such as the Deen Dayal Upadhyay Gram Jyoti Yojana (DDUGJY) and the Integrated Power Development Scheme (IPDS).

Higher Investments

According to the National Infrastructure Pipeline 2019–25, energy sector projects made for the greatest proportion (24%) of the overall planned capital expenditure of Rs. 111 lakh crore (US$ 1.4 trillion).

Between April 2000 and December 2021, total FDI inflows into the electricity industry are US$ 15.84 billion.

India has a wealth of natural resources for the development of renewable energy, and numerous corporate, non-governmental, and international enterprises have invested in renewable energy in India. To lessen financial risks for all parties involved, particularly investors, transmission and distribution network development must be coordinated with power plant construction. According to the current scenario, renewable energy, particularly solar energy, has risen quickly in several specific locations. Karnataka has 7100 MW, Telangana has 5000 MW, Rajasthan has 4400 MW, and Andhra Pradesh has 3470 MW. Gujarat's capacity is 2654 MW [10].

This review has resulted in a number of policy implications.

- The Government of India, in partnership with its states, may need to lay out a clear path for educating the energy sectors to become more market-driven; this would help to increase market liquidity, resource allocation efficiency, and even promote investment. The pipeline might be divided into many portions with various timescales, allowing investors from both local and international sources to see more clearly defined opportunities.
- To simplify applicability to various contexts, energy efficiency programs and rules must be customized to certain energy industries and identical across India, omitting special circumstances if required. Government procedures should be streamlined to speed up application processes.
- In order to assure timely supply of fossil fuel resources, the power development plan must be updated on a regular basis, taking into account new technology and economic conditions in the nation, worldwide situations, and specific trade partner countries.
- Prior to attracting and building new plants, electricity transmission networks must always be properly analyzed and developed so that investors are not at risk of losing energy outputs from their power plants. Estimates and developments should take regional characteristics such as income, energy consumption, and infrastructure into account.

Agenda for Future Research

Research-based discoveries are inextricably linked to national growth. It is particularly important in policymaking. To put it another way, the link between scientific research, development goals, and policy-making processes must be maintained and enhanced. In order to meet policymakers' expectations, extensive research should be conducted. EIA for Solar PV Cells for energy produced vs total trash generated might be researched (Electronic and Electrical). A life cycle analysis can also be performed. In addition, a comparison analysis between India and other nations in terms of policy decision-making, resource use, and energy future may be performed.

5 Conclusion

1. India being an agriculture-intensive country and a major exporter of wheat and other products needs to focus on the Research and development of energy-efficient system that can fulfill agricultural demand at peak times, such a solution is a Solar energy (PV cells) which can generate sufficient amount of energy at a much smaller area.
2. Currently, the Indian Government controls only 24.6%, State government controls 26.2%, and private sector controls 49.0% energy markets and this mechanism leads to inefficient resource allocations, as well as lower attraction for investments.
3. India has abundant natural resources but it's not utilized to its fullest, there is enormous scope of power generation in hydropower, solar, and wind as India has sufficient area for power generation through these sources.
4. Indian Government has opened up for 100% FDI in the power sector which has boosted FDI inflow in this sector as well as other manufacturing and service sectors such as IT.
5. India's Agriculture which is just powered 52% has to be strengthened using the Solar power, Photovoltaic cells for agriculture requirements such as irrigation pumps, lighting, heating, and household can be supported.
6. Even India has Coal reserves till more than 100 years (as of now) but if we use the same in the manner we are using we can never compensate the SDGs by UN as the Carbon footprint is increasing day by day. Capital region is facing worst climate in the entire world and that's a major issue for resolution.
7. For any country, to tackle global climate change the financial and institutional structure of a country should be strong enough to support the policies of the UN Sustainable Development Goals.
8. A detailed understanding of the climate, topography, and market capacity is needed to support the energy developments in that region or in the country.

6 Executive Summary

India has seen extraordinary successes in its recent energy development, but many challenges remain, and the Covid-19 pandemic has been a major disruption. In recent years, India has brought electricity connections to hundreds of millions of its citizens; promoted the adoption of highly efficient LED lighting by most households; and prompted a massive expansion in renewable sources of energy, led by solar power. The gains for Indian citizens and their quality of life have been tangible. However, the Covid-19 crisis has complicated efforts to resolve other pressing problems. These include a lack of reliable electricity supply for many consumers; a continued reliance on solid biomass, mainly firewood, as a cooking fuel for some 660 million people; financially ailing electricity distribution companies, and air quality that has made Indian cities among the most polluted in the world [8].

Declaration of Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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High-Transparency Clear Glass Windows and Agrivoltaics with Large PV Energy Outputs

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1 Introduction and Background

At present, widespread energy innovations, in terms of optimizing both the on-site distributed energy generation and the energy use intensity, are urgently required in the built environment and in agricultural production facilities. This is due to the vast amounts of energy being consumed in buildings (more than 40% of the total nationwide energy consumption occurring in the US buildings sector already in 2018) [1], and the necessity to decarbonize the built environment, preferably by offsetting carbon emissions and materials-embedded carbon through the use of advanced materials capable of carbon offsetting in their installed "use phase". New advanced construction materials combining the benefits of ongoing energy savings (e.g. in HVAC and lighting) and on-site production of renewable energy using solar resources are urgently required. Ideally, these novel materials and products must be able to be integrated into the structure of either new or existing buildings and be able to provide substantial energy benefits through occupying substantially large sun-exposed building envelope areas. Energy-generating energy-efficient solar façade materials can provide substantial momentum for decarbonization of the built environment, because of the much greater deployment-ready surface areas (typically by a factor of >10, relative to any conventional roof-mounted PV) which are available for solar-harvesting façade technologies. Effective, long-term decarbonization of buildings is only possible if an optimized combination of all available solar generation technologies, utilizing all possible building envelope areas is deployed,

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providing near net zero operation capability while being integral to the building structure.

The development of high-transparency solar PV window products with climate-tailored thermal properties is expected to provide a useful pathway towards effective and widespread decarbonization in both the urban and agricultural (agrivoltaic) settings.

Even with surging commodity prices increasing manufacturing costs for solar PV industry, its generation capacity additions were forecast to grow by 17% in 2021. This growth magnitude sets a new annual record of almost 160 GW in added generation capacity. In the recent past, solar PV alone accounted for 60% of all renewable capacity additions [2]. Even though the building-integrated PV sector is growing fast worldwide, deploying a broadening range of new technologies and products (reviews at [3, 4]), the majority of installed PV capacity growth still takes place in conventional installations within solar farms and rooftops. A new segment of PV industry enabling improved energy efficiency in agricultural production has recently emerged, known as agrivoltaics, where the optimized arrangements of partially transparent PV and BIPV modules are required to balance the requirements of achieving energy savings simultaneously with maintaining crop growth productivity and land-use efficiency [5]. Efficient production of commercial crops in greenhouses requires maximum possible delivery of the photosynthetically active radiation (PAR, where the wavelength ranges between 400 and 700 nm) to plant leaves, placing substantial constraints on the design of agrivoltaic installations, where the PV modules must be either highly transparent, or occupy only a limited fraction of wall or roof areas. On the other hand, in commercial buildings, dependent on local climate, semi-transparent BIPV window modules require multi-parameter optimizations, enabling the correct balance between the energy generation per unit area and energy savings. Therefore, engineering of the highly customized and climate-dependent combinations of the thermal (insulation U or R-value), optical (visible transmittance and solar heat gain), and electric (W_p/m^2) properties are required to ensure wide acceptance of emergent BIPV technologies. A range of novel BIPV and high-transparency window-integrated PV (WIPV) products has been developed by ClearVue Technologies [6], already tested and proven to be suitable for deployment in both the construction sector and greenhouses.

ClearVue solar WIPV systems have the following innovative features:

- Custom-designed energy-saving glazing systems utilizing special types of glass and low-emissivity coating(s) to provide substantial thermal energy savings in a range of deployment climates (adjustable SHGC, U or R-value, and visible light transmittance).
- Glazing-integrated luminescent solar concentrator (LSC) panel harvesting primarily the UV-blue and near-infrared solar radiation components while providing maximized visible light transparency and reducing the energy harvesting losses dependent on the incidence angles of solar radiation and weather conditions. LSC technologies have been reviewed in [7], and the details of their characteristic features, performance metrics, typical implementation designs, and

recently demonstrated benchmark results have been reported in [8–12], among multiple other literature sources dating back to the 1970s.

- 3D-structured, custom-shaped, custom-interconnected energy harvesting PV surfaces placed around glazing perimeter regions [13], maximizing the visual transparency and further reducing the efficiency losses that would normally occur in conventional BIPV with increasing incidence angle of the incoming sunlight.
- Customized, installation-specific electrical interconnections circuitry involving combiner boxes and microinverters, enabling optimization of the energy production from a large-scale building structure containing multiple solar windows.

Several recent showcase implementations of ClearVue high-transparency solar window technologies in built environments, including both the research-oriented and commercial agrivoltaic facilities, are shown in Fig. 1.

The following sections of this article outline the current status and recent trends and results demonstrated in BIPV sector, focussing on the materials, approaches, and technologies necessary to broaden the acceptance of high-transparency BIPV that are rapidly evolving at present.

2 Recent Developments in BIPV and Challenges in Transparent Window-Integrated PV

In recent years, there has been a significant progress demonstrated in both the R&D and industrialization of novel BIPV products, materials, technologies, and also the window-integrated PV (WIPV) solar window systems. Research progress has been made throughout the last decade in fields such as the development of large-area semi-transparent luminescent solar concentrators and functional materials for use in solar windows and LSC [10–12, 14–17]. Among the latest materials-related advances reported are the synthesis results of specialized types of eco-friendly, composition-tunable core-shell quantum dots for use in high-efficiency LSC devices [18]. Active research efforts aimed at improving the power conversion efficiency, aesthetic appearance, and commercialization potential of LSC-type devices suitable for practical building integration are ongoing at multiple groups worldwide.

Trends and Technologies in Conventional BIPV and Agrivoltaics

It is possible to broadly define “conventional BIPV” as a group of established, deployment-ready or already commercialized technologies reliant on using silicon-based or thin-film-based PV components, working without incorporation of additional light collection, wavelength conversion or light redirection mechanisms

Fig. 1 High-transparency ClearVue solar windows deployed in commercial property-based and agricultural R&D and production facilities. Top: shopping centre atrium incorporating PV windows installed in 2019 in Perth, Australia; Middle: solar glazing-based greenhouse installation (2021) at Murdoch University (Perth, Australia); Bottom: wall of solar windows installed at a commercial greenhouse built in Sendai, Japan. (Image reproduced from Tomita Technologies website, 2022)

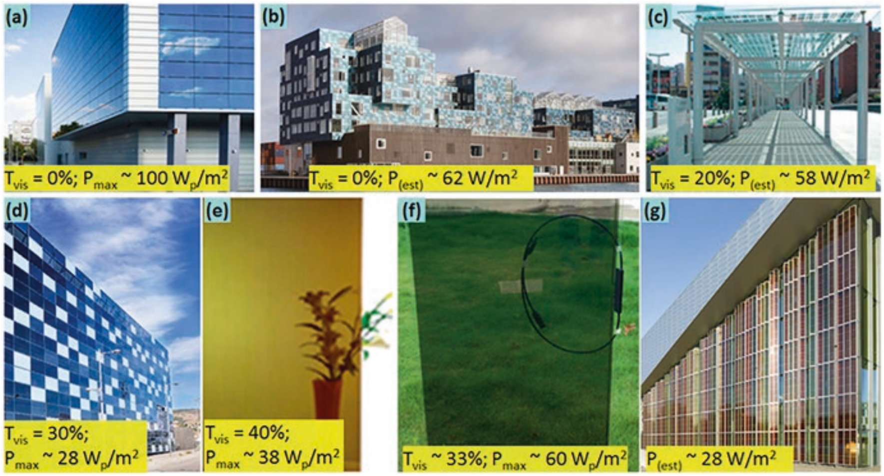

Fig. 2 Conventional BIPV (or building-applied photovoltaics (BAPV)), colour-optimized, and semitransparent commercially available technologies at a glance. (**a**) Avancis PowerMax Skala $CuInSe_2$ panels; (**b**) Multilayer-coated, colour-optimized BIPV facade by EPFL (Ecole Polytechnique Federale de Lausanne, Switzerland) and Emirates Insolaire; (**c**) AGC (Asahi Glass Corporation, Japan) Sunjoule product; (**d**) Onyx Solar a-Si high-transparency BIPV panels; (e) Hanergy BIPV panels using a-Si; (**f**) High-transparency CdTe BIPV panels; (**g**) Solaronix BIPV façade based on semi-transparent dye-sensitized solar cells. The figure is reproduced from Vasiliev et al. [4], according to the applicable Creative Commons Attribution 4.0 International (CC BY 4.0) license. Some of these BIPV products (e.g. Sunjoule) are no longer available; other products have recently improved their power conversion efficiency (e.g. Avancis PowerMax Skala $CuInSe_2$ panels currently featuring ~133 W_p/m^2 (Avancis PowerMax Skala Datasheet (2022), [19])

aimed at modifying the spectral and/or directional response of PV modules to the incoming sunlight. Examples include mono- or polycrystalline silicon, or thin-film (amorphous silicon, CdTe, $Cu(In,Ga)Se_2$) modules, including semi-transparent mosaic-type glass-laminated PV and thin-film PV area-patterned for increased transparency, or coated to modify visual appearance and colour. Modern BIPV module suppliers have continued to offer an increasing range of products, trending towards systems of continually increasing power conversion efficiency (PCE), the choice of reflected colours, and with a broadening range of semi-transparency options. Multiple new technologies have appeared on the market in recent years, utilizing new materials and system design types.

Comprehensive reviews of recently developed BIPV technologies (including both the conventional and also the forward-looking types, which employ optical functional materials and light management structures) are available, examples [3–5, 17]. Newer sources also continue to appear in the literature. Figure 2 provides an outlook on the BIPV technology types which have been commercialized widely at present, including the most commonly known semi-transparent patterned-semiconductor-based glazing systems. The naturally occurring and fundamental trade-off between glass transparency and power generation per unit module area is approached differently in systems utilizing different energy-conversion materials, resulting in a range of power-vs-transparency options, most of which do not result in colour-free visually-clear appearance. Additionally, no technological pathways towards increasing the PV Yield (measured in kWh/kW$_p$/year) compared to the roof- or wall-mounted monocrystalline silicon PV systems have been demonstrated in conventional BIPV to date, since these systems rely intrinsically on single-plane-oriented patterned active materials, usually deployed without sun-tracking or light concentration options. At the module level, the manufacturing scalability of large-area (> approx. 2m^2) BIPV panels is only possible when tiled mono-Si wafers (or tiled substrates of thin-film PV) are laminated in-between glass plates, covering a substantial fraction of visual aperture (e.g. Fig. 2c). This is due to the current range-to-resolution ratio limitations in industrial laser-patterning machines used to remove semiconductor material layers from parts of substrate area; also, the lithography processes used to deposit a fine grid of conductors have similar limitations (e.g. Fig. 2d, e, f). With increasing thickness of the front cover glass used to laminate conventional mono-Si, which may be necessary for environmental safety reasons (e.g. wind load resistance, or if requiring walkable-roof safety assurance), the module PCE drops rapidly beyond ~3 mm of the front glass thickness, for reasons such as geometric shading, light scattering and absorption by glass, refraction and reflectance.

While there is continued materials-related progress being made in terms of increasing PCE and novel PV materials (e.g. perovskites, kesterites, dye-sensitized) are being proposed for BIPV and window-integrated PV systems, new approaches are required to broaden the range of available PV glass products and improve energy harvesting performance. This is particularly true for the manufacturers targeting the development of high-transparency, area-scalable, and high-efficiency clear solar windows, which could then even resemble ordinary window types while providing energy savings and generation. Conductor grids collecting the photocurrent from large patterned-semiconductor areas deposited onto glass substrates invariably introduce visual image distortions in many BIPV window products. Solar windows of moderate visible light transmission have the potential to provide a combination of large energy savings with significant energy harvesting (tens of W per m^2) in both hot and cold climates (due to effectively blocking solar heat gain and heat loss from buildings, if using advanced low-emissivity coatings, providing at the same time a greater fraction of the incoming solar energy for conversion to electricity).

Technology Development Approaches and Functional Materials and for High-Transparency Window-Integrated PV

Due to the globally recognized need to effectively decarbonize the built environments, novel types of BIPV and high-transparency solar windows are currently receiving increasing attention. Of special importance is the emergence of newly commercialized glass-based high-transparency and completely visually clear BIPV technologies and systems, which have been demonstrated in practical architectural deployment applications. In buildings with high window-to-wall ratios, installing glazing systems with electricity generation provides perhaps the only viable way to decarbonize, even if window-generated electric power per unit area is only a fraction of that available from conventional PV or wall-mounted BIPV.

In order to find innovative ways of designing semi-transparent solar windows of higher PCE and improved PV yield characteristics (though only the PV yield can be meaningfully compared to standard PV modules, due to substantial differences in transparency level), not only novel functional materials but also modifications in the structure of PV-integrated glazing systems are required. Several novel and recently developed approaches to the solar windows design utilizing the latest results from the well-established field of luminescent solar concentrators (LSC), in combination with recent developments in the materials science of thin films, luminescent materials, and photonics were reported in [10, 11, 14–18]. The task of designing highly transparent LSC-type devices of relatively high PCE involves considering fundamental trade-offs and theory limits described by Yang et al. [20]. It is possible to design LSC-type solar window systems featuring enhanced probability of the incident photons collection by the solar PV elements, simultaneously with enhanced quantum yield of PV conversion. For example, installing additional front-facing narrow PV modules near the system perimeter would effectively reduce the geometric gain factor, but increase the overall light capture efficiency [21, 22]. Utilizing the luminescent downshifting (LDS) functionality by selecting the appropriate luminophore materials for use in transparent LSC can increase the system PCE due to improving the spectral response matching between the solar cells and the wavelength-converted luminescent emissions [12, 22, 23].

It is important to note that the main performance characteristics of any LSC-type device are governed by Eq. (1), where G is geometric gain (the ratio between the light-collecting front area of device to the area of near-edge, or edge-mounted cells), P is photon collection probability (the ratio of the number of photons escaping through glazing system edges to the number of photons incident onto front surface of concentrator). This quantity is often also called “optical efficiency”; however, some terminology-related disagreements still exist in the LSC-related body of literature, related to the definition of optical efficiency, with newer publications focussing on the external and internal photon collection efficiency. C_{opt} is optical power concentration factor; detailed definitions for these parameters are available from Desmet et al. [9] and other sources [12].

$$C_{\text{opt}} = G * P \tag{1}$$

In Eq. (1), the geometric gain is adjustable by the window system designer, and is largely governed by the window dimensions and the design of PV modules placed near window perimeter/edge areas to collect light. Typical values of G for ~1 m^2 windows are between ~5 and 10, dependent on whether solar PV strips are also placed around backside perimeter near glass edges. The photon collection probability, on the other hand, is a function of core technology used within the LSC-type glazing system, especially the luminescent and/or scattering materials and components used, for example, glass panes chemistry, heat-mirror-type optical coating(s), any diffractive elements, and the overall optical arrangement of these components. In most (or practically all) high-transparency large-area solar windows and LSC devices of different design types reported to date, the optical concentration factor C_{opt} quantifying the radiation flux density reaching the near-edge solar cells is less than unity (data tables containing relevant literature-reported figures of LSC performance parameters have been reported in for example [4, 10]; the optical efficiencies demonstrated in most LSC devices to date were also modest (typically well below 10%, [12]). This is due to the fact that allowing a substantial fraction of total incoming visible-range sunlight energy through the window strongly reduces the energy available for the wavelength conversion and internal redirection. Luminescent materials can only convert a fraction of the available incident spectrum, with finite quantum yield (QY); only quantum dot materials can currently compete with organic-dye pigments reaching QY >(~80%); most of inorganic phosphor materials embedded into polymer matrices have QY limited to max. ~40%, with very few of these featuring near-infrared excitation and/or emissions.

The following theoretical analysis of the energy harvesting process efficiencies involved in semitransparent LSC-type solar windows is adopted from [4] and the literature references therein. The optical power efficiency η_{opt} of LSC, or other types of light-collecting semi-transparent PV energy harvesters (which can utilize several physical mechanisms other than total internal reflection-guided luminescence, e.g. diffractive optics), is itself a product of multiple efficiency factors, each relating to a particular physical process harnessed for re-routing the incident photons towards the solar cell surfaces. For "classical" (non-transparent) luminescent concentrator systems, η_{opt} can be represented in terms of the contributions of all physical phenomena taking place within the concentrator volume, in the following way [7, 24]:

$$\eta_{\mathrm{opt}} = (1-R) P_{\mathrm{TIR}}\, \eta_{\mathrm{abs}}\, \eta_{\mathrm{PLQY}}\, \eta_{\mathrm{Stokes}}\, \eta_{\mathrm{host}}\, \eta_{\mathrm{TIR}}\, \eta_{\mathrm{self}}, \quad (2)$$

where R is the reflectivity of the front surface of the luminescent waveguide; P_{TIR} is the probability of total internal reflection governed by the difference between the refractive indices of waveguiding material and outside air; η_{abs} is the fraction of the incident solar energy absorbed by the luminophore(s); η_{PLQY} is the photoluminescence quantum yield of the luminophore(s) used; η_{Stokes} is the efficiency factor characterizing the energy losses due to heat generation during the absorption and emission events (Stokes shift loss); η_{host} is the transport efficiency of the waveguide; η_{TIR} is the reflection efficiency of the waveguide determined by the smoothness of the waveguide surface, and η_{self} is the transport efficiency of the waveguided photons related to re-absorption of the emitted photons by another luminescent centre. For glass-based waveguiding structures and using a 4% figure for the front-side reflectivity, 75% for P_{TIR} corresponding to the refractive index of glass being $n = 1.5$, and by simplifying all other efficiency factors to equal 0.9, an estimate of the practical upper limit of the optical efficiency η_{opt} can be made, which is about 38%. Then, presuming 22% of optical-to-electric power conversion efficiency (PCE), if using monocrystalline Si cells, the practical upper limit for the total (device-level) LSC PCE can then be estimated to be near 8.4%. This simplified estimate of the upper limit of efficiency is unrelated to the idealized-case theory-limit calculations, but rather refers to what may be achieved in the near future, provided that luminescent materials and waveguiding structures are improving continually. This PCE figure (8.4%, corresponding to 84 W_p/m^2 in electric power generation output per unit window area) also relates to completely non-transparent LSC systems and will need to be reduced for all semitransparent systems, corresponding to the reduction in the incident optical power fraction being harvested. An excellent and detailed analysis of the theoretical performance limits applicable to semitransparent luminescent concentrator systems is available from [20].

Following the optical efficiency formula (2) and the theoretical treatment from the review in [4], and by modifying Eq. (2) for use with semitransparent window systems, the practical energy harvesting efficiencies can be estimated using a realistic set of waveguide-related and luminescence process-related parameters. The first term $(1 - R)$ can be replaced with $(1 - R - T)$, where T is the transmitted fraction of the total incident harvestable solar energy, including the diffused transmittance. For practical high-transparency solar windows, T values of near *0.5* should be used, and R values of near *0.1*.

Thus, $(1 - R - T)$ = (approx.) a factor of *0.4* for use in the first multiplication factor in the modified Eq. (2). This removes the necessity to include the strongly spectrally-dependent luminophore absorption efficiency η_{abs} (though a replacement factor of $\eta_{abs\ (lum)}$ is still needed in the equation, to represent the fraction of the incident optical power absorbed within luminophores, being a fraction of the total absorption, which also happens within glass panels or other glazing system components, e.g. coatings or polymer interlayer materials). This approach allows approximating the achievable optical efficiencies in highly transparent concentrator-type systems.

The same 75% (*0.75*) figure should be used for P_{TIR} corresponding to the refractive index of glass concentrator plate being $n = 1.5$. The absorbed fraction of the incident solar optical power η_{abs} is perhaps the most system-specific variable in Eq. (2), dependent on the functional materials contents and the concentration-thickness product of the absorbing luminescent interlayer, added material layers, or films, and is also dependent on the spectral absorption properties The realistic value of fractional absorption efficiency parameter $\eta_{abs\ (lum)}$ can be approximated by ~0.9.

For most inorganic luminophore pigments (including even most of the available types of quantum-dot materials), the photoluminescence quantum yield η_{PLQY} (defined as the ratio between the numbers of the emitted and absorbed photons) can be presumed to be limited to about *0.8*. The value of parameter η_{Stokes} can be in excess of *~0.95* for downconverter luminescent materials with relatively small Stokes shifts. It can also be similarly large for two-photon (quantum-cutting) luminescent downconversion processes. For luminescent downshifting processes involving large Stokes shifts, η_{Stokes} will be smaller, yet the solar-cell spectral responsivity curve usually favouring the photoelectric conversion of long-wave photons will in many cases compensate for the larger Stokes' process losses involved, at the stage of final PCE calculation. For high-quality waveguiding structures with very smooth external surfaces, relatively low luminophore concentrations (< 0.5 wt%), and without excessive particle agglomeration, light scattering and reabsorption, the product of the remaining terms η_{host} * η_{TIR} * η_{self} can be approximated by ~0.9*0.95*0.95, or approx. max. *0.812*.

By multiplying the above-estimated maximum-expected partial efficiency terms, we can then evaluate the expected upper limit for the optical efficiency in practical large-area highly transparent ($T = 50\%$) luminescent concentrator windows employing high quantum yield functional materials, to be

$$\eta_{opt} = 0.4^{*}\, 0.75^{*}\, 0.9^{*}\, 0.8^{*}\, 0.95^{*}\, 0.812 = 0.166\left(\text{or}\,16.6\%\right).$$

The higher the optical clarity and visible-range transmission required, the more stringent materials-related limitations apply to all of the parameters in Eq. (2). In particular, the currently available inorganic (and especially the near-infrared absorbing) luminophores have limited quantum efficiencies, which is why the highest optical efficiencies demonstrated in the LSC field to date are only a fraction of the upper limit evaluated; typically reported values are of the order of several per cent. The refraction, multiple reflection, diffraction, and scattering-related light transport phenomena can also assist in improving the probability of photon collection by the energy-converting solar cell surfaces installed inside solar windows [15–17].

Visual examples of transparent luminescent concentrators employing inorganic phosphor particles dispersed inside glass lamination interlayers are shown in Fig. 3.

Work is ongoing at multiple research groups worldwide on the design of LSC using giant Stokes shift inorganic phosphors capable of avoiding the well-known reabsorption problem, which is another limiting factor in large-area LSC design.

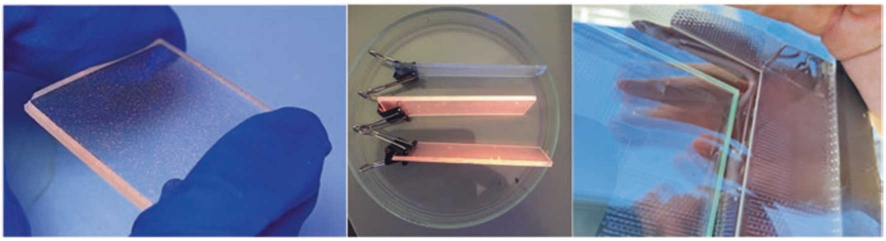

Fig. 3 High-transparency laminated glass samples linked by prototype fluorescent polyvinyl butyral (PVB) interlayers demonstrating visible component of fluorescent emissions concentrated at glass edges, shown under UV irradiation and also in comparison with a glass sample laminated using conventional PVB (left and middle image parts); visual appearance of a factory-assembled ClearVue solar window photographed under natural daylight illumination and showing near-edge concentration of a visible part of fluorescent emissions originating from a high-transparency luminophore-doped PVB interlayer

Another factor of special relevance to the industrial production of solar windows is the necessity to develop suitable and reliable technologies for the incorporation of inorganic phosphors (or semiconductor nanocrystals) into the glass-based industry-standard window designs, without causing strong haze, colouration, and preferably avoiding the use of polymer slabs and any organics-based media not proven to provide decades-long lifetimes of solar exposure.

To the best of our knowledge, no other research group worldwide have so far demonstrated the industrialized development of high-power (tens of W/m^2), clear, and size-scalable solar windows and published (e.g [6].) flash-lamp PV I-V curve testing results for large-area (> 1 m^2) high-transparency glass-based clear and building standards-compliant solar windows (e.g. certified by IEC, UL, CE etc.) In particular, the measured performance data for product-level windows demonstrating Ampere-scale currents at the maximum-power point with large corresponding system voltages (V_{MPP} near ~50 V) and transparency levels exceeding 50% have not been so far published by any competitors. Our most recent development results in large-area (1.91 m × 0.95 m) solar windows (exported to Japan and installed at a commercial greenhouse in Sendai, built by Tomita Technologies, see Fig. 1) demonstrated electric power outputs (measured at STC) of up to 50.5 W_p (27.83 W_p/m^2), proving both the scalability of technology and product development progress (data shown in Fig. 4). Compared with the commercially available ClearVue solar windows of size 1.2 m × 1.2 m made 1–2 years ago, the current (2021–2022) window models of the same dimensions have shown the I_{sc} improvements of up to 16.7% (~980 mA vs ~840 mA, at the same V_{oc} and FF), as recently measured in field testing experiments, at the optimized (natural-sunlight) incidence-angle conditions, with the best incidence geometry being different from normal incidence. The latter feature (not reported in any conventional PV modules) makes ClearVue solar windows particularly attractive for BIPV applications on vertical façade and wall areas.

Optimization of solar window performance in terms of ensuring high transparency, largely colour-free and haze-free appearance, while maximizing the electric output per unit module area is an active area of multidisciplinary research. Key new advances in this area are expected to result from the ongoing optimizations of inorganic luminescent material compositions and concentration-thickness products, glazing system structure and its components, and the improvements of customized PV modules and associated electrical circuitry details.

3 High-Transparency Window-Integrated PV: Recent Development History, Installation Examples and Results

Large-area (200 mm × 200 mm, 500 mm × 500 mm, and larger) high-transparency solar windows employing glass-based glazing systems, custom-designed low-emissivity coatings, and inorganic luminescent materials have been designed and demonstrated at Edith Cowan University (ECU, Perth, Australia) between 2012 and 2019. Oxide and sulphide-based rare-earth-doped phosphor particles excitable by

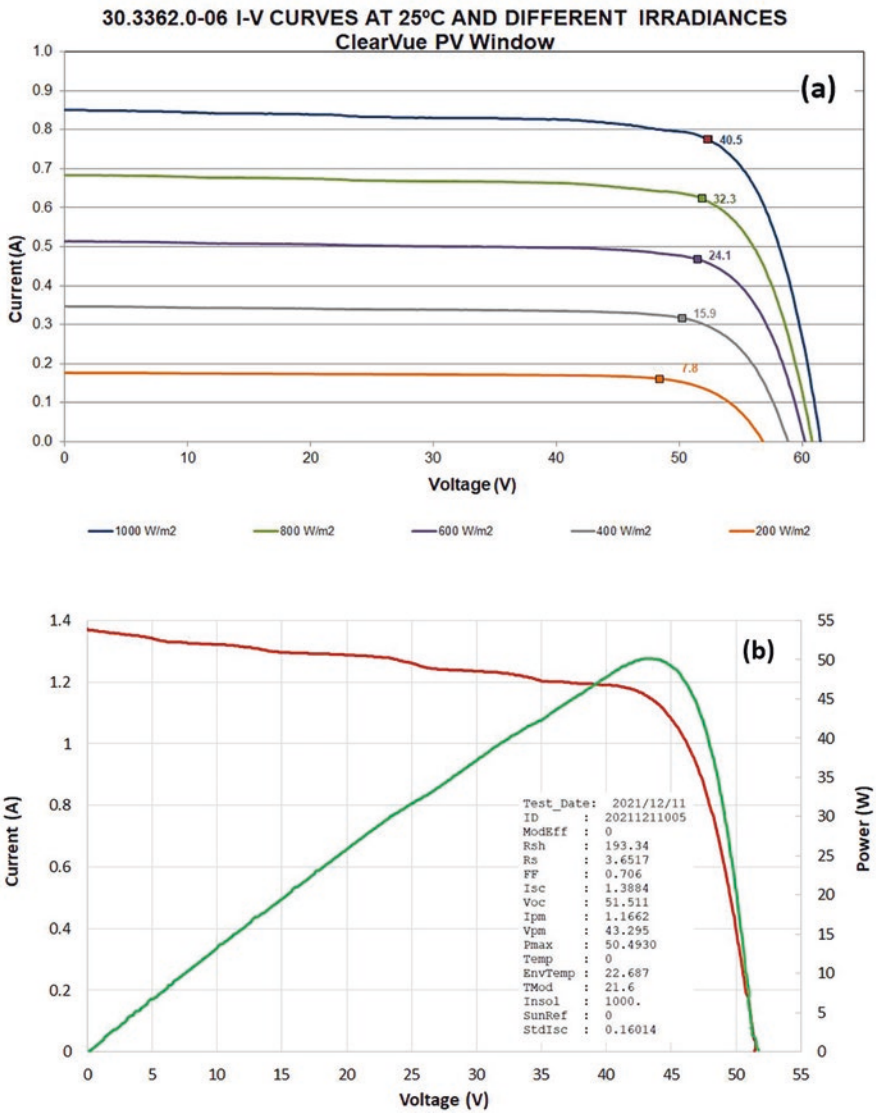

Fig. 4 Flashlamp standardized PV I–V curve measurement results of ClearVue solar windows. (**a**) Solar intensity-dependent I-V curves of 1.2 m × 1.2 m windows; (**b**) I–V curve and measured PV performance data obtained from large-area (1.9 m × 0.95 m) ClearVue windows demonstrating approx. 28 W_p/m^2 rating at the standard test conditions at normal incidence

the UV-blue and also the near-infrared solar radiation components, and featuring both the luminescent downshifting and upconversion-type emissions, were incorporated into epoxy-based lamination interlayers. The early-development solar glazing samples and framed installation-ready solar window prototypes dating back to 2014 are shown in Fig. 5.

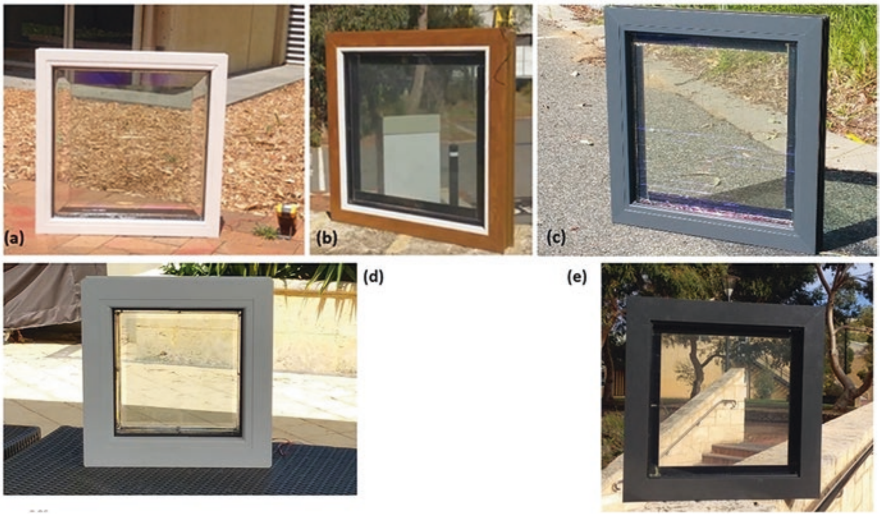

Fig. 5 R&D solar window prototypes (2014–2016) of various transparent solar glazing configurations. The image is reproduced from https://www.nature.com/articles/srep31831

The prototypes shown in Fig. 5 employed CIS ($CuInSe_2$) custom-shaped PV modules of nominal efficiency near 13%, and the PV strips were directly attached to glazing system edges and also (in some systems) were positioned around the backside glazing perimeter regions. The electric power outputs from smaller (200 mm × 200 mm) high-transparency low-haze samples using edge-attached 26 mm-wide PV strips (similar to Fig. 5d) reached up to ~0.7 W (I_{sc} = 72 mA, V_{oc} = 16.8 V, FF = 0.57, measured at peak orientation in outdoor sunlight). In 500 mm × 500 mm internally structured window samples similar to Fig. 5a, the electric outputs reached about 3 W; windows of same dimensions featuring backside-perimeter CIS PV demonstrated electric outputs of over 5 W in natural sunlight conditions, dependent on the internal glazing structure design. The performance characteristics of first factory-made ClearVue solar window designs also featuring CIS PV back in 2016–2017 in outdoor test installations have been reported in [21].

The first commercial property-based installation of ClearVue solar windows (Fig. 6) was made at Warwick Grove Shopping Centre in Perth, in early 2019. A comprehensive analysis of its observed energy harvesting performance is available from [25].

Solar windows of dimensions 1.2 m × 1.2 m were installed onto NE roof area (4 windows), NW roof area (4 windows), Nth wall (8 windows just below entry sign), and strongly shaded east wall (2 windows). The maximum instantaneous electric power output so far observed, measured at the AC battery by Enphase Envoy datalogging interface was just below 300 W; the yearly generation was ~0.5 MWh, in line with the predicted performance considering the relevant capture loss and system loss factors.

Fig. 6 Warwick Grove Shopping Centre Atrium (Perth, Australia) built using ClearVue solar windows and a summary of measured solar installation performance (18 multi-oriented solar windows in total)

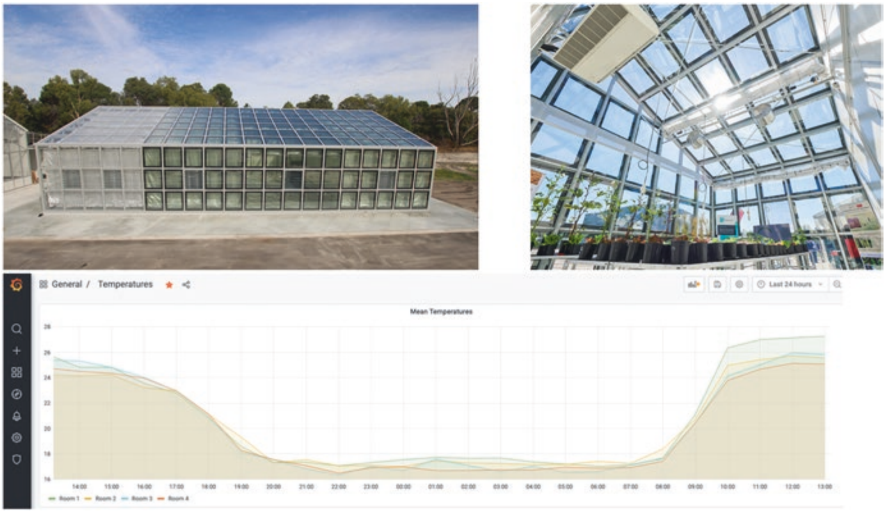

Fig. 7 ClearVue solar windows installed at Murdoch University Solar Greenhouse (Perth, Australia). Mean (volume-averaged) room air temperature datalogs recorded in mid-June 2021 are also shown

A more recent (2021) installation example of ClearVue solar windows is Murdoch University Solar Greenhouse (Fig. 7), in which 3 out of 4 grow-rooms (~50 m^2 floor area each) were built using solar windows on the north wall, on the 20-degree tilted north-facing roof, and also on the west-facing wall. 153 solar windows in total represented an installed capacity near 6.2 kW_p, which has led to strongly offsetting the running costs of greenhouse during 2021 in terms of HVAC system operation. In summary, the wintertime daily electric energy consumption in

ClearVue grow-rooms was at about a third of that needed to maintain microclimate in the reference grow-room glazed with conventional glass. The PV installation contained 13 Enphase IQ7+ microinverters each connected to a parallel bundle of ~12 windows; the system is also exporting energy to the grid, with the self-consumed energy fraction being near 70%.

The microclimate in each grow-room was finely controlled using a custom-designed HVAC system, keeping the temperature setpoints within ±2 °C to optimize the plant growth. Even with this fine control of microclimate applied continually, the PV installation has offset approximately ~40% of the total energy costs in ClearVue grow-rooms.

The amounts of solar energy harvested by the solar windows installation at Murdoch University Solar Greenhouse (Building 899) were data-logged continuously, as enabled by Enphase Enlighten online data interface processing the data from each of the 13 Enphase microinverters connected to parallel-bundled solar window arrays. Continuous observations of the logged power and energy data were made throughout 2021–2022, and the observed energy generation trends were also analysed in comparison with a reference conventional (roof-based, optimally tilted) 6.6 kW_p rooftop PV installation located in Perth metropolitan area. Figure 8 shows the comparative energy generation trends observed during autumn and winter of 2021.

The energy harvesting performance of various types of solar PV installations in the "real-world" operating conditions (as opposed to the standard laboratory flash-test testing conditions (STC)) remains an area of active research [26–28]. Each PV

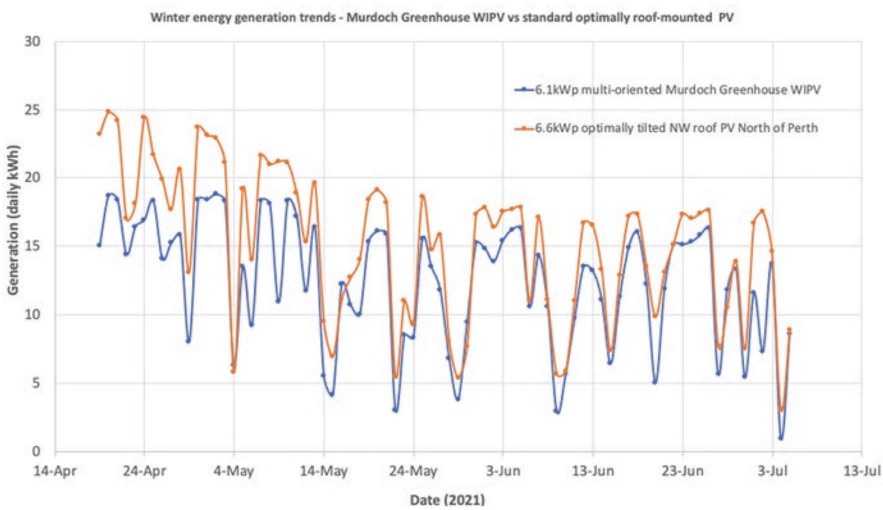

Fig. 8 Solar PV energy generation trends measured during winter of 2021. Murdoch University Solar Greenhouse installation performance shown in comparison with an optimally tilted, conventional rooftop PV installation in Perth. Data sources: Enphase Enlighten data (greenhouse), and Fronius Solar.Web app. (Home PV system owned by Dr. M. Vasiliev)

system responds to its own uniquely local operating environment and its limitations, especially the external shading conditions, and the local climate type and its variations. It is well known that in the case of BIPV, where the installations often invariably involve multiple and non-optimum tilt angles (e.g. vertical walls) and azimuth orientations, significant (and season-dependent) discrepancies may be expected between the modelled energy outputs and actual measured system performance.

Our main findings over the autumn-winter of 2021 were that Murdoch University Solar Greenhouse performed as expected, despite having a large area of vertically oriented windows (e.g. at North and West Walls), and on some rainier days even outperformed a standard 6.6 kWp PV panels installation on an optimally tilted roof area (considering the installed PV capacity difference; data shown in Fig. 8). Both the North and West wall areas performed as expected (or better, particularly on some wall areas in the summer months of 2021–2022), considering the non-optimum orientation/tilt angles, as well as the weather conditions during the winter of 2021. The energy amounts harvested daily approached ~19 kWh/day. Some energy harvesting limitations were also observed, arising due to the maximum AC power output limitations of microinverters used, and affecting primarily the roof-mounted arrays on summer days. The data of Fig. 8 confirms that ClearVue solar windows are particularly suitable for efficient solar energy harvesting in adverse environmental conditions (e.g. during rainy winter days), even when installed at a range of different azimuth and tilt angles. This finding was expected, due to the window design features providing the capability of capturing the incoming sunlight energy from a wide range of incidence angles.

Significant energy savings were demonstrated in greenhouse grow-rooms fitted with ClearVue solar windows, which demonstrated approximately 40% of total energy self-sufficiency, due to the renewable energy generated. Figure 9 shows the

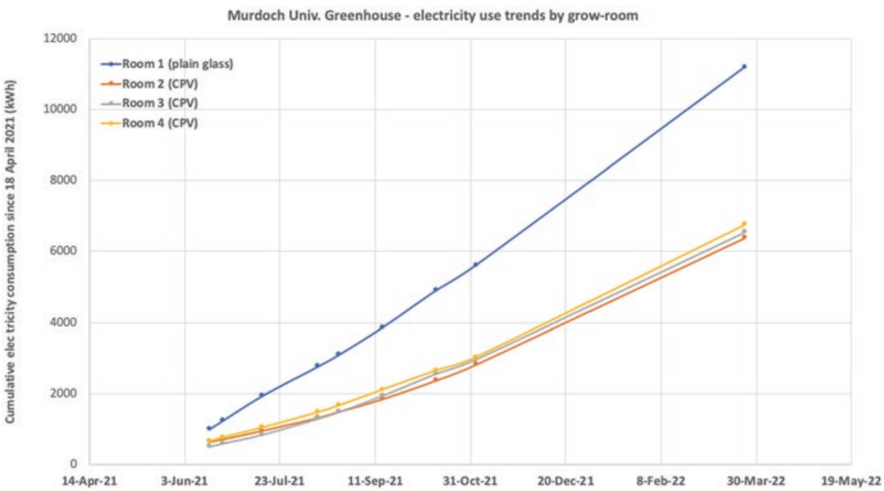

Fig. 9 Electric energy use trends in Murdoch University Solar Greenhouse grow-rooms observed during 2021–2022

measured electric energy consumption trends in all 4 grow-rooms, on a time scale of almost 1 year. Further optimizations to be applied to the internet-of-things (IoT)-based HVAC control algorithms, involving more efficient air cooling applied through high-pressure evaporation of water mist, are expected to further improve the energy self-sufficiency, reducing the running time of high-power reverse-cycle air conditioners.

As was expected, conventionally glazed Room1 used electricity at a significantly higher rate, compared to solar grow-rooms, due to its significantly larger (by almost 30%) solar heat gain coefficient. Marginal (few %) energy use differences were noted between grow-rooms fitted with solar windows, possibly also correlated with their solar heat gain differences.

The following metered and documented electricity consumption data were obtained between 11 am June 21, 2021 and 11 am Jul 21, 2021 (a period of 30 full calendar days):

Room1: 981.65 kWh (32.72 kWh/day, or 0.68 kWh/m^2/day); Room2: 347.6 kWh (11.58 kWh/day, or 0.24 kWh/m^2/day); Rooms 3 and 4 both consumed near 0.25 kWh/m^2/day. The grow-room floor areas were ~ 48 m^2 each.

The total sum of rooms 1–4 energy use meterage was 5222.22 kWh (readings seen on 21 July 2021, and the energy consumption measurements started on 16 Apr 2021 when the meters were first installed). The total additional energy used by the corridor area (mainly corridor lighting) was measured at 331.93 kWh; therefore, the total 3-monthly greenhouse energy use sum metered was 5554.14 kWh. However, the total energy shown on the greenhouse smart energy meter as Imported from the grid was 4815 kWh. The balance (739.15 kWh) was self-consumed during the observation period in all greenhouse rooms (1–4) during PV generation. The energy exported to grid was measured to be near 420 kWh.

Considering the energy imported from the grid between 16 Apr and 21 July 2021 (4815 kWh) and the grid-exported 420 kWh, the net total grid energy import of 4395 kWh was recorded in 3 months of operation, for the entire greenhouse. At the same time, the 3-month total PV generation in 3 ClearVue grow-rooms was 1165 kWh.

The energy used in 3 rooms (incl. The self-consumption of 739 kWh), less small errors (due to reactance effects etc.) – the sum of 3 consumption meters for rooms 2–4 was at 3082.42 kWh. These data mean (accounting for the self-consumed energy) that the 3 ClearVue rooms have imported from grid in total only 3082.42kWh – 739kWh = 2343.4 kWh during 3 months of operation time.

The 3-monthly averaged energy self-sufficiency level (for all 3 CPV rooms) was then equal to: PV Generation Total/Total Energy Used = 1165 kWh/3082.42kWh = 37.8% – averaged between 16 Apr – 21 July 2021, with the record rainy June and July months in 2021. On the other hand, during the same 3-month period, the ratio of total energy generated in Rooms 2, 3, and 4 to the Grid-Imported energy was as high as 1165 kWh/2343.4 kWh = 49.7%. The costs of importing from grid only ~2.3 MWh in 3 months' time (~$ 300/month, using off-peak Perth tariff of $ 0.3896/kWh) indicate small running costs, compared to, e.g. the expected running costs of energy in other R&D greenhouses at Murdoch Campus.

The designs of solar windows installed in 3 ClearVue grow-rooms slightly differed in terms of the number of luminescent material-doped polyvinyl butyral (PVB) lamination interlayers used and the concentrations of these materials distributed inside the polymer interlayers. Two differently doped PVB designs were used, namely (1) “PVB-1” of lower doping concentration for higher-clarity windows, and (2) “PVB-2” of slightly higher luminescent particle concentration. One major finding made immediately after the greenhouse construction was that, despite the differing luminescent/scattering inorganic particle densities in different PVB interlayer types used in different grow-rooms, no substantial haze-related visual clarity or visual appearance differences were noted between windows of different design modification. This was due to the rather modest concentrations of functional materials incorporated into both types of 0.76 mm thick PVB, being below ~0.1 wt%. The following interlayer design differences related to the glazing design differences between grow-rooms 2, 3, and 4:

- Room 2 windows used two slightly higher-haze, but identical interlayers (“PVB-2” + “PVB-2”).
- Room 3 windows used two differently doped interlayers (“PVB-2” + “PVB-1”).
- Room 4 windows used a single fluorescent interlayer (high-clarity “PVB-1”), with the other interlayer being “Ordinary PVB”.

Two PVB interlayers were needed to laminate the inner pane (integrated LSC-type panel) of each triple-glazed window system; each inner pane was itself composed of three 4 mm-thick low-iron glass plates. During the initial (pre-installation) field testing of all windows conducted at Murdoch Campus in February 2021 in outdoor natural-sunlight conditions, some performance differences between different window design types were noted, even though testing at standard test conditions (STC) could not be then performed, and the factory flash-lamp STC tests revealed only marginal (few %) peak power-output differences when measured at normal incidence angle. When measured at the optimized (by way of measuring the short-circuit current I_{sc}) angles of incidence, and at peak outdoor sunlight irradiation, the windows (expectedly) showed the same open-circuit voltages near 61 V; however, the measured I_{sc} values differed systematically from ~840–860 mA in windows of Room 4, up to ~950–980 mA in windows designed for installation in Rooms 2 and 3. Therefore, the solar energy harvesting performance was expected to also differ by up to ~10% between the extremely-low-haze Room 4 and other ClearVue rooms.

It is important to note that the energy production outputs of any PV or BIPV system are seasonally dependent, very installation-orientation-dependent, and, while being correlated quantitatively with the peak power generation (kWp installed), still require a close examination and performance monitoring across multiple seasons, especially if direct comparisons between different BIPV system design types are to be made. The overall objective of any PV/BIPV system design is to maximize the PV Yield (measured in kWh/kW$_p$/year), in order to maximize the yearly renewable energy production output from each installation site. The Enphase Envoy online data interface allowed to map the PV energy production of all individual PV arrays (bundles of parallel-connected solar windows distributed over the greenhouse building envelope). Thus, the total energy production at different sections of greenhouse installation could be monitored online. Due to the electrical system design-related and geometric constraints of this greenhouse BIPV installation, it was not possible to install all separate 12-window PV arrays mounted on identically oriented surfaces and using identical window design types. Instead, we ensured (to the extent possible, since some windows also required replacement during the construction process) that windows installed in each grow-room featured the same glazing design variation. However, most 12-window arrays featured a combination of wall- and roof-mounted windows, often extending over 2 different rooms per array. The power generation on roof areas would have been affected by factors such as weather-induced soiling and (during warmer seasons) the microinverters AC output limits. Figure 10 shows the electric design schematic of the distribution of different north-facing PV arrays placed over the window and roof areas in all 3

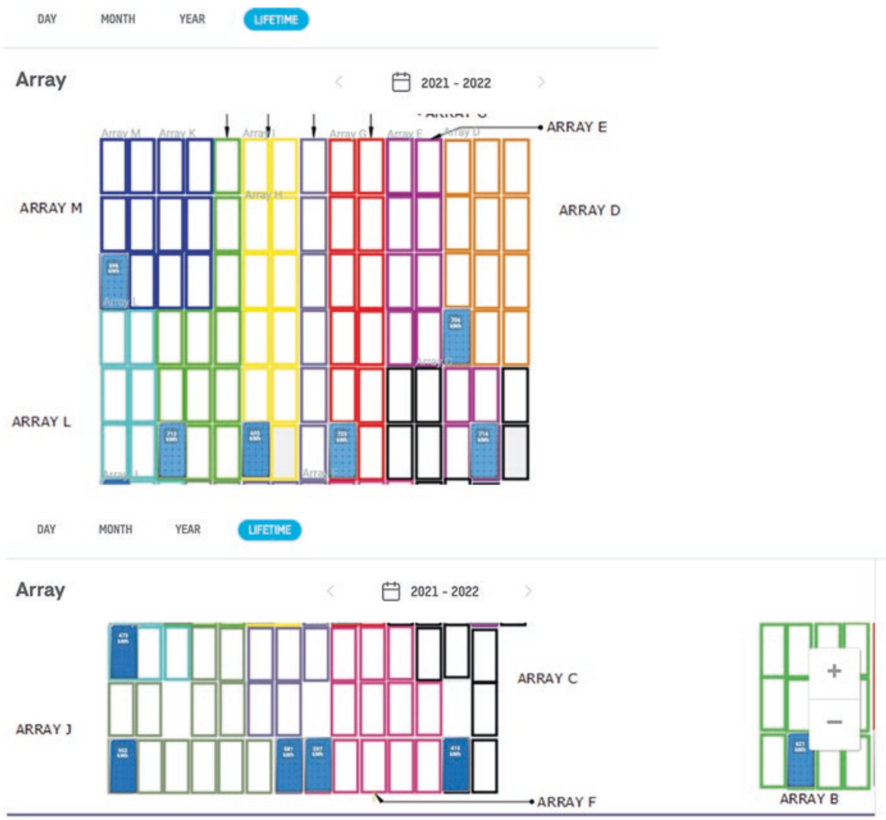

Fig. 10 Roof-mounted arrays (top) and Nth Wall arrays (bottom image) long-term energy generation data. (Note that the north-facing Array C long-term production figure was actually 621 kWh, erroneously swapped in the installer's array diagram with Array B production data (415 kWh)). Each of the grow-rooms (2, 3, and 4) had 5 vertical columns of solar windows installed across the north-facing wall and roof areas; the wall height was 3 rows of windows. A conventional louvre-type window was placed in the middle of solar-window wall in each room, shown as clear space in diagram

grow-rooms, with roof and wall areas shown in separate diagrams. Array B had 3 windows placed onto the north wall and another 9 on the west wall; Array A (not shown) was also placed on the west wall. The web interface allowed energy production data collection summarized over user-defined time-frames.

The vertical wall areas are better representative of BIPV-deployed system energy yield performance, due to the expected reductions in energy amounts harvested, compared to roof areas, and also due to relatively smaller area contamination induced by weather. The wall-mounted PV windows were also expected to be less affected by the temperature-induced efficiency variations, due to their placement closer to ground level (in contact with cooler layers of greenhouse air) and receiving less direct incoming solar radiation flux per unit area. Long-term north-facing wall windows performance averages were observed between the different rooms of greenhouse between 16 Apr 2021 and 21 Oct 2022.

Array J windows data were representative (11/12 windows) of Room2 (Nth Wall) energy harvesting performance during the long-term observation period (18 months), amounting to 41.83 kWh/window.

Array F (split between Rooms 3 and 4 on the north wall, with 7 windows being of Room3 glazing design, and Array C (split between the Nth Wall and roof of Room4) provide the reliable estimate for the long-term comparative data trends for different window design types. Given that the long-term average rooftop generation per window on roof of Room4 was 59.167 kWh/window (data from roof-based Arrays D and E), the total contribution of 6 wall-mounted windows of Array C (Room 4) can be derived to be (621–6*59.167) kWh = 265.99 kWh, or 44.33 kWh/window.

The 12 windows of Array J (Room 2) generated only ~41.83 kWh/window (~ 5.6% less than wall windows of Room 4), however, there were vehicles frequently parked (during peak insolation hours) outside and near the wall of Rooms 1 and 2; strong external shading effects could have been expected, possibly affecting the generation data of Room2 northern wall.

The 12 windows of Array F (mainly belonging to Room3 glazing design type, with some (max. 2) windows on the Room 4 part of Array J also being replaced during construction with the windows of Room3 interlayer design type) generated 49.75 kWh/window during the observation period. These data suggest the minimum long-term energy-harvesting outperformance of Room3 Nth-wall windows, compared with Room4, to be ~12%. This figure also correlates well with the original field performance evaluation tests performed in February 2021, prior to the installation of solar windows into greenhouse structure. Array F windows have also consistently demonstrated significant PV Yield performance differences during warmer months (compared with the predicted energy yields calculated using a conventional-PV-based model, based on installed capacity, physical orientation, and local climate).

Figure 11 shows the results of the summer-time PV Yield comparison made with a conventional PV or BIPV system installation of identical installed capacity placed onto a north-facing vertical wall in Perth. The energy production data for December

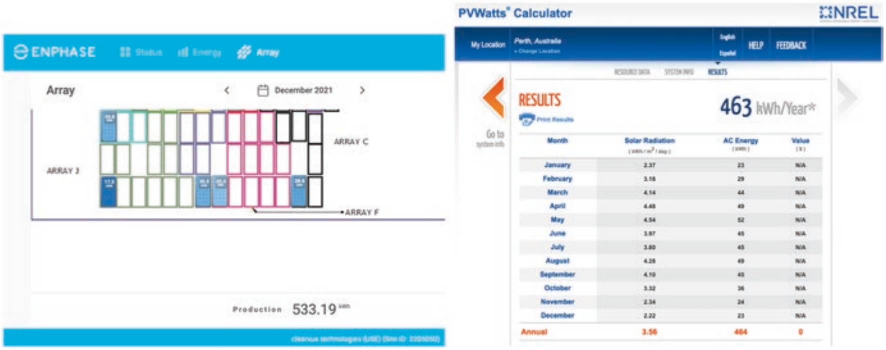

Fig. 11 Measured monthly energy production of 12-window bundle (Array F, 35.3 kWh) mounted on a north-facing vertical wall of Murdoch Greenhouse versus the predicted monthly energy output (23 kWh) of a conventional PV or BIPV installation of identical installed capacity (0.4752W_p) also mounted in the same geometric orientation, in Perth climate

2021 from Enphase Envoy interface shows a 53.4% energy production increase, compared to that expected from a conventional PV installation of same capacity.

Similar PV Yield comparison results for the wall-based windows were also observed in other months (e.g. Nov 2021 and Jan 2022, when the weather was at its most stable for Perth). The PV Yields exceeding these available from conventional BIPV systems were expected, due to the design of ClearVue windows featuring the reduced angle-of-incidence sensitivity of electric power output, simultaneously with peak-output window orientation being slightly away from normal incidence. This makes these solar windows attractive for the (intrinsically multi-oriented) BIPV installations.

The main findings related to the performance of Murdoch University Solar Greenhouse were as follows:

- Greenhouse microclimate control hardware and software configuration has been optimized for providing high energy efficiency.
- Accurate temperature control was demonstrated, maintaining microclimate at ±2 °C from the required setpoints, during both the daytime and night-time periods.
- Energy-efficient mist-evaporator cooling strategy has been demonstrated, also providing humidity control and reduced cooling-related energy use.
- The summer-season HVAC/greenhouse climate monitoring results have confirmed that the HVAC and IoT climate-control systems designed specifically for Murdoch Greenhouse by the ClearVue team were capable of providing the required fine climate control during the hot summer months in Perth. During the winter months, relatively small amounts of energy were used to provide the effective heating.
- Electric energy production by multi-oriented window-integrated PV (WIPV) solar windows installation demonstrated to be in line with the expected performance.

- Different window design types resulted in different energy harvesting performance characteristics (as was expected); the results of energy production monitoring will be utilized for further fine-tuning of the PVB interlayer recipes.
- High levels of energy self-sufficiency (averaging up to ~40%, and up to ~60% demonstrated in window-integrated solar greenhouse on sunny autumn days in Perth), provided the most energy-efficient climate control algorithms were used.
- Greater efficiency of water use in ClearVue rooms demonstrated (up to ~20% during winter grow-season), due to high thermal insulation and lower solar heat gain, compared with conventionally-glazed room.
- Substantial PV Yield improvements in ClearVue solar windows over the conventional wall-based BIPV systems have been demonstrated, comparing the data for identical installed capacities (kW_p) and physical window orientation.

4 High-Transparency WIPV: Decarbonization Potential

With BIPV field installations continuing to grow worldwide, using an increasing range of products and different design features, there is an increasing research attention to the contributions these systems will be making in terms of decarbonization and sustainability. Of special interest is the significant decarbonization potential of transparent and semi-transparent BIPV and solar windows, which could become the only widely used construction materials featuring a combination of ongoing energy savings and generation, and offsetting carbon emissions in products previously using materials with high embedded carbon (glass and framing).

During the second half of 2021, ClearVue commissioned energy efficiency and sustainability specialists, Footprint (Canada) to develop an energy-efficient archetype model office building named “ClearZero” to demonstrate how ClearVue’s window-integrated photovoltaics can be used to assist in the design of highly energy efficient, energy neutral buildings. We completed the design of an Archetype model building of 15,000 m^2 internal area (an artist’s rendering based on architectural design software is shown in Fig. 12 [29], to demonstrate how ClearVue windows can achieve a Net Zero or Near Zero energy-use building operation. Modelling was completed on a design in Toronto, Canada, benchmarked against the Toronto Green Standard (TGS) from 2030 - one of the world’s highest standards of building performance. The Archetype was shown to achieve the highest level of performance under the TGS from 2030 (V6 Tier 1) and an ENERGY STAR score in the top 1% of Canadian office buildings for energy performance.

The Archetype demonstrates the energy performance of a low-carbon energy-efficient building design along with the renewable energy generation of the on-site photovoltaic arrays in the form of ClearVue’s PV glazing across all glazed surfaces – and 50% of the roof area of the building covered with a typical roof-mounted PV array – together delivering approximately 40% of the energy needs for the building during its in-use phase. Net Zero energy use was also shown to be easily achieved by covering only 37% of the mandated car parking spaces for a building of the Archetype’s size and scale with additional roof-based PV. ClearVue has achieved

Total Energy Use Intensity (TEUI)	CPV TEUI	Canadian Median TEUI	% Reduction from Current Canadian Median
	(ekWh/m^2)	(ekWh/m^2)	
CPV Windows Only	62.7	228	-72.5%
CPV Windows + Roof PV	39.8	228	-82.5%
CPV + Roof+Car Park to Net Zero	0	228	-100%

Greenhouse Gas Emissions Intensity (GHGI)	CPV GHGI	Canadian Median GHGI	% Reduction from Current Canadian Median
	(kg eCO$_2$/m^2)	(kg eCO$_2$/m^2)	
CPV Windows Only	3.2	74.2	-95.7%
CPV Windows + Roof PV	2	74.2	-97.3%
CPV + Roof+Car Park to Net Zero	0	74.2	-100%

Fig. 12 Artist's impression of the front view of the "ClearZero Archetype" and technical data summary on the energy use intensity from the report by footprint

the 2030 TGS benchmarks all while maintaining window-to-wall ratios on the building elevations of 90% on the South, 70% East, 70% West and 40% North. These high fenestration ratios mean more natural light is available to end users of the building – a key factor in the movement towards "building wellness" design – all without compromising on the carbon footprint of the building.

5 Conclusions

We have provided an up-to-date outlook on the recent trends in the field of semi-transparent BIPV, focusing on the development of high-transparency solar window systems. Advances in solar window development and related materials and technologies have been described; installation examples have been reviewed, together with a discussion on the relevant technical performance characteristics. The wide applications potential of this novel type of energy-generating transparent construction materials includes commercial buildings, public infrastructure, and agrivoltaics. We demonstrated that significant energy savings and precise control over internal microclimate parameters are possible in commercial greenhouses using solar windows. The substantial role which high-transparency solar windows will play in the near future in helping decarbonize the built environments has also been illustrated, using the data and results from a third-party case study of an archetype building using ClearVue solar windows at a high fenestration rate, showing the potential for substantial carbon footprint reductions.

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Modelling and Energy Analysis of a Solar Cooling System Powered by a Photovoltaic (PV) System for a Net-Zero Energy Building (NZEB) Using TRNSYS-PVsyst

Mohammad Mehdi Salehi Dezfouli, Alireza Dehghani-Sanij, and Kushsairy Abdul Kadir

Abbreviations

AC	Air-Conditioning
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BIPV	Building Integrated Photovoltaics
CFCs	Chlorofluorocarbons
CHWR	Chilled Water Return
CHWS	Chilled Water Supply
COP	Coefficient of Performance
DC	Direct Current
FCU	Fan Coil Unit
FiT	Feed-in Tariff
GHGs	Greenhouse Gases
HDCS	Hybrid Desiccant Cooling System
HVAC	Heating, Ventilation, and Air-Conditioning
LHR	Latent Heat Ratio
MBIPV	Malaysian Building Integrated Photovoltaics
NEM	Net Energy Metering
NZEB	Net-Zero Energy Building

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PV	Photovoltaic
SEDA	Sustainable Energy Development Authority
SHR	Sensible Heat Ratio
UKM	Universiti Kebangsaan Malaysia

1 Introduction

Because of the impact of greenhouse gases (GHGs) on the ozone layer, the average temperature of land and ocean surfaces has risen by approximately 1.5 °C between 1880 and 2020 [1, 2]. Buildings consume a massive amount of energy, mainly supplied through fossil fuels. Heating, ventilation, and air-conditioning (HVAC) systems are responsible for about 40% to 60% of a building's overall energy use [3, 4]. The need for air-conditioned cooling systems has surged even in certain regions where natural cooling was formerly sufficient. Ironically, the high energy consumption and use of chlorofluorocarbons (CFCs) that are inherent in conventional air-conditioning (AC) systems contribute to this environmental crisis (e.g., global warming and climate change) [5]. There are two types of approaches to reducing a building's energy consumption: active and passive. Moreover, both active and passive energy-efficient measures can improve the energy performance of a building [6]. The heating systems, appliances, cooling systems, and lighting systems fall under the active category, whereas improvements to the building's envelope (e.g., the walls [7], windows [8], and roofs [9]) would be considered the passive category. As depicted in Fig. 1, this chapter focuses on energy-saving active design techniques. Using an energy audit, a case study zone is chosen to investigate the cooling system's energy efficiency. Following the findings of energy measurement, a method of optimization is used to assess the energy-saving potential of designing and executing a solar desiccant cooling system as a possible solution.

In general, the consumption of energy by a cooling system (e.g., an air-conditioner) relies on various parameters, including the internal design temperature, external conditions, construction materials, and orientation of the building [10]. AC systems must be capable of removing both latent and sensible loads from each zone in order to provide effective cooling. The humidity and thermal load that must be removed from a building to attain thermal comfort are measured using the latent heat ratio (LHR) and the sensible heat ratio (SHR) [11, 12]. The SHR is the proportion of sensible heat to the total load, while the LHR is the proportion of latent heat to the total load [13]. Due to excessive dehumidification, the cooling systems' energy usage in hot and humid environments is more than in temperate regions since the value of LHR in tropical buildings is greater. AC application without adequate dehumidification raises the possibility of condensation on the walls and sick building syndrome, as cooling coils are incapable of handling the whole latent load [14]. Whereas, to offer sufficient mechanical dehumidification, certain issues, such as excessive cooling and inadequate indoor air quality, may arise. Consequently, balancing the cooling coil for the sensible cooling and dehumidification process is

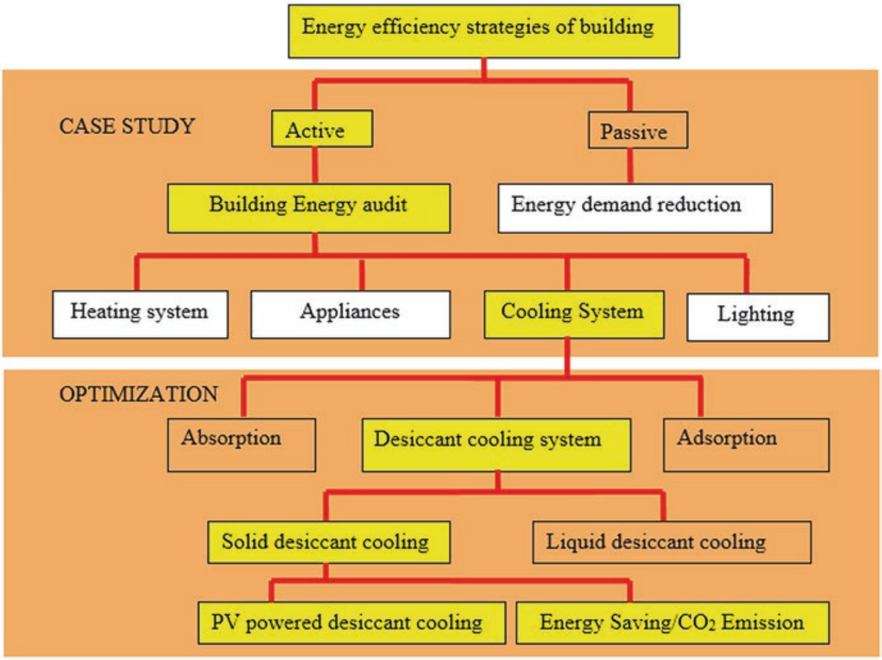

Fig. 1 The scope of the current research

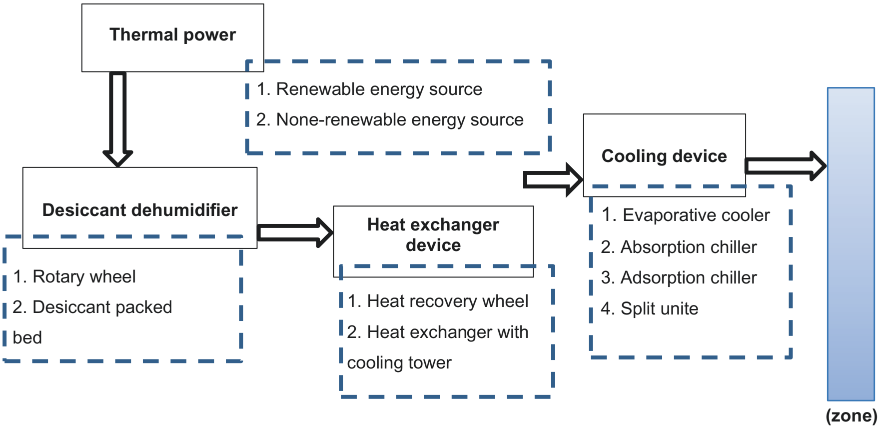

Fig. 2 Schematic diagram of the solid desiccant cooling system

the most significant hurdle. Desiccant cooling systems are capable of doing dehumidification and sensible cooling processes independently [15–17]. As shown in Fig. 2, generally, the desiccant cooling system consists of four main parts: desiccant dehumidifier [18], thermal regeneration source [19], heat exchanger device [20], and cooling device [21]. For each part, there is potential for using different materials and equipment that the cooling system designer can select based on the operation and weather conditions. Normally, the humid air becomes dry in the first step by crossing through the dehumidifier. In the second step, the heat exchanger acts as per-cooling to reduce dry air temperature while at the same time per heating for the regeneration side. Then, the air's temperature can reach the requirement set point in the cooling device by reducing temperature.

Desiccant cooling methods have a lower coefficient of performance (COP) than AC systems [22]. In recent decades, significant attempts have been made to improve the efficiency of desiccant cooling systems by simulating [23–25] and conducting experiments [26–28] in regions with diverse climatic conditions.

This chapter details the three steps of the design process for a PV-powered desiccant cooling system. To design and analyze a desiccant cooling system to be replaced with a conventional cooling system for a building or zone, an energy audit is required to achieve several variables, including cooling load, energy consumption, and thermal comfort. According to cooling load distribution, the LHR, and the SHR could be detected as well as potential energy saving. The desiccant cooling system will be recommended for building with high LHR (>40%). In the second step of the design process, the configuration of a desiccant cooling system can be selected and simulated in the TRNSYS software. The result obtained from the energy usage of a conventional cooling system and a desiccant cooling system can be compared, and according to the energy consumption profile, a PV system can be designed.

2 Building Energy Audit

Auditing a building's energy usage is a crucial step in the process of managing energy initiatives [29]. Energy audits are carried out for a number of reasons. In general, they are performed to specify when, where, and how much energy is used in buildings [30]. Energy audits are also carried out to propose strategies on how to cut energy expenses. There are three different levels of energy audits [31], according to the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE). In the level one audit, possible energy efficiency enhancements are identified, the basic building configuration is described, and the kind and nature of energy systems are assessed. In the level two audit, energy monitoring in building systems is used to conduct an exhaustive evaluation of energy consumption. In the level three audit, the potential energy savings, appropriate technology, implementation processes, cost, and payback period of all identified energy-saving measures are investigated in depth. For level three objectives, the building must be modelled in an energy modelling software package to discover the most efficient assessment of different efficiency scenarios [32].

Case Study

A case study in Malaysia adopted three levels of ASHRAE energy audit to evaluate building energy performance. The chosen case study contains one fan coil unit (FCU) as the conventional cooling system in the seminar room. The study space is situated on the fifth floor of a building (Fig. 3a) at the UKM that was built in Malaysia in 2013. This building's particular coordinates are 2° 55′ 13.0″. Malaysia

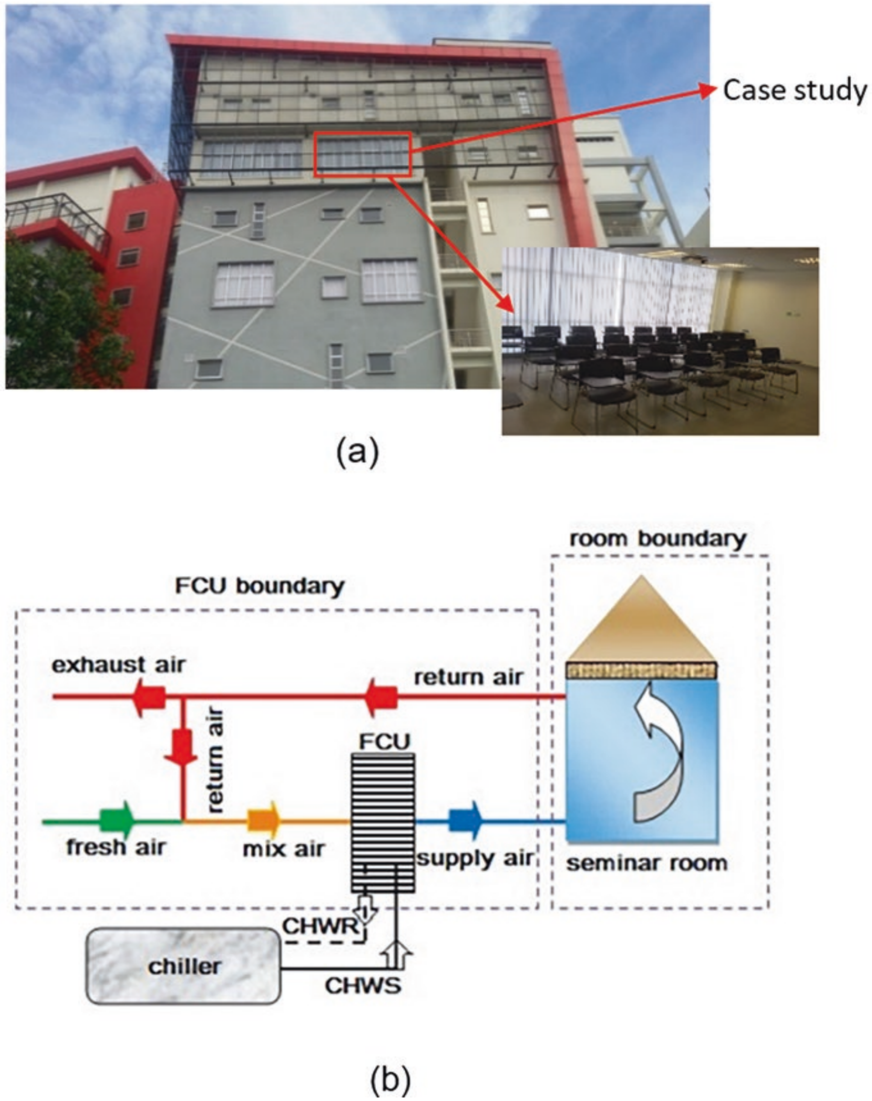

Fig. 3 (**a**) Case study location and (**b**) limitations of the case study [33]

is a country that is primarily located in a tropical climate—between 3° 5′ N and 101° 43′ E with a hot and humid environment. The maximum air temperature and humidity values are 30–38 °C and 70–90%, respectively. The case study was classified into two boundaries, namely, as depicted in Fig. 3b, an FCU's system and a room.

The FCU's system is equipped with four networks (fresh air, supply air, mixed air, and return air), a fan, a cooling coil, chilled water return (CHWR), and chilled water supply (CHWS).

Seminar Room Specifications

The selected space is 24 m^2 in size, and is employed for conferences and academic sessions with a 30 people-maximum occupancy. The space contains a total of four walls: two exterior (A and D) and two interior (B and C). Walls A, B, C, and D, respectively, face southeast (SE), northeast (NE), northwest (NW), and southwest (SW) (Fig. 4a). Windows make up 95% of wall area D (Fig. 4b). Both of the room's entrances are placed on wall B (corridor wall). Wall C connects the two rooms being used for the research. Walls, windows, and doors all play a role in the amount of heat gained or lost in a given space. Table 1 displays the details of these factors.

Fan Coil Unit (FCU) Specifications

The ceiling of the seminar room is outfitted with an FCU that sized 429 × 899 × 1475 (mm), has a capacity of 56,277 Btu/h, and discharges 9.5 (igpm) of water. Heat is transferred in the FCU's cooling coil using an air/water flow method. Figure 5 depicts the FCU's air and water flow mechanism that contributes to the case study's border. The sensible and latent heat of the room is transferred to the water (CHWR) in the cooling coil via a combination of both fresh air (green line) and return air (red

Fig. 4 (**a**) Position of room and (**b**) an internal view of the room [33]

Table 1 The room specifications

Subject	Dimension (cm)			Type	Material	U-value (W/m²K)
	Length	Width	Thickness			
Wall A	690	274	15	External wall	Brick plaster	2.16
Wall B	646	274	15	Internal wall	Brick plaster	2.16
Wall C	646	274	15	Internal wall	Brick plaster	2.16
Wall D	690	274	15	External wall	Brick plaster	2.16
Ceiling	690	646	35	Poorly insulated	Cement concrete	1
Floor	690	646	35	Poorly insulated	Cement concrete	1
Window	600	295	1	Single glazed	Glass	5.7
Doors	204	143	5	Swing door	Wood	3.05
Shades	600	295	0.2	sliding panels	fabric panels	–

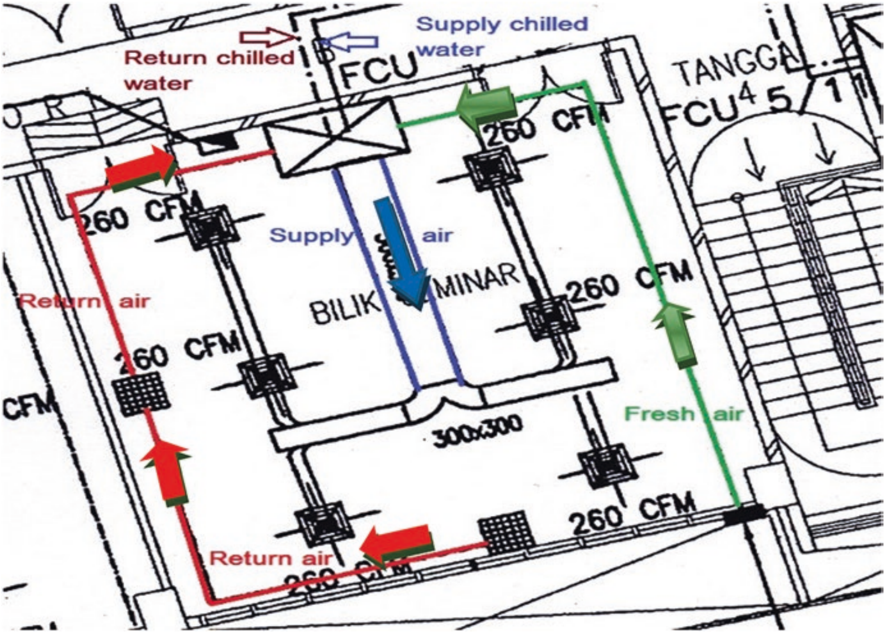

Fig. 5 The airflow mechanism in the fan coil unit (FCU) [33]

line). The blue supply air is dispersed throughout the room by means of six diffusers after having been mechanically dehumidified and cooled in the cooling coil. Three energy-intensive FCU parts were analyzed: the fan, the pump, and the chiller. The pump and chiller energy usage were tracked using the hydraulic power and cooling coil capacity, respectively. The fan system consists of a rotor and a direct current (DC) motor with a capacity of 2 kW.

Energy audits are a helpful tool for building owners in assessing energy use and adjusting boost efficiency. Three ASHRAE energy audit levels were employed to evaluate the seminar room in this research. Site assessments, often called preliminary audits, are a high-level overview of a building's energy system that can reveal missing pieces of information necessary for a thorough consumption breakdown [34]. According to observation, the seminar room's ambient temperature decreased to a level below that at which its occupants could remain comfortable, forcing them to dress in warm clothing. A rigorous energy audit at ASHRAE level two comprises in-depth studies into how energy is used and the identification of energy-saving methods. At level three, the auditing procedure also includes monitoring, data gathering, and engineering analysis. These were utilized as a reference to determine the precise energy allocation in the suggested cooling systems [35].

3 Measurement and Data Collection

According to the scope of the case study, the energy distribution in the FCU should be examined based on the seminar room load. Prior to measuring the cooling load and FCU energy consumption, each boundary's measurement parameters were defined. There are two types of measurement parameters: (a) the FCU-related parameters and (b) the room-related parameters. Both sorts of parameters must be measured and recorded concurrently. Table 2 illustrates the FCU's measuring parameters and their respective placements within the FCU system.

In most cases, the FCU perimeter will include a chiller, a pump, and a fan. To define the overall energy of the FCU, it is needed to measure and log the energy utilization of each component. By determining the air characteristics of the four air channels (fresh air, mixed air, supplied air, and return air), the FCU boundary may calculate the total energy consumed by the chiller in terms of the cooling coil capacity. Due to the fact that each fan is connected to its own FCU, its energy consumption can be monitored in real time via a fan key. Meanwhile, the rate at which chilled water is being pumped through the FCU can be employed as a proxy for the energy required to run the FCU pump. In this study, we installed the appropriate measurement equipment to track the parameters of the case study. The seminar room's initial temperature, temperature fluctuations throughout monitoring, and the room's

Table 2 Fan coil unit (FCU) measuring parameters

Purpose of energy monitoring	Requirement data	
	Parameters	Locations
Fan	Voltage	Key of fan
	Ampere	Key of fan
Chiller-cooling coil	Temperature of air	Mixed air, return air, supply air, fresh air
	Relative humidity	Mixed air, return air, supply air, fresh air
	Airflow rate	Supply air, fresh air
Pump	Chilled water flow rate	Chilled water pipe
	Differential ahead	Distance between pump to FCU

Table 3 The room's measuring parameters

	Measurement parameters	
Purpose of monitoring	Parameters	Locations
Sensible load	Temperature	Supply air
	Temperature	Return air
	Airflow rate	Supply air
Latent load	Humidity	Supply air
	Humidity	Return air
	Airflow rate	Supply air

sensible and latent loads were all measured by placing sensors along the room's perimeter. The case study involved continuous monitoring and recording of the room-related characteristics (Table 3), which were then used to calculate the sensible and latent loads.

All of the sensors, such as thermometers and hygrometers, as well as the flow metres for both water and air, were placed in their designated areas, as shown in Table 4. Figure 6 represents the setup of a data logger with all instruments attached to its channels for PC-based data logging. The data logger was configured to record data every 20 min between 8 AM and 6 PM in April 2019.

The accuracy of the installed apparatus, wiring, network, and data logger outputs was verified using manual measurements. The FCU temperature was set to 25 °C in accordance with ASHRAE standard indoor conditions. All over the six-month period of data collection, the room and FCU conditions remained unchanged. The collected data was analyzed to determine the cooling load and FCU performance.

Data Analysis

The acquired data are analyzed in terms of cooling load, cooling coil capacity, and energy distribution, which are explained below.

Cooling Load Analysis

The cooling load refers to the quantity of sensible and latent heat that a cooling system needs to eliminate from a closed space. In this study, the quantities of sensible and latent loads were determined based on the obtained data from the energy audit. According to the airflow rate and the temperature discrepancy between supply and return air, the sensible cooling load is estimated using the following equation [37]:

$$Q_{sl} = 1.26 \times m \times (T_2 - T_1) \tag{1}$$

Table 4 Measurement parameters of the room [36]

Type	No.	Equipment	Measurement parameter	Location of installation
Room	1	CR110 solar radiation transmitter, range from 0 to 1500 W/m^2, accuracy: 5% of reading	Solar radiation level, W/m^2	Staircase area
	2	TH-100 T/RH transmitter, accuracy: 2%, response time: 15 s	Temp/RH, °C/%	Staircase area
	3	Pt100 temperature probe SF 50–CRYO, the operating temperature of PTFE cable: from −100 to +80 °C	Temperature, °C	Outside of wall A
	4		Temperature, °C	Outside of wall B
	5	TH-100 T/RH transmitter, accuracy: 2%, response time: 15 s	Temp/RH, °C/%	Outside of wall C
	6	Pt100 temperature probe SF 50	Temperature, °C	Attached to window
Fan system	7	MAX-355 compact TRMS 400 A AC/DC clamp multimeter	fan unit Vrms (V), Irms (A)	Fan unit
Cooling system	8	TH-100 T/RH transmitter, accuracy: 2%, response time: 15 s	Temp/RH, °C/%	Before cooling coil
	9	TH-100 T/RH transmitter, accuracy: 2%, response time: 15 s	Temp/RH, °C/%	Seminar room ceiling
	10	GHD-30 T/RH transmitter for HVAC, accuracy: 3%	Temp/RH, °C/%	After mixer
	11	TH-100 T/RH transmitter, accuracy: 2%, response time: 15 s	Temp/RH, °C/%	Fresh air
	12	Type K thermocouple SKCT with a measuring range of −50 to +250 °C	Temperature, °C	CHWS (water piping)
	13		Temperature, °C	CHWR (water piping)
	14	DBM610-airflow meter, measuring range: 40–3500 m^3/h	Airflow rate	Diffuser
Data collection	15	Graphtec - GL840-WV Data Logger, ±20 mV to ±100 V over 12 ranges	Data logger	Control room

where the Q_{sl} (kW) is the sensible load, m (m^3/s) is the airflow rate, and the supply and return air temperatures are T_1 (°C), and T_2 (°C), respectively. In Eq. (2), the latent load is determined using the airflow rate and the humidity ratios between supply and return air [37].

$$Q_{ll} = 0.8232 \times m \times \left(HR_2 - HR_1 \right) \tag{2}$$

where Q_{ll} (kW) is the latent load, HR_1 (kg/kg) is the supply air humidity ratio, and HR_2 (kg/kg) is the return air humidity ratio (room air). When the sensible and latent loads are determined, the total cooling load needs to be calculated. The sum of sensible and latent loads is the total cooling load.

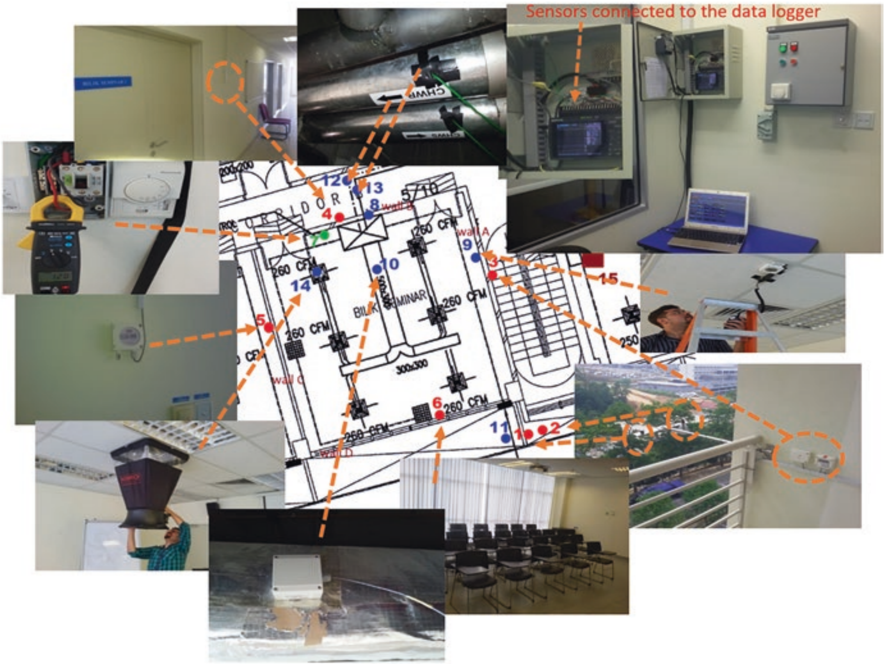

Fig. 6 Data collection setup for an energy audit of the case study [36]

$$Q_{tl} = Q_{sl} + Q_{ll} \tag{3}$$

Therefore, the total cooling load of the room, Q_{tl} (kW), is determined using the room's measured parameters.

Energy Usage Analysis

As discussed in the previous section, an FCU has three energy systems: a fan, a chiller, and a pump. To determine the energy allocation for the FCU, it is necessary to identify the parameters of each system. This section describes how energy is measured for each system. Voltage and current are necessary quantities in Eq. (4) to calculate the fan's energy usage.

$$P_{\text{f}} = V \times I \tag{4}$$

Here, P_{f} (kW) stands for fan power, V (V) for voltage, and I (A) for ampere. The energy usage of the chiller is determined by [38]:

$$E_{CH} = Q_{\text{cc}} / \text{COP} \tag{5}$$

where E_{CH} (kW) is the energy used by the chiller, and Q_{cc} (kW) is the cooling coil capacity. The catalogue provides information on the chiller's COP, which is stated there to be 3.2. The capacity of a cooling coil is defined as the combination of its sensible and dehumidification capacities. Eq. (6) is used to calculate the cooling coil's sensible capacity [37].

$$Q_{sc} = 1.26 \times m \times \left(T_{bc} - T_{ac}\right) \tag{6}$$

Here, the sensible cooling capacity of the cooling coil is denoted by Q_{sc} (kW), and the air temperatures before and after the cooling coil are represented by T_{bc} and T_{ac}, respectively. The dehumidification capability of the cooling coil is governed by [37]:

$$Q_{dh} = 0.8232 \times m \times \left(HR_{bc} - HR_{ac}\right) \tag{7}$$

HR_{bc} (kg/kg) represents the humidity ratio before the cooling coil, while HR_{ac} (kg/kg) signifies the humidity ratio after the cooling coil. Using the recorded differential head and chilled water flow rate, the following calculation is used to calculate the pump's energy consumption, as follows [39]:

$$P_{\mathrm{h}} = \left[q \times \rho \times g \times h\right] / \left[\eta\left(3.6 \times 10^{6}\right)\right] \tag{8}$$

where P_{h} (kW) denotes the hydraulic power, q (m^3/h) signifies the flow capacity, ρ (kg/m^3) is the density of the fluid, g is the acceleration of gravity (9.81 m/s^2), h (m) denotes the differential head, and η signifies the pump efficiency (equal to 0.6).

4 Results of the Energy Audit

The data from the case study's measurements are broken down into four categories for analysis: cooling load, air characteristics, cooling coil capacity, and energy consumption.

Cooling Load Profile

Cooling systems are designed to remove both the sensible and latent heat from a closed space [40]. Investigating the room's characteristics and cooling demand is vital to compute the necessary capacity of an AC system. The sum of the sensible and latent cooling loads in a given zone is proportional to the amount of heat gain in that zone. A building's heat gain can be broken down into two categories: external and internal. Infiltration, solar radiation, and heat conduction via walls, ceilings, and floors are all examples of external heat acquisition. In contrast to external heat gain,

Table 5 Details of cooling load of the seminar room

Subject	Details		Sensible load (kW)	Latent load (kW)
Building conduction load	Walls	Wall A: Orientation at SW, external wall, area: 17.7 m^2	0.646	–
		Wall B: Orientation at SE, area: 12.82 m^2	0.184	–
		Wall C: Orientation at NE, area: 17.7 m^2	0.119	–
		Wall D: Orientation at NW, area: 3.5 m^2	0.234	–
	Ceiling	The total area: 44.5 m^2	0.241	
	Floor	The total area: 44.5 m^2	0.239	–
Solar gain	Windows	Type: Clear single glass, orientation at NW, area: 16.44 m^2	0.996	
Service load	Lighting	Number of lights: 17, the capacity of each light: 36 W	0.762	–
	People	10 students	0.615	1.025
	Equipment	Data projector: 1 unit, capacity: 0.4 W	0.059	
	Infiltration	Door type: Double swing door number of doors: 2, area: 29,172 cm^2	0.344	2.135
		Windows type: Clear single glass, orientation at NW, area: 16.44 m^2	0.150	1.683
Total load			4.589/1.30	4.843/1.377
Total load (sensible + latent)			**9.432 kW = 2.677 tonnes**	

In this table, SW, SE, NE, and NW represent southwest, southeast, northeast, and northwest, respectively

which comes from the sun or other external sources, internal heat gain comes from things like people, lights, and appliances that are already present in the space. The results of the load calculation for the seminar room are shown in Table 5.

All load elements that have an effect on the cooling load of a seminar room are analyzed. Cooling loads are computed to show the impact of external and internal heat gains on sensible and latent cooling loads while cooling loads are observed to show how the sensible and latent loads were distributed at that moment. There are 1.30 tonnes of sensible load and 1.37 tonnes of latent load altogether. The latent load is mostly affected by air leakage through the door and windows, while the sensible load is primarily affected by solar gain via the windows. Therefore, the case study's total cooling capacity was 2.67 tonnes.

An illustration of the seminar room's measured cooling demand over the course of a day is presented in Fig. 7. The latent load of the room is higher than the sensible load, as seen by the total distribution of cooling load versus time. The data shows that every 20 min, the sensible and latent loads alternate between 4 and 5 kW.

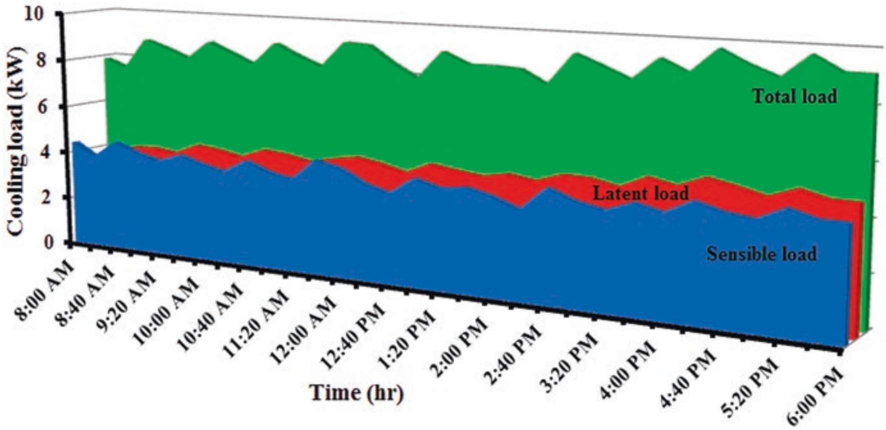

Fig. 7 Cooling load profile of the seminar room for 1 day

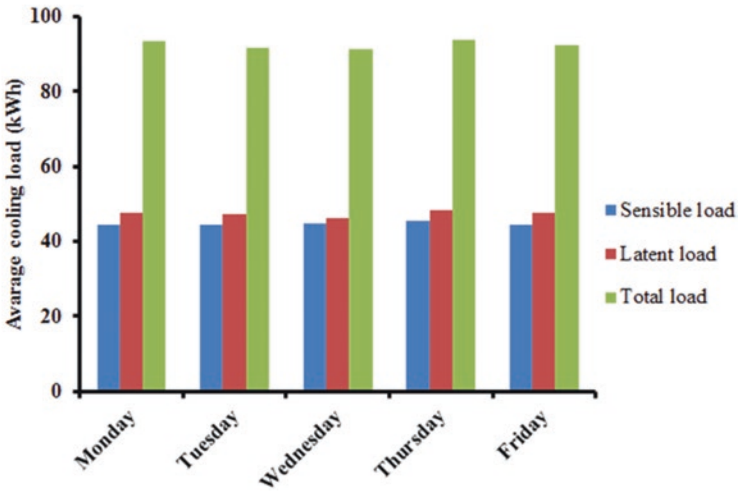

Fig. 8 Average cooling load during working days

The average sensible and latent loads for each day of the working days, broken down by hour, are displayed in Fig. 8. During those working days, the latent load exceeds the sensible load by a significant margin. Based on the numbers, it seems that the typical sensible and latent loads during those working days are around 40 and 50 kWh. The average daily cooling demand ranged from 90 to 95 kWh. In comparison with the latent load, which accounts for 51% of the total load, the sensible load only accounts for 49%. Thus, the SHR of the seminar room is 0.49. The mean sensible, latent, and total loads are 4.59, 4.77, and 9.36 kW, respectively.

Cooling Coil Capacity

The capability of a cooling system to dissipate heat is quantified by what is known as the system's cooling capacity [41]. Therefore, the sensible and latent capabilities of FCU can be considered as the amount of sensible heat removed in the cooling coil of FCU and the amount of latent heat removed in the FCU, respectively.

For one day (between 8 AM and 6 PM), Fig. 9 displays the FCU's sensible, latent, and total capacity. The time-capacity distribution of FCUs shows that the dormant capacity is greater than the active one. The total capacity is about 11 kW, with latent and sensible capabilities each around 4–5 kW.

Figure 10 demonstrates the typical weekday FCU capacity within 10 hours. When comparing sensible and latent capabilities throughout the working days, it appears that latent capacity is generally higher.

While the average latent capacity is between 60 and 70 kWh, the average sensible capacity is typically between 50 and 60 kWh. The total FCU capacity is between 90 and 125 kWh. The latent load is eliminated through the process of dehumidification. The FCU's latent capacity can be considered as its dehumidification capability. 7.28 kW is the average dehumidification capacity, and 5.78 kW is the average sensible cooling capacity. The cooling coil's overall capacity is 13.06 kW.

Allocating the capacity of the cooling coils shows that 44% of the entire capacity is used for sensible cooling, and 56% of the total capacity is utilized for dehumidification. In conclusion, mechanical dehumidification accounts for 56% of the energy used in the chiller's cooling coil. As a result, switching to chemical dehumidification from mechanical dehumidification can save 56% of FCU capacity.

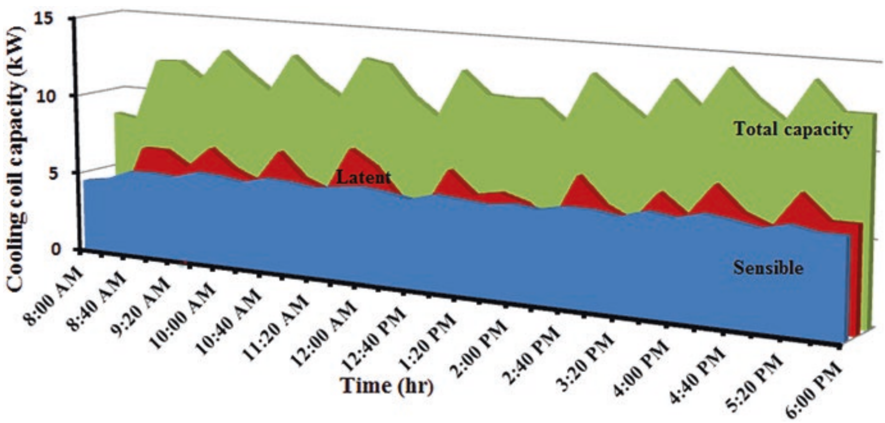

Fig. 9 Distribution of cooling coil capacity for one day

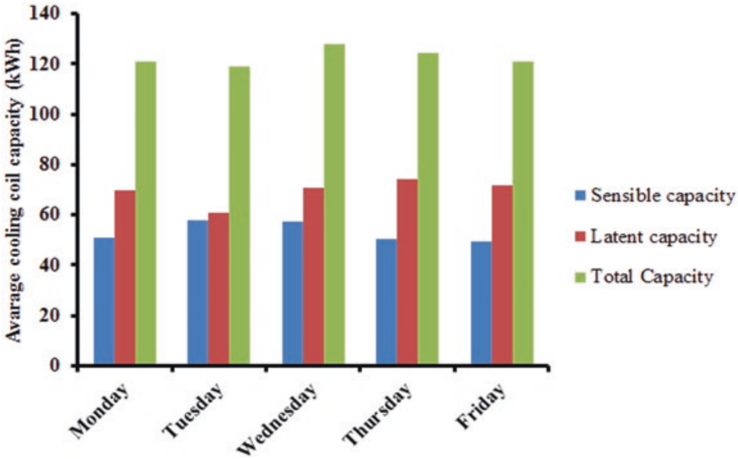

Fig. 10 Average capacity of cooling coil during working days

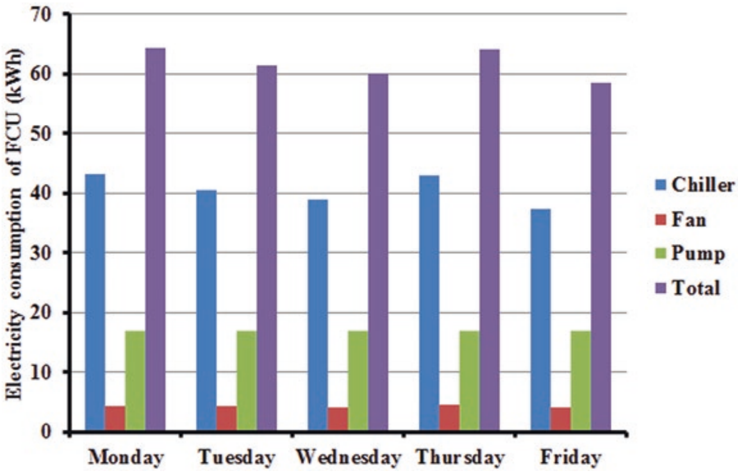

Fig. 11 Energy consumption of FCU components in working days

Energy Consumption

FCU's energy consumption is monitored and analyzed for two reasons. The first reason is to calculate daily, weekly, and monthly energy consumption. The second reason is to identify the aspect of FCU that has the potential to save energy. In the following, these two subjects are evaluated.

All three FCU components—the fan, pump, and chiller—are factored into the overall FCU energy consumption. Monday through Friday average energy use is displayed in Fig. 11. Throughout the working days, the chiller's power usage can range from 35 to 45 kWh. Both the fan and the pump have relatively consistent energy needs, at around 4 and 16 kWh, respectively. FCU's overall energy use fluctuates from 58 kWh on Mondays to 66 kWh on Fridays.

The energy consumption breakdown for FCU reveals that the fan, pump, and chiller are responsible for 7%, 27%, and 66% of the facility's overall energy needs. The chiller accounts for the vast majority of energy use, whereas the fan contributes only a fraction.

Since the chiller accounts for a sizable share of FCU's total energy consumption, this component seems like a natural place to look for opportunities to cut costs (the chiller). Chilled water is generated by the chiller and used in the cooling coil to aid in the dehumidification and sensible cooling processes. However, the cooling coil serves a dual purpose due to the chiller's energy use: both dehumidification and sensible cooling. Therefore, two broad categories can be applied to the chiller's total energy consumption: dehumidification and sensible cooling. Figure 12 reveals the measured energy use for dehumidification and sensible cooling during a month's worth of 20 working days. The average monthly energy use for dehumidification is 20–25 kWh, while the average monthly energy use for sensible cooling is 15–20 kWh.

The total energy, which is utilized in the chiller, is the sum of the sensible cooling and dehumidification energy used. The total energy ranges from 35 to 45 kWh for 20 working days. Figure 13 illustrates the energy consumption of sensible cooling and dehumidification during working days (i.e., Monday to Friday).

Energy usage in FCU is the sum of the energy used for different processes in the three main FCU components. Table 6 shows the average daily, weekly, and monthly amounts of energy consumption for each FCU process. The measurement results

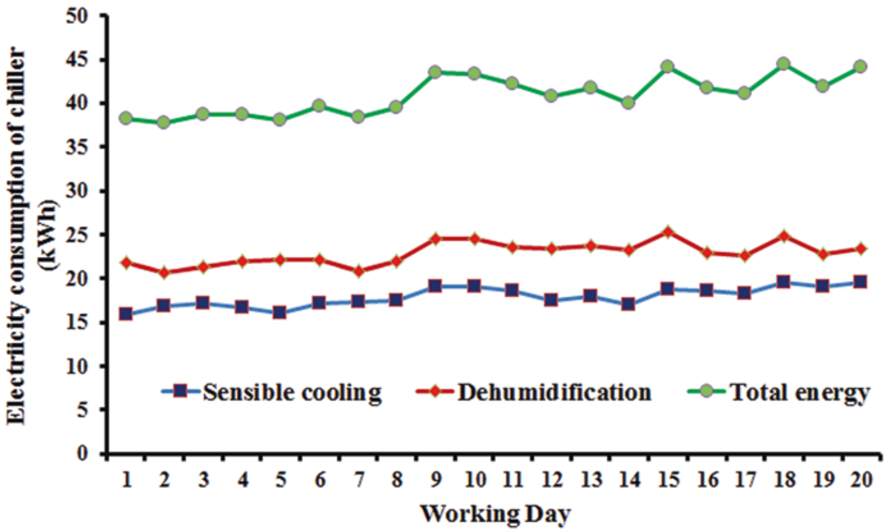

Fig. 12 Sensible and dehumidification energy consumption during working days in one month

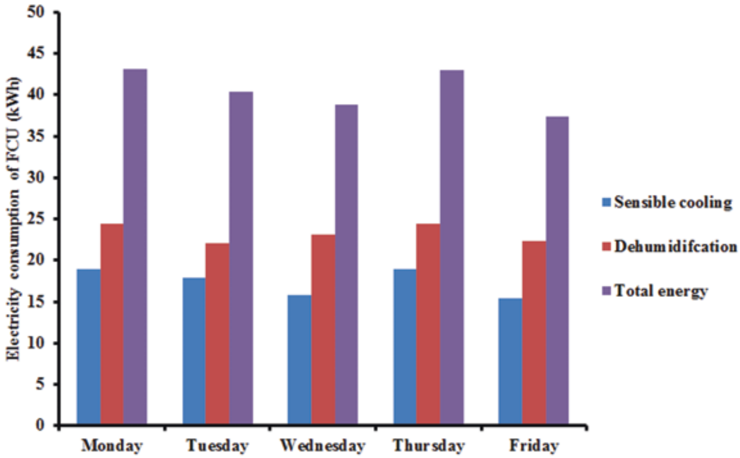

Fig. 13 Average sensible and dehumidification energy consumption during working days

Table 6 Average energy consumption of FCU components (kWh) during the day, week, and month

Period time	Dehumidification	Sensible cooling	Fan	Pump	Total (kWh)
1 day	22.8	18	4.28	16.8	61.88
1 week	117.4	94.73	21.40	83.77	317.30
1 month	454.63	360.97	83.32	338.34	1237.26

indicate that FCU's total daily, weekly, and monthly energy use are 61.88, 317.30, and 1237.26 kWh, respectively. The daily, weekly, and monthly energy use for the dehumidification process are respectively 22.8, 117.4, and 454.63 kWh, whereas those for sensible cooling are respectively 18, 94.73, and 360.97 kWh. Among the energy usage amounts in FCU processes, the daily, weekly, and monthly energy usage for dehumidification are clearly higher than those for the others.

To recognize the potential of saving energy in FCU, the energy distributions in various parts of FCU are clarified in Fig. 14.

The dehumidification process, sensible cooling, pump, and fan are responsible for 37%, 29%, 27%, and 7% of the total energy use, respectively. The energy distribution in FCU reveals that the largest portion of energy use in FCU is associated with dehumidification, which accounts for 37% of the total energy used in FCU. This energy amount can be saved if chemical dehumidification is employed instead of mechanical dehumidification.

Mechanical dehumidification in FCU needs significant energy under the hot and humid Malaysian climate [42–44]. Thus, dehumidification should be considered to save energy while using AC systems in Malaysia. In this study, chemical dehumidification is utilized instead of mechanical dehumidification to save energy.

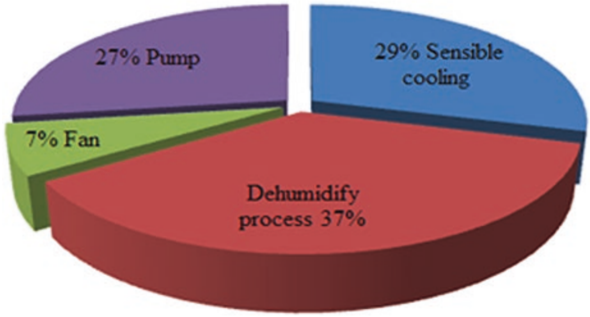

Fig. 14 Energy distribution in FCU process

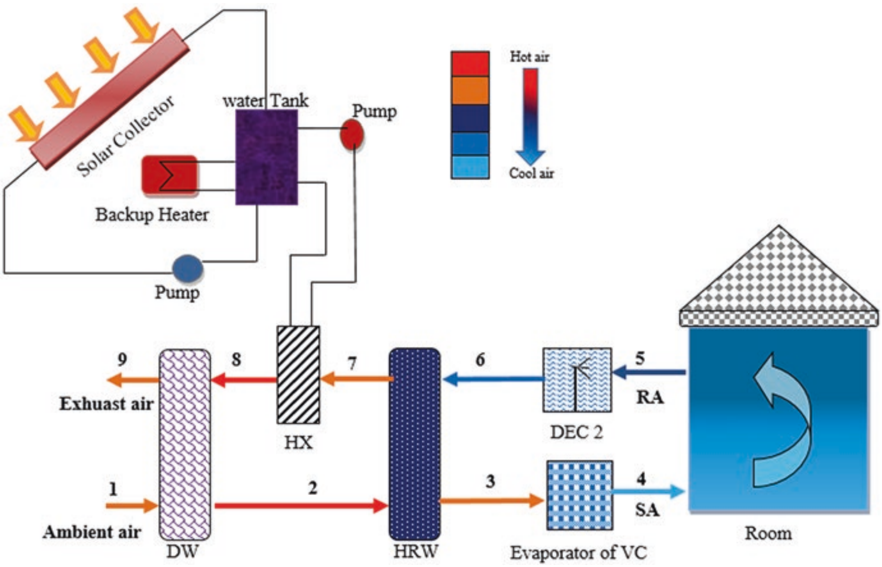

Fig. 15 Schematic design of a hybrid desiccant cooling system (HDCS) [36]

Hybrid Desiccant Cooling System (HDCS)

The hybrid desiccant cooling system (HDCS) is a form of the desiccant cooling system in which air is chilled by a split unit [45], chilled ceiling [46], or absorption chiller [47] following the chemical dehumidification process. Solar thermal energy has several applications in industry, such as dryers [48], adsorption cooling [49], and desiccant cooling system [50]. A schematic design of an HDCS is represented in Fig. 15. The desiccant wheel, heat recovery wheel, direct evaporative cooler on the regeneration side, and cooling coil on the process side are the essential elements that make up this system. Following the completion of the chemical dehumidification process (1–2), the heat recovery wheel (2–3) is responsible for cooling the process air, which is then completed by the cooling coil (3–4). The cooling coil is

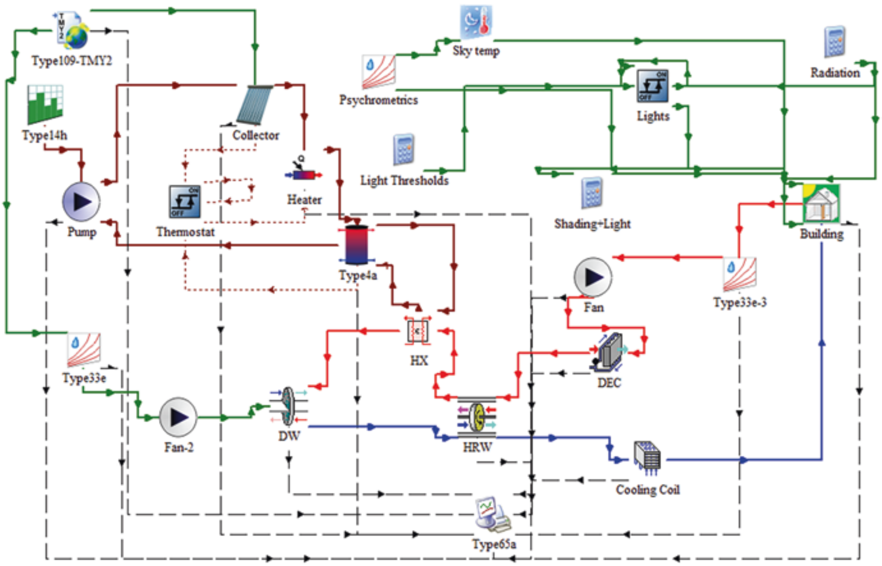

Fig. 16 Modelling of the hybrid desiccant cooling system (HDCS) in TRNSYS [36]

responsible for the mechanical process of dehumidification. Nevertheless, its capacity for dehumidification is considerably less than that of the FCU. The process side (1–4) of the hybrid system provides an airflow rate of 2321.1 kg/h, while the regeneration side (5–9) retained the same rate.

The TRNSYS16 software was utilized to simulate the performance of the proposed model (Fig. 16) when employed as an alternative cooling system to the FCU for the seminar room. The primary simulation components that are employed by the TRNSYS software are shown in [36].

The results of HDCS modelling were analyzed regarding thermal comfort and energy consumption. Case study cooling load and the ASHRAE standard indicate that supplied-air temperatures of 18.3 °C and humidity levels of 0.007 kg/kg are necessary to maintain a thermal comfort condition in the seminar room. The HDCS's psychometric chart is depicted in Fig. 17. By increasing the temperature to 54 °C (1–2), a one-stage chemical dehumidification method reduced the humidity ratio to 0.010 kg/kg. At point 3, the heat recovery wheel was used to reduce the temperature to 29 °C while maintaining a consistent humidity (2–3). The relative humidity in the supply air was dropped to 0.007 kg, and the temperature was dropped to 18.3 °C using a cooling coil (3–4).

The thermal comfort in the seminar room during FCU operation has been measured and analyzed in Sect. 2. Through a simulation in TRNSYS and the implementation of HDCS for the seminar room, the thermal comfort in the seminar room under the HDCS was determined. Due to the difference in the amount of supplied air produced by the FCU and HDCS, the temperature and relative humidity of the interior space were varied. The detected temperature and humidity of the seminar

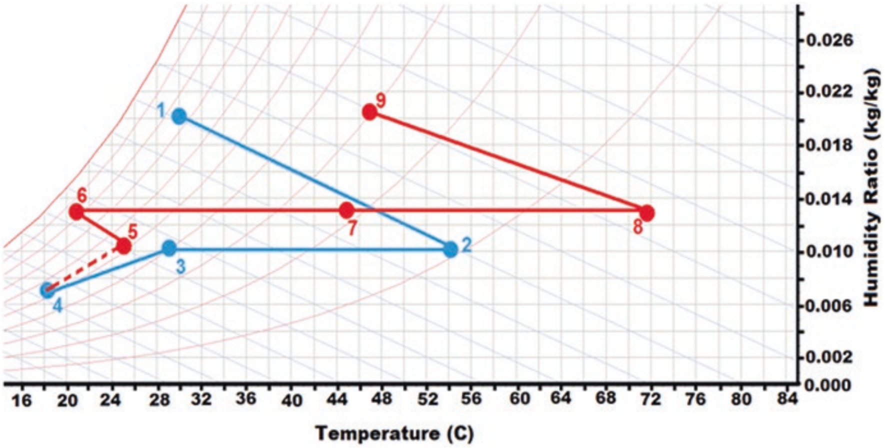

Fig. 17 Psychrometric chart of hybrid desiccant cooling system (HDCS) for the seminar room [36]

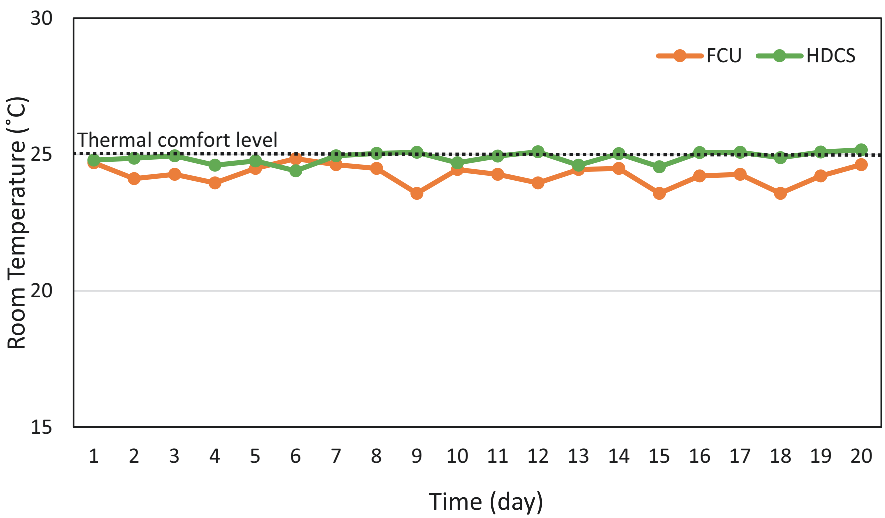

Fig. 18 Temperature of case study room under fan coil unit (FCU) and hybrid desiccant cooling system (HDCS) for one month

room under the application of both HDCS and FCU throughout the course of 20 business days are illustrated in Figs. 18 and 19, respectively.

According to these figures, the room temperatures under HDCS and FCU operation are close to the thermal comfort level (25 °C). In terms of achieved relative humidity of the room, HDCS was obtained to attain relative humidity close to 50%, whereas the relative humidity of the room under FCU was more than 75%. Therefore, model HDCS could deliver suitable supply air for the seminar room by combining

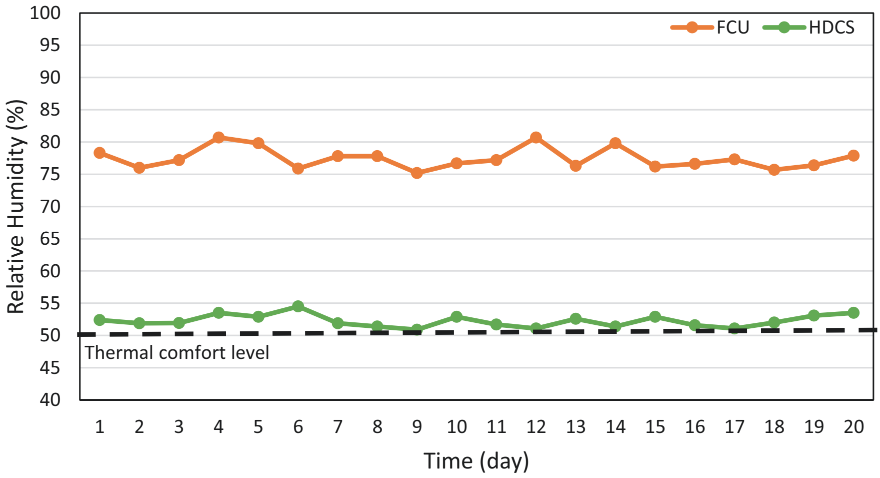

Fig. 19 Relative humidity of case study room under fan coil unit (FCU) and hybrid desiccant cooling system (HDCS) for one month

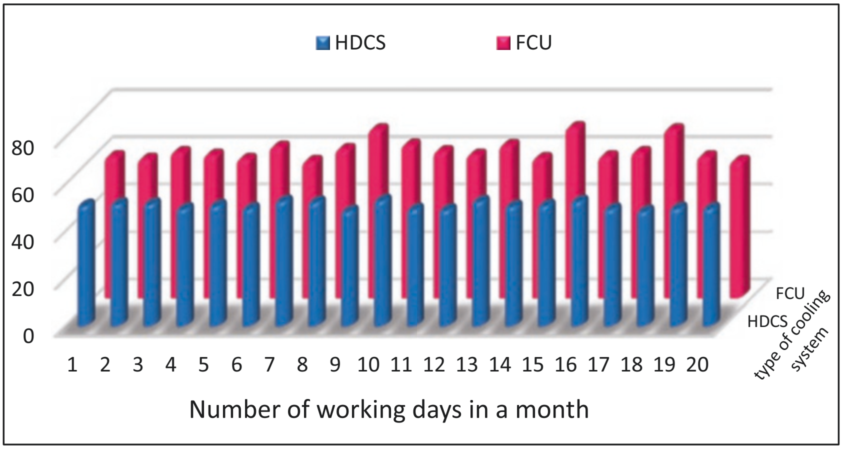

Fig. 20 Energy consumption of the case study fan coil unit (FCU) and hybrid desiccant cooling system (HDCS) for one month

a chemical dehumidification process in the desiccant wheel with a mechanical dehumidification process in the cooling coil.

When deciding on the most effective cooling system, it is vital to take into account both energy efficiency and the current thermal condition of the room [51]. The HDCS and FCU's (measured) energy consumption throughout the course of 20 working days in a month is shown in Fig. 20. The findings show that the daily average energy usage in HDCS was 50.99 kWh, with a range of 48.04–52.6 kWh. The average daily energy use at the FCU is 61.86 kWh, ranging from 57.3 to 71.5 kWh.

Hence, HDCS's overall energy consumption was 18% lower than FCU's overall energy consumption.

The FCU used 1237.26 kWh every month to keep the temperature and humidity at a constant 24 °C and 75%, respectively, as determined by the data collected through measurements and simulations. This means that the suggested model may replace FCU with large potential energy savings when results from both systems (FCU and HDCS) are compared in terms of room temperature and monthly energy usage.

In Sect. 2, an energy audit was employed to analyze the energy efficiency of a traditional cooling system (i.e., FCU). A desiccant cooling system has been modelled in Sect. 3 in accordance with the potential energy savings of FCU. A PV system is created for the case study in the following section using the PVsyst software in accordance with the energy demand profile of the desiccant cooling system.

Photovoltaic (PV) Systems in Malaysia

Malaysia is a tropical country close to the equator, having latitudes at 1° and 7° north and longitudes at 100° and 119° east, and has a high solar radiation potential between 3.7 and 5.56 kWh/m^2/day [52]. Since 2005 until the present, the Sustainable Energy Development Authority (SEDA) of Malaysia has established three main policies that encourage the development of PV system applications in Malaysia: Malaysian Building Integrated Photovoltaics (MBIPV), Feed-in Tariff (FiT) mechanism, and Net Energy Metering (NEM). In 2005, the MBIPV initiative brought solar PVs to the country as the first renewable energy policy. The goal was to speed up the switch to solar PVs, reduce the cost of Building Integrated Photovoltaics (BIPV) over time, and cut down on carbon emissions from traditional power plants. The initiative was a successful tool for overcoming obstacles and raising knowledge about the solar PV segment. Up to 2010, the program resulted in an installed capacity of 1.5 MW for an on-grid generation [53].

However, in 2011, Malaysian authorities enacted a FiT act to enhance renewable energy further and become more energy independent in the fight against climate change. Under the FiT procedure, the utility companies (Tenaga Nasional Berhad or Sabah Electricity Sdn. Bhd.) would acquire electricity produced from renewable resources from feed-in approval holders at the agreed-upon FiT rate for a fixed duration of 21 years, based on a power purchase agreement. Under the FiT program, the self-consumption of power is prohibited, and all electricity produced by solar PV systems must be transmitted to the grid. With initial rates of 1 and 1.2 RM/kWh, the FiT program in Malaysia enticed and encouraged the local community to install solar PVs. Since consumers instantly began reaping the financial rewards of the program, the FiT rates for solar PV technology decreased to RM 0.7 throughout the course of 6 years (2012–2018). As of the end of 2018, a total of 381.5 MW of solar PVs has been installed during 2011–2018, and work on a few more megawatts is still ongoing [53].

In 2016, the NEM program was introduced to encourage utility customers to reduce their overall electricity use by producing and consuming their own renewable energy. In this setup, a two-way energy meter is utilized to keep track of the inbound and outbound quantities of power. As a result, the consumer pays just for their actual net electricity consumption [54]. Government green initiatives in Malaysia are currently geared toward fulfilling the country's 20% renewable energy mix goal by 2025. However, sources of renewable energy (including solar PVs) account for only 2% of the total electricity-generating capacity in Malaysia despite various incentives and policies to support the growth of the renewable energy sector. In particular, only 9.14 MW of the total installed capacity of solar PVs in Malaysia comes from the residential sector. The majority of the country's PV capacity (i.e., 25.60 MW) is utilized by commercial enterprises and industries (i.e., 355.76 MW) [55]. Thus, further work is needed to promote the use of solar PV technologies, particularly in Malaysian homes [56]. In Malaysia, 3.2 million landed residential properties are mainly undeveloped. Approximately more than 1000 residences have installed solar PV panels currently [57].

The BIPV is an impressive sight for Malaysian buildings that employ a cooling system year-round. It can greatly minimize cooling system energy consumption by reducing the cooling load and producing electricity. The concept of BIPV is solar energy generation products or systems that are concealed within the structure envelope. As cladding components, PV systems can be integrated into external shading devices, roofing tiles, rain-screen cladding, curtain walling, and ventilated facades. Figure 21 shows various strategies for PV panel integration with architectural elements.

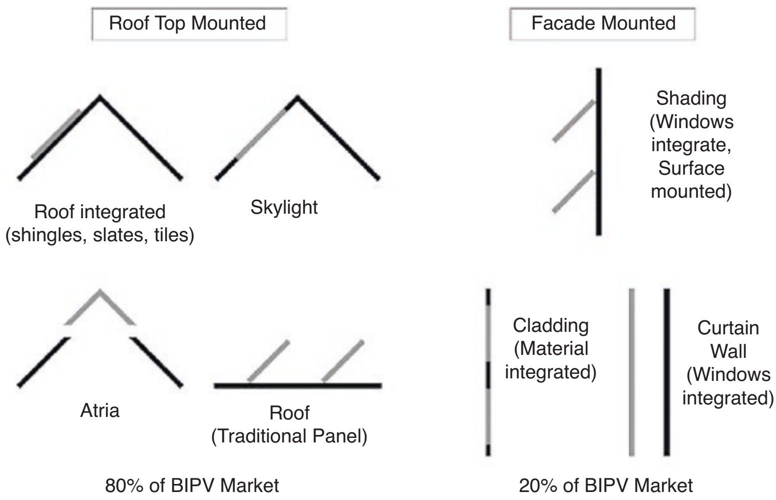

Fig. 21 Diverse building integrated photovoltaics (BIPV) implementation strategies and methodologies [58]

Fig. 22 7.8 kWp photovoltaic (PV) rooftop installation in a Malaysian home [59]

Rooftop PV systems are the most prevalent BIPV in Malaysia, as they are the most practical option for the vast majority of villa homes. Figure 22 depicts a BIPV system installed in a Malaysian residence with a capacity of 7.8 kWp under the FiT program.

Local production of PV panels is an additional factor boosting the adoption of PV systems in the country. Malaysia was the world's third-largest producer of solar equipment in 2014. Table 7 lists the primary manufacturers, plant locations, number of production lines, and annual production capacities of Malaysia's PV panel manufacturers.

Numerous multinational manufacturers, including First Solar, SunPower, Q-Cell, and Jinko Solar, invested in Malaysia's PV production lines due to favourable banking loans, fair regulation, beneficial tax incentives, competitive labour costs, and superior infrastructure and services.

PV systems' energy production potential depends on solar radiation and local weather conditions. The effective weather data of Kuala Lumpur, Malaysia, including solar radiation, temperature, and wind velocity, are displayed in Figs. 30, 31, and 32, respectively, in Appendix. The data are extracted from the PVsyst software.

Photovoltaic (PV) Simulation for the Case Study

In order to design a PV system with the PVsyst software, three steps are required, consisting of site location and meteorological data (step 1), load profile, a PV and an inverter selection (step 2), and the evaluation of the results (step 3). As demonstrated in Fig. 23, an on-grid PV configuration was selected, containing a PV array, an inverter, and a grid connection.

Table 7 Photovoltaic (PV) manufacturers in Malaysia [60]

Manufacturer	Location	Production capacity (annually)	Production line
First Solar	Kulim Hi-Tech Park	2000 MW (solar cells), 100 MW (solar modules)	24
SunPower	Malacca	1400 MW (solar cells)	28
Q-Cells	Cyberjaya	1100 MW (solar cells), 800 MW (solar modules)	4
Jinko Solar	Penang	500 MW (solar cells), 450 MW (solar modules)	7
Panasonic	Kulim Hi-Tech Park	300 MW solar modules	–
LONGi Solar	Kuching, Sarawak	600 MW (solar cells), 600 MW (solar modules)	–
TS Solartech	Penang Science Park	500 MW (solar cells)	7
JA Solar	Penang	400 MW (solar cells)	–

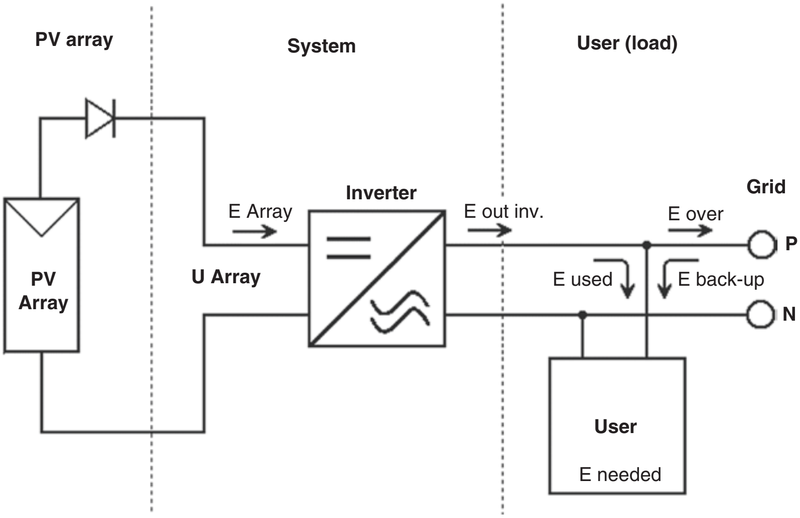

Fig. 23 Configuration of a photovoltaic (PV) system

Meteorological Data

According to the case study building location described in Sect. 2, meteorological data (Table 8), such as temperature, solar radiation intensity, and average wind speed, were imported into the software.

Table 8 Meteorological data of the case study location

	GlobHor (kWh/m²)	DiffHor (kWh/m²)	T_Amb (°C)	WindVel (m/s)	GlobInc (kWh/m²)	DifSInc (kWh/m²)	Alb_Inc (kWh/m²)	DifS_Gl (ratio)
January	134.5	76.33	27.32	1.6	146.0	51.42	0.810	0.000
February	132.7	73.69	27.93	1.6	137.6	46.04	0.799	0.000
March	154.2	85.73	28.27	1.6	151.2	51.85	0.930	0.000
April	143.2	76.35	27.96	1.5	131.7	46.72	0.863	0.000
May	145.3	79.31	28.72	1.7	126.5	50.60	0.876	0.000
June	133.0	76.84	28.21	1.7	113.7	48.20	0.802	0.000
July	134.7	86.20	28.21	1.8	117.5	56.04	0.812	0.000
August	136.9	82.86	28.20	1.7	124.7	52.04	0.825	0.000
September	133.6	75.50	27.38	1.7	128.4	46.84	0.806	0.000
October	140.5	84.87	27.77	1.6	142.8	54.17	0.847	0.000
November	124.9	70.71	26.85	1.4	133.2	46.57	0.753	0.000
December	121.6	67.46	27.27	1.5	132.3	48.18	0.733	0.000
Year	1635.3	935.85	27.84	1.6	1585.6	598.67	9.856	0.000

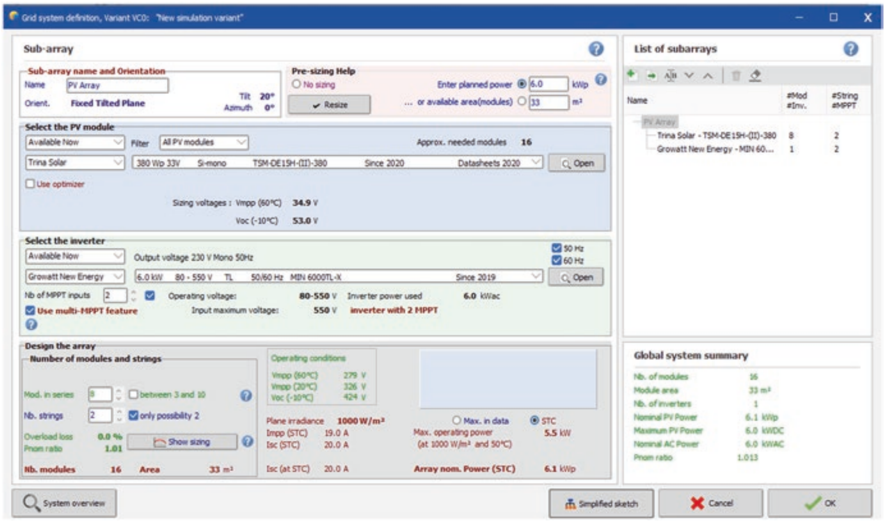

Fig. 24 Power load, photovoltaic (PV), and inverter selection in the PVsyst software

Load Profile, Photovoltaic (PV), and Inverter

Based on the load profile of the desiccant cooling system depicted in Fig. 20, a PV system with a 6-kW capacity is selected. As illustrated in Fig. 24, sixteen 380-W PV panels and a 6-kW inverter are chosen for the PV and inverter selection.

PV-inverter sizing optimization was analyzed based on the I–V curve and inverter output. Figure 25 demonstrates that the PV output voltage (340–380 V) falls within

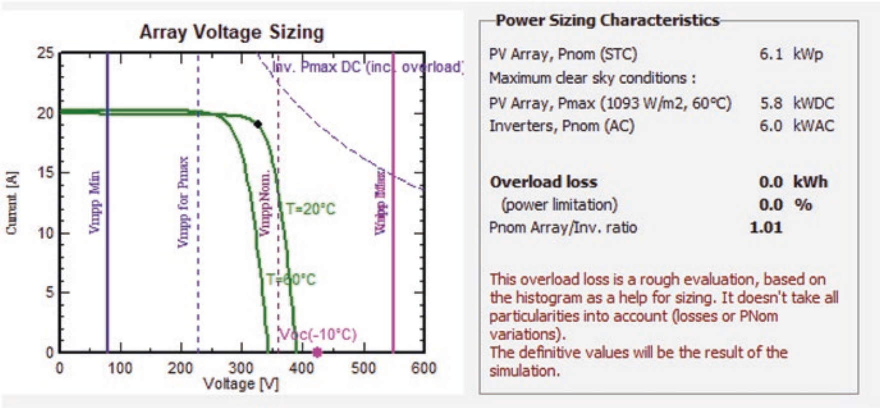

Fig. 25 I–V curve and inverter output

the inverter input capacity range (80–550 V). The Pnom array/inverter ratio was 1.01, which is optimal and resulted in zero per cent overload losses.

Results of PVsyst Simulation

Figures 26 and 27 show the simulation results in terms of daily energy generation and PV system performance, respectively. The daily energy production of the PV system ranges between 30 and 40 kWh, which is nearly equal to the daily energy use of the proposed desiccant cooling system. The PV system has an overall efficiency of 83%.

After PV system installation, the amount of power injected into the grid during the day is determined by two primary factors: PV system losses and total solar radiation received by the panels (global incident). Figure 28 depicts the amount of losses in the PV-array and the inverter, as well as the output power from the inverter (useful energy), for the intended system throughout the course of the year.

Figure 29 represents the impact of the second effective variable (global incident) on the system's energy production. By boosting solar radiation from 2 to 8 kWh per square metre per day, the amount of energy fed into the grid will increase from 10 to 40 kWh per day.

5 Conclusion

The viability of a solar-powered cooling system was evaluated in three phases in this chapter. In the initial phase, an energy audit was conducted to define the potential for energy savings by analyzing the performance and energy consumption of an FCU cooling system as the principal building energy consumer in a tropical region. The findings of the FCU energy audit indicated that the seminar room could not

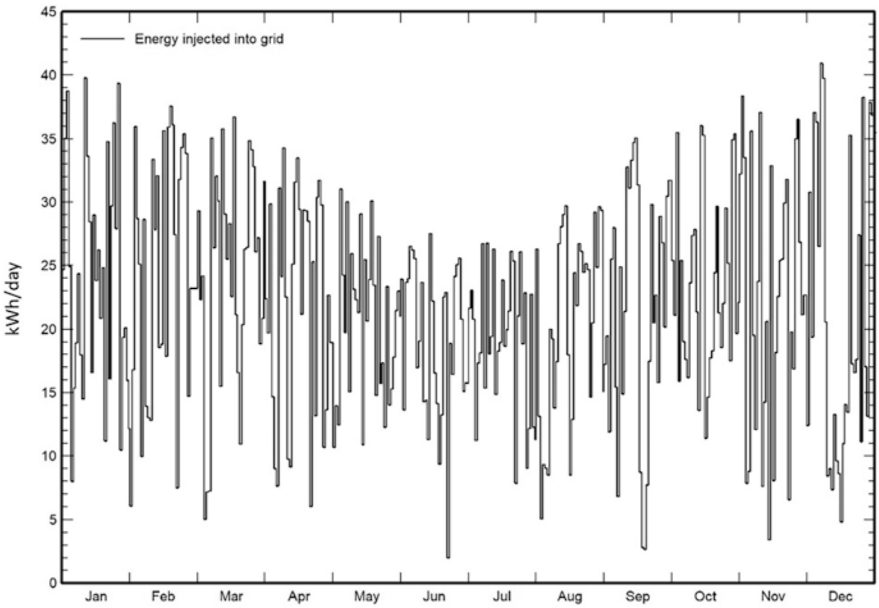

Fig. 26 Daily photovoltaic (PV) system output per kWh for one year

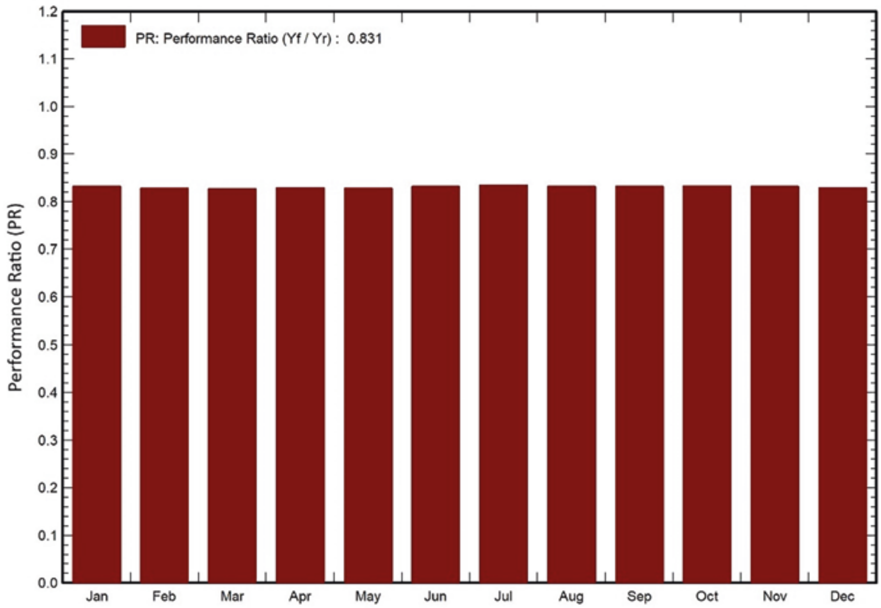

Fig. 27 Performance of photovoltaic (PV) system for one year

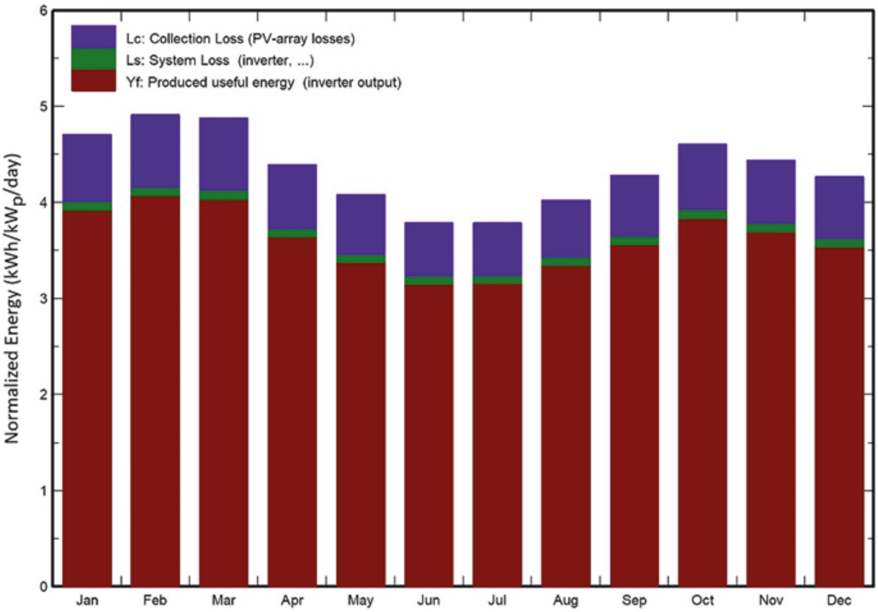

Fig. 28 Apportion of energy losses and useful energy for one year

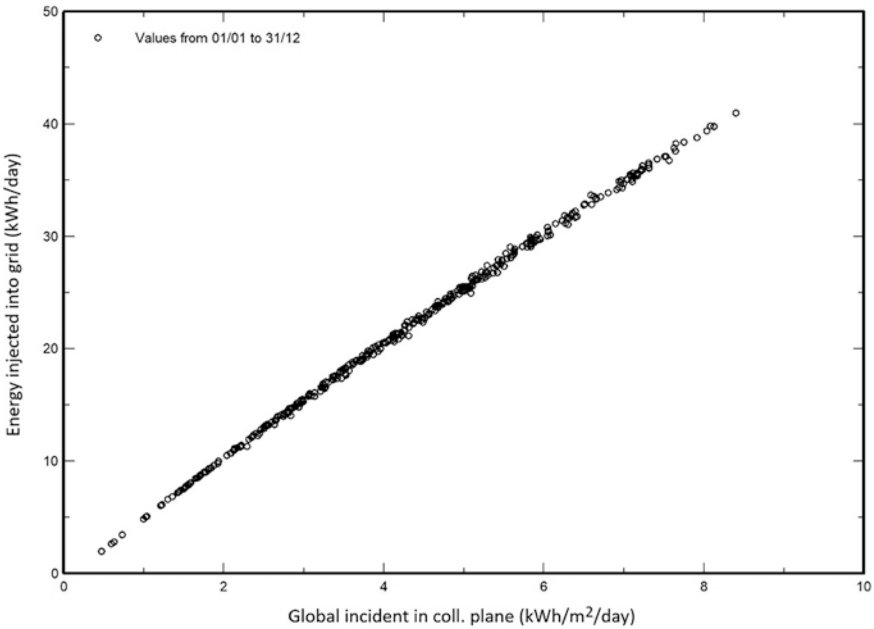

Fig. 29 Energy injected into the grid versus total solar radiation on the PV-array

achieve thermal comfort under FCU because the relative humidity was greater than 50%. It was determined that the high energy use of cooling systems in hot and humid climates is attributable to mechanical dehumidification, which accounted for 37% of FCU's overall energy consumption. Hence, the dehumidification process has been identified as a crucial component of the cooling unit that can be replaced by chemical dehumidification to conserve energy.

In phase two, an HDCS was simulated in TRNSYS and implemented in the case study room. The TRNSYS simulation demonstrated that the HDCS is able to deliver thermal comfort conditions for the case study room with the possibility of energy savings ranging from 17% to 37% based on desiccant cooling system configuration and operation conditions.

In phase three, a PV system is constructed based on the HDCS energy profile using the PVsyst software. It was determined that sixteen 380-W PV panels and a 6-kW inverter with an efficiency ratio of 83% can supply the daily energy requirements for the HDCS. Overall, this study can be used for other buildings located in tropical regions.

Appendix: Effective Weather Data for Kuala Lumpur, Malaysia

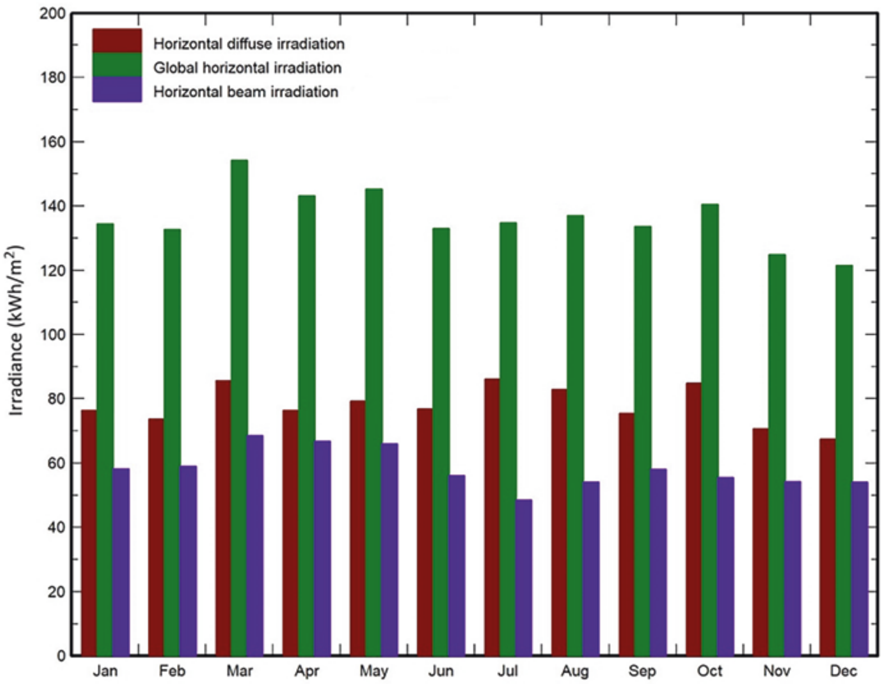

Fig. 30 Solar radiation at site location for one year

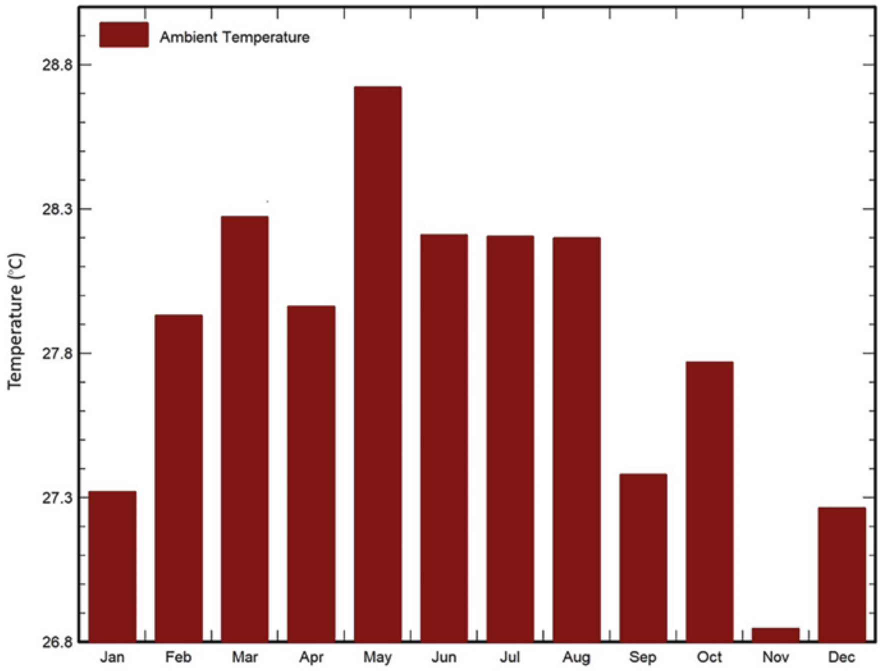

Fig. 31 Temperature profile at site location for one year

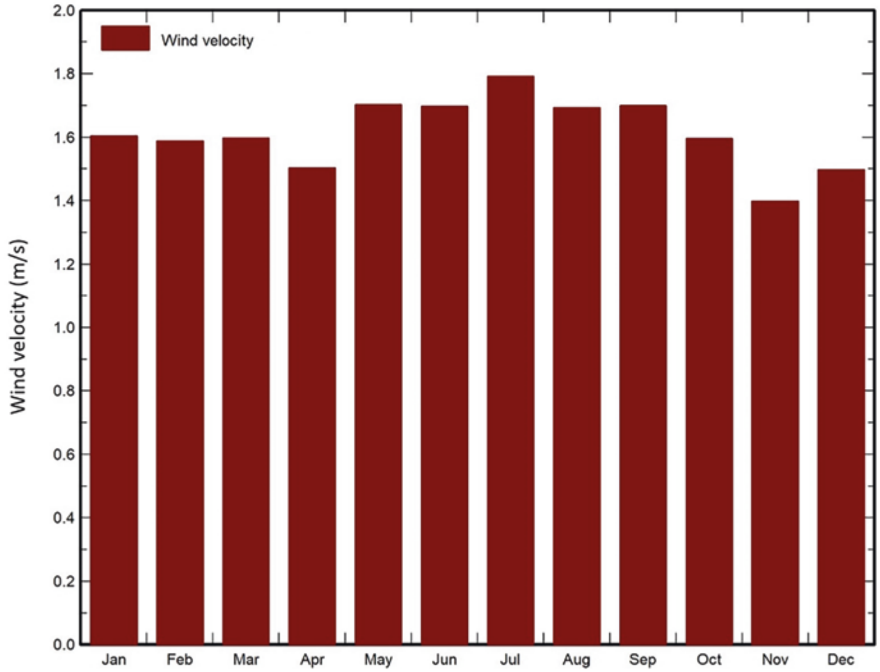

Fig. 32 Wind velocity profile at site location for one year

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Photovoltaic Applications in the Built Environment in the UK

Tony Book and Ali Sayigh

1 Introduction

Since 2020, electricity prices have gone much higher in a shorter period (2020–2022) than expected due to the Ukraine War. This is shown clearly in Table 1 [1]. However, in 2022, the kWh UK prices rose from 28 to 34 p it then was capped by the government. UK now has the highest electricity price globally.

However, as far as PV installation is concerned the UK is ranked number 13, globally, and third in Europe, see Table 2.

Globally PV power by the end of 2021 was **843.086 GW**. It is estimated that PV power is supplying 5% of global electricity.

According to the contributor in this book, their countries' situation in having PV installation is shown in Table 3.

2 Photovoltaic Application in the UK

Starting with London, the plan is to make the city achieve zero carbon emission before 2050. So far over 2100 homes have PV panels and more than 160 homes have battery storage. UK employs more than 5500 people in the PV industry and there are more than 80 companies which are specialized in installing PV systems.

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Table 1 Cost of domestic electricity price in UK Pence per kWh

No	Country	2016	2021	% difference
1	Norway	4.78	9.11	91
2	Finland	8.28	11.31	37
3	Czech Republic	9.41	12.69	35
4	Denmark	8.80	11.85	35
5	United Kingdom	14.35	19.31	35
6	Greece	9.62	12.63	31
7	Netherlands	10.84	13.98	29
8	France	8.61	11.05	28
9	Poland	8.96	11.09	23
10	Ireland	15.86	18.99	20
11	Germany	11.35	13.58	20
12	Spain	15.67	18.51	18
13	Belgium	13.66	16.34	18
14	Austria	10.13	11.76	16
15	Slovakia	10.49	12.03	15
16	Luxembourg	10.42	11.92	14
17	Canada	7.09	8.08	14
18	Switzerland	12.97	14.00	06
19	Japan	15.07	15.64	04
20	Australia	13.61	14.01	03
21	Portugal	10.04	9.87	02
22	Hungary	7.33	6.76	–08
23	Korea	7.76	6.93	–11
24	Turkey	8.34	5.67	–30

According to the UK Government at the end of 2020, there are 970,000 homes with PV installations which is representing only 3.3% of the 29,000,000 UK homes [3].

A typical solar home development in the UK is shown in Fig. 1 [4].

In addition to solar homes, there are 500 solar farms in the UK with 10 GW installations, the largest five of them are:

1. **Shotwick Park solar farm**, is located in Flintshire, Wales having 72.2 MW power covering 250 acres of land and supplies 70% of the paper mills's electricity requirement, saving more than 22,500 tonnes of CO_2 emission per year. It is one of the largest solar farm, in Europe, see Fig. 2.
2. **Lyneham solar Farm,** it was developed by the Ministry of Defence in Bradenstoke, Wiltshire in 2015 with power capacity of 69.8 MW, covering an area of 213.3 acres, covered with 160,000 PV panels, supplying electricity to 10,000 homes.
3. **Owl's Hatch solar Farm** was built in March 2015 with power capacity of 51.9 MW.

Table 2 Top 12 countries that installed most PV power in the World. At the end of 2021, [2].

No.	Country name	PV power – GW	% of world total
1	China	306.973	36.41
2	USA	95.209	10.47
3	Japan	74.191	8.16
4	Germany	58.461	6.43
5	India	49.684	5.47
6	Italy	22.698	2.50
7	Australia	19.076	2.10
8	South Korea	18.161	2.00
9	Vietnam	16.660	1.83
10	Spain	15.952	1.76
11	France	14.718	1.62
12	Netherlands	14.249	1.62
13	**United Kingdom**	**13.689**	**1.51**
14	Brazil	13.055	1.44

Table 3 Additional 10 countries PV power installation by the end of 2021 [2]

No.	Country name	PV power – GW	% of world total
1	Poland	6.257	0.74
2	Portugal	1.801	0.21
3	Malaysia	1.787	0.21
4	Oman	0.138	0.02
5	Austria	2.692	0.32
6	Egypt	1.675	0.20
7	Canada	3.630	0.43
8	Bahrain	0.011	0.001
9	Iran	0.456	0.054

The farm was built on 212 acres south of Herne Bay, in eight locations, installed at 22-degree with the horizontal and standing at 2.4 m high, supplying electricity to 14,000 homes with the land is being used for agricultural purposes.

4. **Wroughton Airfield solar Park is** funded by private investors, then by Public Power Solution and the Science Museum Group, covering an area of 165 – acre.
5. **West Raynham solar Farm** was built also in March 2015 and consists of 200,000 PV panels covering 225 acres. The Farm has power capacity of 49.8 MW, supplying its power to 11,000 homes. The Farm was built on a disused airfield near Fakenham.

The installed PV capacity by the end of 2022 was more than 14.6 GW. Cornwall is the best site in the UK having 8076 PV installations. Regarding solar farms, there are 58 sites already located to have 17 GW of PV installations before 2030.

Fig. 1 A typical home development, in the UK with PV installation.

Fig. 2 Shotwick Park, solar farm, [5]

PV panels can be installed in various orientations whether in BIPV or in BAPV. Figures 3, 4, and 5 show the various systems including when they are installed in northern climate zones in order to benefit from additional daylighting in the buildings. Therefore, it is possible to use PV on a vertical service.

Fig. 3 *Office Buildings Complex in Shorewood, WI, USA, more than 25 m high, has* "120-module, 54 kW solar array is producing 58,000 kWh annually". Planned to avoid shading with full safety in mind [6]

Fig. 4 The use of PV for agriculture, project AIAS, an EU project representing different countries [7]

Fig. 5 Architectural solar glass – PV canopy, https://www.polusolar.co.uk, [8]

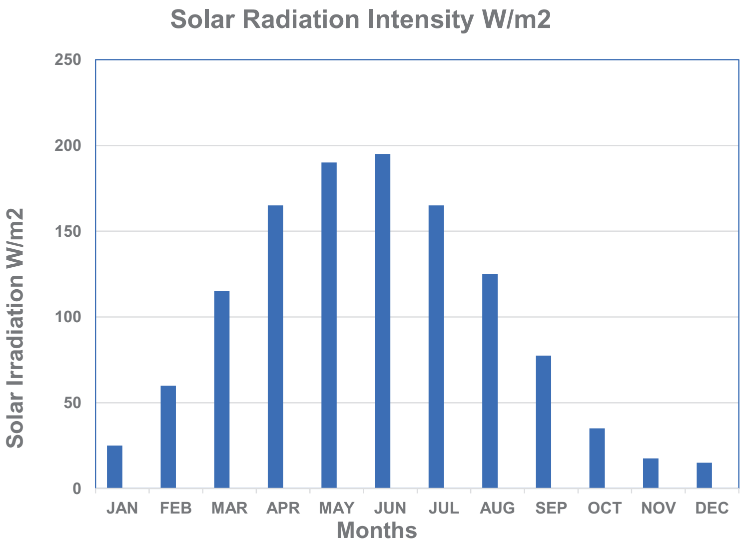

Fig. 6 UK solar irradiation in W/m^2 during the year [9]

3 Some Radiation Data of London, UK

Although the variation among different cities in the UK is not great, it was decided to use London as the main reference. Figure 6 shows the UK solar irradiation in W/m^2 during the year. This is an average during the last 7 years [9].

Fig. 7 PV output in kWh per radiation intensity kW_p at various locations in the UK [10]

Figure 7 illustrates on the map of the UK, despite the small variation in solar intensity of various regions, the amount of electricity in kWh can be generated from one installed kW_p of PV panel.

The average temperature in three locations in the UK is shown in Table 4 [11].

Table 5 shows the hours of sunlight in three different locations in the UK (Table 6).

Table 4 The daily average high and low air temperature at 2 m above the ground [11]

High	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
London	9°C	9°C	11°C	14°C	17°C	20°C	23°C	22°C	19°C	15°C	11°C	9°C
Manchester	8°C	8°C	10°C	13°C	17°C	19°C	20°C	20°C	17°C	14°C	10°C	8°C
Newcastle	6°C	7°C	9°C	11°C	14°C	17°C	19°C	19°C	16°C	13°C	9°C	7°C

Low	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
London	4°C	4°C	5°C	7°C	10°C	13°C	15°C	15°C	13°C	10°C	7°C	5°C
Manchester	3°C	3°C	4°C	6°C	8°C	11°C	13°C	13°C	11°C	8°C	5°C	3°C
Newcastle	2°C	2°C	3°C	4°C	7°C	9°C	11°C	11°C	9°C	7°C	4°C	2°C

Table 5 The number of hours during which the Sun is at least partly above the horizon

Daylight	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
London	8.4h	10.0h	12.0h	14.0h	15.7h	16.6h	16.1h	14.5h	12.6h	10.6h	8.8h	7.9h
Manchester	8.1h	9.9h	12.0h	14.1h	16.0h	16.9h	16.4h	14.7h	12.6h	10.5h	8.6h	7.6h
Newcastle	7.9h	9.7h	12.0h	14.2h	16.2h	17.3h	16.7h	14.8h	12.6h	10.4h	8.4h	7.3h

Table 6 The average monthly wind speed in the UK in three locations

Wind speed (kph)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
London	21.1	20.3	19.5	17.6	16.9	16.0	15.8	16.0	17.1	18.5	19.0	20.1
Manchester	21.9	21.0	20.0	17.7	17.0	16.1	16.0	16.1	17.4	18.9	19.6	20.6
Newcastle	26.6	25.0	23.1	19.6	18.0	16.9	16.7	17.8	20.0	21.9	23.6	25.0

4 Panel Orientation

This concept is very important to achieve maximum solar intensity gain by having the optimum tilt of the PV panels facing south but at an angle which depends on latitude, azimuth angle, and sun declination angle with the months of the year. It is important to set PV panels to get the maximum power. This effect is demonstrated in Fig. 8.

According to reference [12], the best tilt in the UK is 35° with the horizontal and facing south which results in 95% solar radiation collection. However, panels facing east or west with 35° with the horizontal can receive 80% of the solar radiation, while similar configuration for panels at northeast or northwest receive 60% of the

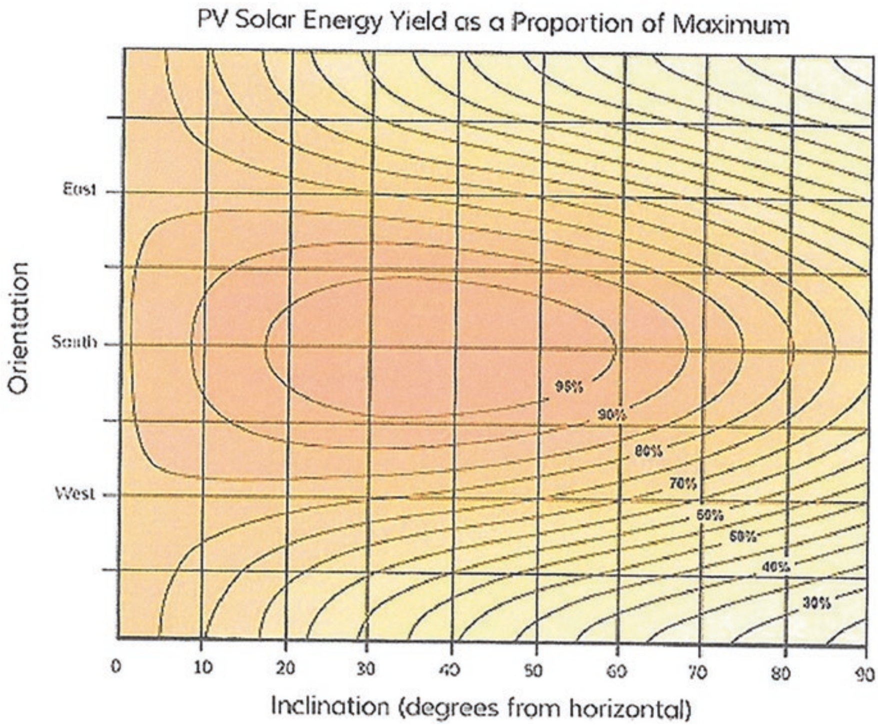

Fig. 8 Effect of orientation and inclination from the horizontal [12]

solar radiation. Roofs with the same configuration but facing north will receive 55% of the solar radiation only.

As far as the cost of various photovoltaic cells, see Fig. 9 [13].

If one looks at the progress of PV installation per each quarter since 2019, see Fig. 10, one can predict that during 2023 and 2024, the progress can be 1.5 and 2.00 GW respectively. As for the third quarter of 2022, the PV installation will be 1.25 GW.

An example of rooftop installation of PV systems is quoted in Table 7. However, in the UK, there are more than 80 companies are specialized in PV installation.

5 British: Sahara £18 Billion PV and Wind Xlinks Project (Fig. 11)

> The energy startup Xlinks hopes to provide 8% of Britain's electricity supplies through a 3,800km (2,360-mile) cable linking Morocco with the UK, powering 7m homes by 2030.

The Xlinks will have 12 million PV panels and 530 windfarms covering an area of 960 km^2. and 20 GWh batteries storage capacity. The Xlinks will generate power of

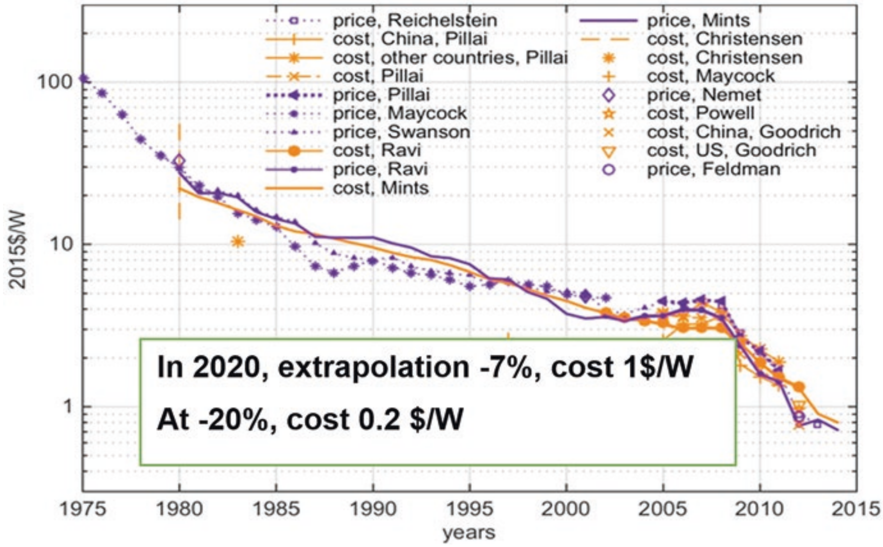

Fig. 9 The decline of the PV cost according to 19 well-known sources

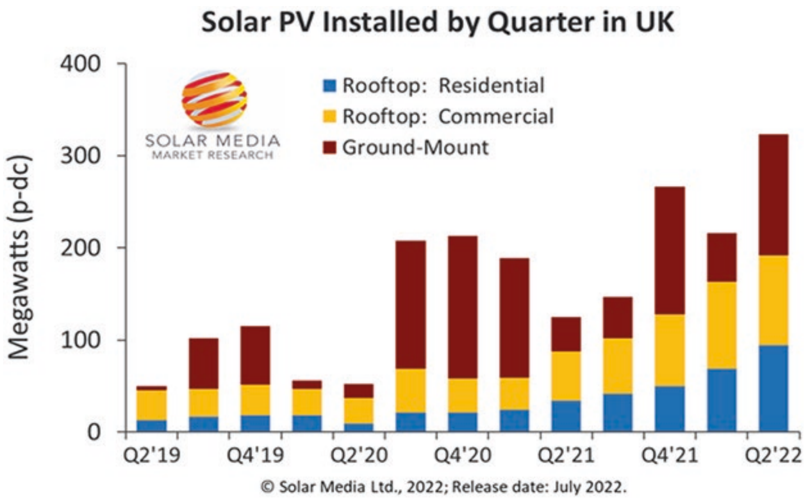

Fig. 10 Solar PV installation – MW by Quarte in the UK [14]

1.8 GW transmitted by cables through Portugal, northern Spain and France before it is looping around the Isles of Scilly to terminate at Alverdiscott in north Devon, see attached figure (Fig. 12).

Table 7 Estimated cost of installed PV system in the UK in 2022, according to one company [15]

System size	Estimated cost in £	No.of 250 W panels	Space area m^2	Financial yearly saving £	25 years saving £
3kW	5000 – 6000	12	22	850	21,250
4kW	6000 – 8000	16	29	980	27,150
5kW	8000 – 9000	20	32	1460	29,550
6kW	9000 – 11000	24	43	1460	40,325
The calculation based on typical type of panels at 2022 £ price. VAT is scraped by the Government, without Storage System					

Fig. 11 Moroccan Desert for Xlinks Project [16]

6 Mr. Tony Book PV: Home

The house was built in the 1950s and was refurbished to a high standard in 2017.

The result has been that reliance on the grid for electricity has been reduced considerably over the years with the addition of PV and batteries.

Initially, a 5.4 kW_p PV array was installed in 2018.

The electricity was provided by a standard twin tariff meter (off peak from 23:30 to 06:30) and the annual consumption was 3658 kWh split 55% peak and 45% off peak.

During off peak the laundry, dishwasher and hot water heating was used in the winter months.

Additionally, a hybrid car with a 12 kW, battery capacity was charged from time to time.

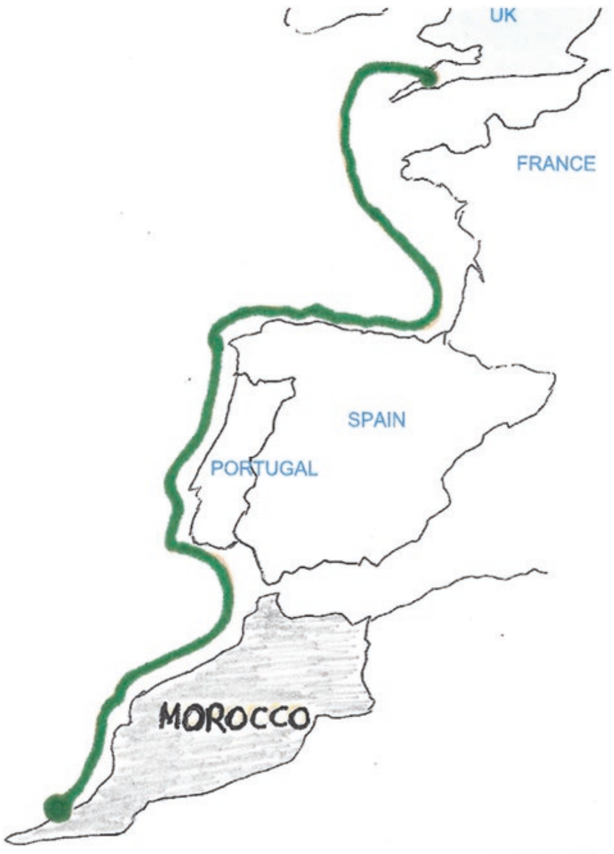

Fig. 12 Scheck of the cable path Morocco to the UK

Cooking was done during normal hours, principally between 5 pm and 8 pm.

5400 kWh was generated from the PV; 80% of which was between March and October and at the time about 50% was being exported. The size of the array was deliberately large as it was expected that batteries and a fully electric – car (EV), would take up the excess generated electricity in due course. See Fig. 13.

Also, two inverters were installed as part of the system, see Fig. 14.

The 2019 electricity consumption remained broadly the same. 3617 kWh was consumed of which 53% was used on peak tariffs.

In 2020 an EV was purchased, (50 kW Capacity) over the next year this had an impact on the use of PV-generated power and export. Whilst the overall peak/off-peak ratio remained the same. The export amount was reduced by over 1000 kWh representing 4500 miles (7200 Km) of car travel. At the same time a smart power diverter was also purchased to automatically switch exported power to heat the hot water in a 250-litre storage cylinder and/or power the EV. About 3–5 kWh per day

Fig. 13 Mr. Tony Book home

Fig. 14 Two inverters, on the left the PV inverter; on the right a charge inverter which controls the 10 kW battery system, which will be explained later

was required to heat the hot water. They made the household to be self-sufficient in hot water, from late February to early October.

The smart tariff meter was installed which allowed off-peak heating from 2.30 am for 4 h until 6.30 am, at the rate of 5p/kWh.

During that time the car, if needed, could also be charged up at a variable rate of amps, (Up to 32 A).

In 2021 the battery system was installed, and this was charged by the sun in daylight hours. Again a few weeks before the Equinox in the spring and for some weeks after the Equinox in the Autumn. There was virtually no exported power. Any potential exported energy was taken up by the batteries, in the first instance, and then to the hot water cylinder and or the car. This became a very impressively efficient system.

The overall consumption remained the same over the year at 3700 kWh but only 14% was at peak tariffs. That was 1.52 kWh per day.

Once the system became fully operational over a 12-month period, in 2022, the overall consumption dropped by 9% and the peak per cent down to 12%. In fact for 190 days during 2022 the house was using less than 1 kWh per day, 30 W per hour, and deemed in self-sufficient mode (Figs. 15 and 16).

As of 2023, the expected consumption is only 2800 kWh and 90% of that is off-peak at the current rate of 7.5 pence, (p) per kWh unit. (The peak rate is about 28 pence, (p) per kWh).

When making a household purchase such as a kitchen, bathroom suite or carpets, one does not normally expect a payback, but generally thinks it is a piece of kit that will last many years and indeed may be sold as part of the curtilage of the property when moving out. These types of additions to the home are a type of investment as they improve the home and its perceived value. Whilst we personally do not like discussing payback, as the cost of renewable equipment should regarded as a lifestyle choice, nevertheless, It is outlined below later on.

The costs are based on prices at the time of purchase which may not be what they are at the time of publication as there is now inflation. The war in Eastern Europe has also had a major effect on the energy supply and its cost and consequently on the prices of electricity and gas.

Fig. 15 EV is being charged

Fig. 16 The CALB 16 × 2000 mAh battery set

This means that those who fortunately kitted out their properties pre 2020 will have made a killing on payback. Those who are doing now are not doing so bad either.

The hybrid car was exchanged for an EV which has an average 5 miles (8 km) per kW in the summer and 3 miles (4.8 km) per kW in the winter.

The 50-kW battery has a range of about 225 miles in the summer.

At the time of writing this article, the car has travelled about 5000 miles and consumed 1306 kW, 589 kW from the grid at 5p/kWh, 546 kW from the PV system on the roof. In addition, 150 kW at 25p was purchased on journeys. (The balance was free charging at various locations.) This works out at about 1.3 pence per mile or 1 Euro-cent per km.

Although there is a price premium on EV purchase when compared to ICE cars (Internal Combustion Engines), EVs have very low maintenance expenses and running costs. The financial break-even, presently is about 30,000 miles when compared with an equivalent ICE car.

7 Progress and Improvement After 3 Years

The incorporation of a charge inverter and battery pack to "time shift" electricity consumption throughout the year. The purchase of an all-electric car (EV), and the installation of **BMS smart card** to ensure the batteries run between 20% and 90% charge, and do not over voltage or over heat, see Fig. 17.

The acquisition of a smart car charger which 'fuels' the car only when there is surplus on the house. This works in tandem with the smart hot water diverter and is very efficient.

There is the opportunity to obtain split plunge pricing of electricity from a utility company and pay for power by the half hour and even get paid for using it in the off-peak times. This is dependent on the Carbon Intensity which is difficult to predict from week to week.

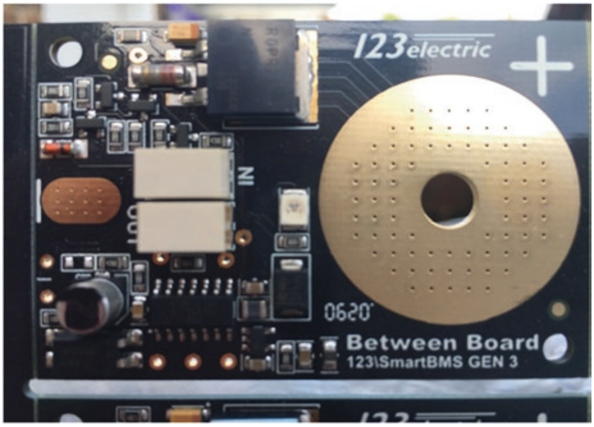

Fig. 17 BMS smart card

By definition the Carbon Intensity tends to be higher in the summer as the grid sources more 'clean', due to the available energy from PV, wind, and other renewables.

The storage system comprises of 16 × Calb 2000 mAh, lithium-ion phosphate batteries controlled by a set of 123 Smart BMS micro-processors. These cards calibrate the batteries to ensure they neither are over charged or under discharged. The parameters are set at 90% and 20% respectively. The BMS prevents the batteries from over voltage and over/under temperature. The charge-inverter was sized to match the PV array (5.4 kWp) with charge and discharge rates of 4 kW from the grid or the PV system.

In the winter months the Charge-Inverter is scheduled to come on during off-peak times at 2.30 am. To charge from 20% to 90% it generally takes about 2.5 h and uses about 10 kW and costs 50p (5p/kWh on the Octopus GO-Faster Tariff). At 5.00 am the Hot Water is boosted for 90 min. This uses 5 kW (15p). The charge-inverter is held until 0630 am, before being switched back on. This stops the batteries supplying the hot water and using up some of the battery storage. It also allows the BMS time for absorption and to float the cell units, conditioning them, and increasing their life. The EV can be charged during this time if it is required, but that depends on driving plans and current car range levels.

During the day in the winter the property runs on off-peak electricity stored overnight and released during the day. Without any added PV energy. During a typical winter's day, the batteries will last until early evening and may or may not cover the whole of the evening cooking meal. Gradually as the PV energy increases in late January and early February, the battery supply goes through to at least 02:30 am, with a combination of off-peak grid and solar energy.

As the spring comes round, the battery State of Charge (SOC) is reduced to 60–80% allowing the increasing solar radiation to make up the difference during the day.

Similarly, the grid-sourced water heating is cut back too. By late March the batteries and solar input are capable in meeting all the system charging, hot water heating, house requirements of cooking, washing, drying and the EV, round the clock.

This continues until late September when the grid starts to be used more frequently.

8 Examples of Spring and Summer Energy Usage

<u>**Note:**</u> The baseline when away on holiday is 2 kWh. This is the amount required just to keep the tank hot at 60C from 1 day to the next.

The total consumption was 27 kWh, of which 20 kWh was generated by the PV.

The hot water was boosted for an hour around 06:00 am as there had been no sunshine during the previous day.

The car was charged during the morning and more water was heated around the middle of the day and early afternoon.

Only 13 kW was imported (purchased). The evening consumption shows a small increase around supper time and the rest for lighting and evening TV are functioning well.

A small car boost is first thing, then followed by a lot of water heating on a sunny day.

Only 4 kW imported all day while, 7.5 kW only is used.

The car was charged overnight with off-peak electricity and there was washing machine usage as well as cooking was in the morning.

A good summers' day produces over 30 kW. (The annual amount is 5500 kWh.)

Once again plenty of hot water was produced. There is 84% green contribution on this day, which is typical for the summer months, (twice that gained in the winter) additional saving was made due to energy management using the diverter. The running costs are very attractive.

Earlier, the hybrid car was filled with petrol about every 5–6 weeks. Most journeys were local except for occasional one 400-mile journey round trips.

During the recent coronavirus lockdown, from March 2020 to July 2020, the car was used for short journeys only. About 900 miles was covered in, up to 40-mile journeys using electricity only. NO petrol was purchased for 5 months.

It is estimated that about a third of the PV generated off the roof is used to charge the car. This produces a very economical result, about a quarter of the PV output heats the hot water and the 'roof' contributes significant savings to the utility bills.

On a slightly cloudy day the PV system is generating 2.6 kW, the batteries are floating and the hub is balancing the car and hot water.

From 06:00 am the PV starts generating electricity and the batteries (home) get charged up first.

The car gets a good 15.6 kW which is the equivalent of about 62 miles (100 km) and the hot water takes nearly 6 kW. In all 34.5 kW was generated by the PV and 2.2 kW imported. Only 0.9 kW was exported, so that 95% of the PV-generated energy was used up. Once the sun goes down the batteries cover evening cooking, TV, lighting and all consumption needed through the night.

The household consumes 7500 kWh per year excluding space heating (gas).

5400 kWh comes from the PV system. About half the year the property is self-sufficient, defined as importing of energy of 1 kWh or less, per day. It takes 1 kW per day to run the 16 battery control cards. 11 kWh per day is in winter average consumption, most of that from the batteries. There's a lot of debate about the economics of the PV and or batteries. It depends a lot on one's lifestyle choice. These days, and it's improving all the time, **PV will pay back in 5–7 years and batteries in 7–9 years**.

Buying this technology is equivalent to buying energy forward which stays at today's price whilst the actual tariffs rise with inflation and government's energy policies, not only in this country but throughout the world.

It is important to choose the most economical electricity tariffs, and this is best researched from the price comparison websites. The best prices can be found from products that use Smart Meters where supplies are priced by the half hour and can be monitored by an IDH (In Home Display).

For space heating which is still using a gas boiler (at least for another decade) shopping around for the most economic tariff is important. 10,000–20,000 kWhs of gas are being purchased per year so even small variations in tariff can make a difference to the budget also taking into consideration the daily standing charge.

The monthly consumption of the household is 600 kWh/month throughout the year.

Apart from gas space heating, all cooking, washing, drying, TV, etc. are electric. All lighting is by LED.

The consumption of grid electricity in the winter months: Per month.

About 200 kWh comes from the PV system, the rest from the batteries.

The time shift of supply from off-peak to peak times has changed the ratio of grid consumption from 60:40 to 10:90 with commensurate savings.

On summer months: Per month.

700 kWh is supplied by the PV. On, average the only 35 kW is imported, and monthly bill is £12–£14 of which £7.50 is the standing charge.

9 Conclusions

The system has been operating for 4 years and has been constantly monitored, using smartphone apps. It is proving to be very efficient in making significant savings of both energy and running costs. The return on investment is about 20% and the residence uses about half the normal fossil fuel energy compared to a similar sized house without such a system.

The system is saving about 6 tons of $\mathbf{CO_2}$ per year. The gas boiler uses about 3 tons of $\mathbf{CO_2}$ per year. If it was realistic to equip half the homes in the UK similarly over the next 10–15 years, then the savings (**of** $\mathbf{CO_2}$) would be over 30 million tons per year.

We fully recommend all countries in the world, especially in Europe and the USA to legislate that all new buildings which will be built in 2030 and after to be equipped with PV systems. They will have, cheaper electricity, reducing $\mathbf{CO_2}$ emission and creating healthier environment.

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Policies and Trends to Mitigate Climate Change Impacts by Integrating Solar Photovoltaics in Buildings and Cities: Emphasis on Egypt's Experience

Mohsen Aboulnaga and Maryam Elsharkawy

> Achieving a just and equitable energy transition is one of the biggest challenges facing our world.
>
> Climate disasters and skyrocketing fuel prices have made the need to "end our Global addiction to fossil fuel" Crystal clear, he said, underscoring the importance of investing in renewables, building resilience, and scaling up adaptation. (António Guterres, Secretary-General of the United Nations, September 18, 2022 [1])

1 Introduction

Climate change severely affects cities worldwide with soaring temperature that is coupled with river droughts in Europe, storms and floods in Asia, the USA, and Africa, which occurred in July and August 2022 [2]. Clean energy utilization in cities has become no more optional, but rather mandatory amidst global energy and food crises during 2022 and 2023 [3]. In fact, mitigation and adaptation were among the high-level priorities of the United Nations Climate Change Conference of Parties (COP27) held in Sharm El-Sheikh, Egypt between 6 and 20 November 2022, where governments aimed to drive more application of renewables to meet their clean energy target and cap or mitigate CO2 emissions [4].

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The insistence of nations to survive and the availability of renewable energy resources (RES) are considered one of the main drivers/motive to transform to green and sustainable cities in light of the current skyrocketing energy costs globally. Therefore, it is imperative to increase the awareness level of actors and governments to the significance of clean energy. Renewable energy resources (RES) have become a sustainable alternative to fossil fuels that are considered the main contributor to world climate change. Carbon emissions that result from reliance on fossil fuels on electricity production need to be reduced to 50% by 2030 and reach net-zero by 2050 [5].

Goals and initiatives are set and proposed to offset climate change (CC) severe events and provide reliable solutions to the crisis, including recent initiatives derived from COP27 [6]. Hence, the worldwide increased awareness of the significance of renewable energy resources including hydro, wind, solar, bio, geothermal, and others have become obvious [7]. Utilizing renewable resources in mitigating CC impact has urged global policies and trends to support latest innovations and technologies aiming at zero-carbon cities [8]. A special emphasize on solar energy generation and related high-generation capacity exists within countries with long solar radiation hours such as Egypt [9].

Box 1: Role of Building-Integrated Photovoltaics (BIPV)

The increase in implementing building-integrated photovoltaics (BIPV) or building-applied photovoltaics (BAPV) will not only generates clean energy, but also contributes to mitigating climate change server impacts.

2 Global Building-Integrated Photovoltaics

Building-integrated photovoltaics (BIPV) or building-applied photovoltaics (BAPV) realization is vital to mitigate climate change globally (Box 1) as well as climate change adaptation in Egypt since it is considered one of the countries with huge potential towards utilizing sunshine in generating clean energy and power supply from RES such as solar photovoltaics (PVs) technologies. Many countries worldwide took vast steps in promoting BIPV as earlier as 2005 like Germany, Spain, The United Kingdom (UK), Singapore and China; as well as Denmark and the United States (US). Examples of BIPV have been manifested in Madrid and Barcelona (Spain), Manchester (UK), Oulu (Finland), California and Massachusetts (US), Munich, Hannover, Berlin (Germany), and Copenhagen (Denmark) as shown in Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19. Figure 2 summarizes these BIPV examples.

It is clear from Fig. 3 that the BIVP on the façade is not only generating clean energy for the building, but also creating shading and cooler air near the inner walls, hence providing cooling in summer by buoyancy. Figure 4 presents the integrated PV on the façade of the CIS Tower in Manchester City, England, UK – was originally built in 1960 marking the first skyscraper in the city of Manchester. The 118-m

Fig. 1 Integrated solar photovoltaic façade of the municipal building, social services, Centre Jose Villarreal in Madrid, Spain. (Image credit and source: Hanjin, https://upload.wikimedia.org/wikipedia/commons/f/f8/BAPV_solar-facade.JPG)

high façade of this building, during the refurbishment in 2004, has been cladded with PV panels at a cost of 5.5 million GBP. Also, the CIS Tower, which is an office skyscraper operated in 2005, started feeding electricity to the national grid [10, 11].

Another example is the Toppila bio-power plant in Oulu, Finland, it is one of the largest peat-fire in the world with an installed capacity of 210 MW of electrical power and 340 MW thermal power (Fig. 5). The facility operates two units of 75 and 145 MWe combined heat and power (CHP) [12]. One of the Toppila Power Plant's buildings is covered with 825 solar PV panels on the building façades which generates 270 kW power as shown in Fig. 6. New technologies in solar PV glass are used to provide a better installation which is re-shaping architecture as illustrated in Apple new headquarters in Cupertino – California, USA (Fig. 7). As illustrated in Fig. 7, the solar power station is one of the largest BIPVs in the world that generates 17 MW power for Apple Park in California, where the PV array is built over the roof of Apple new headquarters (the largest solar array) which is installed by First Solar manufacture in the world; the roof compromises thousands of solar panels (Fig. 7). Moreover, new technologies such as the ETFE Cushions' roof with integrated Photovoltaics have been used in the AWM Munich's Municipal waste management department in Munich, Germany as presented in Fig. 8.

A unique example of BIPV is Copenhagen International School at Levantkaj in Nordhavn, the City of Copenhagen, Denmark. The distinctive and iconic building furnishes the state-of-the-art technology in PV glass technologies as illustrated in Fig. 9. The building facades feature 12,000 blue-green colour photovoltaics that cover almost the entire facades of the school to generate 300 MW of electricity per

Fig. 2 Global examples of building-integrated photovoltaics. (Images' credit and source: Authors)

year, this responds to 50% of the school energy demand. The colour comes from a process of light interference, one of the means to produce colour, developed over a 12-year process in EPEL laboratories [13]. Figures 10, 11, and 12 present various images of the glass PV facades.

The General Electric sustainable headquarters in Boston – Massachusetts, USA showcases another example of BIPV, where a "Solar photovoltaics veil" is integrated with the façade to offset energy cost as shown in Fig. 13. Furthermore, the 525 kW BIPV CoolPly commercial roofing system furnishes clean energy to the Patriots Place Complex adjacent to the Gillette Stadium in Foxborough, Massachusetts – the largest BIPV in the state of Massachusetts as per 2010 as illustrated in Fig. 14 [14].

Other examples of building-integrated photovoltaics (BIPV) or building-applied photovoltaics (BAPV) were manifested in Hanover, Berlin and other cities in Europe and Singapore. Figure 15 illustrates the Photovoltaics on top of the rooftop Hannover – Schwarze Heide generating 1 MW power, while Fig. 16 presents a PV-system on rooftop of block of buildings in Berlin, Germany, while Fig. 17 shows BIPV in Singapore.

Fig. 3 Building-integrated photovoltaics of the MNACTEC Terrassa in Barcelona, Spain. (Image credit and source: Chixoy, https://upload.wikimedia.org/wikipedia/commons/0/0f/Façana_Fotvoltaica_MNACTEC.JPG)

Globally, the total installed capacity of BIPV between 2019 and 2020 amounted to 1.15 and 2.3 GW respectively, i.e., doubled in 1 year [15]. It is expected that by 2026 the global BIPV market to reach US$ 20.1 billion. Nonetheless, amidst the COVID-19 crisis, the global BIPV market in 2020 was estimated at US$ 10.3 billion. By looking at the BIPV market in the USA, it is projected at US$ 1.6 billion;

Fig. 4 Building-integrated photovoltaics of the Façade of the CIS Tower in Manchester, England, UK. (Image credit and source: Pit–yacker, https://upload.wikimedia.org/wikipedia/commons/6/6e/CIS_Tower.jpg)

whereas, it is predicted to reach US$ 4.1 billion in China, an increase by more than two and a half [16]. In this context, China accounted for more than 50% of the production of PV industry worldwide [15]. In contrast, the global newly installed capacity of PV reached 130 GW (up 13% year on year (YoY)); whilst China's newly installed capacity of 48.2 GW (up 60% YoY), making China ranked first worldwide for eight consecutive years [15].

Fig. 5 The Toppila power plant in the Toppila district in Oulu, Finland including building-integrated photovoltaics – the building on the right. (Image credit and source: Estormiz, https://upload.wikimedia.org/wikipedia/commons/7/72/Toppila_Power Plant_Oulu_20160403.JPG)

In fact, an integrated solar PV array could be incorporated on top of a roof or walls of a building or a set of buildings. Not only that but also an array of PV panels could be added to existing buildings to enhance performance in terms of energy efficiency and reduce their carbon footprint through the generation of clean energy as well as their impact on the environment, yet mitigate climate change. In BIPV systems, there are dual functions of the building envelop-replacing conventional building skin materials and generating power. By avoiding the cost of conventional

(a) General view of the Toppila power plant showing the BIVP on the southern façades

(b) Close up of the BIPV façade of the Toppila power station

(c) Building-integrated photovoltaics of the southern façade of the Toppila power plant generating clean energy

(d) The site of the Toppila power station where the Solar PV array is installed on its façades

Fig. 6 Building-integrated photovoltaics' façades of the Toppila power plant in the Toppila district Oulu, Finland. (Images' credit and source: (**a**) Estormiz, https://upload.wikimedia.org/wikipedia/commons/6/63/Toppila_Power Plant_Oulu_20160122.jpg; (**b**) Viesti18, https://upload.wikimedia.org/wikipedia/commons/8/83/AurinkoseinaToppilaOE.jpg; (**c**) Estormiz, https://upload.wikimedia.org/wikipedia/commons/6/6e/CIS_Tower.jpg; (**d**) Viesti18, https://upload.wikimedia.org/wikipedia/commons/2/29/Toppila_MG_7242-01.jpg) **(a)** General view of the Toppila power plant showing the BIVP on the southern façades. **(b)** Close up of the BIPV façade of the Toppila power station. **(c)** Building-integrated photovoltaics of the southern façade of the Toppila power plant generating clean energy. **(d)** The site of the Toppila power station where the Solar PV array is installed on its façades

Fig. 7 Building-integrated solar photovoltaics panels generate 17 MW power at Apple Park, the corporate headquarters of Apple Inc., in Cupertino – California, USA. (Image credit and source: Daniel L. Lu (user: Dllu), https://upload.wikimeda.org/wikipedia/commons/5/5a/Aerial_view_of_Apple_Park_dllu.jpg)

materials, the increment cost of photovoltaics is reduced and its life-cycle cost is enhanced. Therefore, BIPV systems are often characterized by lower overall costs compared with PV systems that would necessitate space and dedicated mounting systems [17] and [18]. Figures 18 and 19 (above) show the mounting solar PV arrays on the main wall of a residential building, the roof of Pacifica wastewater treatment plant in California, and Electrical and Mechanical Services Department Headquarters' Photovoltaics in Hong Kong, China respectively.

An additional model of a large-scale BIPV is the German Environmental Agency (UBA) building in Dessau near Berlin, Germany. The UBA has large solar PV arrays on the rooftop of the building that generate 9000 kWh (90 MW). Figure 20 presents the largest solar PV array rooftop on a public building in Germany and in Europe. These solar panels are mounted on top of a glazed frame. Another example in Europe is the REC Conference Center in Szentendre, north of Budapest, Hungary. The REC Center is considered a low-carbon building. The solar system on rooftop has 140 solar photovoltaic panels that harnesses 19% of sun rays' capacity, and produces up to 29 kW of electricity during summer, yet it generates a surplus that feeds into the local grid (Fig. 21); would correspond as a rebate from the local operator during winter darker days. These panels have operated maintenance-free from the first day they were switched on. The building is free from light switches, but automatically adjusted with the natural light penetrating when required; besides the roof is integrated with a solar thermal system as seen in Fig. 21.

Fig. 8 ETFE Cushions' roof with integrated Photovoltaics of the AWM Munich's Municipal Waste Management Department in Munich, Germany. (Image credit and source: MdCAlmeida Villafuerte, https://upload.wikimedia.org/wikipedia.commons/a/ac/AWM-Munich-ETFE-Cushions-Photovoltaics.jpg)

Moreover, the application of the concept of BIPV or BAPV has been extensively manifested in Masdar City, a city designed into two phases by Sir Norman Foster. This smart city is mainly to showcase how to create a city with zero carbon and zero waste by exploiting solar PV arrays that can be integrated at a larger scale on top of buildings' roofs in hot desert climate, clean and smart transport (no car run by liquid fossil fuel inside the city), and recycling waste. The BIPV in Masdar City are low-carbon/net-zero energy buildings, that are fitted with large arrays of solar PV panels on the buildings' roofs to generate clean energy, power buildings and reduce CO2 emissions, hence reduce the negative impact on the environment. The use of renewable energy contributes to the goal of achieving net-zero cities and mitigating climate change. The photovoltaic arrays constructed above the laboratories and residential building in Masdar City are illustrated in Figs. 22, 23 and 24. The solar tracking PV panels to catch the best light photon from the sun to maximize the production of clean energy are seen in Fig. 24a, b.

With the above narrative of the various examples of BIPV or BAPV, one should not forget the iconic BedZED eco-village with 100 dwellings over 2500 m^2 plot which is characterized as an inspired example of low-carbon homes or zero-energy homes worldwide. It was built in 2002 in Beddington, south of London, England, UK to generate clean energy, lower bills and achieve major energy savings [19]. On top of the 100 dwellings, 107 kWp of Photovoltaics have been integrated to power 40 electric cars as shown in Fig. 25. According to POLIs, the design measures of BedZED 100 dwellings achieved the reduction of electrical power use of 3 kW per

(a) General view of the eye-catching facades of Copenhagen International School.

(b) Part of the façade depicting the green-blue PV glass panels.

Fig. 9 Building-integrated blue-green colour photovoltaics of Copenhagen International School at Levantkaj in Nordhavn in the City of Copenhagen, Capital of Denmark. (Image credit and source: (**a**) Copenhagen International school; (**b**) Leif Jørgensen, https://commons.m.wikimedia.org/wiki/File:Copenhagen_International_School_03.jpg) (**a**) General view of the eye-catching facades of Copenhagen International School. (**b**) Part of the façade depicting the green-blue PV glass panels

person per day, where 11% is produced from solar PV panels, when compared with UK homes [20].

Tesla incorporation built the largest factory based on BIPV system to generate 100% of its energy demand from renewable sources (14 GWh + total) in Nevada, USA (Fig. 26). Tesla's Gigafactory is powered by a huge array of solar PV cells on top of the building roof and the Gigafactory is capable to produce 35 GWh of battery sales yearly as shown in Fig. 27 [21].

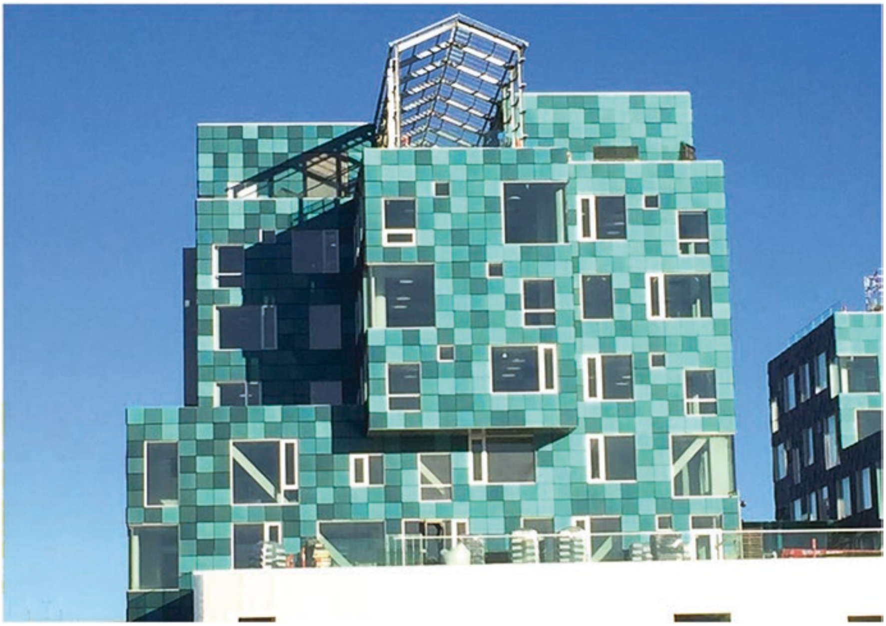

Fig. 10 Side view of the blue-green coloured Glass PV panels of Copenhagen International School in Nordhavn, Copenhagen, Denmark. (Image credit and source: Jens Cederskjold from København S, Denmark, https://actu.epfl.ch/news/the-school-with-the-largest-solar-facade-in-the%2D%2D9/)

Other utilization of PV is that Solar PVs could be used for shading facades. The solar PVS are not only installed in building to generate electric power but also are exploited as a mean for shading plus generating power on buildings' facades. Figure 28 presents mounted solar shading louvres on a window of the Vale Living with Lakes Centres, Greater Sudbury – Ontario, Canada, while Fig. 29 shows the use of solar PV as external shading devices in a zero-energy building in the City of Singapore, Singapore.

3 Solar Power Stations

Solar PV are not only used in building but also utilized in large solar parks to generate clean energy and contribute to decarbonization actions worldwide. Spain and Germany took earlier steps since 2005–2010 to develop many Solar PV power stations either by mega solar PV arrays or by concentrated solar power (CSP). For instance, Germany developed the Jännersdorf solar park, which generates 40.5 MW of clean power in Prignitz as presented in Fig. 30. Spain also took further steps in adding capacity of PV and installed Andasol Solar Concentrated Power Station that produces 150 MW near Guadix in Granada as illustrated in Fig. 31.

Fig. 11 Back view of the 1200 blue-green colour Photovoltaics façade's panels of Copenhagen International School in Nordhavn, Copenhagen, Denmark. (Image credit and source: MdCAlmeida Villafuerte, https://upload.wikimedia.org/wikipedia.commons/a/a8/Copenhagen_International_School_-_Nordhavn.jpg)

Moreover, Spain is also the home of the first three concentrated solar power (CSP) units of Slovona Power Station as depicted in Fig. 32. In terms of adding more capacity of PV in Germany the Senftenberg Solar Park which is located in the former open-pit mining areas near the city of Senftenberg, Eastern, was installed. This Solar power station generates 78 MW as presented in Fig. 33.

Furthermore, Fujisawa smart city (phase 1 was built over an area of 190,000 m^2) in Yokohama, Greater Tokyo, showcases a model of Economic sustainability. The solar Monocrystalline high-efficiency PV panels, produced by Panasonic – Eco Solutions Company, are integrated with the city fence to generate power (Fig. 34). These solar PV panels are grid-connected and the generated power is sold to Yokohama Utilities Company via a smart grid. In addition, each of the 1000 houses and the public social club buildings in Fujisawa city is a net-zero energy building (NZEB) as shown in Fig. 35.

In terms of other large power plants, Masdar City exhibited an example of such efforts. The city is oriented on the south-east-northwest axis of Abu Dhabi, UAE, which led to providing shaded streets and walkways throughout the day. The shaded routes minimize thermal gain into buildings and provide cooler street environment. It encourages pedestrians' activities and provides a healthy high environment for citizens with the lowest environmental impact or pollution; this mainly contributes to less power demand from the Solar Park which generates clean power of 10 MW from solar Photovoltaic farm (Fig. 36). The solar farm provides clean energy supply to the Masdar Institute of Science and Technology (MIST) campus, Masdar's offices on site, and other buildings, besides other activities [22]. Figure 36 depicts the

Fig. 12 Close up of the distinctive and eye-catching Copenhagen International School with the blue-green colour Photovoltaics cladded all building's facades at Orientbassinet in Nordhavn, City of Copenhagen, Denmark. (Image credit and source: Leif Jørgensen, https://upload.wikimedia.org/wikipedia.commons/1/1d/Copenhagen_International_School_06.jpg)

10-MW solar park in Masdar city which produces about 17,000 MWh of clean electricity annually and leads to mitigating 15,000 tonnes of carbon emissions. This plant provides power to the Masdar Institute of Science and Technology (MIST) campus and Masdar's offices on site and other buildings. Moreover, the solar photovoltaics plant, which encompasses 87,780 Multicrystalline and thin-film arrays supplied by Firs Solar, is the first of its nature that is connected to the grid in Abu Dhabi, UAE and opened in 2009 [23].

4 Overview of Renewable Energy Added Capacity in Africa

Energy transition is manifested strongly in 2022 and 2023 for many reasons, particularly energy skyrocketing prices, security and supply due to the Ukraine and Russia war in early 2002. Africa is home for 52 nations, including Egypt. According to the International Energy Agency (IEA), Africa has abundant sources of renewable energy. The solar PV capacity additions in Africa and the world between 2010 and 2012 are shown in Fig. 37.

It is clear from Fig. 37 that the highest solar PV capacity additions are in year 2019 (1.8 GW) followed by year 2021 (1.65 GW) slightly near the same capacity [24]. Nonetheless, it declined sharply in 2020 to less than 1 GW (about 750 MW)

Fig. 13 General view of General Electric New Boston QH featuring 'Solar photovoltaics veil' to offset energy cost, Boston, Massachusetts, US. (Image credit and source: General Electric (GE), https://www.treehugger.com/solar-powered-buildings-will-forever-change-architecture-4868157)

due to the severe impacts of the COVID-19 pandemic, which affect the economy and development in all nations, specifically the investment and adding solar PV capacity [25].

By comparing the world's added capacity with that of Africa in the same years (2019–2021), it shows a steady increase from 110 GW, 130 GW, and about 150 GW in 2019, 2020, and 2021 respectively. It is worth mentioning that the Solar PV capacity addition in 2021 Africa is due to Egypt's large installed a mega solar PV (grid-connected) power plant of 1.65 GW capacity in Ben Ban, Aswan, south of Egypt. Hence, more added capacity of renewable sources is needed to adapt to climate change risks. However, the rapid increase of population in Africa, specifically in its three megacities (Cairo, Lagos, and Kinshasa) as illustrated in Fig. 38 indicates the urgent need to add more capacity of PVs, not only to produce clean energy, but also to create job opportunities.

In fact, Africa will have five megacities by 2030, i.e., this means additional two megacities will be added to the existing two megacities (Lagos and Cairo), which collectively account for 11% of Africa's urban population (Fig. 38). In accordance with the IEA scenarios for Africa, Fig. 39 presents the total final energy consumption by sector and modern fuel use per capita by region (Africa as a whole, North Africa, South Africa and Sub-Saharan Africa) in the Sustainable Africa Scenario (SAS). It is clear from Fig. 39 that for the household sector with the traditional use of biomass (TUoB) for cooking in Sub-Saharan Africa is the highest followed by mobility and industry in all regions in 2020 and 2030. Based on IEA recent report, it is important to note that eradicating inefficient biomass for cooking in

Fig. 14 Integrated solar photovoltaics panels on the roof of Gillette Stadium in Foxborough, Massachusetts in the USA. (Image credit and source: Chris Bills, Chris Erickson, Calla Leonard, and Patrina Eiffert, https://upload.wikimedia.org/wikipedia/commons/c/c1/Solar_cell_panels_on_roof_Gillette_Stadium_2010.jpg)

Sub-Saharan Africa halves total household energy use in Africa by 2030, whilst use in other sectors increases in most regions.

By looking at the total primary energy supply by fuel and region in the SAS (Fig. 40), it shows that natural gas and oil are the dominant sources in 2010 and 2020, but renewable sources will reach almost 30EJ (Exajoules) by 2030, mainly in Sub-Saharan Africa. According to IEA, renewable sources grow rapidly in all regions by 2030, but oil and gas remain to dominate the fuel mix in North Africa and Coal in South Africa [26].

In contrast, for the world's electricity generation by source, Fig. 41 indicates that renewables are still low compared to the other sources such as coal and gas, but oil is steadily flat. However, Hydropower, wind and solar is increasing steadily from 2010 to 2020, where the high increase (wind, solar) is between 2015 and 2020.

5 Egypt's Experiences for Solar Energy

Egypt has long hours of sunshine throughout the year (average 2400 h), with high-intensity values (2600 kWh/m^2) [9]. Therefore, such potential drives local authorities and government in Egypt to prioritize the use of renewables in cities. The IEA report indicates the role of solar in producing electricity worldwide in 2021.

Fig. 15 A large integrated PV on the rooftop of Hannover building generating 1 MW power. (Image credit and source: AleSpa, https://upload.wikimedia.org/wikipedia/commons/b/b8/Photovoltaik_Dachanlage_Hannover_-_Schwarze_Heide_-_1_MW.jpg)

Figure 42 presents the share of electricity generation from solar in 2021, where the highest countries are highlighted in burgundy, red, and then by orange, including Egypt [27].

Historical Background

Over a century, the world's first sun-powered control plant was built in 1913 in the Cairo suburb of Maadi, Egypt as presented in Fig. 43 [28]. Nonetheless, during a world of coal and manual work, the sun supernaturally fuelled a motor and easily pumped the Nile's water to parched crops and dried soil. Inspired and staggered spectators were welcomed to the amazing disclosing. It was a vision of idealistic future of everlasting, free and clean energy. This vision should be considered presently in confronting the disastrous worldwide warming. In this context, an American unconventional innovator for his time, Shuman in cooperation with his company – Sun Sparkle Control, had chosen Egypt for its all-year-long sun to test out concentrated solar power (CSP) system which is a possibly world-changing innovation. This CSP system includes a few expansive 62-m-long concave mirrors that are extended along a flexible metal structure to take after the sun from morning to evening; and focus the heating sun into long glass tubes filled with water.

Fig. 16 Mounted Solar Photovoltaics' arrays on the rooftop of a block of buildings in Berlin, Germany. (Image source: https://upload.wikimedia.org/wikipedia/commons/4/45/Berlin_pv-system_block-103_20050309_p1010367.jpg)

The sun heated the water and as a result, the steam forcefully fuelled a roughly 60–70 drive motor with around 88 kW of control as shown in Fig. 44. This amazing sum of control, generally comparable to the Soviet-era Lada Riva car, pumped out 60,000 gallons of water per hour from the river Nile and conveyed it to the encompassing water-hungry cotton areas. The solar control plant operated incessantly for a long time and indeed within the winter months. It was a clear sign that controlling the sun to influence energy demand seems to work.

According to the New York Times published on second July 1916, stated that Shuman announced "*We have demonstrated the commercial profit of sun control and have especially demonstrated that after our stores of oil and coal are depleted, the human race can get boundless control from the beams of the sun*." In this context, Maadi was committed to provide clean energy resource and to offset the negative impacts of climate; have recorded innovative minutes of history; in Annalise J.K. DeVries's book [29] appears to position Egypt within the history of renewable energy.

The energy consumption in Egypt by all sectors from 1965 to 2020 is illustrated in Fig. 45. It indicates the highest consumption is in year 2020. It is crystal clear that such patter of consumption has urged the need to rethink for sustainable substitutes. Since the year 2014, Egypt launched a feed-in tariff to encourage the installation of Renewable energy [30]. Egypt developed its sustainable energy policy roadmap with the aim to increase the operating and technical efficiency of distribution utilities, improve energy conservation and load management and diversify the sources

Fig. 17 A set of integrated solar PV arrays on the front façade of a residential building in Singapore, Singapore. (Image credit: https://www.yoursunyourenergy.com/upload, source: https://energypedia.info/wiki/File:BIPV.jpg#/media/File:BIPV.jpg)

of the regional electricity supply [30]. The goals of this roadmap are fourfold as shown in Fig. 46.

The Government of Egypt is committed to expanding the share of renewables within the power blend to 22% by 2022 and reach 42% by 2035 [31]. The nationally determined contributions (NDC) have been also driven to the appropriation of empowering measures to count plans to draw in public and private ventures beneath the renewable energy umbrella especially for solar power where Egypt location is considered favourable as illustrated in Fig. 47. However, such expansion covers to over 1500 MW utility-scale ventures, grid-connected small-scale (housetop, conveyed) sun-based photovoltaics (SbPV) and around 63,000 Industrial small-medium undertaking (SME) foundations in Egypt and other entities estimates of PV potential surpass 1000 MW (1 GW) [32].

With the national introduced capacity of ~60 GW, and industry that consume around 27% of national electric energy from the carbon-intensive national lattice, which accounts for 12% of the national GHG emissions [33], partners, specialists, and others ensure that using solar energy in the industrial sector could be improved only via specific tailor-made measures. The most common obstructions to renewable energy utilization can be summarized into six main points: (a) Restricted monetary support; (b) The risk involved of speculation and financing of PV in all sectors; (c) Powerless project authority; (d) constrained and expensive choice back for potential recipients and lenders; (e) powerless frameworks with few partner engagements; and (f) Complexity of administrative arrangements (Fig. 48).

Fig. 18 Solar panels mounting system on the roof of Pacifica wastewater treatment plant in Pacifica, California, the U.S. (Image credit and source: Robert Scoble, https://www.wikiwand.com/en/Photovoltaic_mounting_system#Media/File:Photovoltaic_mounting_system.jpg)

Egypt, with the increase of sun energy utilization in the previous years and the urge to optimize the use of sustainable energy resources, aimed to remove all mentioned barriers to operate an empowering system that permits sun-oriented PV models to become monetarily self-sustainable [34]. In particular, the NAMA Support Project's (NSP) objective is to booster change to market-driven wide-scale utilization of on-grid sun-oriented PV in all building sectors [35]. For example, through the establishment of an excellent 125 MW PV, co-benefits of the NSP incorporate expanded competitiveness of the industrial market, neighbourhood fabricating advancement, green work creation, and quality enhancement [36]. The NSP is extraordinary to illustrate that public and private funds are utilized, inventive monetary arrangements are practical and empowering frameworks are enhanced. The financial component of the NSP comprises four components: (a) a loan from the own resources of two commercial banks; (b) grant with cooperated finance of loan entity; (c) equal value from claim assets of SMEs; and (d) fractional awards to SMEs as venture motivation from NAMA Office stores. The NSP is extraordinary to use EUR 44 million of open co-funding [35]. Such results are reflecting a huge mitigation potential, where the NSP is anticipated to straightforwardly result in at slightest 192,000 tCO2e dodged amid the NSP and 1.5 million tCO2e dodged over the innovation lifetime [31].

Fig. 19 Mounted solar photovoltaic arrays on rooftop of Electrical and Mechanical Services Department Headquarters' Photovoltaics in Hong Kong, China. (Image source: WiNG, https://commons.m.wikimedia.org/wiki/File:Electrical_and_Mechanical_Services_Department_Headquarters_Photovoltaics.jpg)

6 Solar Photovoltaic (PV) Market in Egypt

Egypt has very favourable solar resources for a variety of solar energy technologies and applications whether implementing photovoltaic panels (PV) or Concentrated solar power plants (CSP) [37]. Both the Solar Radiation Atlas and the German Aerospace Center estimate Egypt's economically viable solar potential in the range of 74 billion MWh/year, which counts for many times Egypt's current electricity production [38].

The Egypt solar photovoltaic (PV) market is expected to grow at a compound annual growth rate (CAGR) of around 20% by 2026 [39]. The outbreak of COVID-19 has significantly impacted the market with a decrease in the installation of solar PV projects [40]. The lower deployment was primarily due to the negative impact on the economy.

Factors such as the declining price of solar PV modules and installation are expected to drive the market. However, increasing adoption of alternate renewable technology such as wind and hydropower is expected to hinder the market growth during the period [8]. The increasing deployment of on-grid solar PV projects is expected to significantly grow during the period.

On account of growing carbon emissions, Egypt is likely to increase the share of renewable energy to around 30% by 2050 [34], and such target is based upon Egypt's vision 2030 and Sustainable Development Strategy (SDS). Furthermore, the Egypt government has an untapped solar photovoltaic generation capacity of

Fig. 20 Mounted solar photovoltaic arrays on the rooftop of the German Environmental Agency (Umweltbundesamt – UBA) building in Dessau, near Berlin, Germany. (Image source: (**a**) UBA, http://www.umweltbundesamt.de/en/the-uba/uba-offices/visit-us; (**b**) Janine Pohl, https://en.m.wikipedia.org/wiki/Dessau#media/File:Dessau_uba_05.jpg; (**c**) C. Stadler/Bwag, https://commons.m.wikimedia.org/wiki/File:Umweltbundesamt_in_Dessau_(UBA)_2005.jpg) (**a**) The largest solar PV array of 9000 kWp on the rooftop of UBA building in Dessau, Germany. (**b**) One of the facades of the UBA building, where the solar PV arrays are mounted. (**c**) The atrium with the translucent glazed frame holding the solar PV long arrays

74,000 TWh per year. Hence, such a scenario is expected to create an opportunity for the market during the upcoming years.

Egypt has several government initiatives or schemes which are expected to drive the market during the forecast period [31]. The Egyptian Government has also set plans to increase the share of Renewable Energies (RE) in its electricity supply from the current 9% to 20% by 2020. Therefore, many laws, by-laws, regulations and decrees have been developed and endorsed. Given that RE only made up 2% of the total energy mix in 2012, and that Energy Efficiency (EE) measures were not yet deployed at a large scale, the targets are ambitious, indicating a strong political will to reduce the energy consumption. In line with such vast ambition, the Renewable Energy and Energy Efficiency Comprehensive Law (EG-REEEL) No. 203 of year 2014 has been developed to promote RE self-consumption, which has a comprehensive basis for supporting schemes and incentives and promotes the use of renewable

(a) Main façade of the REC Conference Centre with mounted 140 solar PV array on its roof

(b) Close up of the 29 kWp Solar PV array generating clean energy

Fig. 21 Mounted solar photovoltaic on the rooftop of the REC Conference Center in Szentendre, north of Budapest, Hungary. (Image credit and source: (**a**) and (**b**) Mohsen Aboulnaga) (**a**) Main façade of the REC Conference Centre with mounted 140 solar PV array on its roof. (**b**) Close up of the 29 kWp Solar PV array generating clean energy

energy. The EG-REEEL is a unique law made specifically for the MENA region, since it is a dedicated and comprehensive law with incentives for the private sector to invest in RE. This law proved that REEE has been effective in increasing renewable power capacity and has put the country on track to meet its RE target of 20% by 2020. The New and Renewable Energy Agency (NREA) has been actively promoting large-scale wind and solar energy projects for a long period, but not

Fig. 22 Integrated solar photovoltaics arrays on top of buildings' roofs in Masdar City in Abu Dhabi, UAE. (Image credit and source: Mohsen Aboulnaga)

small-scale RE projects until recently [41] and [42]. In 2017, an initiative for solar energy projects to include small scale was launched by the NREA. Moreover, in the last 4 years, several Net-metering and Feed-in-tariff incentives were announced and have led to the construction of roughly 6000 rooftop PV systems in remote areas, which also contribute to environmental protection and achieve Sustainable Development Goals (SDGs). The EG-REEEL allowed the private sector to have 720 MW of RE capacities under construction, resulting from the establishment of merchants' IPP scheme. The REEEL addresses three main issues as shown in Fig. 49.

On-Grid PV Is Expected to Witness Significant Growth in Egypt

Types of Solar energy systems depend largely on the nature of use and location. There are only three types of PV systems as depicted in Fig. 50. The solar photovoltaic installed capacity in Egypt in 2020 reached around 1.6 GW. Out of the total, nearly 90% of the capacity is on-grid, while others are off-grid and hybrid; the latter is explained in Fig. 51. In addition, Egypt has connected a large capacity of solar energy to the grid over the past few years. Most of this capacity is from large-scale

Fig. 23 Building-integrated solar photovoltaics arrays on top of roofs of various buildings in Masdar City in Abu Dhabi, UAE. (Image credit and source: Mohsen Aboulnaga)

ground-mounted projects such as generating around 1.8 GW Benban Solar Park (Fig. 52). However, many grid-connected small-scale solar system projects have also been connected to the grid during the same time, increasing the on-grid solar capacity. The New and Renewable Energy Authority (NREA), the national entity responsible for renewable energy in Egypt, promotes and collaborates with the National Project Grid-Connected Small-Scale Photovoltaic Systems (Egypt-PV) to promote the design and implementation of small-scale solar systems with capacities less than 500 kW [43].

The Solar PV project in Egypt is implemented by the Industrial Modernization Centre (IMC) in cooperation with the United Nations Development Program (UNDP) and funded by the Global Environment Facility – GEF [44]. Egypt solar PV has already provided technical and financial assistance for about 150 pilot PV projects in various sectors such as industrial, educational, commercial, public, tourism, and residential sectors, of these, 123 solar PV projects with capacities between 5 and 500 kW were completed across Egypt, with many other projects currently under progress. Hence, considering the existing and the upcoming projects, the segment is likely to have a significant presence in the country during the study period.

Fig. 24 Close up of building-integrated solar photovoltaics arrays on top of the roofs in Masdar Net-Zero City in Abu Dhabi, UAE. (Image credit and source: (**a**) and (**b**) Mohsen Aboulnaga) (**a**) Part of the solar tracking solar PV panels on top of the roof. (**b**) Rooftop Solar PV arrays seen from a street canyon, Masdar city

Fig. 25 Mounted solar photovoltaics (PV) on the rooftop of BedZED complex in Beddington, South of London – England, UK. (Image credit and source: Tom Chance, https://upload.wikimedia.org/wikipedia/commons/0/05/BedZED_2007.jpg)

Fig. 26 An impression of Tesla's Net-zero Gigafactory powered by huge roof-mounted PV arrays in Nevada, USA, the largest building by physical areas worldwide and powered by renewable sources. (Image credit and source: Tesla, https://www.treehugger.com/solar-powered-buildings-will-forever-change-architecture-4868157)

Government Renewable Energy Policies to Drive the Market

The high costs of PV system in all sectors, as demonstrated in Fig. 53, have led the Egyptian Government to identify a clear roadmap for expanding power capacity over the next decade, with renewable energy remaining a key focus. Over the past 6 years, renewable energy (RE) in Egypt has grown by around 8.5% [45], with solar power being the fastest-growing sector. In 2014, Egypt's introduction of a feed-in tariff (FiT) [46] to promote solar power attracted international attention [36]. The Egyptian Government is committed to promoting solar energy application by three various types of PV utilization (Fig. 54), and that is underscored by Kyoto protocol that Egypt signed [47].

In addition to supporting government policy on utility-scale solar energy projects, the government has also launched a number of initiatives on small-scale distributed solar power generation. Some of these are the CoM initiative, launched in 2013 [48], which facilitates the installation of combined efficient lighting and PV systems in government buildings and provides technical support to employees in various governorates. In December 2020, an Egypt-based company named ENARA Group signed a cooperation protocol with the Chinese Chint energy company to establish a project to manufacture solar panels from silica- rich sand [49, 50].

Fig. 27 Aerial view of Tesla Gigafactory with 14 GWh mounted PV arrays on top of the building in Nevada, USA. (Image credit and source: Tesla, https://www.tesla.com/blog/continuing-our-investment-nevada)

Fig. 28 Mounted solar shading louvers on a window of the Vale Living with Lakes Centres, Greater Sudbury – Ontario, Canada. (Image credit and source: Student3132021, https://commons.m.wikimedia.org/wikipedia/File:Exterior_solar_shading_fins_on_the_Vale_Living_with_Lakes_Centre.jpg)

Fig. 29 Solar PV external shading devices in a zero-energy building in Singapore, Singapore. (Image credit and source: Esmail7, https://www.wikiwand.com/en/Photovoltaic_mounting_system)

BIPVs: Total Production Capacities and Local Examples in Egypt

In contrast, building-integrated photovoltaics (BIPV) refers to the application of PV in which the system, as well as having the function of producing electricity [51], also takes on the role of a building element; it is an integral part of the building not an added complementary part. Moreover, BIPV is concerned with the overall image of the PV system in the building. There is no general classification for BIPV systems. However, a general approach for this is to nominate the systems according to the part of the building they are integrated into. Each of these typologies has different distinctive integration methods, physical properties, aesthetical characteristics, and requirements which will affect the building design in different ways.

Fig. 30 Jännersdorf solar park generating clean power in Prignitz, Germany. (Image credit and source: Parabel GmbH, https://upload.wikimedia.org/wikipedia/commons/4/48/Solarpark_Jännersdorf.jpg)

Fig. 31 Andasol Solar Concentrated Power Station (150 MW) near Guadix in Granada, Spain. (Image credit and source: Kallerna, https://commons.m.wikimedia.org/wiki/File:Andasol_Guadix_4.jpg)

Fig. 32 The first three concentrated solar power (CSP) units of Slovona Power Station in Spain. (Image credit and source: Abengoa Solar, https://upload.wikimedia.org/wikipedia/commons/4/54/Foto_aére_de_Solnovas_y_torre_junio_2010.jpg)

Fig. 33 Part of the Senftenberg 78 MW Solar Park located in the former open-pit mining areas near the city of Senftenberg, Eastern Germany. (Image credit and source: Z Thomas, https://upload.wikimedia.org/wikipedia/commons/4/45/Blick_vom_aussichtsturm_Hörlitz4.jpg)

(a) Part of the city-integrated photovoltaics (CIPV) at its fence

(b) The solar PV array, each generates 6 kW power output.

Fig. 34 Part of solar high-efficiency PV arrays at the fence of Fujisawa smart City in Yokohama, Greater Tokyo, Japan. (Images' credit and source: Mohsen Aboulnaga) (**a**) Part of the city-integrated photovoltaics (CIPV) at its fence. (**b**) The solar PV array, each generates 6 kW power output.

Fig. 35 Part of solar high-efficiency PV array installed at the fence of Fujisawa smart City in Yokohama, Greater Tokyo, Japan. (Image credit and source: Mohsen Aboulnaga)

Accordingly, BIPV systems can be classified into the following systems as shown in Figs. 55 and 56 [32].

Recent Egyptian examples for the integration of PVs on buildings' roofs or walls in all sectors of urban development [44] are summarized in Table 1. In commercial, industrial, educational, tourism, public and residential sectors, different modules of PV systems are integrated within buildings, normally on rooftop as a secondary source of electric energy, besides the available utility electricity grid. The contribution of solar PV in all building sectors is estimated to be highest in the industrial sector as presented in Fig. 57.

Urban-Integrated Photovoltaics: Total Added Capacities and Egyptian Examples

Solar PV application in urban areas is immense worldwide. In this section, the focus is on the integration of photovoltaic applications in the urban context as a function of the cumulative process starting with photovoltaic technology and its application, to the importance of the integration that occurs between urban planning processes and BIPV- related themes. This approach therefore brings the urban ecosystem closer to balance, considering the use of solar energy in urban planning and urban development as well. In this balance, it is worth noting what role solar energy can

Fig. 36 The 10 MW solar PV farm in Masdar City, Abu Dhabi, UAE. (Images' credit and source: (**a**) Masdar, https://Masdar.ae/Masdar-Clean-Energy/Projects/Masdar-City-Solar-Photovoltaic-Plant; (**b**) Karin Kloosterman, https://www.greenprohpet.com/2011/06/masdar-solar-energy-plant/; (**c**) Steve Griffiths & Benjamin Sovacool, https://doi.org/10.1016/j.erss.2019.101368) (**a**) The solar power PV plant in Master City. (**b**) Close up of the 87,780 solar PV power plant. (**c**) View of two arrays of the PV plants

play at the level of the planning process, which occurs through the adjustment of the inputs of the urban planning process. Many attempts have been made to apply this concept, including Solar City Guide, Urban Integrated Renewable Energy Program, Amersfoort City, Masdar City, Solar Cities [33, 52, 53].

However, the UIPV process is a combination of all these attempts. As such, the UIPV development process approach should integrate all elements involved in these experiments. The key elements of the UIPV process can therefore be summarized into four main categories as presented in Fig. 58. For urban planning, there are also four areas that solar PV can be implemented (Fig. 59).

Regarding the solar photovoltaic (PV) market in Egypt, it is moderately fragmented. The key owners in the market including many public and private companies such as Egyptian Electricity Holding Company (EEHC), KaramSolar, Infinity Solar, Cairo Solar, Scatec ASA (a Norwegian Company operating in Egypt) and several others as mentioned in Fig. 60 [44]. In terms of urban-integrated photovoltaics

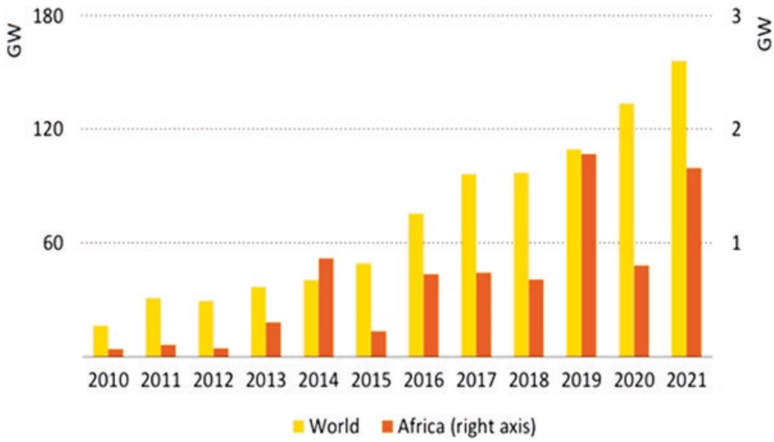

Fig. 37 Solar PV capacity additions in Africa and the world between 2010 and 2021. (Image credit and source: IEA (International Energy Agency), https://www.iea.blob.core.windows.net/assets/6fa5a6c0-ca73-4a7f-a243-fb5e83ecfb94/Africa EnergyOutlook2022.pdf)

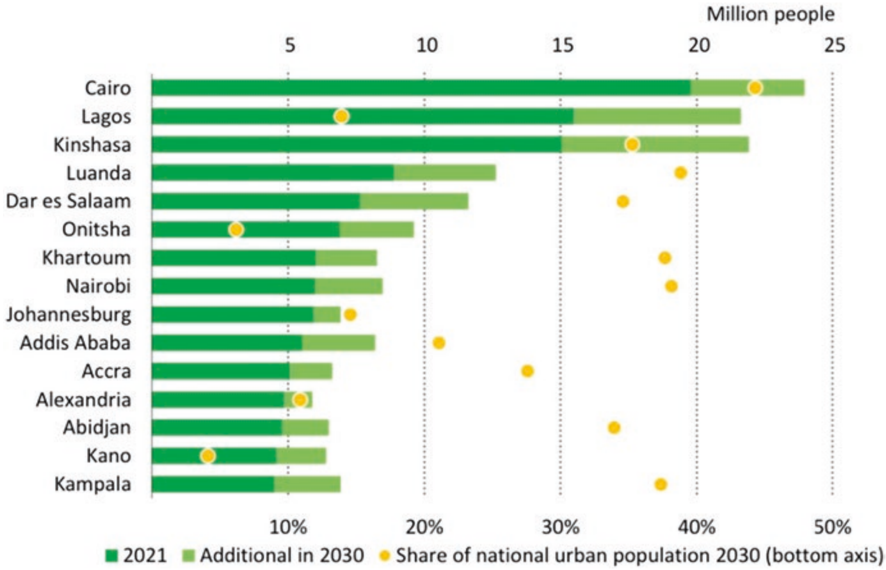

Fig. 38 World's electricity production by source from 2000 to 2020. (Image credit: Demographia 2021, source: International Energy Agency (IEA), https://www.iea.blob.core.windows.net/assets/6fa5a6c0-ca73-4a7f-a243fb5e83ecfb94/AfricaEnergyOutlook2022.pdf)

(UIPV) Table 2 lists some examples in Egypt, particularly in New Cairo, Nasr City, Sharm El Sheikh and Hurghada.

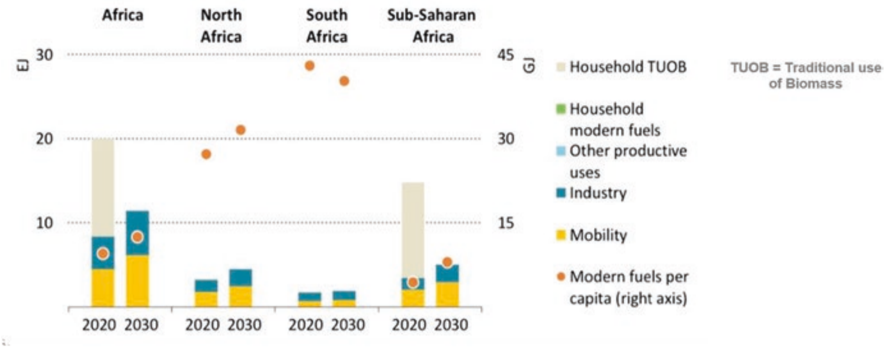

Fig. 39 Total final energy consumption by sector and modern fuel use per capita by region (North Africa, South Africa and Sub-Saharan Africa) in the Sustainable Africa Scenario – SAS. (Image credit and source: International Energy Agency (IEA), https://www.iea.blob.core.windows.net/assets/6fa5a6c0-ca73-4a7f-a243-fb5e83ecfb94/AfricaEnergyOutlook2022.pdf)

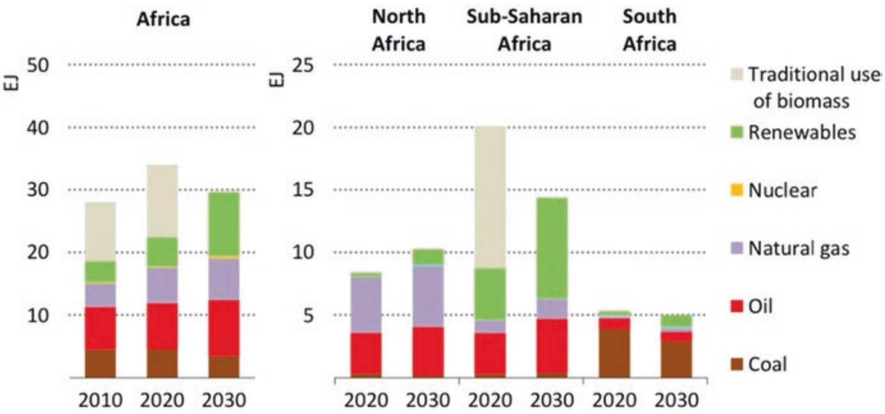

Fig. 40 Total primary energy supply and region in the Sustainable Africa Scenario – SAS. (Image credit and source: International Energy Agency (IEA), https://www.iea.blob.core.windows.net/assets/6fa5a6c0-ca73-4a7f-a243-fb5e83ecfb94/AfricaEnergyOutlook2022.pdf)

Solar Power Plants: Total Production Capacities and Examples in Egypt

Solar Photovoltaics Parks (Utility Scale)

Solar photovoltaic power generation stations are grid-connected large-scale solar power specifically designed to supply utility-scale electricity [9]. Government initiatives to support land use allocation to solar parks and sign international agreements with various potential countries to ensure mutual energy benefits have provided sufficient fund to raise the solar energy production capacity [46].

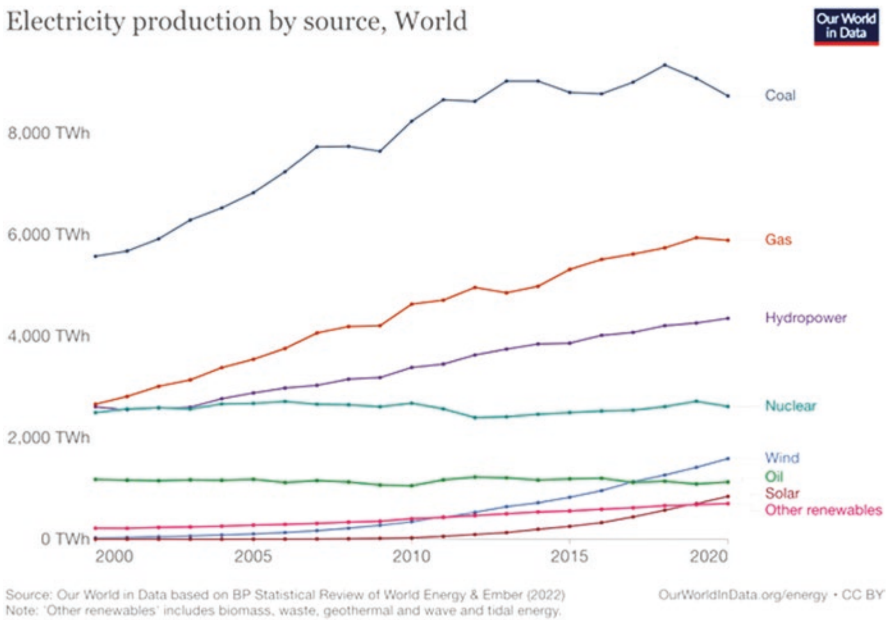

Fig. 41 World's electricity production by source from 2000 to 2020. (Image credit and source: IEA (International Energy Agency), https://www.iea.blob.core.windows.net/assets/6fa5a6c0-ca73-4a7f-a243-fb5e83ecfb94/AfricaEnergyOutlook2022.pdf)

Currently, vast development in solar PV parks has increased solar generation capacity in Egypt by almost nine times between 2018 and 2019. As a result, the energy generation increased from 172 MW 2018 to 1597 MW 2019, which led to the mitigation of CO2 emissions from 8.4 million tons to 11.4 million tons respectively [31]. This has been recognized by the newly developed large solar parks in BenBan Solar PV Park in Egypt, which have a mega generation power capacity [54].

Most Solar parks are operated and/or owned by Independent power providers in which they run and maintain the facility and then sell the electricity to end users through the national utility grid [55].

As illustrated in Fig. 61, the high-capacity solar power stations in Egypt are summarized in Table 3 to demonstrate their power capacity, commissioning date, along with their operators. These large solar parks are distributed along the map in various locations in Egypt as shown in Fig. 62. The wide distribution of solar parks all over the country indicates the suitability of Egyptian land to serve the technology.

Saint Anthony Monastery Solar Power Plant

The German Federal Ministry for Economic Cooperation and Development (BMZ) participated in the construction of a 300 kWp hybrid solar system as presented in Fig. 63. The electricity generated by diesel generators and solar is continuously

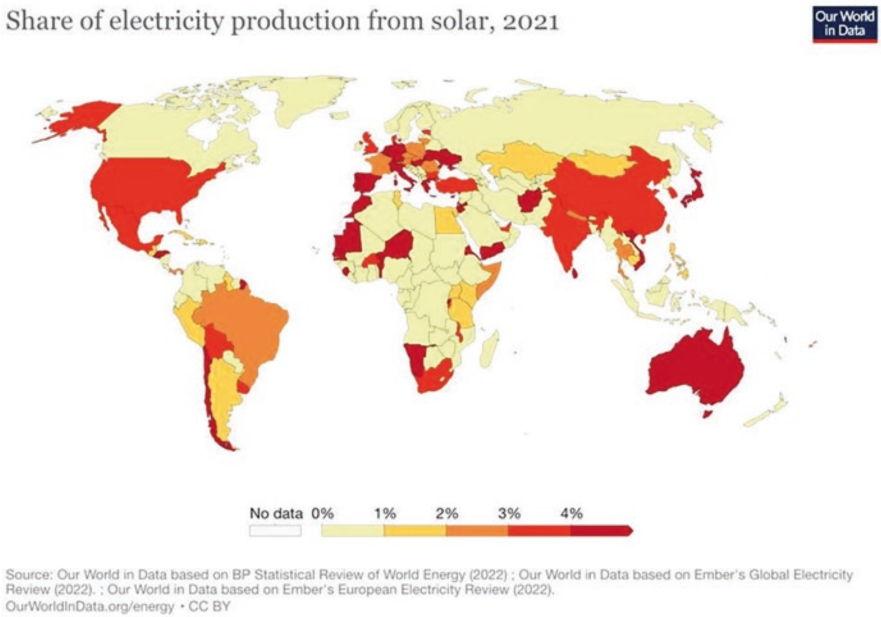

Fig. 42 World's electricity generation share from solar in 2021. (Image credit and source: IEA (International Energy Agency), https://www.iea.blob.core.windows.net/assets/6fa5a6c0-ca73-4a7f-a243-fb5e83ecfb94/AfricaEnergyOutlook2022.pdf)

adapted every second to energy demand. The core of this system is a control unit that is fed by signals from the synchronization of the generators and the solar inverters. With the old design, the feed-in limit was 50%, but it aimed at achieving a ratio of 25% generator and 75% solar power [61].

Benban Solar Park in Aswan

Benban Mega Solar Park is located in Aswan Governorate, the western desert, approximately 650 km, south of Cairo and 40 km northwest of Aswan (Fig. 64). Benban is currently the fourth-largest solar power plant in the world. The venture was started as portion of the Egyptian government's Economic Vitality Technique 2035 [8]. At first, NASA helped in finding the leading area to arrange the sun-based park [56]. Benban Sun oriented Station size 37.2 km^2 (14.4 square miles), which is subdivided into 41 isolated plots orchestrated in 4 columns with each plot run in estimate from 0.3 km^2 to 1 km^2 (0.12 to 0.39 sq. mi.). Each plot is accessible to diverse companies to create 41 plants which will be associated with the voltage arranged through four unused substations; this has bas been built on the location by the Egyptian Power Transmission Company (EETC).

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H. W. SECOR ASSOCIATE EDITOR

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The Utilization of the Sun's Energy

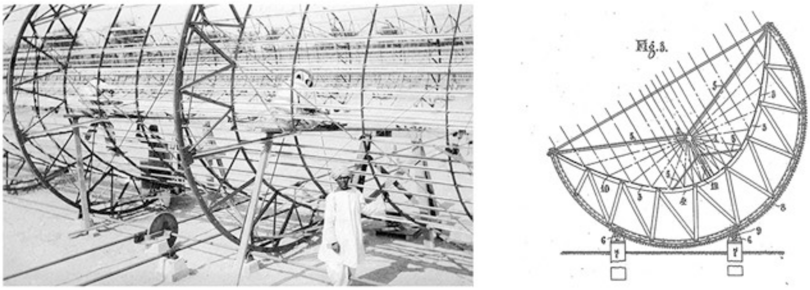
Years Ago Man Endeavored to Make Practical Use of the Energy Contained in the Sun's Rays—Even Tesla, the Electrical Wizard, Has Patented a Sun Motor, While the Shuman-Boy's Engine and Sun Boiler Has Developed 100 H. P. There Is Great Promise Held Forth to Future Engineers Who May Work on This Problem.

IT has been given to astrophysicists to measure the heat generated by the sun and calculate the force emanating from it. We know that the surface of our luminary gives out a heat estimated to be about 6,000° centigrade, and that its light equals that of 27,600,000,000 candlepower a quarter of a mile away. The heat which the were lacking, our planet, with all its thousandfold life, its thick forests and fruitful plains, would turn into a dead, rigid ball of rock, for the average annual temperature, which is now one of 15° centigrade of warmth for Europe, would, without the heat of the sun, sink to [illegible] centigrade of frost, it is calculated. the untaught son of nature brightens his hut, the twigs with which he stokes his fire, what are they but pieces of trees that grew in the sunlight? The gas of the city dweller, the coals with which he heats his house and from which the gas has been soaked, what are they but transformed sunbeams? The coal in the grate is the

A Successful 100 H.P. Sun Power Plant Located at Meadi, on the Nile, Egypt.

Fig. 43 First invented solar cells in 1913. (Image credit and source: Gernsback, Hugo, https://en.wikipedia.org/w/index.php?title=File:The_Electrical_Experimenter,_Volume_3.pdf&page=643)

These substations will in turn interface to an existing 220 kV line, which passes close to the Benban plant (about 12 km), where EETC to build an extra association with the neighbouring 500 kV line [62]. Concurring to estimations detailed within the natural and social appraisal assessment [56], the sun-based location asset is around 2300 kWh/m^2-yr. Accepting a crest insolation of 1000 W/m^2, this deciphers to a potential plant capacity calculated of roughly 26%, i.e., the normal capacity will



(a) General view of the solar concentrated panels (b) Section of the solar concentrated panels

Fig. 44 Egypt first Solar Panels metal structure [28] (**a**) General view of the solar concentrated panels; (**b**) Section of the solar concentrated panels

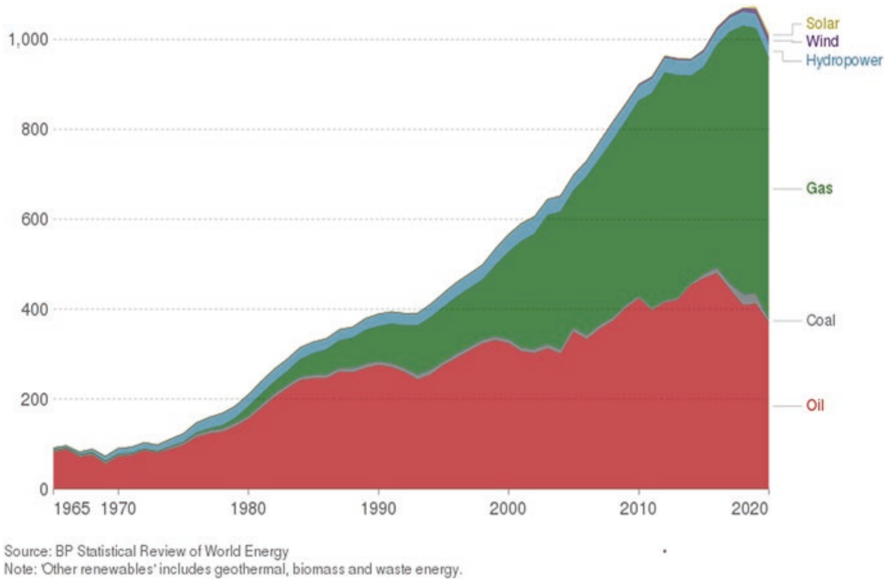


Fig. 45 Energy consumption in Egypt by source from 1965 to 2020. (Image credit and source: Max Roser, https://upload.wikimedia.org/wikipedia/commons/9/99/Energy_consumption_by_source%2C_Egypt.svg)

be 26% of the nameplate capacity. If the arranged capacity of 1.8 GW is utilized, the potential yearly vitality generation will be somewhat more than 4 TWh/yr. The Benban Solar Stop could also be a part of Egypt's Nubian Suns Feed-in Duty program – a major activity to impact private division capital and skill, in arrange to back the objective of creating 20% power from renewable assets by 2022 [62]. The station is so expansive that it is obvious from space.

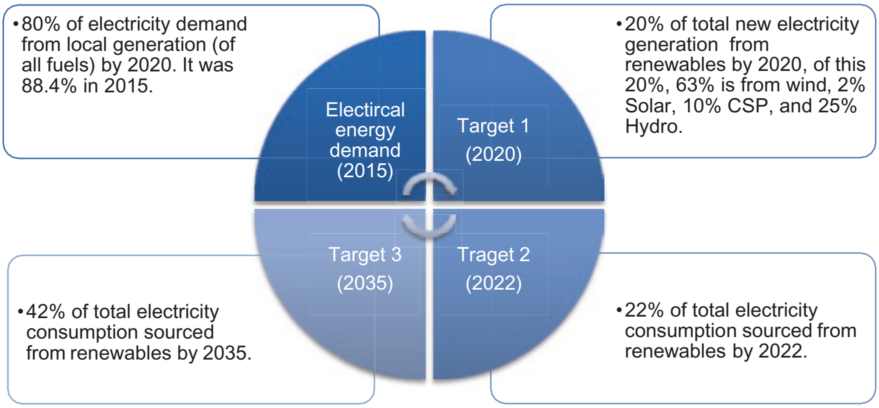


Fig. 46 Energy consumption in Egypt by source from 1965 to 2020. (Image credit and source: CES-MED, https://www.climamed.eu/wp-content/uploads/files/Egypt-Governorate-of-Hurghada-Sustainable-Energy-and-Climate-Action-Plan-(SECAP).pdf)

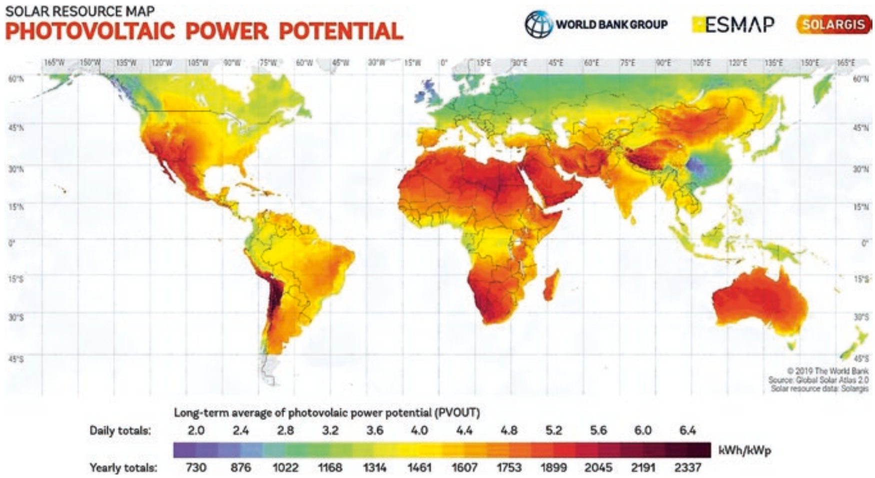


Fig. 47 Photovoltaic power potential in Egypt. (Image credit and source: World Bank, https://upload.wikimedia.org/wikipedia/commons/e/e7/World_PVOUT_Solar-resource-map_GlobalSolarAtlas_World-Bank-Esmap-Solargis.png)

Helwan Solar Power Plant

Helwan Solar Power Station has a total capacity of 24 MW A/C power. It comprises 62,400 solar modules (400-W peak) spread across 42 ha of land. The electricity production of the solar power plant is about 43 GWh/year [63]. Developing module layout and spacing to be typically optimized to balance energy production versus

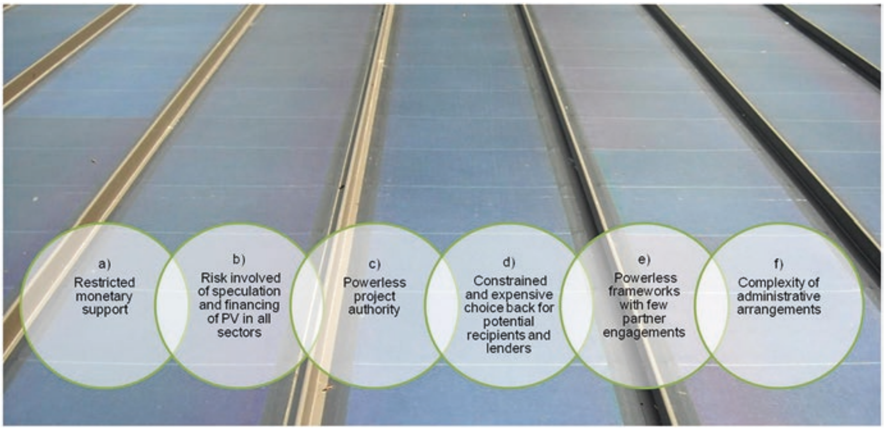


Fig. 48 Energy consumption in Egypt by source from 1965 to 2020. (Image credit and source: Max Roser, https://upload.wikimedia.org/wikipedia/commons/9/99/Energy_consumption_by_source%2C _Egypt.svg)

Fig. 49 The main three issues addressed by REEEL in Egypt. (Image credit and source: Authors after CES-MED, https://www.climamed.eu/wp-content/uploads/files/Egypt-Governorate-of-Hurghada-Sustainable-Energy-and-Climate-Action-Plan-(SECAP).pdf)

peak capacity; and designing the electrical distribution system to transform the output power from the PV modules from DC to AC and then from low voltage to transmission level voltage for connection to the grid.

Kom Ombo Solar Power Plant, Aswan

A ground-mounted solar park, located in Kom Ombo, Aswan, is expanded to generate 20 MWh of electricity and supply clean energy to power 130,000 house units. It is expected to offset 336,000 t of carbon dioxide (CO2) emissions per year as illustrated in Fig. 65. The plant was developed between 2021 and 2022, Owned by International Company for Water and Power Projects (ICWPP) with a purchase

Fig. 50 Different types of PV systems. (Source: Authors, images' credit: (*1*) Klaus Holl, https://commons.wikimedia.org/wiki/File:Photovoltaikanlage.jpg; (*2*) Gary Watson, https://upload.wikimedia.org/wikipedia/commons/8/85/Solar_panels_on_house_roof_winter_view.jpg; (*3*) Wing, https://upload.wikimedia.org/wikipedia/commons/2/26/Electrical_and_Mechanical_Services_Department_Headquarters_Photovoltaics.jpg)

agreement for a period of 25 years, and has a stake of 100% and a total initial cost of around $156.4 m [64].

Marsa Shagra Solar Power Station, Red Sea

Red Sea Global, formerly known as The Red Sea Development Company, appointed a consortium led by ACWA Power to design, build, operate and transfer the project's utility infrastructure powered entirely by renewable energy. The consortium partners include China's SPIC Huanghe Hydropower Development Company and the Saudi Tabreed district cooling company, a significant step towards the Kingdom's vision of achieving a 50% energy mix by 2030 [59]. The solar power station, shown in Fig. 66, currently encompasses the production of first-phase energy of 210 MW. It will be powered by a 340-MW solar photovoltaic panel. Also, this complex will depend on the world's largest battery storage at 1000MWh, according to Red Sea Global.

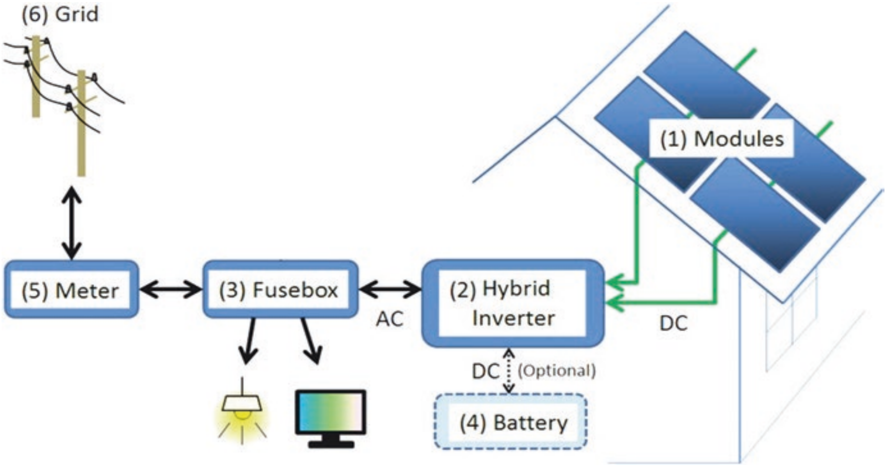


Fig. 51 System diagram of intelligent hybrid inverters used in domestic setting. (Image credit and source: Glider Maven, https://commons.wikimedia.org/wiki/File:PV-system-intelligent-hybrid-inverter.png)

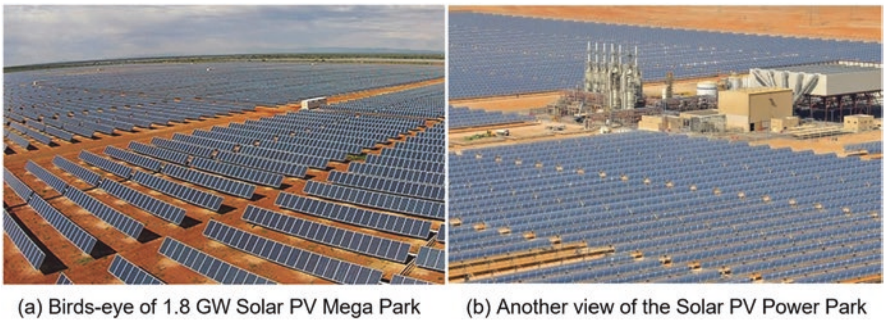


Fig. 52 Ben Ban Solar PV Power Plant in South of Egypt – One of the World largest Solar Parks. (Images' credit and source: (**a**) ES BUSS, Egyptian Streets, https://www.egyptianstreets.com/2020/12/05/the-story-of-how-egypt-built-one-of-the-worlds-largest-solar-park/; (**b**) Sarah Samir, Oil and Gas, https://egyptoil-gas.com/news/benban-solar-park-attracts-over-2-b-invesments/) (**a**) Birds-eye of 1.8 GW Solar PV Mega Park. (**b**) Another view of the Solar PV Power Park

SOMA Bay Power Plants and Suez Golf Power Plant

The construction of two new power plants in Soma Bay, the Red Sea, which has a capacity of 5 MWp, will be provided by TAQA Power. The solar plant's investment costs USD 4 million. The larger solar plant will have a capacity of 3.8 MWp, and its facility will be built under a 30-year management agreement.

A power purchase agreement (PPA) with Abu Soma Touristic Development (ASDC), which manages the beach resort of Soma Bay has been finalized. The

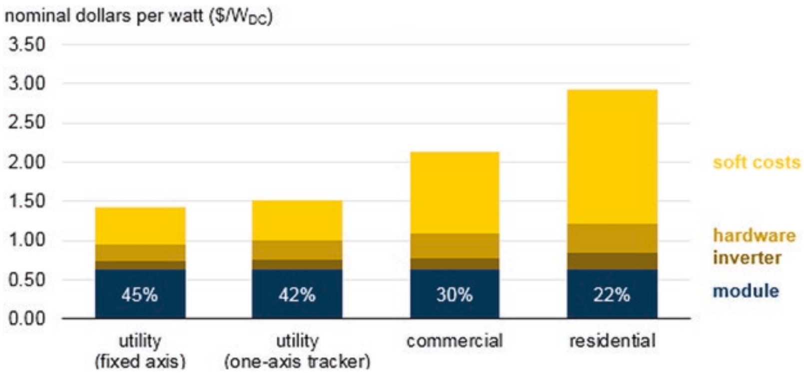


Fig. 53 PV total system costs by sector. (image credit and source: U.S. Energy Information Administration, https://commons.wikimedia.org/wiki/File:Photovoltaic_(PV)_total_system_costs_by_sector_(25410070907).png)

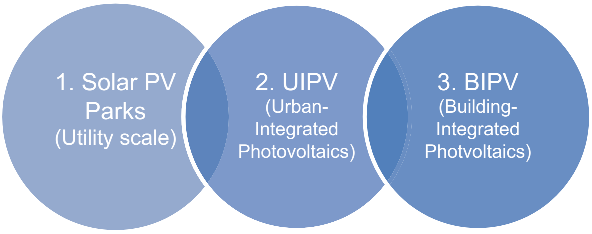


Fig. 54 Types of photovoltaics utilization in Egypt. (Image credit and source: Authors)

signed agreement also includes the construction of a second solar photovoltaic plant of capacity of 1.2 MWp, and the operation of the second plant will then be transferred to ASDC. The electricity produced will power the city with clean energy resources and provide a sustainable alternative to the on-grid electricity source.

In addition, the Suez city – at its triangular plot area – has been allocated for solar energy generation plant with a capacity of 10 GW/h annually as shown in Fig. 67. A partnership agreement between JUSHI and INARA Capital, a leading renewable energy company, led the project [65].

Siwa Solar Park, Siwa

The Siwa solar park is located in Siwa, west of Egypt. The first utility-scale and formerly largest solar PV plant in Egypt by 2015 is presented in Fig. 68. The solar plant generates 10 MW (about 17,500 MWh per year), which supplies electricity to nearly 6000 homes. This supplied power accounts for 30% of the power demand in

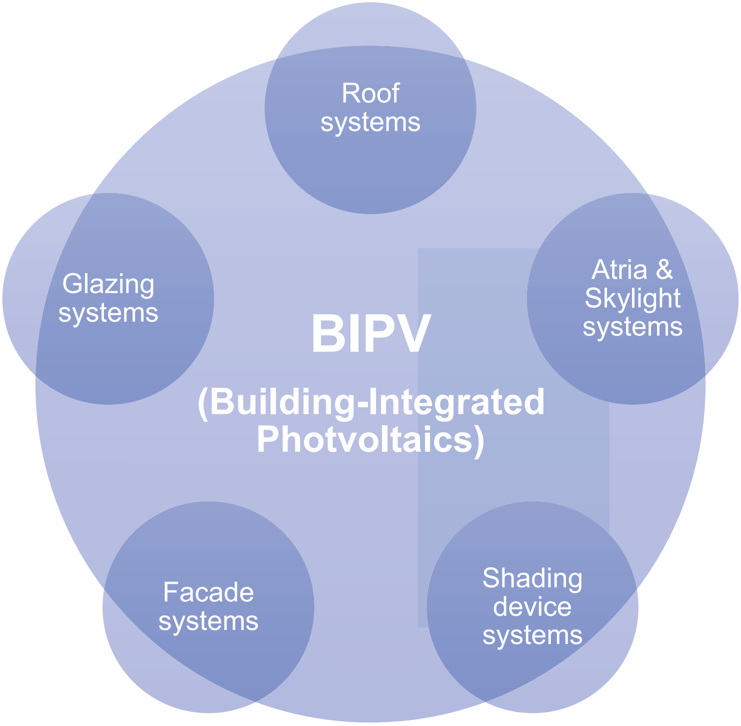


Fig. 55 Building-integrated photovoltaics (BIPV) types. (Image credit and source: Authors)

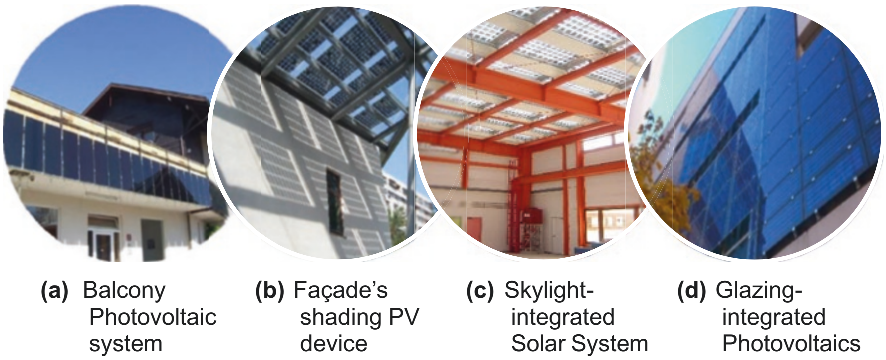


Fig. 56 BIPV successful types used in buildings. (Image credit and source: (**a**) https://commons.wikimedia.org/wiki/File:Dornbirn-Montfortstrasse_21-balcony_photovoltaic_system-01ASD.jpg; (**b**) https://commons.wikimedia.org/wiki/File:Taipei_Public_Library_Solar_LEO_House_BIPV_20110207.jpg; (**c**) https://commons.wikimedia.org/wiki/File:BIPV.jpg; (**d**) https://upload.wikimedia.org/wikipedia/commons/f/f8/BAPV_solar-facade.JPG) (**a**) Balcony Photovoltaic system. (**b**) Façade's shading PV device. (**c**) Skylight-integrated Solar System. (**d**) Glazing-integrated Photovoltaics

Table 1 Egypt's BIPV successful stories across building sectors

Building sector	**Industrial project (Nissan Motors)**	**Educational project (Alhayah School)**	**Public sector (Housing & Building National Research Center – HBRC)**
Construction year	1996	2003	1954
Location	Industrial zone, 6th of October, Giza	Fifth Settlement, New Cairo, Cairo	Dokki, Giza
Installed solar PV capacity	500 kWp	383.1 kWp	92.9 kWp
Payback	4.2 years	5.7	6.5 years
IRR	32%	22%	17.50%
Image of the project			
Building sector	**Tourism sector (JW Marriot Mirage City)**	**Residential sector (El-NADA Compound)**	**Commercial sector (Sodic Developments)**
Construction year	2003	2002	1996
Location	First Settlement, New Cairo	El Sheikh Zayed, 6th of October, Giza	El Sheikh Zayed, 6th of October, Giza
Installed PV capacity	150 kWp	335 kWp (5–10 kWp per villa)	330 kWp
Payback	5.5 years	4.8 years	6 years
IRR	19%		211%
Image of the project			

Source: Developed by Authors after UNDP; https://www.undp.org/egypt/publications/egypt-pv-success-stories#:~:text=The%20total%20number%20of%20implemented,of%20electricity%20 13%20GWh%20%2F% 20year

Siwa City and its outskirts. The solar plant covers a land area of 175,000 m^2 and displaces approximately 14,000 tons of CO_2 annually.

The plant consists of 74,640 micromorph thin-film silicon panels [66], and it provides electricity to about 6000 homes. The project is part of UAE-funded grant for rural electrification in Egypt, which includes solar energy solutions to electrify 264 villages and rural communities currently lacking reliable access to electricity and cut off from the national grid. The project was initiated by Masdar in cooperation with NREA in March 2014 with the sponsorship of the UAE-Egypt Taskforce

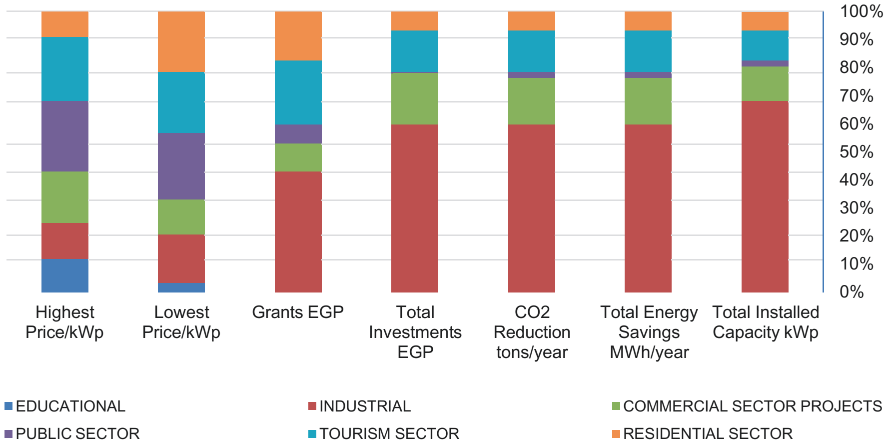


Fig. 57 Building-integrated photovoltaics (BIPV) in all sectors, Egypt. (Image credit and source: Author based on data from https://www.undp.org/egypt)

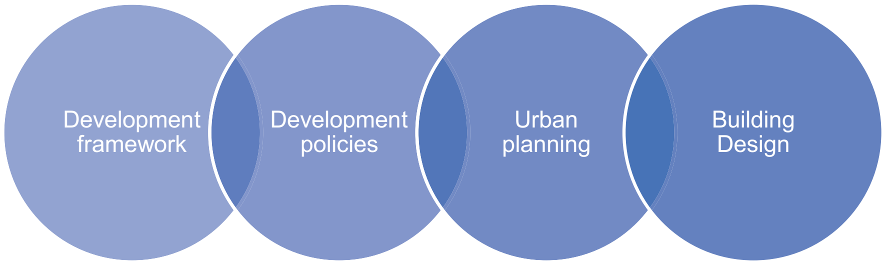


Fig. 58 Recommended PV successful integration in Egypt. (Image credit and source: Authors)

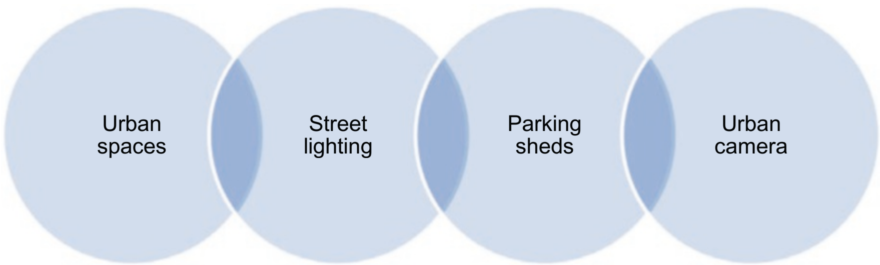


Fig. 59 Urban-integrated photovoltaics (UIPV) categories in Egypt. (Image credit and source: Authors)

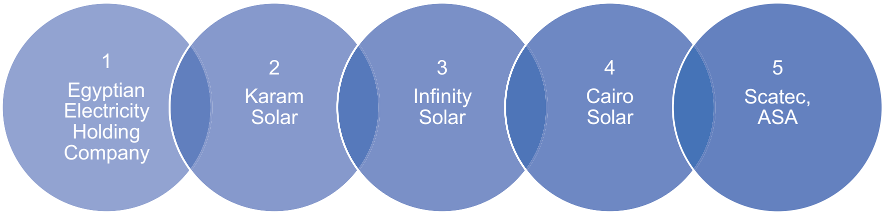


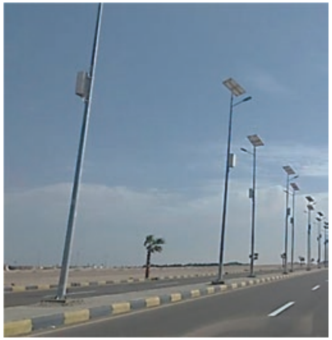
Fig. 60 Solar photovoltaics role players in Egypt. (Image credit and source: Authors after Modern Intelligent, https://www.mordorintelligence.com/industry-reports/egypt-solar-photovoltaic-market)

and it was fully commissioned in March 2015 [60]. The solar power plant is operated by Al-Behira Electrical Distribution Company, owned by the state utility Egyptian Electricity Holding Company [60].

7 Conclusion

Building-integrated photovoltaics (BIPV) or building-applied photovoltaics (BAPV) examples have been tackled and discussed. An overview on the global building-integrated photovoltaics examples was conducted, including the world's largest BIPV (Apple Headquarters in California and Tesla net-zero Gigafactory in Nevada, in the USA). Renewable energy added capacity in Africa was also reviewed and highlighted in terms of solar PV capacity additions in Africa and the World between 2010 and 2021 was presented in addition to the total final energy consumption by sector and modern fuel use per capita by region in North Africa, South Africa. Historically, Egypt witnessed an early manifestation when it comes to clean energy sources, where the world's first sun-powered control plant was built in 1913 in Maadi, south of Cairo, Egypt. The experience for solar energy in Egypt is recognized by the long hours of sunshine throughout the year (average 2400 h), with high solar radiation intensity of 2600 kWh/m^2 and considered one the highest solar intensity on earth. Hence, this potential derived local authorities and central government in Egypt to prioritize the utilization of renewables in cities and urban areas. Moreover, the role of solar energy in producing electricity worldwide and the share of electricity generation from solar in 2021 were presented. In terms of solar photovoltaic (PV) market in Egypt, it is clear from the aforementioned narrative that the country has very favourable solar resources for a variety of solar energy technologies and applications whether implementing photovoltaic panels (PV) or concentrated solar power plants (CSP). Since types of solar energy systems depend largely on the nature of use and location, on-grid PV realization is expected to witness significant growth in Egypt in the next 7–15 years. BIPVs in terms of the total generation capacities and local examples in Egypt have been also reviewed and presented. It has been stated that government policies on fostering renewable energy to

Table 2 Egypt's UIPV successful stories

	Urban PV integration		
Street lights			
	(a) Street PV lights, Business District, CFC, Cairo (Image credit and source: Maryam Elsharkawy)	(b) Street lighting of the road to Al-Gouna, Hurgada City, Red Sea (Images' credit and source: Mohsen Aboulnaga)	
Parking sheds			
	(c) PV parking shed at Sharm El-Sheikh Airport, City of Sharm El-Sheikh, South Sinai	(d) PV parking shed at City center, Almaza, Nasr City, Cairo (Image credit and source: Maryam Elsharkawy)	(e) Close-up of the PV parking shed at City center, Almaza, Nasr City, Cairo (Image credit and source: Maryam Elsharkawy)

(c) Image source: https://dailynewsegypt.com/2022/11/09/irsc-complement-sharm-el-sheikh-airport-with-world-class-solar-power-solutions/

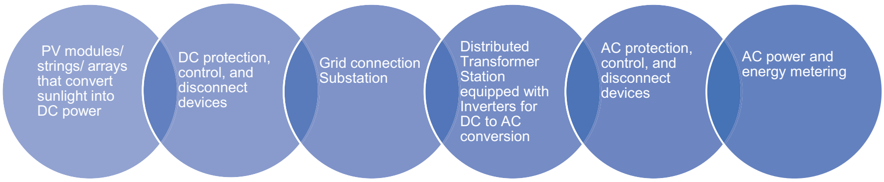


Fig. 61 Solar power plant energy route to final users. (Image credit and source: Authors)

Table 3 Summary for high capacity Solar PV power stations located in Egypt

Solar power plant's name	Operator	Governorate	Type	Capacity (MW)	Commission date	References
Benban Solar Park	New and Renewable Energy Authority of Egypt (NREA)	Aswan	PV power station	1650	2019	[56]
Kom Ombo Solar Park	NREA	Kom Ombo	PV power station	200	2021	[57]
Access Egypt Solar One Power Plant	Access Power Limited	Aswan	PV power station	50	2018	[58]
Helwan Solar PV Power Station		Helwan	PV power station	25	2014	
Marsa Shagra Solar Power Station	ACWA Power Consortium	Red Sea	PV power station	210	2022	[59]
Siwa Solar Park	Al Behira Electrical Distribution Company	Matrouh		10	2015	[60]

Source: Authors based on https://en.wikipedia.org/wiki/List_of_power_stations_in_Egypt

drive the market were significant from 2014 till present. Urban-integrated photovoltaics (UIPV) in terms of total added capacities and the examples have been received and illustrated in three Egyptian cities. Solar power plants with total production capacities where manifested in seven examples in Egypt show the output of solar photovoltaics parks as grid-connected utility scale. The largest solar power plant with 1.8 GW capacities in Benban, in Aswan, Egypt, has been presented and

Fig. 62 Solar photovoltaics power plants location in Egypt. (Image credit and source: Authors based on https://earth.google.com/web/)

(a) Solar PV power plant in Saint Anthony **(b)** Arial view of the PV solar arrays

Fig. 63 The PV power plant in Saint Anthony Monastery, Egypt. (Images credit and source: (**a**) Source: https://commons.wikimedia.org/w/index.php?search=pv+in+egypt&title=Special:MediaSearch&go=Go&type=image; (**b**) Google Earth) **(a)** Solar PV power plant in Saint Anthony. **(b)** Arial view of the PV solar arrays

discussed. Such mega-power park highlights the pursued efforts towards achieving the target of reaching 42% of Egypt's energy mix by 2035. Finally, COP27 which was held in Sharm El-Sheikh, Egypt highlighted the opportunity of Egypt to be the hub of the world's renewable energy, mainly solar PV and wind energy, not only

(a) PV Panel arrays of the solar power farm **(b)** Aerial view of the power plant

Fig. 64 The PV power park in Benban, Egypt. (Image source: (**a**) https://www.dw.com/en/desert-large-solar-plants-also-pay-off-in-countries-with-less-sun/a-58284114; (**b**) Authors after Google Earth) **(a)** PV Panel arrays of the solar power farm. **(b)** Aerial view of the power plant

Fig. 65 The PV panels in Kom Ombo's Power station, Egypt. (Image source: Authors after Google Earth)

that but also in terms of investment. It is worth mentioning that sunlight is the future to mitigate climate change, reach decarbonization targets of 45% by 2030, and reach net zero by 2050.

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(a) PV panels at Marsa Shagra, Red Sea (Image source: Egypt seeks to quadruple desalination to ease water shortages | | AW (thearabweekly.com))

(b) Aerial view for Marsa Shagra Power Station, Red Sea, to be expanded (Image Source: Authors via Google Earth)

Fig. 66 Marsa Shagra Solar Power Station on Egypt's Red Sea **(a)** PV panels at Marsa Shagra, Red Sea. (Image source: Egypt seeks to quadruple desalination to ease water shortages | | AW (thearabweekly.com). **(b)** Aerial view for Marsa Shagra Power Station, Red Sea, to be expanded. (Image Source: Authors via Google Earth)

Fig. 67 Suez Golf solar park in Egypt. (Image source: Authors after Google Earth)

Fig. 68 Siwa solar park in western desert, Egypt. (Image source: Authors after Google Earth)

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