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CSIR-NIIST

Indian BIPV Report 2022: Status and Roadmap

Status Report
2022

Report by

SUPSI-Swiss BIPV Competence Centre
Paolo Corti, Pierluigi Bonomo

The here involved Institute for Applied Sustainability to the Built Environment (ISAAC) is part of the University of Applied Sciences of Southern Switzerland (SUPSI). The institute, under ISO 9001 accreditation, covers several research areas in the field of renewable energy, rational use of building energy with particular attention to green building standards, building maintenance and refurbishment, as well as technological development.

The building sector is active in the field of research concerning building operation, advanced solar building skin, sustainable materials and constructions. The Research unit, with almost 20 years of experience in BIPV, is one of the leader groups active in federal, European and international projects of applied research, including R&D, services at industries, communication and sensitization. The team is active in global experts groups of International Energy Agency, in scientific expert committees for international conferences and journals, in standardization bodies and in the main networks supporting BIPV. The Institute also has a PVlab covering a wide range of electrical, climatic and mechanical tests according to IEC– standards and accredited ISO 17025.

The main research activities of ISAAC and specifically of the BIPV group are focused on:

- Applied R&D for developing, testing, validating, demonstrating and industrializing innovative construction solutions for multifunctional building envelope systems, conceived designed and engineered on the basis of an integrated approach;
- Developing, in collaboration with partners (architects, industries, real estate managers, etc.), innovative pilot buildings integrating PV with the role of building skin components;
- Methodologies and techniques that favor the exploitation of solar energy in the built environment, both for new and existing building stock, by analysing the techno-economic feasibility, the market needs and innovation trends;
- Development of a digitized and integrated process within the BIM-based approach involved simulation and analysis of BIPV systems

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CSIR-National Institute for Interdisciplinary Science and Technology
Animesh M Ramachandran, Adersh Asok

CSIR-National Institute for Interdisciplinary Science and Technology (NIIST), is a constituent Laboratory of the Council of Scientific and Industrial Research (CSIR), New Delhi, India. CSIR, established in 1942, is an autonomous society whose Presidential position is carried by the Prime Minister of India. It holds one of the largest R&D conglomerates in the world with a dynamic pan-India network of 37 national laboratories, 39 outreach centres, 3 Innovation Complexes and 5 units located across India. CSIR, known for its cutting edge R&D knowledge-base in diverse S&T areas, is a contemporary R&D organization and categorized amongst the foremost scientific and industrial organizations in the world. CSIR is ranked at 84th among 4,851 institutions worldwide and is the only Indian organization among the top 100 global institutions, according to the Scimago Institutions Ranking World Report 2014 (CSIR holds the 17th rank in Asia and leads the country at the first position).

CSIR-NIIST, one of the prime laboratory of the CSIR conglomerate is located at Thiruvananthapuram, Kerala, the south most part of India. CSIR-NIIST is mandated to conduct interdisciplinary research and development activities of the highest quality in areas related to the effective utilisation of resources of the region and of fundamental importance to the country. Apart from fundamental research of interdisciplinary nature, technology-based interventions have been greatly carried out in the last decade, especially in the field of solar energy. Innovative technological approaches like planar light concentrators, building integrated agrivoltaics, dynamic power windows, organic and inorganic hybrid solar cells, etc., can be mentioned as a few in the BIPV headway. The institute has already established and functionalised state-of-the-art facilities for conducting advanced research in the area of interest.

Council of Scientific & Industrial Research –
National Institute for Interdisciplinary Science and Technology
(CSIR–NIIST)

ARKA Experience centre

Offering advanced solar roofing solutions to Indian consumers

Completion year	2022
Planning & Installation	SunEdison, ARKA Energy
Building typology	Open House
Category	New building
Installed PV power	4.4 kWp
Energy production	6,970 kWh/yr

+91 1800 102 0765
sunedison.in/arka-collection
sales@sunedison.in

Renewable energy pioneer SunEdison launched a new type of residential solar solution in collaboration with ARKA Energy, a Silicon Valley based startup. The 'ARKA Collection' by SunEdison is designed for durability, performance & aesthetics. The PowerGazebo is an architectural solar installation that can help one expand their living space and the PowerRoof provides a way to create a roof that can power your home. SunEdison believes that the Arka Collection is the finest BIPV solution which is designed and manufactured in India for Indian customers.

The first activity that the teams undertook was the ideation phase, in which SunEdison reached out to architects specializing in green buildings for design ideas.

Since the ARKA Collection is an experiential product line which has not been seen before in India, setting up an experience center was one of the first projects that SunEdison wanted to accomplish. The project called for an open-house architecture design followed by a fibrocement cladding with a provision for a sky roof. The experience center is placed in the center of a busy residential neighborhood surrounded by independent housing. The center is equipped with the latest installation of their SunEdison ARKA collection's flagship products – the PowerRoof & the PowerGazebo.

Three PowerGazebos are also constructed in the available open-floor area which can be used as breakout zones inside the hub. The space doubles up as a corporate meeting space and an experience center setup.

The glass-on-glass PV tiles offer an elegant monochromatic black finish. Non-PV tiles which look like PV tiles can be used in areas with persistent shadow and nooks of any slopped roof structure; they are also available in smaller sizes to cover the complete roof.

A false ceiling is added as the final layer in the PowerGazebo. This can be fitted with lights and plug points to make it a pleasing usable space.

The cascading roof design is tested for hail and cyclonic weather. The tiles are tested as per the most stringent BIS, IEC and UL standards. Additional testing shows that the tiles are up to six times more resilient than the sturdiest clay tiles available.

SunEdison uses its expertise in the retail solar industry for harvesting solar power in a safe and efficient manner. Robust processes govern the installation of power electronics, cabling and other protective equipment. The mounting structure is tested for wind load calculation of upto 170km/hr from a 3rd party reviewer.

A dedicated app allows the performance data from the system to be viewed at 15 minute intervals.

Preface

In agreement with the IPCC special report, emissions must drop dramatically if we stand a chance of keeping global warming below 1,5°C [1]. Curtailing our dependency on fossil fuels and faster adoption of renewable energy sources to meet our energy demands are necessary to limit global warming below 1,5°C, avoiding environmental degradation. Currently, India is the third-largest energy consumer after China and the United States, and 80% of it is met by coal, oil, and biomass [2]. In this context, the Government of India's (GoI's) ambitious "Mission 500 GW", recent COP26 climate goals and favourable policies are expected to propel the green energy revolution in the Country. With the trend of rapidly rising per capita energy consumption, renewable energy growth, electrification in sectors like automobiles, and the urge of urbanisation and industrialisation, the electricity demand will be set to have a rapid rise in the coming years. Hence, the Country's energy requirement is expected to grow more than 2,5 times from 2019 to 2040, and it will be equivalent to an addition of the European Union's current electricity generation [2]. In this framework, the operation of buildings consumes a significant portion of electrical energy generated. As per projections among all regions of the world, India's fastest growth in buildings energy consumption will occur with an expected average increase of 2,85% per year between 2020 and 2050, which is more than twice the global average [3].
Renewable energy integration in the building is critical for the intended energy transition. Its importance has been recognised globally, supported by the 21% global increase of renewable energy sources from buildings from 2010 to 2018 [4]. This shows a positive development in the energy transition, but there is still a long way to achieve the 2050 net-zero emission target [5].
Among various renewable energy sources, solar energy is the fastest growing renewable energy resource globally, especially in Indian and EU settings, with the potential for promoting inclusive economic growth without contributing to the carbon footprint. To meet the Country's targeted Intended Nationally Determined Contribution (INDC), the GoI advocated an ambitious plan targeting the installation of 175 GW of renewable energy capacity by 2022, majorly promoted through grid-connected solar photovoltaics (PV) [6]. The fact that around 21% of electricity is lost in transmission and distribution in India (in the year 2019-20) [7], which is more than twice the average across the world, highlights the importance of more Decentralised Distributed Generation (DDG), as recommended in National Energy Policy by National Institution for Transforming India (NITI) Aayog, GoI [8]. In this context, the integration of PV in building construction as Building Applied Photovoltaic (BAPV) and Building Integrated Photovoltaic (BIPV) has a vast potential for onsite green power generation, with the reduced transmission losses, zero space wastage and improved overall building performance. Today, existing BIPV products offer architects, building owners, façade makers and real estate developers a diversified range of products that can be manufactured and customised like any conventional building envelope solution. Even though the importance of BIPV is extensively recognised in the rest of the world, the perception of some barriers and constraints, such as energy production, costs, technical feasibility, and lack of specific standards still exists, which hamper its diffusion in India. Some typical limitations in existing urban areas are seen as no go rather than boundary conditions, which can be optimised and presented with application advantages through design and technical solutions.
In this purview, the "Indian BIPV Report 2022: Status and Roadmap" aims to provide an overview of the Indian solar market by retracing historical milestones and the Country's evolutionary process, including policies, regulations, technological improvements and case studies. The report provides insights to the stakeholders of the solar value chain by focusing on the integration of photovoltaic systems into the built environment. An overview of standard building technology systems and their solar potential is presented and discussed to support investors, manufacturers, architects, and the construction value chain stakeholders in making the timeliest decisions. Further, to construct future milestones in the Indian BIPV sector, an overview of the current scenario and deliberations on expected stakeholder efforts are also discussed to generate a critical roadmap. The crucial business model questions, barriers and boundary conditions are illustrated with actual data from some case studies realised in recent years in India. Today, in the EU, BIPV has achieved a high level of technical maturity, and the market perspective looks promising [9]. The report is structured around four chapters to provide an in-depth overview of the status of solar PV installations in Indian buildings, the possible implementations and BIPV roadmap contemplation. Five BIPV case studies realised in India are presented at the end of the report, including an architectonic and energetic analysis of the showcase.

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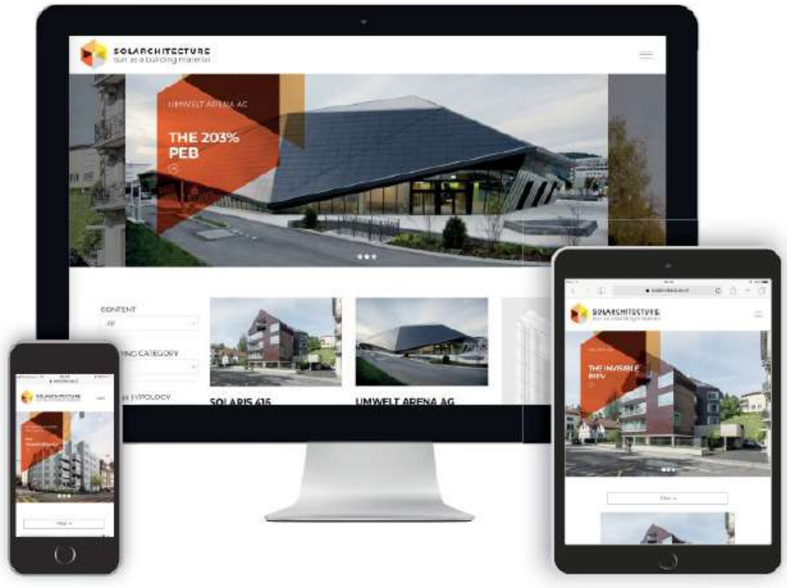


www.solarchitecture.ch

In the age of sustainability, most architects still see the issue of energy in buildings primarily as a constraint to work on. Particularly in the case of solar energy many of the new technological possibilities and integration potentials are not known and therefore not applied in the current design practice due to perceived barriers. Nowadays, new technological possibilities and inspiring projects of solar architecture have been demonstrated and need to be promoted in order to captivate architects, showing the architectural quality of "solar" and the huge potentials of a multidisciplinary approach bridging energy, design and construction. To appeal to architects, it is important to communicate in their language, in an innovative way and using a more complex approach where energy, architecture and construction are part in a unique design concept.

The main goal of www.solarchitecture.ch is to promote the construction of solar buildings by shifting the attention from technology to architecture. Real examples and stories of best practice prove today the feasibility and the quality of solar buildings in terms of aesthetics, construction technology and sustainability.
Solachitecture.ch, as a multidisciplinary and inclusive Swiss platform on solar energy, is managed and defined thanks to the collaboration between four main partners:

- SUPSI – ISAAC
- ETH Zurich
- Swissolar
- SwissEnergy

Table of content

Nomenclature

BAPV: Building Applied Photovoltaic
BEEP: Building Energy Efficiency Project
BIPV: Building Integrated Photovoltaic
BIS: Bureau of Indian Standards
CAGR: Compound Annual Growth Rate
CASE: Commission for Additional Sources of Electricity
CEA: Central Electricity Authority of India
CEL: Central Electronics Limited
CFA: Central Financial Assistance
CPSU: Central Public Sector Undertaking
DDG: Decentralized Distributed Generation
DISCOM: Distribution Company
DNES: Department of Non-Conventional Energy Sources
FiT: Feed-in-Tariff
FYP: Five Years Plan
GDP: Gross Domestic Product
GHI: Global Horizontal Irradiance
GoI: Government of India
GRIHA: Green Rating for Integrated Habitat Assessment
IGBC: Indian Green Building Council
IREDA: Indian Renewable Energy Development Agency
JNNSM: Jawaharlal Nehru National Solar Mission
LCOE: Levelized Cost Of Electricity
MNRE: Ministry of New and Renewable Energy
NASPAD: National Solar Photovoltaic Energy Demonstration Program
NISE: National Institute of Solar Energy
NZEB: Net Zero Energy Building
PPA: Power Purchase Agreement
PV: Photovoltaic
RAV: Rooftop Agrivoltaic
RESCO: Renewable Energy Service Company
RTS: Rooftop Solar
SECI: Solar Energy Corporation of India
SNA: State Nodal Agency
STIP: Science, Technology and Innovation Policy
TRL: Technology Readiness Level
UT: Union Territory

Chapter 1
Photovoltaic sector and its potential in India

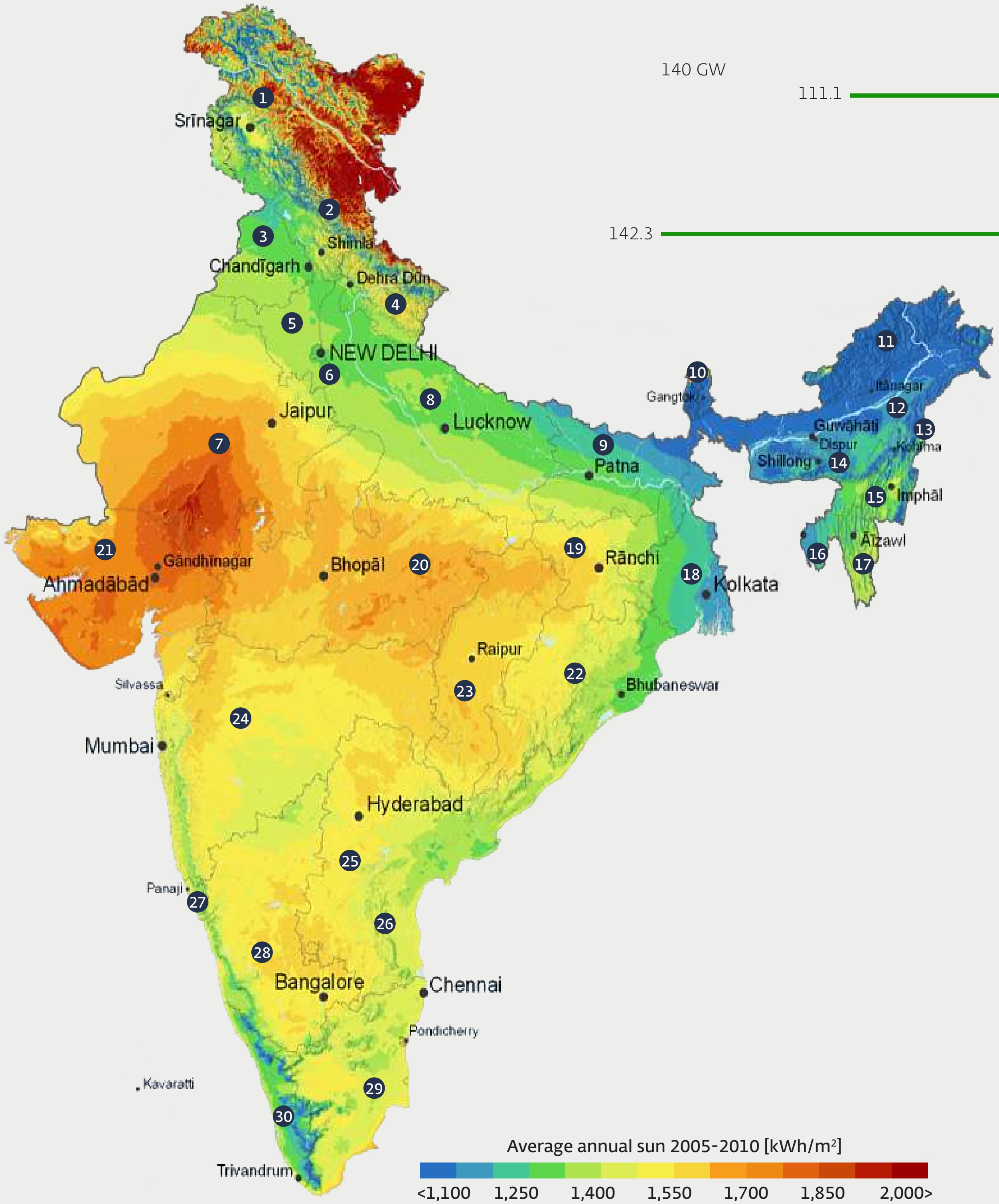
1.1 PV sector: potential, market and growth

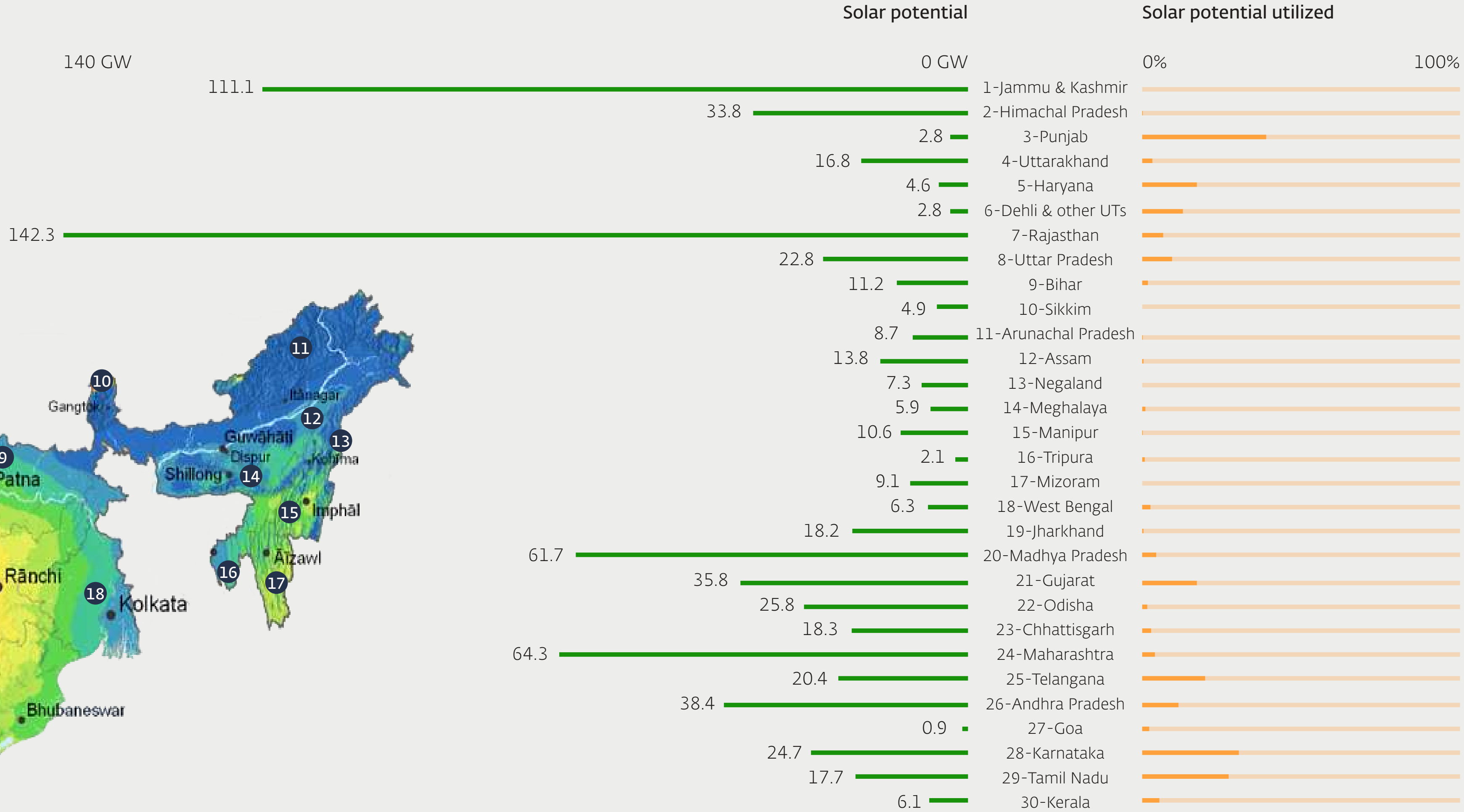
According to the 2016 Paris Climate Accords, countries have established their Intended Nationally Determined Contribution (INDC) by setting their targets and policies for gas emissions. In line with this, India has set an ambitious target to reduce the emissions intensity of Gross Domestic Product (GDP) by 33-35% by 2030 from 2005, by committing a 40% non-fossil-based electricity production by 2030 [1]. Renewable energy targets of 175 GW (with 100 GW from PV and among that 40 GW of grid-connected solar rooftop) by 2022 and 450 GW (with 300 GW from PV) by 2030 was announced to address the cause [2] [3] [4]. Further, in the recently concluded COP26 Glasgow meeting, the Government of India (GoI) announced its timeline to achieve net-zero carbon emissions by 2070. In addition to this, GoI increased its renewable energy target from 450 GW to 500 GW by 2030 to achieve half of its energy from renewables, a reduction of emissions by one billion tonnes and emissions intensity of the GDP by 45% in the same year [2]. Solar energy, being an abundant resource of the country, will play a significant hand in coping with the situation; the rising trend in solar photovoltaics (PV) capacity compared with other renewable energy sources in recent years accords the same [5].

The National Institute of Solar Energy (NISE), under the Ministry of New and Renewable Energy (MNRE) has assessed the solar photovoltaic potential of the country as about 748 GW [6]. India has been ranked 104th in the Global Horizontal Irradiance (GHI) and 98th in the average practical PV potential (Photovoltaic long-term power output produced by a utility-scale installation with fixed-mounted, monofacial c-Si modules with optimum tilt; measured in kWh/kWp/day.) [7]. However, the country has been ranked third in the Renewable Energy Country Attractive Index (RECAI: it ranks the world's top 40 markets on the attractiveness of their renewable energy investment and deployment opportunities) and first in Solar PV according to EY May 2021 Report [8]. Yet the country's solar power generation constitutes less than 4% of total value in contrast to 75% contribution from coal and gas, during the fiscal year 2019-20 [5]. Even though there are conspicuous changes in the PV development and its associated cost reduction in the past decade, yet their deployment is hindered by the limiting spatial availability and disadvantaged locations for grid-connected or Decentralised Distributed Generation (DDG).

India has tremendous potential to harness solar radiation while considering its geographical advantage favouring more solar energy tapping. The country's solar potential is estimated to be 5 quadrillion kWh per year, with an average GHI of 5.1 kWh/m2 per day [7] and an average of 2,300-3,200 sun hours [9]. The PV seasonality index (Ratio between the highest and the lowest of monthly long-term PV output averages) is 1.75 across India, advocating PV output reliability in Indian conditions [4].

The **Fig. 1.1** shows the annual solar irradiance distribution across the country. The irradiation distribution is higher and even for North-West, Central and most Southern states, covering the majority land area in India. As mentioned, the solar potential of India is about 748 GW, as estimated by MNRE, assuming only 3% of the wasteland area to be covered by solar PV modules [4] [10]. India's current solar power installed capacity (including ground mounted, rooftop and other off-grid installation) is around 49.3 GW till December 2021, which is 47% of renewable energy capacity, and contributing to 46% of India's total renewable energy generation in 2021 (exclusive of large hydroelectric power plants) [10]. The trend of installed PV capacity addition in India for the last decade, according to the MNRE data for the period of 2010-2021, is as shown in **Fig. 1.3** [10] [11]. For the last decade, a cumulative capacity of 40.1 GW was installed in India, and in 2021, India had added another 9.2 GW (from April 2021 to December 2021) marking the highest yearly addition till date, and reaching a total installed capacity of 49.3 GW. The Indian PV sector is experiencing a positive growth trend, with a more stepper growth during the last 5 years, which persuaded the GoI to raise their target of 22 GW solar power capacity to 100 GW by 2022 (**Fig. 1.3**) [4]. This can be accounted for around 13% of the MNRE estimated solar PV potential of 748 GW. Hence, there exists a massive opportunity for the Indian PV sector to tap this potential. However, this assumption does not consider the potential of PV integration in the major possible deployment opportunities like buildings that can exploit the market in congruence with the rapid growth of the construction sector in India.





The solar potential of India is about 748 GW assuming a 3% of the wasteland area to be covered by solar PV modules. India's current solar power installed capacity (including ground mounted, rooftop and other offgrid installation) is around 49.3 GW till November 2021.

Fig. 1.1 left Indian solar irradiation map. Source: 2011 GeoModel Solar s.r.o.
Fig. 1.2 up Indian PV potential and utilised potential. Source: [11].

sustainability

MDPI

Review

A Review of Building-Integrated Photovoltaics in Singapore: Status, Barriers, and Prospects

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Abstract: Energy consumption enhancement has resulted in a rise in carbon dioxide emissions, followed by a notable greenhouse effect contributing to global warming. Globally, buildings consume one-third of the total energy due to the continued expansion of building areas caused by population growth. Building-integrated photovoltaics (BIPVs) represent an effective technology to attain zero energy buildings (ZEBs) via solar energy use. This research begins with the tropical green building concept in Singapore associated with renewable energy and gives an overview of the potential of solar photovoltaic energy. Strategies for BIPV spread in Singapore are also provided. Considering both BIPV system life cycle assessment (LCA) and BIPV industry standards and recent developments, this research determines whether Singapore should adopt this technology. Although the BIPV product market has expanded regarding BIPV products, systems and projects, there remain certain barriers to BIPV adoption in Singapore. Additionally, future research directions for tropical BIPV applications are outlined. The Singapore BIPV system serves as an example for a number of other tropical countries facing comparable challenges.

Keywords: building integrated photovoltaics (BIPV); photovoltaics; solar energy; Singapore; green building

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1. Introduction

Energy is considered an essential resource for economic and technological development [1]. Currently, fossil-based fuel remains the main energy source for providing power including electricity and heat. The accelerated emission of CO_2 has resulted in global warming caused by a severe greenhouse effect. In order to reach the Paris Agreement's long-term temperature objectives, the IPCC Spatial Report on Global Warming of 1.5 °C emphasizes the need of carbon neutrality, according to ref. [2]'s research, carbon emissions must decrease by 7.6% each year. It is undeniable that the increasing population and pursuit of a modern lifestyle have dramatically boosted the energy demands and energy consumption per capita, whereas fossil fuel resources are decreasing.

The building sector accounting for one-third of the overall electricity consumption, it is estimated that by 2035, world energy consumption will increase by 50% over the 1990 level [3]. Although building energy consumption sector growth in European countries has decelerated and efforts have been made to renovate buildings to enhance energy efficiency (2% annually) [4], the rest of the world, especially the emerging economies in Asia, still faces housing pressure because of population growth [5]. In addition, the employment of various household appliances, such as computers, monitors, refrigerators, air conditioners, and ovens, has increased the consumption of household electricity because these appliances are ever more readily available today [6]. Therefore, there is an urgent need to determine alternative sustainable energy sources.

With the rapid economic development occurring over the last two decades, Singapore has evolved into a high-density city-state, and Singapore is now the second most densely populated country worldwide. Singapore, is located at 1 latitude north of the equator, at the southern end of the Malay Peninsula. The Straits of Malacca border Singapore to the west, while Indonesia and the South China Sea lie to the south and east, respectively. Due to substantial land reclamation operations, the aggregate land area has grown by 25% since the independence of Singapore. Singapore, similar to the majority of Southeast Asian countries (including Malaysia, the Philippines, Indonesia, and Brunei, which form maritime Southeast Asia, and Cambodia, Laos, Myanmar, peninsular Thailand and Vietnam), features a tropical rainforest climate, with no obvious seasonal changes, an overly high temperature, high humidity, and plentiful annual seasonal rainfall. The temperature usually varies between 23 °C and 32 °C. Southeast Asia is one of the most vulnerable places to climate change globally. Climate change poses major challenges to various industries, such as agriculture and fishery, in regard to rainfall and runoff, water quality and water supply. Climate change and the rising sea level will significantly influence the low-lying shoreline of Singapore over the next several decades.

Tropical countries mentioned above, such as Singapore, experience overly hot and high-humidity climates, and 30–50% of all electricity is consumed for cooling and ventilation purposes because heating, ventilation, and air conditioning (HVAC) systems in urban life consume much electricity [7]. Therefore, the formulation of strategies to reduce emissions, especially carbon dioxide emissions, constitutes an indispensable part of the overall emission reduction task for these countries. Additionally, Singapore is located at a low sea level and will be the first to bear the brunt of the global warming impact under the greenhouse effect. A rise in the sea level and overheated climate conditions may yield a serious negative impact on human health and ecosystems. Although Singapore contributes only 0.1% to global CO_2 emissions, it should cooperate with other countries to actively respond to the threat of global climate change and realize emission reduction commitments, which is also an overall challenge for this island country that is lacking land and natural resources [8].

Recently, photovoltaic (PV) technology has gained notable attention as a viable means of supplying energy to buildings due to the promotion of various actions in tropical countries [9]. Studies have indicated that at the end of 2017, the global installed PV capacity exceeded 400 GW [10]. Although building-integrated photovoltaic (BIPV) systems remain a niche technology, various types of PV products are increasingly available on the market. In recent years, Singaporean architects and urban planners have considered BIPVs necessary systems to achieve renewable energy production and reduce greenhouse gas (GHG) emissions [11].

A BIPV system can seamlessly integrate PV modules into external building surfaces, such as walls, roofs, shading devices, and decorative components. Moreover, it can generate clean energy. From an environmental and economic perspective, PV energy generation provides more advantages than fossil fuel-based energy generation. First, in contrast to the limited storage of fossil fuels, the solar radiation reaching the Earth's surface every day contains 10,000 times the energy requirements of humans on a daily basis [12]. Second, the manufacturing process of PV modules produces only a small amount of carbon dioxide (20–30 g carbon dioxide equivalent (CO_2e/kWh)) [13].

Since the price of silicon has steeply fallen by 90%, providing a good opportunity to economically implement large-scale grid-connected PV systems [14]. Currently, connected grid PV systems are common, and smart networked energy distribution systems have gradually been established [15]. Compared to nonintegrated PV systems, BIPV installation is more convenient, as it does not use additional building space and other assembly components, such as brackets and guide rails [16]. Therefore, the use of an integrated BIPV design can reduce the total construction and material costs of a project [17]. BIPV systems represent one of the most rapidly growing market segments in the PV field. The BIPV market is expected to grow at a rate of 30% per year after 2020 [18]. This enormous growth potential allows these systems to satisfy building energy consumption requirements while lessening the dependence partially or completely on fossil fuels, thereby reducing carbon emissions and mitigating global warming. Global warming is exerting a growing and notable impact on the world. Singapore, as a small island nation on the equator, is particularly vulnerable to the effects of global warming due to its low-lying coast and high temperatures. Hence, comprehensive action is needed to mitigate this issue. Singapore has revealed its long-term emission reduction plan. Ref. [19] showed that, compared to 2005 levels, Singapore will reduce its emissions by 36% by 2030 under the Paris Agreement to 65 Mt CO_2e and by 50% to 33 Mt CO_2e by 2050 and attain net-zero emissions by the latter period of the century [20]. The cooperation between different industry sectors is necessary due to the high challenging targets.

While countries in South Asia, such as Singapore, benefit from ample solar irradiance, solar energy only supports 5% of the total energy requirements of Singapore [21]. The current research challenges include the effective application of BIPVs, whether this technology can effectively reduce carbon dioxide emissions in Singapore and its future research directions. This study illustrates Singapore's current carbon emission scenarios and the country's goals and progress toward GHG emission (GHGE) reduction to achieve its commitments under the Paris Agreement. Starting from the concept of green buildings in Singapore, this study examines the emission reduction role of BIPV technology and its indispensable significance. In addition, this study compares the PV energy payback time (EPBT) and greenhouse emission (GHGE) levels mentioned in other studies to those under the conditions in Singapore, explores the feasibility of BIPV technology implementation in Singapore and reviews the latest developments of BIPV technology. In addition, the current barriers in Singapore to BIPV implementation are identified. It is necessary to contribute a framework of PV manufacturers and consumers to promote finite resource efficiency in PV modules and its life cycle economy [22], including South Asia countries like Singapore. The opportunities for future BIPV research in Singapore and other tropical countries are described in the manuscript.

2. Green Building Concepts in Singapore

2.1. Singapore Building Energy Consumption Landscape

The major GHG contributor in Singapore is CO_2, primarily produced by the electricity generation sector due to the use of fossil fuels [23]. Although oil-fired energy plants have largely been replaced by gas-fired energy plants since 2005, 95% of all electricity is generated by natural gas in Singapore [20]. It is necessary to develop a fuel mix-based electricity generation strategy, especially including the application of renewable energy. However, Singapore is a resource-constrained city-state and has limited renewable energy options [20]:

(1) The average wind speed in Singapore reaches approximately 2 m/s, which is lower than the 4.5 m/s criterion of commercial wind turbines.
(2) There is no potential to implement tidal power generation due to the narrow tidal range and calm seas.
(3) Hydroelectric power cannot be employed because there are no year-round river systems with fast-flowing water.
(4) There are no geothermal energy sources available.
(5) Biomass-based energy generation is not appropriate in Singapore due to the high population density and land scarcity constraints.
(6) Nuclear power cannot be safely implemented in cities with high population densities.

Given the above reasons, solar energy is the only renewable energy source with the potential to impact the energy grid. As previously stated, BIPV systems may represent a viable solution given the limited land resources and dense metropolitan regions in Singapore. Moreover, suitable acreage for PV plants is lacking. Although rooftop surfaces can receive ample sunlight, the usable space in high-rise buildings is constrained owing to the placement of mechanical, electrical, and plumbing (MEP) infrastructures. The taller a given building is, the higher the ratio of the façade area to the roof area, and the more areas suitable for BIPV deployment occur on the façade [24]. The Singapore Building and

Construction Authority (BCA) has established stringent building standards to achieve zero energy (ZEBs) and positive energy buildings (PEBs). Hence, BIPV systems comprise a critical GHGE mitigation strategy while also achieving tropical green buildings [25].

2.2. Definition and Indicators of Green Buildings in Singapore and Singapore Green Building Masterplan (SGBMP)

Globally, the green building concept varies because local economic and technical environment conditions should be considered. In Singapore, a certain building can receive Green Mark certification, thereby designating it as a green building. The latest Green Mark certification program revised in 2018 addresses the following 5 key sections:

(1) Sustainable design and management, which includes Base Building Selection, integrative design and management commitment & employee engagement;
(2) Energy and resource management, which includes air conditioning, lighting, and plug loads, water and waste;
(3) Office environment which includes occupant evaluation, spatial quality (lighting, acoustics, office design) and indoor air quality;
(4) Workplace health and wellbeing, which includes healthier eating & physical activity, smoking cessation and mental well-being;
(5) Advanced green and health features which includes smart office, renewable energy and health promotion.

The Green Mark, as a certification tool, can evaluate building energy performance in the tropics and guide building stakeholders to achieve energy efficiency enhancement through the processes of site selection, design, operation, maintenance, occupant engagement, and empowerment. In addition to Singapore's Green Mark certification system, other green building ratings and certification systems include Building Research Establishment Environmental Assessment (BREEAM) in England, Leadership in Energy and Environmental Design (LEED) in the United States, the German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen or DGNB), and Green Building Evaluation and Labeling (GBEL) in China. Table 1 compares the Green Mark certification system to other major green building grading and certification systems [25–27].

Furthermore, the Green Mark and Singapore Green Building Masterplan (SGBMP) was launched by the BCA in 2005 and considers the 2005 building consumption level as the baseline. Three key long-term development targets were set. First, Singapore will continue to green 80% of buildings by 2030. Currently, 43% of buildings in Singapore have been assigned Green Mark certifications. Moreover, the minimum energy performance standards have been raised, requiring both new buildings and current buildings with retrofitting to achieve 50% and 40% higher energy efficiency levels, respectively, over the 2005 levels. Second, starting in 2030, 80% of the gross floor area of new development should comprise super low energy buildings (SLEBs), which are 65% more energy efficient over 2005 levels. Finally, best-in-class buildings should aim to realize an 80% higher efficiency over 2005 levels by 2030 [25]. The above future aggressive scheme of the BCA regarding energy efficiency improvement indicates that it is essential to define green buildings and the technology that can facilitate goal realization.

2.3. Technologies to Achieve Super Low Energy Buildings (SLEBs) in the Tropics

In 2018, the BCA announced the launch of a new program, the Green Mark for Super Low Energy Building Program (GM SLE program), as the next wave of Singapore's green building movement, which aims to improve best-in-class building energy efficiency, the application of renewable energy either onsite or offsite, and intelligent energy management tools. The SLE program encompasses the following three types of buildings: super low energy buildings (SLEBs), zero energy buildings (ZEBs), and positive energy buildings (PEBs). These three building categories all require energy savings of at least 60% over 2005 levels, and the accounting system includes heating, cooling, ventilation, domestic hot water, indoor and outdoor lighting systems, plug load, and transportation within the building [25]. SLEB realization is a prerequisite to achieve both ZEBs and PEBs. ZEBs require all energy consumption, including the plug load, to be supplied from renewable sources onsite or offsite, while PEBs must realize an energy surplus of 10%.

To adapt to the local climate, economy, and technology conditions in Singapore, relevant technology strategies were suggested to assist best-in-class buildings in SLE program realization. The following four broad areas were identified: passive strategies, active strategies, smart energy management, and renewable energy. Figure 1 lists these four areas with the corresponding technology options [25].

Table 1. Comparison of the four green building certification systems [25–27].

	Green Mark	DGNB	LEED	BREEAM	China Three Star
Nation	Singapore	Germany	US	UK	China
Foundation agent	Building and Construction Authority (BCA)	German Sustainable Building Council	US Green Building Council (USGBC)	Building Research Establishment (BRE)	Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD)
Foundation time	2005	2007	1998	1990	2006
Focus phases	Planning, design, operation, maintenance, occupant engagement and empowerment	Planning, operation	Design, construction	Planning, operation	Planning, design, construction, operation
Evaluation sectors	(1) Sustainable design and management (2) Energy and resource management (3) Office environment (4) Workplace health and well-being (5) Advanced green and health features	(1) Ecological quality (2) Economical quality (3) Sociocultural and functional quality (4) Technical quality (5) Process quality (6) Location quality	(1) Sustainable sites (2) Water efficiency energy and atmosphere (3) Materials and resources (4) Indoor environmental quality (5) Innovation & design (6) Regional credits	(1) Management (2) Health and wellbeing (3) Energy (4) Transport (5) Water (6) Materials (7) Waste (8) Land use & ecology (9) Pollution	(1) Land savings and outdoor environment (2) Energy savings (3) Water savings (4) Material savings (5) Indoor environmental quality (6) Operations and management
Features	Suitable for tropical climates, focusing on energy efficiency and health.	Life cycle analysis of environmental, economic, and social aspects	Energy and resource consumption efficiency	Oldest method	Mainly evaluate residential and public buildings in huge quantities with large energy consumption
Reference to standards	ASHRAE 55	DIN EN ISO 14,040, 14,044, 14,025, RT 2020	ASHRAE 90.1	DIN EN ISO 14,040, 14,044, ISO 21,930	GB 50,176, 501,89, 50,736, 50,785

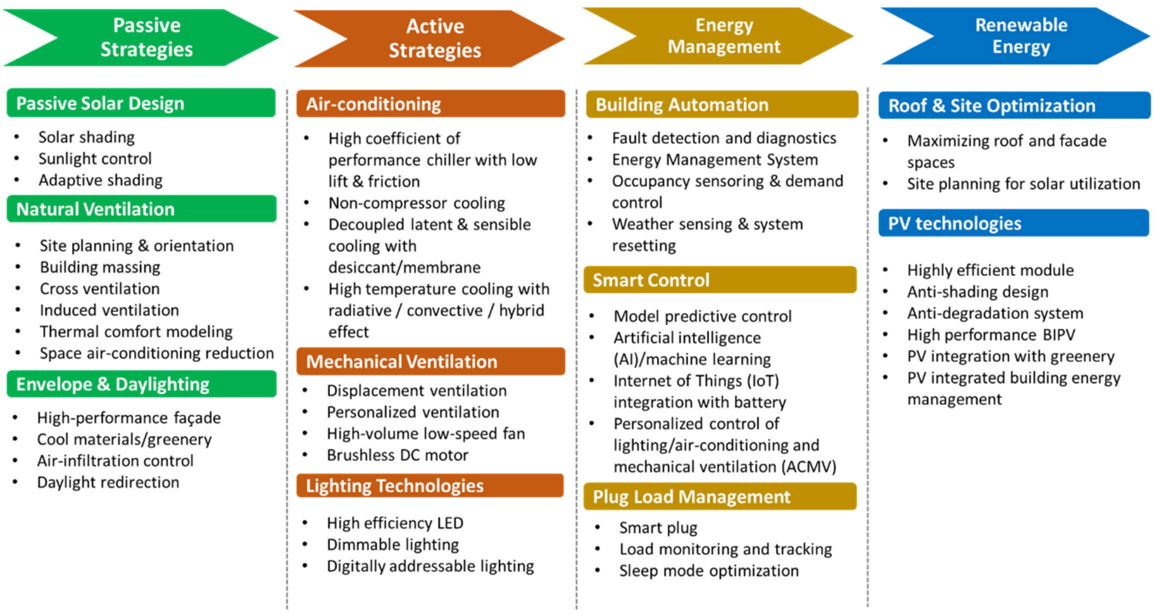

Figure 1. Four main strategies to achieve SLE programs in the tropics [25].

Through the definition of green buildings in the Singapore Green Mark program and future SLE programs, it is clearly found that the employment of renewable energy, especially BIPV technology, may be the key measure to achieve tropical green building construction in Singapore.

2.4. BIPV Applications in Green Buildings in Singapore

Based on the above discussion, the application of renewable energy, such as BIPV, is the key to achieving zero energy and positive energy building conditions. In addition, different types of buildings should target the realization of different levels in the SLE program. For example, low-rise and medium-sized buildings should strive to be certified as ZEBs or even PEBs because their roof areas usually provide sufficient space for PV installation. Although high-rise buildings consume much more HVAC energy and possess smaller rooftop areas than low-rise and medium-sized buildings, they have larger façade areas that can be used for PV integration, which can achieve, at a minimum, SLEB certification.

Currently, as the first Southeast Asian country to do so, Singapore has implemented a carbon tax at a rate of 5 SGD/t CO_2e if any industrial entity releases GHGEs equal to or beyond 25,000 t CO_2e from 2020 to 2023 and plans to increase this carbon tax to 10–15 SGD/t CO_2e by 2030 [28]. Stakeholders in the building industry should consider these policies as a guide for decarbonization and apply the above information when setting future targets for BIPV building design and construction.

3. Solar Energy Potential and Its Implementation Target in Singapore

Solar Energy Potential in Singapore and Promotions

Solar energy is the largest potential renewable energy source for power generation in Singapore. Singapore receives an average solar irradiation of 1580 kWh/m^2/year, which is almost 50% more solar radiation than that received by other countries in temperate areas [29]. Solar energy development can provide several benefits to Singapore, including carbon emission reduction, energy security enhancement and peak demand reduction. Due to the limited land and the rapid changes in tropical weather, in order to promote PV industry development, SERIS of Singapore has set up a short-term solar radiation prediction system with hourly observations as well as forecasts for short periods in the future. To promote PV industry development, SERIS has developed a live solar irradiance map with a 1-s resolution for Singapore based on real-time data collected from 25 irradiance stations across Singapore on a 5 km × 5 km grid, as shown in Figure 2 [21]. The total annual solar radiation value for Singapore is 1580 kWh/m^2/year, which already covers the average solar radiation value for the region [30]. In addition to global horizontal irradiance and diffuse horizontal irradiance, other parameters that may impact PV production are also measured, such as ambient temperature, relative humidity, wind speed, wind direction, and air pressure.

According to [31], IEA compares solar potential of several cities such as Tokyo and Stockholm, based on geographical analysis, the results showed that comparing to other cities at higher latitudes, Singapore has a higher solar yield per square meter and a larger solar yield with flat and sloped roofs. Although its building facades have lower solar yield, it has a wider range of good yield areas. Due to Singapore's small inland region and high population density, a holistic strategy based on existing urban contexts must be considered in its BIPV implementation. Through the use of a high-resolution 3D model, SERIS and the Singapore Land Authority conducted solar energy potential assessments. As shown in Figure 3, an area covering 36.8 km^2 that is suitable for PV implementation is available, comprising 35.9% roofs, 26.7% façades and 37.4% other surfaces [32]. If PV technology was implemented on all of these surfaces, Singapore's PV capacity potential would reach 8.6 GW by 2050. Based on the [32] studies, Table 2 provides the estimated installed capacity, energy yield, and CO_2 emission mitigation benefits under both a baseline scenario (BAS) and the accelerated scenario (ACC). The future targets can be achieved without using all of the potential area, it may be beneficial to utilize the building façade area for PV implementation because roofs can be not only converted to greenery roofs to offset, but also affect the heat island effect and provide additional leisure public space for the urban city are. BIPV systems technically and aesthetically compatible with the built environment.

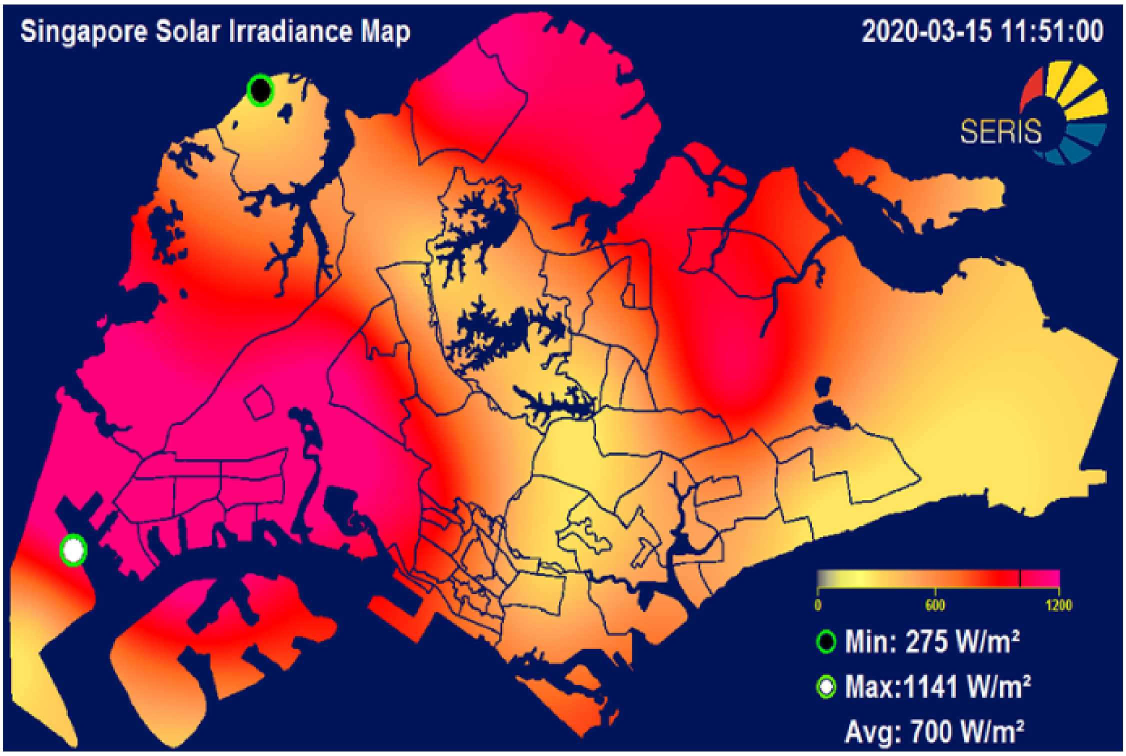

Figure 2. The live solar irradiance map is based on real-time data from 25 irradiance stations on a 5 km × 5 km grid across Singapore [21].

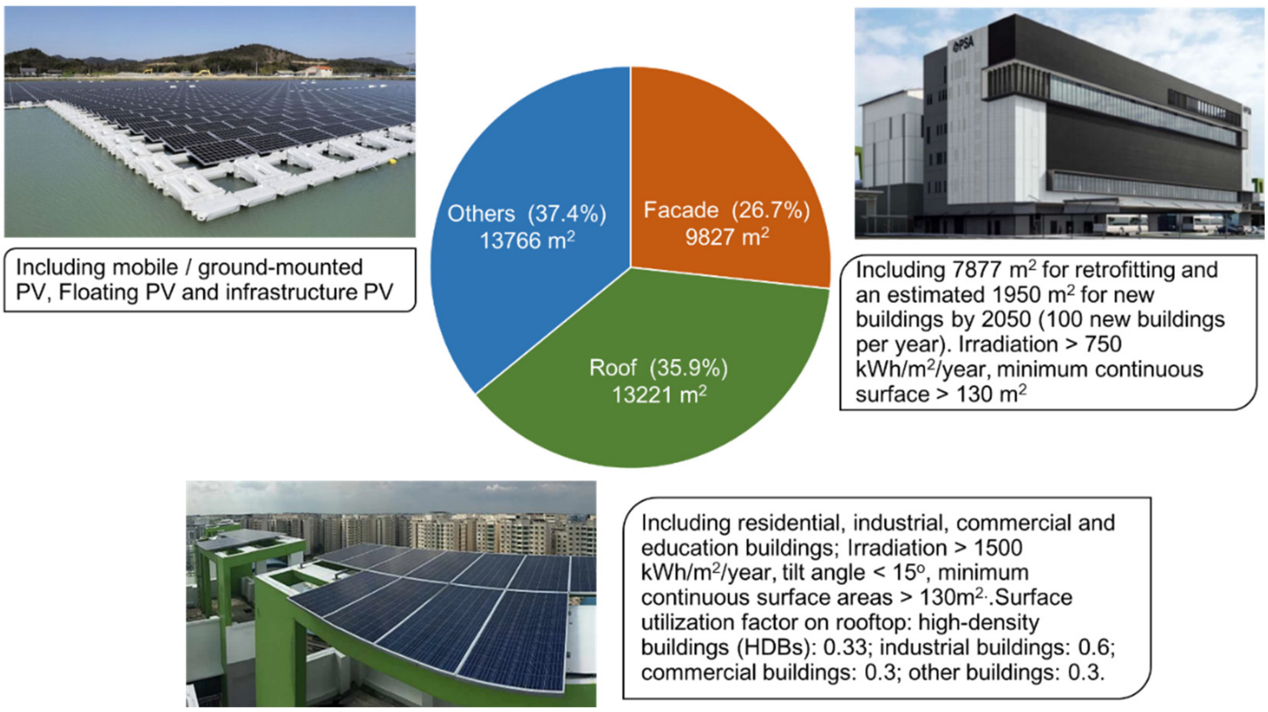

Figure 3. The result of Singapore solar potential analysis based on a high-resolution 3D model [32].

Table 2. An overview of the BAS and ACC deployment scenarios and their impact on PV generation and CO_2 reduction [32].

	Scenario	Estimated System Peak Demand (GW)	Installed PV Capacity (GW_p)	PV Power Penetration Level	Estimated Annual Electricity Generation (TWh) and Percentage of Total Demand (%)	CO_2 Emission Savings (Mt/a) *
2030	BAS	9	1.0	11%	1.28, 1.8%	0.52
	ACC		2.5	28%	3.16, 4.5%	1.29
2050	BAS	11.5	2.5	22%	3.09, 3.4%	1.26
	ACC		5	43%	6.64, 7.4%	2.71

* Singapore's average grid emission factor (GEF) is 0.4080 kg CO_2/kWh in 2020 [33]. CO_2 emission savings equal to the multiplication of annual electricity generation and GEF.

To achieve the goal of PV implementation, Singapore started the largest PV installation project "SolarNova Program" in 2014, aiming to promote PV application in public buildings and housing estates. The SolarNova program is targeted to generate 420 GWh of solar energy every year, which is equivalent to 5% of Singapore's total energy consumption, which is equal to powering 88,000 4-room units. Eighty percent of the population is accommodated in social housing developed by the Housing and Development Bureau (HDB), which coordinates the "solar leasing tender" with green electricity retailers and town councils in the program. The Economic Development Bureau (EDB) is responsible for driving solar ambition among government agencies, while SERIS is appointed as the technical consultant to conduct feasibility studies and site selection. HDB will offer solar developers a percentage of the initial start-up funding as an incentive, and eventually, the town council will purchase the solar system at the end of the lease.

Under this business model, the solar developer of Singapore would be responsible for the entire development cycle of the PV system, including design, financing, installation, operation, maintenance and recycling, and would focus on maximizing the efficiency of the solar system to secure the project. This encourages more solar developers to participate and reduces the cost of procuring solar systems [34].

In addition to the SolarNova Program, Singapore relies on the market to promote PV adoption instead of direct subsidizes. Chang and Li [35] studied the electricity market reform of Singapore, which has developed into a fully divested generation with competition in the retail and wholesale sectors. Supply competition and retail liberalization have brought a 9.11% price decrease in wholesale electricity [36]. Customizers could choose between various electricity retailers and their pricing arrangements. Six electricity retailers provide eco-friendly electricity plans to customers, and Geneco and Sunseap offer a 100% solar electricity option to customers. Customers can offset their carbon emission footprint and carbon tax by purchasing UN Certified Carbon Credits from retailers. Additionally, to solve the land limitation in Singapore, Singapore aims to import 100 MW solar electricity from Malaysia by 2025 and encourages collaboration between solar PV companies and investment between the two countries [37].

4. Recent Development of BIPV Systems

4.1. Historical Evolution of BIPV Systems

In the late 1970s, the US Department of Energy began supporting projects to enhance distributed PV systems, including supporting collaboration with the PV industry to incorporate building materials. By the 1980s, the construction industry had realized the potential of PV technology and its aesthetic acceptance, although the cost of PV technology in the 1980s impeded its development [38]. In Europe, Wohnanlage Richer was built in Munich in 1982; the residential building designed by Thomas Herzog and Bernhard Schilling, which contained polycrystalline cells on a curtain wall, became the first glass surface-integrated PV installation [39]. In 1991, Aachen's Public Utilities building first employed PV panels as semitransparent glass in the façade [40]. The scientific literature on the subject of BIPV structures was published during that time in Europe [41]. Then, the US DOE launched a program called Building Opportunities in the United States for Photovoltaics Program to help commercialize BIPV products [42]. Meanwhile, Europe published Solar Architecture in Europe, and Japan also joined these efforts, announcing similar programs [43]. All of these plans were aimed at facilitating the commercialization of innovative BIPV projects.

The International Energy Agency (IEA) established the PV Power System Initiative in 1997, which attempts to improve the architectural quality, technical feasibility, and economic viability of PV systems in the building industry [44]. Thereafter, the construction industry successfully realized projects that were developed worldwide, which were subsequently reported in a very large number of papers [26]. BIPV systems have been installed in commercial buildings since 1991, and the example usually considered the Public Utilities Building of Aachen. Throughout the world, there are more cases existing in other countries, such as the Hongqiao Railway Station building in China, which was completed in 2010 and incorporated enormous BIPV systems with a total installed capacity of 6.5 MWp; thus, the employment of solar systems integrated into buildings is one of the most important drivers of BIPV development [45].

4.2. Building-Integrated Photovoltaics (BIPVs) and Their Development

BIPV technology refers to a certain technique of PV cell employment that integrates PV cells into conventional building materials. The building skin is not only a protective layer against the elements but also a component of the structure that embodies the architectural language. Stricter building standards and regulations regarding green construction and sustainability urge architects/developers to explore high-performance façade technologies and products, such as PV materials. However, in contrast to conventional PV applications, BIPVs constitute a part of construction systems considering the context of materials, construction, jointing, manufacturing sequence and installation [39]. Because architects require a notable level of design freedom in regard to technological solutions for the customization of building skin, PV modules have greatly advanced in terms of color, form, and performance to accommodate various building skin options [46].

4.2.1. BIPV Systems

The BIPV module can replace conventional building components and function as part of the construction system. BIPV systems involve PV materials that, when combined with conventional building materials, dispense with the need for heat transfer via the building envelope [47]. Generally, there are three types of BIPV systems integrated into the building skin, as follows: roofs (BIPV tiles and skylights), façades (BIPV curtain walls and cladding walls) and accessories (BIPV shading devices and balconies). Figure 4 shows the general types of BIPV systems.

4.2.2. BIPV Roof Systems

Different from nonintegrated PV roof systems (such as building-attached photovoltaic (BAPV) systems), roof BIPV systems incorporate existing building roof materials, such as tiles, into the structure without the need for additional mounting structures, such as racks and rails. BIPV tiles can be similar in appearance to traditional tiles regarding color and size to meet the requirements of sensitive architectural areas. According to [48], since Singapore is located near the equator, the optimal solar radiation reception direction is 10 degrees east. Although BIPV tile products presumably achieve a high-power generation efficiency of 19.5% [49], their actual application requires further local verification. Not only do BIPV skylights generate electricity, but they also allow light into the room, thereby reducing the energy consumption of artificial lighting. According to previous studies [16], when semitransparent solar modules are employed in a sunroom, the power production decreases by 0.52% when the temperature of the PV module rises by 1 degree. When the PV module is installed directly against the building insulation material, research [50], Li et al. [51] has revealed that the temperature of the module may rise and its performance may decrease owing to the absence of circulating air. As such, an increasing number of studies [52] have focused on BIPV ventilation, which may be accomplished via natural or forced ventilation systems, and in these studies, thermal performance modeling and simulation were performed.

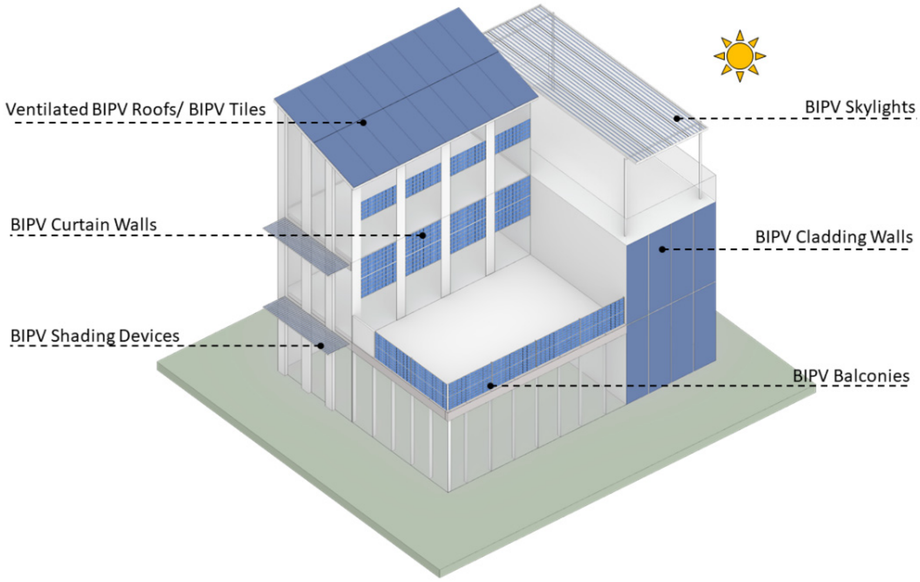

Figure 4. BIPV systems (authors' drawings).

4.2.3. BIPV Façades

According to different integrated PV functions, façade BIPVs can be divided into two categories, i.e., BIPV cladding and curtain walls, which directly constitute the structure of the façade. Hence, it is necessary to consider the basic characteristics of the building envelope, such as weatherproofing and waterproofing. Moreover, when designing the latter wall type, in addition to the façade, indoor visibility and direct sunlight should be considered. It should be noted that previous research [3] has focused on the integration of BIPV cladding walls and phase-change materials (PCMs) to improve the efficiency and heat dissipation of PV systems. Studies have demonstrated that in other regions, BIPV systems integrated with PCMs can maintain a PV surface temperature below 29 degrees for a certain period (130 min) [53]. The BIPV curtain wall must strike a balance between visible light transmittance and power conversion efficiency while also considering the aspects of color and thermal comfort [54]. Semitransparent BIPV modules are framed within extrusions (aluminum, steel, or wood) to withstand wind loads and rainfall penetration. Curtain walls can be constructed in a variety of ways to meet many functional needs, such as thermal insulation, weather tightness, soundproofing, and waterproofing. These systems include stick curtain walls, unitized curtain walls, sealant structures, and point-fixed or suspended façades [39].

Generally, double glazing PV systems perform better in terms of heat insulation than single glazing PV systems [9]. To reduce heat transmission, an insulating layer may be applied to single glazing PV systems [55]. According to relevant research, if a PV system is directly applied to the outer skin in tropical regions, the interior temperature may increase, thereby aggravating indoor thermal comfort and humidity problems [26]. Therefore, in tropical regions, such as Singapore, the application of semitransparent BIPV windows under all building orientations offers notable potential based on indicators such as power production, artificial lighting power, and cooling energy consumption. To obtain the greatest power production advantages from different modules, multiple design methods are required to maximize the window-wall ratio under different orientations.

4.2.4. Accessories

Accessories are the external components of the building façade, such as shading devices, balustrades, and parapet walls. Both transparent and opaque BIPV modules are frequently adopted in accessories. Compared to first-generation PV cells, lightweight second-generation PV cells exhibit a higher tolerance to partial shading and high temperatures [11]. Hence, the latter cells are more suitable for use as shading devices. An adaptive solar façade, i.e., a modular dynamic shading device, should be considered. Ren et al. [56] studies indicate that the influence of shading on individual buildings vary significantly from each other. Compared to the static PV shading system, the adaptive solar façade can yield energy savings ranging from 20–80% [57]. Since this system can control both façade electricity generation and building electricity consumption monitoring, it provides a new building management method.

BIPV balconies, which usually refer to BIPV balustrades and parapet walls, can highlight the architectural character of the building and its surroundings. BIPV balconies can make use of this building surface to absorb sunlight. The PV modules can be grouped together based on their orientation to form DC arrays with an exceptionally elegant appearance [58].

4.3. Singapore BIPV Projects

BIPV roofs offer a variety of design possibilities (Figure 5a–f). The application of BIPV roofs in buildings may be limited due to the challenges associated with URA and SCDF requirements. For example, adding a BIPV roof to an existing building may result in an increased gross floor area, structural issues, and unfavorable functional organization. However, BIPV roofs also offer multiple benefits, such as providing shelter from the weather (solar/rain) while producing electricity. The concept of "PV Sky Gardens" proposed by [59] is shown in (Figure 5a). By controlling the density of the grilles, a good natural ventilated environment is created underneath the canopy, which reduces the energy consumption of the cooling load and allows partial natural light to penetrate. The PV modules combined with the grilles are developed as modular components that are convenient for installation and disassembly. This solution enables the symbiotic use of three resources, i.e., natural light, wind and solar radiation.

The BIPV opaque roof system (Figure 5b−d) is suitable for flat, sloped, and curved roofs. To improve PV performance and reduce heat transfer to the interior, a ventilated air gap is recommended for PV integration, (Figure 5b−d) especially in tropical regions, which have hot summers. When the entire roof is a PV roof, the integration of aesthetics and structure needs to be considered, such as the visual impact as a "fifth elevation" on surrounding taller buildings such as glare and aesthetics, as well as preventing the PV panels from bending due to gravity.

An "urban living room" (Figure 5e) is formed by a PV canopy over an open space in the building complex. This shelter provides protection from solar radiation and rainwater, creating a semi outdoor space for recreation, entertainment, and sports. The BIPV skylight (Figure 5f) replaces the traditional glazing roof and shading louvers. By controlling the PV density, the BIPV skylight provides proper lighting and thermal comfort control. Due to the unique light and shadow effect cast by PV cells, it is very suitable for commercial, public, and medical buildings, creating a vivid architectural experience [60].

In Singapore, if the exterior walls are plaster and paint, the building facade needs to be repainted every five years. The paint cost is estimated at 50 SGD/m^2, while the cleaning fee for cladding walls is only one-fifth of the cost of paint for low- and middle-rise buildings [61]. This is an incentive for implementing BIPV cladding on buildings (Figure 5g). As the BIPV cladding walls are opaque, PV acts as the outermost skin of the building envelope, not only absorbing solar radiation to produce clean energy but also shading the wall behind, which can reduce the indoor air temperature and air conditioning energy consumption. A semitransparent BIPV curtain wall (Figure 5h) is the embodiment of a highly integrated design, which meets the requirements of the building envelope, such as weather proofing and horizontal wind load bearing. Changing the PV color, material and window-wall ratio plays an important role in energy savings of high-rise glass buildings, such as effective control of interior lighting, thermal comfort, and power generation performance [62,63].

BIPV shading devices are generally suitable for all building types, such as residential, school, office, and medical buildings. Both existing and new buildings can easily integrate BIPV shading devices on their exterior walls (Figure 5i), which reduces the thermal and visual discomfort caused by excessive solar radiation, especially for glazing curtain wall buildings and spaces such as balconies and corridors.

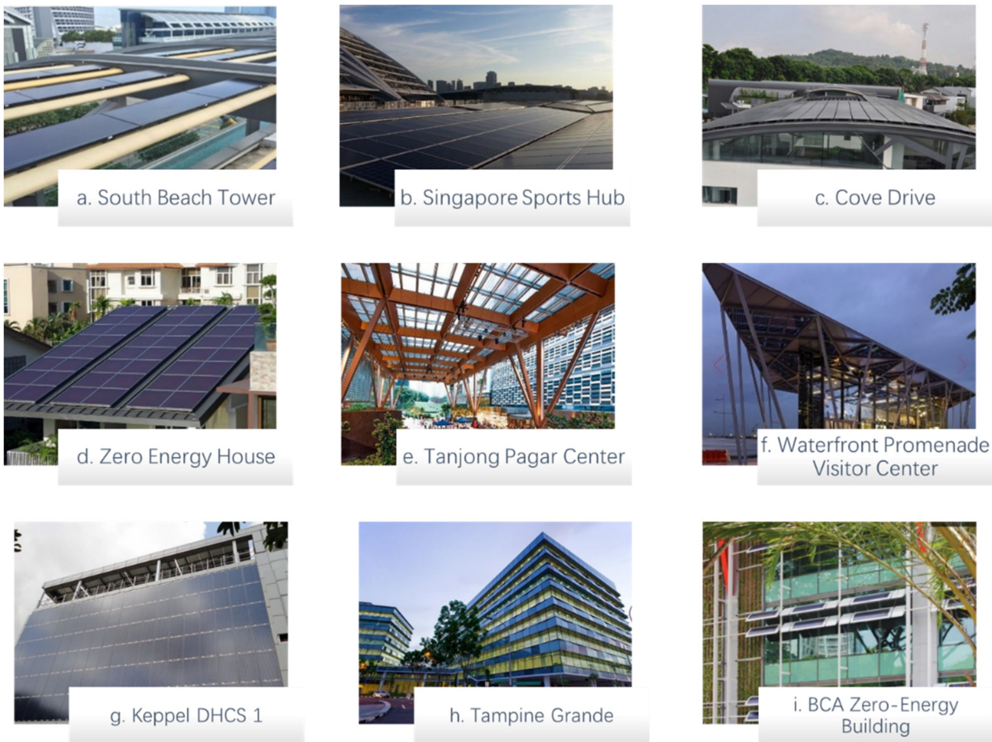

Figure 5. Singapore BIPV projects.

Table 3 and Figure 5 show a collection of BIPV projects in Singapore. The summary information for the BIPV projects includes the BIPV application types, PV module types, installed capacity and titled angle.

Table 3. Singapore BIPV projects.

No.	Project Name	Year	Application	PV Module Type	Installed Capacity (kWp/MWp)	Titled Angle	Ref
a	South Beach Tower	2016	Rooftop ventilated BIPV	CIGS	285.45	0	[64]
b	Singapore Sports Hub	2014	Rooftop ventilated BIPV	p-Si	707.46	10°	[65]
c	Cove Drive	2011	Rooftop ventilated BIPV	Monocrystalline all-back contact	44.84	10°, east	[66]
d	Zero Energy House	2008	Rooftop ventilated BIPV	a-Si	4.8	19°, northeast	[66]
e	Tanjong Pagar Center	2016	Rooftop skylight	Transparent a-Si	125	0	[67]
f	Waterfront Promenade Visitor Center	2010	Rooftop skylight	Semitransparent m-Si	32	0	[68]
g	Keppel DHCS	2013	Cladding façade	p-Si	205.58	90°, northeast	[66]
h	Tampine Grande	2007	BIPV Curtain wall	Thin film a-Si	6	90°, west	[69]
i	BCA Zero Energy Building	2009	BIPV shading device	Thin film a-Si	-	west	[70]

5. Life Cycle Assessment (LCA)

LCA is a method used to evaluate material and energy flows and their consequences during the life cycles of items while also monitoring environmental and resource sustainability. LCA can be applied to evaluate investment and system production levels considering environmental impacts throughout the lifetime of implemented PV systems. The IEA has defined LCA guidelines for PV systems [71] that are accepted by the International Organization of Standardization (ISO) [16]. There are three major LCA phases according to these guidelines, as follows:

(1) definition of the technical specifications and features of PV systems;
(2) description of the modeling methodologies to perform LCA of PV systems;
(3) reporting and dissemination of PV system LCA results.

The energy payback time (EPBT) and GHGE are the recommended and most commonly used metrics for LCA of PV systems.

5.1. EPBT

The EPBT, as a typical indicator used to evaluate energy generation systems, is the required time during which the PV system generates the same amount of energy as that utilized throughout its lifetime [72], i.e., the system creates the same amount of energy as it consumes during its lifetime. The EPBT can determine if and to what degree a PV system achieves a net energy gain throughout its lifetime as follows Equation (1) [16]:

$$\mathrm{EPBT} = \frac{\mathrm{E_{input}} + \mathrm{E_{BOS,E}}}{\mathrm{E_{output}}} \tag{1}$$

where E_{input} is the PV module energy demand (MJ) during its lifetime, including the energy for PV module manufacturing, transportation, installation, operation, maintenance and disposal, $E_{BOS,E}$ is the BOS energy demand (MJ), including cabling, inverters, batteries, other electronic and electrical components, and structural frames, and E_{output} denotes the primary energy savings attributed to electricity generation by the PV system [73].

5.2. GHGE

Other than fossil fuel-based power systems, PV systems convert solar energy into electricity, thus reducing the emissions of CO_2, CH_4, N_2O and chlorofluorocarbon during power generation. Therefore, the GHGE can function as a key assessment indicator for the LCA of PV systems. The GHGE rate is the emission rate of GHG per unit of electricity produced by PV systems (g CO_2e/kWh), which can be expressed as follows Equation (2) [16]:

$$\mathrm{GHGE_{rate}} = \frac{\mathrm{GHGE_{total}}}{\mathrm{E_{LCA\_output}}} = \frac{\mathrm{GHGE_{pv}} + \mathrm{GHGE_{BOS}}}{\mathrm{E_{LCA\_output}}} \tag{2}$$

where GHGE total denotes the total GHGE during the life cycle (g CO_2e), E_{LCA_output} is the total electricity generated by the PV system during its life cycle (kWh), and $GHGE_{PV}$ and $GHGE_{BOS}$ are the $GHGE_{total}$ of the PV modules and BOS components (g CO_2e), respectively [73].

According to [10,74], Table 4 summaries the EPBT and GHGE rates of the five main PV technologies is provided in, including mono-Si, poly-Si, a-Si, CdTe and CIS PV cells.

Compared to other energy sources, wind and hydropower achieve lower EPBT (0.2–2.3 and 0.24–3.09 years, respectively) and GHGE rate (6.2–46.0 and 2.2–74.8 g CO_2e/kWh, respectively) values than those of the considered PV technologies [74,75]. Although PV technologies exhibit higher influence values due to their increased energy consumption in the manufacturing process, they are safer than nuclear energy within high-density urban contexts, such as Singapore, and yield better environmental impacts than coal plants, biomass fuels and combined-cycle gas turbines.

Table 4. Summary of the CED, EPBT and GHGE of the different solar PV technologies.

Type of PV Technology	Range of CED (MJ/m^2)	Range of EPBT (Years)	Range of GHG Emissions (g CO_2e/kWh)
m–Si	2860–5253	2.1–12.1	30–46
p–Si	2699–5150	1.7–3.3	37
a–Si	710–1990	2.7–3.2	37.6
CdTe	790–1803	0.7–3.2	32.4
CIS	1069–1684	1.6–2.9	69

5.3. BIPV Standards

Because PV panels are considered building components, they are required to obey both PV and building industry standards in terms of their electrical, safety and other features. BIPV always has to deal with the following two different standardization and regulation schemes: one is the often-regulated local building codes and international ISO standards derived from the requirements of the building side, and the other is regulated from the electrical side, with international IEC standards and mandatory, not fully harmonized local regulations.

In 2016, the EN 50583 series “Photovoltaics in buildings” was published at the European level, and other suggestions for additional work items were launched globally. In October 2018, the updated ISO/TS 18178 (laminated solar PV glass) for ISO TC160 (glass in buildings) was released, which specified the appearance, durability and safety requirements, test methods and designations for laminated solar photovoltaic (PV) glass for use in buildings. Laminated solar PV glass is defined as laminated glass with integrated photovoltaic power generation. ISO 12543 (Laminated Glass and Laminated Safety Glass for Architectural Glazing) is referenced for many requirements other than electrical characteristics and permits the use of various types of glass (float glass, patterned glass, etc.), solar cells (crystalline silicon solar cells, thin-film solar cells, etc.) and interlayers (polyvinyl butyral, ethylene vinyl acetate, etc.).

Over the course of more than three decades, the International Electrotechnical Commission (IEC) has created a set of standards for photovoltaic (PV) modules and systems in order to describe and evaluate their electrical performance [76]. Furthermore, several ISO (International Organization for Standardization) standards apply to BIPV modules and systems as building components. And, a new attempt was undertaken within IEC TC82 (82/1339/DC) in 2017 to form a project team, i.e., PT 63092 “Building Integrated Photovoltaics (BIPV)”, which includes specialists from ISO, IEC, and IEA PVPS Task 15 which contains IEC 63092 specifies BIPV module requirements and BIPV system requirements.

In Singapore, building professionals, such as architects and planners, are encouraged to refer to the above guidelines while designing and constructing BIPV systems. These guidelines were jointly issued by the Urban Redevelopment Authority (URA) and BCA and cover BIPV installation, safety requirements, maintenance activities, and restrictions for conservative regions. Additionally, the Green Mark program, a sustainable building certification program, grants points for performing solar potential and feasibility studies at the design stage, in addition to PV installation in buildings. Singapore adopted the major international PV standards and modified these standards to satisfy local requirements, e.g., SS IEC 61215, SS IEC 61730, and SS 601.

Moreover, due to the Singapore Statutes, the Codes of Practice for Fire Applications in Buildings published by the Singapore Civil Defense Force (SCDF) highlight roof PV arrangement requirements to ensure fire protection [77]. Additionally, a solar photovoltaic (PV) roof-mounted module is in the scope of fire safety works inspected by appropriate registered inspectors [78]. In addition, the Ministry of Sustainability and the Environment (MSE) regulations state that solar photovoltaic panels are regulated non-consumer products [79] and the solar photovoltaic panel material recovery target is 70% [80]. Moreover, MSE requests the submission of an energy use report each year from Singapore's registered corporations, which shall cover each business activity under the operational control of the registered corporation, and the fraction of photovoltaic material manufactured that uses the fluorinated compound fraction is on the lists of data on processes and activities resulting in greenhouse gas emissions [81].

6. Barriers to BIPV Implementation in Singapore

As a densely populated city-state, Singapore notably contains vast façade areas of high-rise buildings, thus creating an ideal area for BIPV deployment. However, there are several barriers to widespread BIPV implementation in Singapore. Based on several studies [9,82–84] on a multistakeholder approach, it has been demonstrated that even though the driver of BIPV development accomplishes both Green Mark certification and CO_2 emission reduction, the barriers to BIPV implementation in Singapore can be classified into the following five groups: policy barriers, economic barriers, product barriers, human and social barriers, and information barriers, as summarized in Table 5.

Table 5. The barriers to BIPV implementation.

Policy barriers	Difficulties in obtaining governmental approvals
	Uncertainties in BIPV policies in the long-term
	Low electricity tariff from conventional sources
	Lack of standards, codes or guidelines
Economic barriers	The high upfront capital cost of BIPV
	The long payback period of BIPV systems
Product barriers	Lack of BIPV modular products
	The low-energy conversion efficiency of BIPV systems
	Reliability problem
	Heat transfer issues
	Difficulties regarding cabling and connection
	Unstable power generation quality
	The complexity of the BIPV system
Human resources and social barriers	Lack of professionals
	Lack of public education and awareness of BIPV
Information barriers	Lack of information on BIPV products, suppliers and policies
	Lack of life cycle cost analysis knowledge
	Lack of BIPV demonstration projects
	Lack of design tools

7. Future Research Needs of BIPV

7.1. Prefabricated BIPV Façade Module Products

According to a previous study [85], the most cost-effective way to reduce the cost of BIPV systems is to develop prefabricated BIPV façade modules for new buildings and renovations. Both the BIPV industry and prefabrication building industry share similar features in that they both demand a highly automated manufacturing process to produce items offsite, which requires high capital and upfront expenses. In addition, onsite construction simply requires module assembly and erection. The combination of these two areas exhibits the potential to drastically reduce onsite staffing costs. Due to the high level of automation and standardization in the Japanese prefabricated housing industry, a relevant prefabricated BIPV industry business model has been established and disseminated [86].

In recent years, many studies have concentrated on prototype designs of BIPV modules (Figure 6). A façade that integrates PVs with precast concrete (PVPC) has been developed in Shanghai, China [51] and is suitable for high-rise building construction integrated with renewable energy (Figure 6a) which PVPC façades can eliminate the need for steel frames, thus lowering costs and freeing up more outside space for installation, in addition to lowering the building heating gain and cooling load. However, the air gap between the PV panel and concrete surface is a stationary cavity, which may not provide an efficient heat dissipation solution. In addition, in another study, a prefabricated BIPV wooden façade (Figure 6b) was developed comprising the following three major layers: the outer skin of the PV system, a natural ventilated air cavity in the middle and an inner framed wooden panel with thermal insulation [87]. However, this prototype might not fit within the context of Asian countries with high population densities, high-urban density settings and a scarcity of forestland resources. Furthermore, a lightweight glass block-integrated DSSC (Figure 6c) was examined [88]. The PV glass block can be installed, assembled and constructed using joints, allowing for easy dismantlement and replacement. Due to the limitations of third-generation PV cells, their power generation efficiency is limited. The European Commission Horizon 2020 project for modular façade retrofitting with renewable energy technology (MFRRn) was reviewed [89]. There are three distinct ways to retrofit renewable energy technologies, i.e., frame-based systems, layer-based systems, and the combination of these two systems (Figure 6d). Following preceding studies, it is essential to consider all aspects of the integration of a high-efficiency PV module, ventilated PV system, automatic manufacturing process, and convenient installation and erection procedures without sacrificing the range of customizations to adapt to existing and new buildings.

Figure 6. (**a**) Façade-integrated photovoltaics with precast concrete (PVPC) [51]. (**b**) Wood panel-integrated photovoltaics [87]. (**c**) Glass block-integrated photovoltaics [88]. (**d**) Modular façade retrofit with renewable energy technology (MFRRn): upper: frame-based system; middle: layer-based system; and lower: the combination of these two systems [89].

Singapore has unique advantages in PV technology integration with prefabricated construction technologies. First, the majority of the existing housing buildings were built by the Housing Development Board (HDB) in the 1980s, which suggests that the PV system can be integrated with similar dimensions and economically deployed in large numbers [24]. In addition, design for manufacturing and assembly (DfMA) is identified as a game-changing construction method in the construction industry of Singapore, which involves structural steel, advanced precast concrete systems (APCSs) and prefabricated prefinished volumetric construction (PPVC). DfMA provides guidelines to increase the manufacturing efficiency and streamline the assembly process to reduce costs and improve the overall system performance [90]. The Solar Energy Research Institute of Singapore (SERIS) and the National University of Singapore (NUS) Department of Architecture have created a modular pod based on these design principles to assist architects and developers in simply integrating BIPV technology into building façades (Figure 7). A test building was constructed with multiple prefabricated BIPV elements (panelized walls, monsoon windows, unitized walls and fixture walls) to simulate different construction methods. The structure manufacture relied on a highly automated process of light gauge steel roll-forming machines. The multifunctionality of these prototypes enables them to meet the requirements of connection and cabling, dry assembly, and noise- and weatherproofing. The interior thermal performance of the building and the energy generation performance can be monitored and evaluated through various embedded sensors.

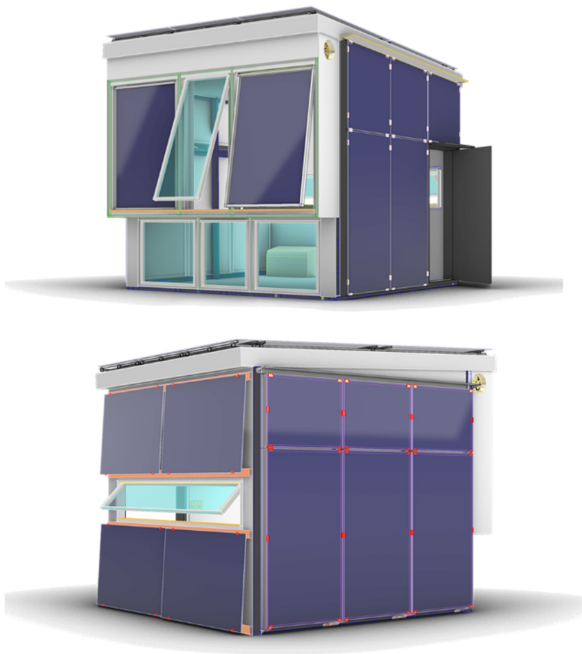

Figure 7. Modular Pod designed by SERIS and the Department of Architecture at NUS (authors' drawings).

7.2. Productive BIPV Façade

Singapore heavily depends on energy and food imports to meet the growing domestic demand. For security considerations, it is essential to gradually increase local food and energy production levels in the future. Due to the pressure of the growing population and limited land, innovative integration of PV shading devices and vertical farming (VF) planters into building façades (Figure 8), referred to as productive façades (PFs), could be an alternative method to achieve self-sufficiency in the field of power and food for Singapore [91].

PF-related investigations have recently been proposed and conducted [91] to examine the potential of PFs in Southeast Asia and Singapore with 57 cases considering the four key aspects of building typology and morphology, plot ratio, site coverage and building height. Their study revealed that PFs could be suitable under all construction orientations in low-latitude regions. In the cases with the lowest plot ratios (PR < 1.9) and smallest building heights (<42 m), food and energy self-sufficiency, respectively, were achieved. Ref. [92] proposed two types of PF-integrated systems, namely, window façades and balconies, with 8 prototypes under four orientations (Figure 8a). The optimal design was selected via the multiple attribute decision-making (Vise Kriterijumska Optimizacija I Kompromisno Resenje or VIKOR) optimization method and installed at the Tropical Technologies Laboratory (T2 Lab) of the NUS, and five critical functions were compared (interior daylight autonomy, power generation, irradiance, vegetable productivity level and viewing angle). Kosorić et al. [20] conducted a door-to-door survey among Singapore social housing residents to collect data on social acceptance, aesthetic requirements, and maintenance of PF designs. A web survey was also conducted of local Singapore building experts regarding certain key design aspects, such as façade aesthetics, material use, views from the inside, operation, functionality, and architectural quality [93]. These two survey studies revealed positive responses among both end users and building professionals. However, the application scalability from the building scale to the city scale requires further investigation.

Figure 8. (**a**) Eight PF prototypes under four orientations; (**b**): Photograph of the constructed PF at the NUS T2 Lab [92].

7.3. BIPV Recycling

Upon BIPV installation enhancement, it is essential to consider the issue of BIPV recycling. Globally, a PV waste amount totaling approximately 250 tons occurred in 2016, and the waste amount is expected to range from 1.7–8 million tons by 2030 and will reach approximately 78 million tons by 2050, with the possible value of the recovered material exceeding 15 billion US dollars by 2050 [32,94]. Therefore, PV panel recycling is an urgent environmental issue but may also yield notable economic benefits in subsequent decades.

The development of BIPV recycling can be divided into the following three fields: policy making, recycling technology and design for disassembly (DfD). In terms of policy making, Europe is the pioneer, as it has established a stringent regulatory framework, while other countries have initiated the implementation of comparable restrictions. Currently, the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU [95] governs the recycling obligations of PV producers within the European Union (EU). Additionally, the Japan Photovoltaic Energy Association (JPEA) has suggested a voluntary standard for end-of-life (EoL) PV panels [10]. However, other countries with large PV deployment markets, such as the United States, India and China, have not formulated such EoL PV panel regulations. PV waste is categorized in these countries as general electronic waste or as hazardous and nonhazardous solid waste materials in the absence of specific PV regulations. Currently, approximately 10% of all EoL PV panels worldwide are recycled [32].

Regarding PV recycling technology, the principle of the circular economy has gained increasing acceptance as a means of transforming the current PV industry into an ideal closed-loop circular recycling system capable of efficiency improvement and energy consumption reduction during the recycling process, in addition to increasing the recycling and recovery rates. Given that crystalline silicon (c-Si)-based PV panels have accounted for 80–90% of the market over the last two decades, these c-Si PV panels are the main types of PV panels for recycling in the future, including their components, such as glass, aluminum frames, solar cells, ethylene-vinyl acetate (EVA) encapsulants, and composite Tedlar back sheets manufactured via lamination as one panel. EVA removal and PV panel dismantling are regarded as the most challenging aspects of the recycling process [46]. Nevertheless, the market for PV recycling is expected to be enormous in the near future, and there are currently only a few specific PV recycling companies in the industry.

Since PV panels on building façades function as both a power generator and building skin, the disassembly of PV panels could greatly affect building functions, involving many factors, such as cabling and connection, water- and weatherproofing features, construction risks for high-rise buildings and numerous other issues. Therefore, in contrast to BAPV and PV farms, the DfD of BIPVs should be considered at the early design stage. Due to the high energy consumption and low recycling rate in the construction industry, the DfD concept was developed in the 1990s and has only recently gained attention in mainstream practice, such as in the London Plan. Although the EU Building as Material Banks (BAMB) project [96] and the United States Environmental Protection Agency (EPA) have published standards [97] for the abovementioned design process, certain sustainability certifications also grant points for DfD, such as LEED and Green Globes. DfD targeting BIPV technology requires a comprehensive and detailed disassembly plan that includes deconstruction instructions and methods for reuse, recycling and reclamation of building components and PV panels, all of which require recording and tracking the entire life cycle. In addition, it is essential to design appropriate PV joints to facilitate disassembly and minimize the employment of heavy equipment. PV joint design should prioritize dry assembly, such as the adoption of bolts, screws or nails in connections, instead of applying chemical methods, such as sealers, glues or welding.

Although the need for PV recycling will be met within the next 5–10 years in Singapore, related regulations have been established under the concept of extended producer responsibility (EPR), which requires PV producers, including importers and manufacturers, to offer free take-back services for EoL PV panels starting in 2022.

7.4. Urban Heat Island (UHI) Effect

Urban heat island (UHI) effects exert a notable impact on the local weather conditions in cities, resulting in temperatures that are higher in urban areas than in rural areas. This phenomenon may increase energy consumption related to air conditioning by altering building thermal conditions [98] and may result in a health crisis as a result of climate warming [99]. This mainly occurs because building surface materials such as concrete and steel absorb solar radiation during the daytime, after which heat is radiated into air at night, thus increasing the ambient temperature.

The implementation of BIPV systems on building roofs and façades modifies the nature of rooftops and façades, respectively, and may affect energy transfer between the atmosphere and buildings. Several studies have demonstrated that BIPV surfaces can mitigate UHIs and reduce cooling loads in the summer. At the urban scale, Taha, Genchi et al. and Masson et al. [100–102] reported that PV systems on buildings exert no negative impacts on the air temperature and UHI phenomenon in high-density cities, such as Los Angeles, Tokyo and Paris, if opaque PV panels are installed in large city areas. In addition, although a considerable temperature change occurs on the building surface at the building scale, there is no effect on the local microclimate, such as in Tianjin city, China [103]. This is mostly attributed to the shading effect of PV panels, which may help reduce cooling load-related energy usage. Additionally, partial substitution of fossil fuels with solar technology may help reduce CO_2 emissions and mitigate the effects of UHIs [104].

However, there are only a few studies focusing on the effects of UHIs on BIPV performance. Studies have revealed that BIPV power generation may decline slightly due to the increased ambient temperature attributed to the UHI phenomenon, e.g., refs. [104–106] compared 27 available PV-related software programs and found that there is a lack of software programs that consider the UHI impact on PV panels integrated into buildings. Further investigation of the relationship between BIPV systems and local urban microclimate conditions is necessary.

Research on the UHI effect on BIPV systems in cities involves collaboration among different professionals, such as urban planners, architects, engineers and policy makers. It is necessary to compile a comprehensive city-scale database of solar potential to evaluate solar technology implementation in building envelopes in the future. An integrated platform should be developed in the future based on existing infrastructure information among various city administrative agencies. This platform can support researchers in the investigation of BIPV implementation and facilitate decision making during policy development [32].

7.5. Conclusions

Although BIPV systems have gained attention recently, the application of BIPV is still in a niche market. Taking Singapore as an example, the establishment of BIPV systems offers insights for other tropical countries facing comparable challenges. Based on the literature review, the following conclusions are highlighted:

To meet the target of the Paris Agreement, Singapore must make use of solar energy due to the limitation of energy resources and land. BIPV is applicable for high-density urban scenarios.

BIPV is an essential factor to help tropical buildings become green buildings, such as super low energy buildings, zero energy buildings and positive energy buildings.

Through a review of the state of PV technologies and BIPV applications in Singapore, the efficiency of PV cells should be improved, and demonstrative BIPV buildings should be encouraged.

Developing holistic BIPV regulation is important, as many still believe that BIPV is a technology material and not a building construction material. The lack of related local BIPV regulations hinders BIPV façade implementation.

Based on the barriers to BIPV implementation in Singapore, an information and knowledge sharing platform should be established among stakeholders and technology developers.

Future BIPV implementation research can focus on prefabricated construction, food and energy, material recycling, and mitigation of the urban heat island effect.

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Abbreviations

A	PV cell area (m^2)
ACC	accelerated scenario
APCS	advanced precast concrete system
BAMB	Building as Material Banks
BAPV	building-attached photovoltaic
BAS	baseline scenario
BCA	Building and Construction Authority
BIPV	building integrated photovoltaic

BOS	balance of system
BREEAM	Building Research Establishment Environmental Assessment
CED	cumulative energy demand (MJ/m^2)
CIGS	copper indium gallium selenide
CdTe	cadmium telluride
DGNB	German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen)
DSSC	dye-sensitized solar cell
DfD	design for disassembly
DfMA	design for manufacturing and assembly
EBOS,E	balance of system energy demand (MJ)
E_{LCA_output}	electricity generated by the PV system during the life cycle (kWh)
EPA	Environmental Protection Agency
EPBT	energy payback time (years)
EU	European Union
EVA	ethylene-vinyl acetate
E_{input}	PV module energy demand (MJ)
EoL	end-of-life
E_{output}	primary energy savings attributed to PV electricity generation
Etot	total incident irradiance (W/m^2)
GHG	greenhouse gas
GHGE	greenhouse gas emissions (g CO_2e)
$GHGE_{BOS}$	greenhouse gas emissions of a balance of system components during the life cycle (g CO_2e)
$GHGE_{PV}$	greenhouse gas emissions of the PV module during the life cycle (g CO_2e)
$GHGE_{rate}$	emission rate of greenhouse emissions per unit of electricity produced by PV systems (g CO_2e/kWh)
$GHGE_{total}$	total greenhouse gas emissions during the life cycle (g CO_2e)
GM SLE program	Green Mark for Super Low Energy Building Program
HDB	Singapore Housing Development Board
HVAC	heating, ventilation and air conditioning
IEA	International Energy Agency
IMP	maximum current (A)
JPEA	Japan Photovoltaic Energy Association
LCA	life cycle assessment
LEED	Leadership in Energy and Environmental Design
MEP	mechanical, electrical and plumbing
MFRRn	modular façade retrofit with renewable energy technology
NUS	National University of Singapore
PEBs	positive energy buildings
PF	productive façade
PPVC	prefabricated prefinished volumetric construction
PV	photovoltaic
PVPC	integrating PVs with precast concrete
SCDF	Singapore Civil Defense Force
SERIS	Solar Energy Research Institute of Singapore
SGBMP	Singapore Green Building Masterplan
SLEBs	super low energy buildings
T2 Lab	Tropical Technologies Laboratory
UHI	urban heat island
URA	Singapore Urban Redevelopment Authority
VF	vertical farming
WEEE	Waste Electrical and Electronic Equipment
a-Si	amorphous silicon
m-Si	mono-crystalline
p-Si	Polycrystalline
η	PV cell efficiency (%)

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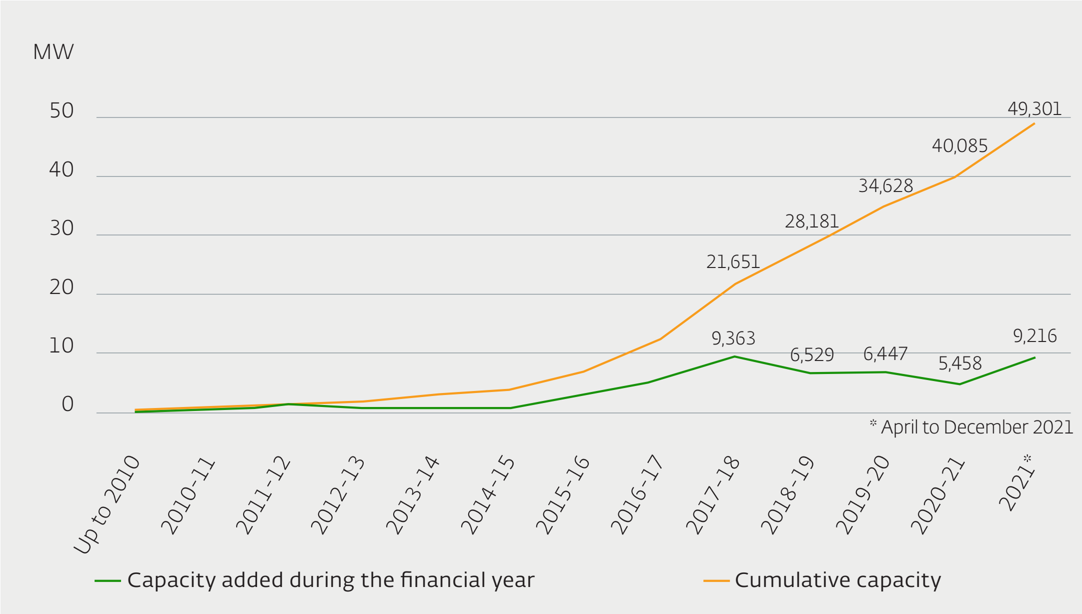


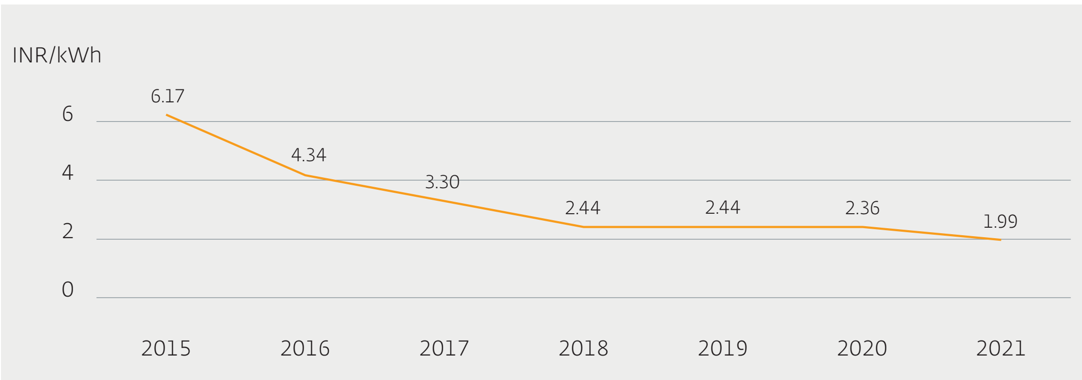
Fig. 1.3 India total solar PV capacity 2010-2020. Source: MNRE and India Renewables Dashboard.

The PV potential of different states, based on land area, has been calculated by MNRE [12]. **Fig. 1.2** (previous page) shows the PV potential of the States & Union Territories of India and their utilised potential (% of PV potential utilized by solar PV installations including grid-connected, off-grid and rooftop installations), drawing their corresponding performance (based on MNRE data). Rajasthan, Jammu & Kashmir, Maharashtra and Madhya Pradesh constitute 50% of the total PV potential in India. However, among the states, only Punjab, Karnataka, and Tamil Nadu utilised more than 20% of the PV potential.

PV tariff and cost breakdown

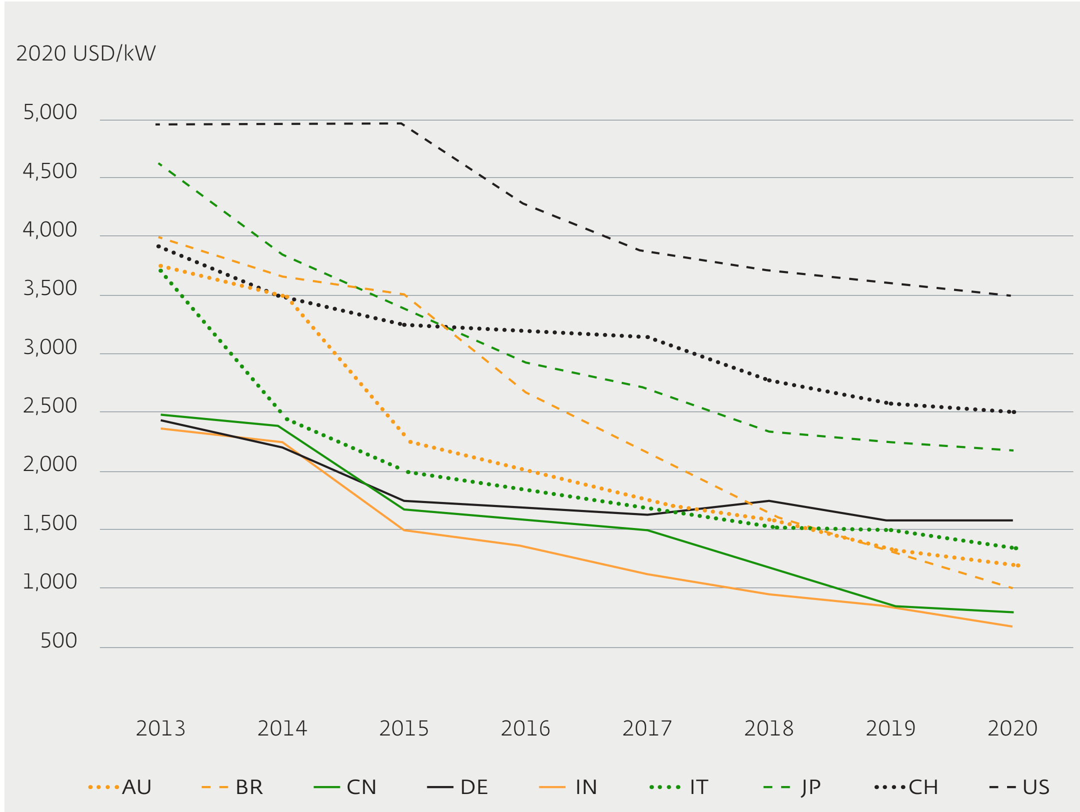
India is now the 5th largest country in terms of installed solar capacity. India intends to procure around 300 GW of its electricity coming from solar by 2030. To achieve that, the two key drivers, as suggested by Solar Power Europe (SPE) for solar energy growth are; i) increasing tender activity and ii) decreasing the solar PV tariff, enabling India to conclude one of the lowest solar auction bids around the globe in 2020. **Fig. 1.4** shows the decreasing trend of solar PV tariff in India from 6.17 INR/kWh in 2014 to a new low of 1.99 INR/kWh in 2020, for a 500 MW tender in Gujarat [12].

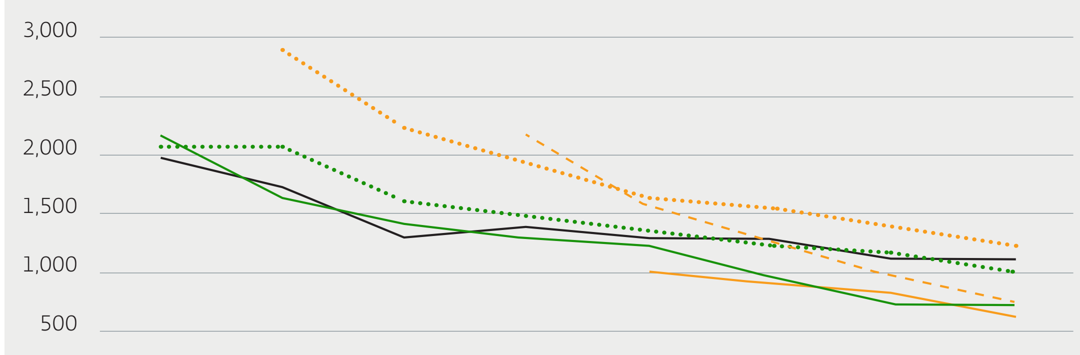
Fig. 1.4 India trend in solar PV tariffs 2015-2021. Source: MNRE.



One of the major drivers for this cost decline is the rapid decrease of installation costs in the last decade. During 2013-2020, the Indian residential sector solar PV total installed cost attained a reduction of about 70%, from 2,401 USD/kW to 658 USD/kW. Together with Brazil, it is the highest cost reduction in the last decade (**Fig. 1.5**). From 2017 to 2020, a cost reduction of about 35% is registered within the commercial sector (**Fig. 1.6**). The primary reason for this reduction is the global decline in PV module cost, which is about 57% in India from 2013 to 2018 for the GW-scale market. Utility-scale PV projects with a very competitive cost in India led to a total installed cost of 596 USD/kW, a value 8% lower than in China. The role of PV modules price is crucial in the Indian PV sector, as it covers a large part of the total installation cost (**Fig. 1.7**) [13].

Fig. 1.5 Residential sector solar PV total installed cost by country, 2013-2020. Source: IRENA.
Fig. 1.6 Commercial sector solar PV total installed cost by country, 2013-2020. Source: IRENA.





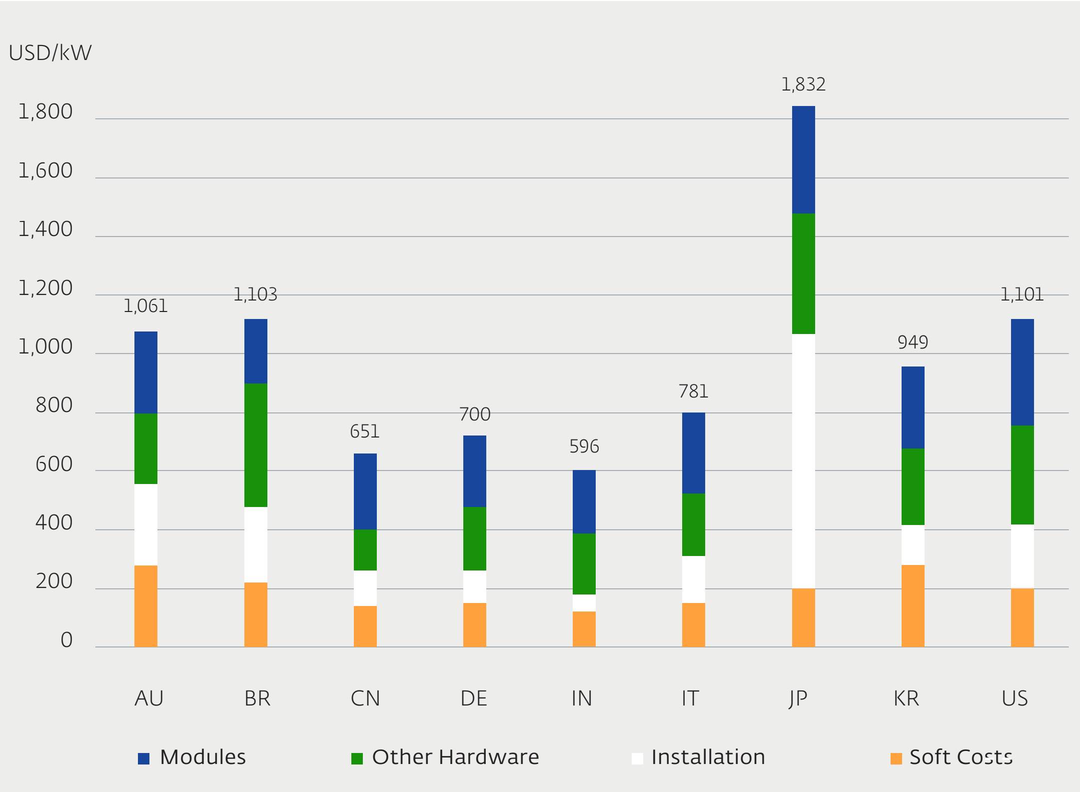


Fig. 1.7 Detailed breakdown of utility-scale solar PV total installation costs by country, 2020. Source: IRENA.

Council on Energy, Environment and Water (CEEW) conducted a recent survey (May 2020) among the major domestic module manufacturing companies in India having an annual manufacturing capacity ranging from 100MW to 2,000MW to value the cost disintegration of PV module manufacturing in India (considered only manufacturing of modules from cells). The manufacturing companies are Adani Solar, Emmvee Solar, Goldi Solar Private Limited, IB Solar, Jakson Limited, Navitas Green Solutions Private Limited, Renewsys India Private Limited, Tata Power Solar, Vikram Solar Limited, Waaree Energies Limited.

The following assumptions have been considered [14]:

- Production of mono passivated emitter and rear cell (PERC) modules with manufacturing plant capacity of 500 MW (IN) and 2,000 MW (CN)
- Plant's capital expenditure (solar cell to solar module) of 0.3 INR crore/MW (IN) and 0.2 INR crore/MW (CN)
- Plant's useful life of 5 years
- Capacity utilisation of 50% (IN) and 100% (CN)
- Return on equity (pre-tax) of 18% (IN) and 10% (CN)

The cost breakdown revealed that around 86% of the module selling price is associated with bill of materials (**Fig. 1.8**), and 58% of it corresponds to solar cell price (**Fig. 1.9**). Thus, the cell price of 9.26 INR/Wp constitutes 45% share of the module selling price of 20.37 INR/Wp. Detailed cost disintegration is shown in **Fig. 1.8** and **Fig. 1.9**. The survey was also extended to Chinese manufacturing companies, to compare the cost analysis. Compared to the Indian sector, the selling price is 5.05 INR lesser per Wp (33% cheaper) in China, owing to insignificant contribution from electricity, land lease, other overheads, cost of debt, and return on equity. Bills of material, including cell price, also cost lesser, compared with the Indian context. India currently has a manufacturing capacity of 10 GW of solar modules from solar cells, 3 GW of solar cells from wafers, and zero production of Polysilicon/ Wafer/ Ingots [15]. India mostly relies on countries like China, Vietnam, and Thailand for cell import and China, Vietnam, Malaysia and some domestic supply for other materials (TPT/PVDF sheets, EVA backsheets, Glass, Ribbons, aluminium frames and junction boxes), this is a major reason for the competitive disadvantage of

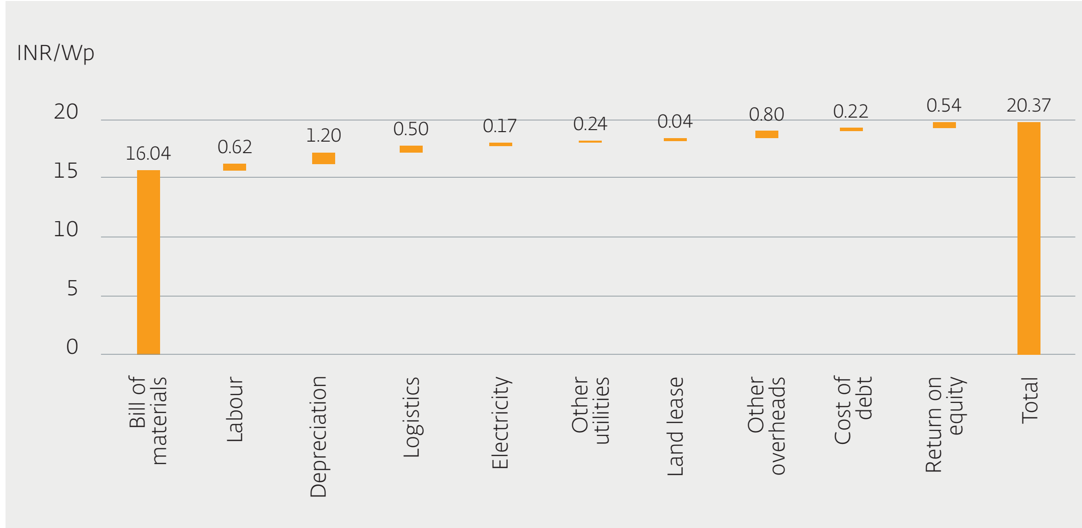


Fig. 1.8 Total cost PV module. Source: CEEW.

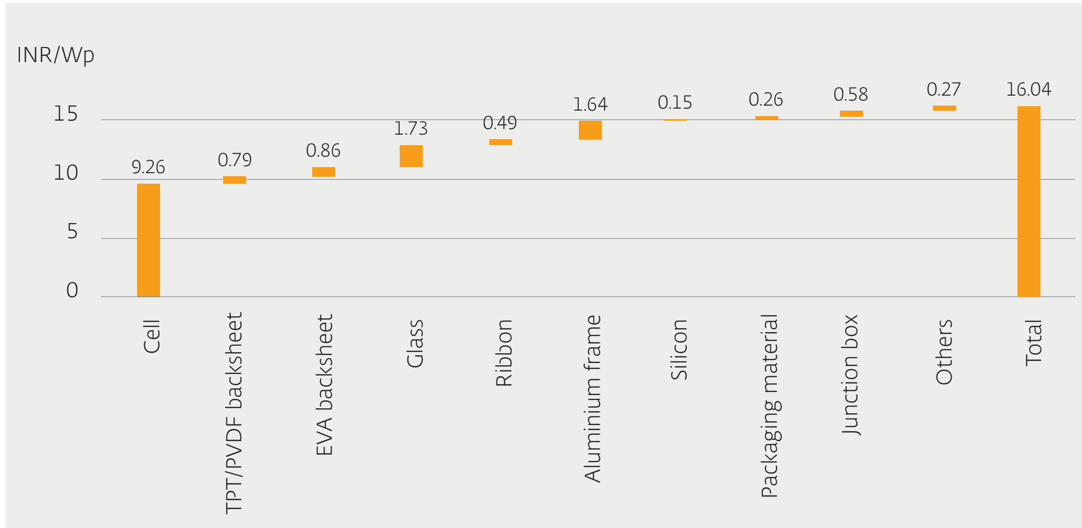


Fig. 1.9 Cost breakdown of the PV module (only material). Source: CEEW.

1.2 Penetration of PV in the building sector

Evolution of PV sector in India

Within this section, the evolutionary process of solar installations in India is analysed with the most representative milestones of the country. The process is assessed by analysing the regulation and policies that influenced the decisions made by the stakeholders of the solar value chain. This historical memory is expected to be useful to foresee new trends and optimise the investments in solar assets. The purpose of this section is to examine and find some key points, trends and breakthroughs defining the evolving path of technological innovation linked to photovoltaic transfer to buildings. The most representative events and case studies within the BIPV framework are shown in a timeline, a graphical tool that includes the core of the first chapter. Finally, an overview of BIPV showcases and best practices is offered to sensitise and apprise architects, designers, industries about the aesthetic, and energetic metrics for BIPV solutions.

The first research and development programs in the field of solar energy utilisation in India were introduced in 1980, about 20 years after the initial discussion of solar energy utilisation in India, in the 3rd Five Year Plan (FYP is introduced for India's economic strategies and planning). The programs initially emphasised industrial energy demand and decentralised implementation potential in rural areas. One year later, in March 1981, the Commission for Additional Sources of Electricity (CASE) was formed, and the National Solar Photovoltaic Energy Demonstration Program (NASPAD) was introduced by Central Electronics Limited (CEL), which marked the beginning of solar photovoltaic activities in India. CASE, more of an autonomous body, was charged with promoting, funding and generally supporting solar power research and integration. The NASPAD program supported R&D activities with CEL for developing reduced cost photovoltaics and improving their efficiency for Multi-Crystalline Silicon Solar Cells and to fabricate Ultra-High Efficiency (UHE) solar cells. During the same year, CEL was engaged in manufacturing solar PV cells and modules, and it achieved a total capacity of 10.35 kW. In 1982, the Department of Non-Conventional Energy Sources (DNES) was formed under the Ministry of Energy for developing the renewable energy sector in India. Between 80's and 90's many groups, agencies and programs have been formed to promote the use of clean energy resources, including the Indian Renewable Energy Development Agency (IREDA), for the promotion and commercialisation of solar-based electricity. IREDA, formed in 1987, focussed for funding, commercialisation and promotion of New and Renewable Sources of Energy (NRSE) programme, which was financially assisted by the Government of Netherlands, World Bank, Asian Development Bank (ADB) and The Danish International Development Agency (DANIDA), and executed by IREDA in coordination with state energy development agencies. In 1992, new ministry was formed for renewable energy sector, with the conversion of DNES to Ministry of Non-conventional Energy Sources (MNES). The Ministry was relabelled as the Ministry of New and Renewable Energy (MNRE) as of now in 2006.

During the 9th FYP, GoI adopted a more far-reaching reform to encourage private sector participation in the renewable energy sector for energy generation, transmission and distribution. The Independent Renewable Power Producers (IRPP) were given the right to power through the existing transmission lines controlled by State Electricity Boards (SEBs) with the liberty to sell the power to any third party. Also, the decentralised approach gave more opportunities to electrify villages in India. Special Action Plan (SAP) was promoted for upgrading and standardising Renewable energy production, especially solar panels in India. With the implementation on one side, GoI also focussed on more technology development through industries for the PV sector with initiatives like, Programme Aimed at Technological Self Reliance (PATSER) promoted by the Department of Scientific Industrial Research (DSIR).

In order to speed up the diffusion of solar installations, around the end of the 2000s, subsidies were introduced by various local governments. In Germany, the Renewable Energy Sources Act came into effect in 2000, and many countries around the world have adopted similar regulatory frameworks. GoI established the Electricity Act in 2003; the act provides a framework for the overall growth of the electricity sector with the private sector's participation and set a reasonable pricing for energy distribution. Provisions for preferential tariffs and quotas were provided for renewable energy. Also, mandatory procurement of renewable energy for distribution licensees and facilitation of grid connectivity were incorporated.

The 2005 National Electricity Policy allows preferential tariffs for power produced from renewable energy sources. It aimed to provide access to electricity to all and increase the minimum per capita availability to 1,000 kWh per year by 2012. The Tariff Policy of 2006 introduced the Renewable Purchase Obligation (RPO) to fix a minimum percentage of the renewable energy purchase of the total energy consumption for the states. Generation Based Incentives (GBIs) were introduced later at that time for small grid solar projects below 33 kW, offering an incentive per kWh of grid-interactive solar and wind energy generation. This was majorly withdrawn for utility-scale plants later due to the rapid growth of the renewable energy sector. Other incentives like accelerated depreciation (AD) and viability gap funding (VGF) were introduced after that.

GoI, under its National Action Plan on Climate Change (NAPCC) launched the Jawaharlal Nehru National Solar Mission (JNNSM) or called National Solar Mission (NSM), in 2010, to revolutionise solar energy as the way forward to attain energy security and mitigate the issue of increasing greenhouse gas emissions. The programme set the foot for rapid photovoltaic implementation in India. In 2010, in India, a PV utility-scale installation cost was about 5,000 USD/kW, while the total installed capacity reached about 11MW/year [16].

Interesting to notice that during the same year in Germany, the cost was about 3,500 USD/kW, 5,000 USD/kW in Italy and 4,000 USD/kW in the United States [13].

Under the JNNSM, Rooftop Phase-I programme was launched in December 2015, which marked the beginning of India's BIPV/BAPV activities supported by GoI. The programme tried to attract residential, commercial, industrial and institutional sectors by providing subsidies and incentives for rooftop PV plants ranging from 1 kWp to 500 kWp capacity. In 2018, India reached their 2022 target of 20 GW ahead of the timeline, and the goal was raised to 100 GW, while in 2019, the Rooftop Phase-II under the JNNSM was launched by targeting a cumulative building rooftop PV capacity of 40 GW by the year 2022. In 2018 the Indian utility-scale solar PV total installed cost achieved a decrease of 84% in comparison with 2010. It represents the highest cost reduction if compared with Countries like China (-77%), Germany (-69%), Italy (-83%), Japan (-74%) and United States (-66%) [13]. The new policies promoted by the GoI permitted to reach a solar PV capacity of about 49.3 GW by the end of 2021, with a rooftop PV capacity of about 6.1 GW, as reported by the distribution companies (DISCOMs) [17] [18] [19] [20] [9] [21] [12].

Landmark PV building installations

The concept of Building Adapted Photovoltaics / Building Integrated Photovoltaics was well realised even before JNNSM, which was marked as the point of growth for the Indian PV sector. Probably the first notable adoption of PV in buildings other than conventional rooftop installations came in 2007, at Samundra Institute of Maritime Studies (**Fig. 1.10**), Maharashtra, commissioned by Tata BP Solar. The campus was installed with a total of 90 kW PV installations, occupied as both translucent and opaque façades. The three hundred feet long photovoltaic solar wall in the Maritime Workshop structures for 60 KW PV installation. The Administration Building utilises northern light through its wavy glass atrium wall, while 30kW PV was placed at the south-facing façade.

Fig. 1.10 Institute of Maritime studies. Source: Ramprasad Akkisetti and Deepak Kaw.

Meanwhile, Tata BP Solar and Moser Baer India Ltd., was also involved in other building projects, such as the façade installation at Tata Consulting Engineers Limited's office building, Jamshedpur in 2009 and 1.8 kWp façade installation at Jubilee Hills shopping complex of Hyderabad in 2011, respectively.

One year after the launch of the JNNSM programme, in 2011, on the administrative building own by Festo in Noida, has been integrated a solar shading device, realised by Tata Power Solar with a capacity of about 20 kWp. This multifunctional installation permits to protect buildings from overheating during the summer and direct solar radiation and, at the same time, it produces renewable electricity for a total of about 17,000 kWh per year. In addition, it helps in avoiding 1.3 tonnes of CO2 per year. The system is south oriented and mounted on a stainless-steel structure to maximise the energy production. The reduction of the building overheating due to the sunlight helped to reduce the cooling energy demand and increase the comfort for the users.

The concept of Green Buildings or Net-Zero Energy Buildings (NZEBs) is prevailing across the world for almost two decades, yet it has not been fully established or penetrated in the Indian context. Nowadays, State and Central governments, policy makers, architects, and builders are pushing for integration of energy efficiency and renewable energy production at the building design stage itself. The Indira Paryavaran Bhawan, building for Ministry of Environment and Forest (MoEF), in Jorbagh, New Delhi, was inaugurated in 2014, which sets itself as an exemplar for a change from conventional building design to net-zero energy approach (**Fig. 1.11**). The building is considered as India's first NZEB, one of the highest rated green buildings in India. It received five-star rating of Green Rating for Integrated Habitat Assessment (GRIHA) by MNRE and LEED India Platinum by Indian Green Building Council (IGBC) rating. The building has a solar PV system of 930 kW installed in a 6,000 m2 area. The total PV area is 4,650 m2 by 2,844 solar panels which generate 14.3 lakh unit annually which meets the building's energy demand. PV panels are covered in the building top, courtyard, and edges which effectively creates shade and cooler microclimate in the building [22].

In 2015, Tata Power Solar successfully commissioned the RSSB-Educational & Environmental Society (RSSB-EES) solar rooftop installation at Radha Soami Satsang Beas in Amritsar (**Fig. 1.12**). It was initially a 12 MW solar rooftop installed across 8 sheltered venues in a single premise. The project was claimed to be the world's largest solar rooftop project, set up in a single phase, and extended to 16 MW later. This rooftop power plant will produce more than 15,000 MWh units of electricity annually, and the whole solar power

Fig. 1.11 Indira Parvavaran Bgawan. Source: Rehau.

Fig. 1.12 RSSB-EES in Beas. Source: L&T Construction.

plant (total of 19.5 MW installation in the whole complex) at the site cumulatively offset over 19,000 tonnes of carbon emissions every year. Multi-crystalline modules were used in the project to achieve high performance and low degradation for a sustained 25-years energy generation. The system is provided with a central supervisor control and data acquisition (SCADA) system, enabling real-time solar power plant monitoring. A synchronised module cleaning system, improving the cumulative performance of the entire block, has also been implemented. To have a negligible downtime due to components failure or malfunction, the necessary spares are managed by using hub & spoke model (refers to distribution/management from a centralised hub), maintaining the availability at all times. The grid-connected system, equipped with net metering, can feed surplus electricity to the grid under the Punjab government's grid-connected rooftop solar projects scheme.

In India, the largest BIPV facade, has been realised in 2020 (**Fig. 1.13**, next page). The U-Solar CtrlS Data Center in Mumbai is an administrative building on which 863 kWp of monocrystalline modules were installed by integrating solar panels in all four walls of the facility, covering over 51,500 square feet of facade area. More than 2,000 high-efficiency PV modules were used to cover the building skin of the construction. The monitored energy production of the Data Center is about 0.6 GWh per year. In this case, the solar modules adopted represent a standardised design intended to be easy to integrate with many common building materials.

This strategy, common in Europe during the first/second decade of the 2000, is a consequence of partnerships among PV manufacturers, architects, and building-materials' suppliers, and approached to address barriers and bring new cost-competitive products and solutions on the market. A detailed specific analysis of this installation is conducted and reported in the case study section at the end of the booklet.

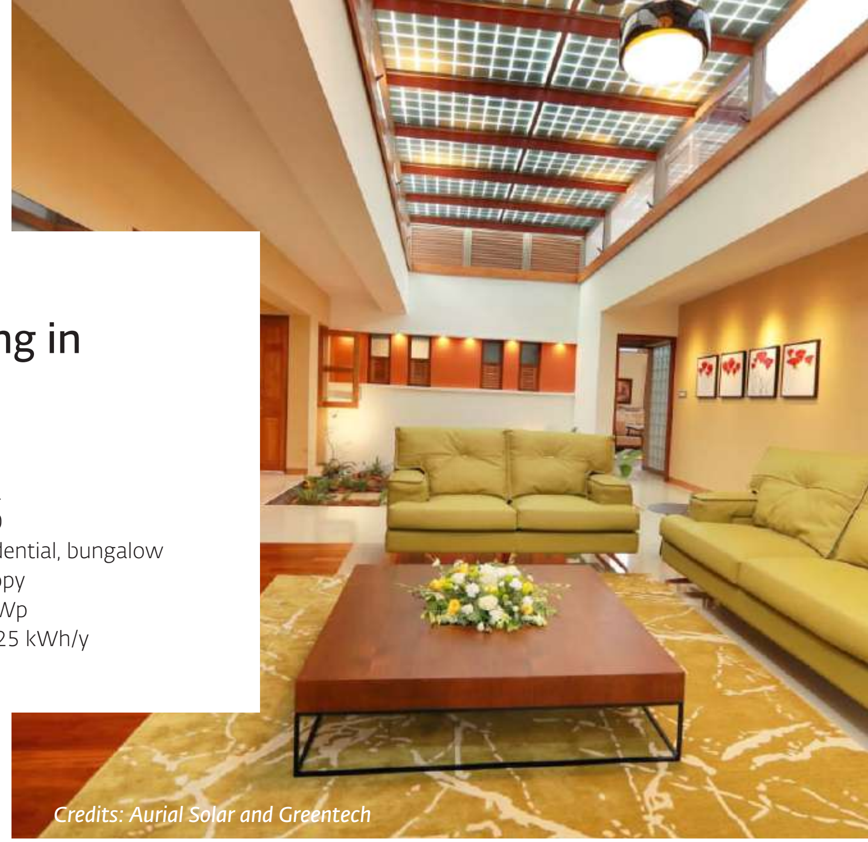
A contemporary and aesthetically pleasant exemplar for simple and effective building rooftop integration of PV is the Rajkumari Ratnavati Girls School located at the Thar Desert of Rajasthan (**Fig 1.14**, next page). The building was designed as elliptical for practical purposes and aligned with the Indian building construction culture. Herein, the PV panels serve the purposes of energy generation. In addition, the solar canopy offers shade and filters the sand from the desert. The stairs and the ramp serve as a play area for children hidden by a large jali (perforated stone or latticed screen, usually with an ornamental pattern constructed through the use of calligraphy, geometry or natural patterns) under the solar canopy. Being placed as a single row with the inward curve and directed to south with a larger inclination angle, the PV system is well integrated with the building design and purposes

Fig. 1.13 CTRLS Data Center, Mumbai. Source: U-Solar.
Fig. 1.14 Rajkumari Ratnavati Girls School, Rajasthan. Source: vinay_panjwani.

TopSun Energy

Residential building in Idukki, Kerala

Completion year	2021
Planning & Installation	2020
Building typology	Residential, bungalow
Category	Canopy
Installed PV power	18 kWp
Energy production	23,725 kWh/y



Credits: Aurial Solar and Greentech

Tel. +91 7573 006 633
www.topsunenergy.com

"TOPSUN'S Solar BIPV can be used in a variety of applications mainly stationary fenestrations for commercial buildings and residential construction and many other areas where energy conservation & comfort are part of the design.
1) Orientation, slope options, sizes or wind loads are some key variables that should be measured accurately in order to get a correct design for the main structure for which we have specialists team which works for tailor made projects with all customization.
2) Green Building design is becoming a great interest for real estate companies today. Qualitative facts such as return on investment (ROI), enhanced indoor comfort and productivity level due to the radiation filtration with optimal natural light contribute in earning Green certifications such as LEED and BREAM and we help you analyze that better with our customizations.
3) Topsun BIPV can be customized in different sizes, shape, colors, thickness & percentage of transparency to suit client taste of aesthetics.

We strongly believe Topsun being an experienced company can prove to be a great association to you as we value work ethics, commitment and business relations. We hope and would be glad to receive you interest in our product range."

1981

The NASPAD marked the beginning of PV activities in India

1983

CEL achieved a module capacity of 31.75 kW

Institute of Maritime Studies

Credits: Ramprasad Akkisetti & Deepak Kaw

2007

The first BIPV building in India

Tata consulting engineers

Credits: Amit Basuri

2009

BIPV facade in Jamshedpur, India

2010

The JNNSM revolutionises solar energy as the way forward to attain energy security and mitigate the issue of increasing GHG emissions. The program set the foot for rapid photovoltaic implementation in India.

Festo building

Credits: Aseem Kumar Sharma

2011

A BIPV shading system (Noida, India)

2015

Rooftop phase-I programme was launched on December 2015, which landmark the beginning of the BIPV/BAPV sector in India

RSSB-EES

Credits: L&T Construction

2015

The largest solar rooftop plant in the world (Beas, India)

Malabar HQ

Credits: Sunsenz

2017

60 kWp installed as canopy

2018

Rooftop Phase II integration of 40 GW of rooftop PV installations by 2022

CTRLS Data Center

Credits: U-Solar

2020

The largest BIPV power plant in India (863 kWp capacity)

Ponnore Group

Credits: TopSun

2020

Cost efficient BIPV curtain wall

R.R. Girls School

Credits: vinay_panjwani

2020

Photovoltaic solar canopy

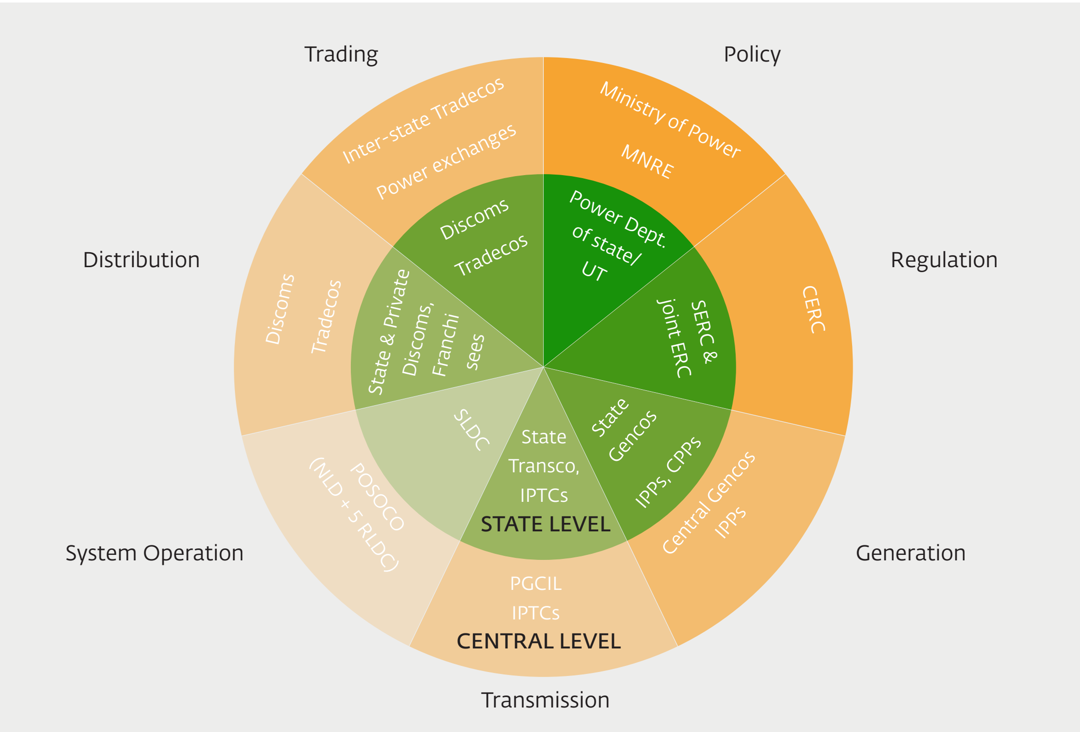
Fig. 1.15 Indian BIPV Timeline. Source: SUPSI.

1.3 Financial schemes in solar buildings in India

Power Sector in India:

The Indian power sector is highly organized with functionally distinct organizations, departments and associations for the generation of electricity, its distribution and operation. The key stakeholders of the India power sector are shown in **Fig. 1.16**, framed with the involvement of both Central and State Governments with other private participants at different levels for efficient functioning. Ministry of Power, which oversees the entire energy sector and the Ministry of New and Renewable Energy (MNRE), is concerned with the central level policy making. Individual energy departments are also concerned with the policy making at the state level for the states & UTs. MNRE and its state nodal agencies are associated with the country's whole renewable energy sector, its promotion, international corporation, R&D activities, etc. MNRE also embodies five technical institutions in India: (1) National Institute of Solar Energy (NISE), (2) National Institute of Wind Energy (NIWE), (3) Sardar Swaran Singh National Institute of Bio-Energy (SSS-NIBE), (4) Indian Renewable Energy Development Agency (IREDA), (5) Solar Energy Corporation of India (SECI). NISE is the apex R&D institute for solar energy, which is also involved in solar component testing and certification. IREDA is a non-banking financial institution engaged in development and extension financial assistance for new and renewable energy projects. SECI is a Central Public Sector Undertaking (CPSU), formed to facilitate the implementation of Jawaharlal Nehru and National Solar Mission (JNNSM) activities. Apart from the ministries, the Central Electricity Authority of India (CEA), a statutory organization, advises the government on policy matters and formulates plans for the energy sector in India. CEA is also responsible for statistical data publishing of the Indian power sector for both state and central government utilities. Along with MNRE, CEA compiles the statistics on electricity capacity addition, generation, trade and forecasts. The Central Electricity Regulatory Commission (CERC) is a statutory body in India functioning to regulate the generation, transmission, and distribution in the country.

Fig. 1.16 Organisational chart for the power sector in India. Source: [23].



The State Electricity Regulatory Commission (SERC), is involved in the rationalization of electricity tariffs, policies, subsidies, inter-state transmission and trade etc. In the electricity generation sector, both public and private involvement (including Central and Sate Generation Companies, Independent Power Producers (IPPs) and Captive Power Plants (CPPs)) equally contributes to India's energy sector [24]. Considering the electricity transmission in India, the Power Grid Corporation of India Limited (PGCIL) is the Central Transmission Utility (CTU) and is held responsible for most inter-state transmission projects. State Transmission Utility (STU) and Independent Private Transmission Companies (IPTCs) set up other transmission projects within the states. For monitoring and ensuring hassle-free operation of the electricity sector, companies like Power System Operation Corporation (POSOCO) and National, Regional and State Dispatch Centres (NLDC, RLDC, SLDC) work in conjunction to ensure grid security and balance. Considering the energy distribution sector, mostly state-owned companies conduct distribution and retail operations. Some private companies are also involved in Indian electricity distribution at different states. In addition to this, inter-state and other energy trading companies, power exchanges, and distribution companies (DISCOM) set the balance for demand and supply. As represented in **Fig. 1.16**; this whole ecosystem makes the energy sector in India, created for the smooth functioning of the power sector at both national and state levels.

Rooftop Solar Program & Policies in India

India launched JNNSM on 11th January 2010, which is the key solar program developed in India until now. The program was developed in accordance with India's National Action Plan on Climate Change to promote the concept of ecological sustainable growth and addressing the issue of energy security in India with the diffusion of solar technology across the country. The mission targeted 100 GW of grid connected solar energy capacity by 2022, and installed a total capacity of 49.3 GW grid connected solar installations as of December 2021. In order to achieve the above target, the Government of India (GoI) has launched various schemes like Solar Park Scheme, VGF Schemes, CPSU Scheme, Defence Scheme, Canal bank & Canal top Scheme, Bundling Scheme, etc. to encourage the solar power sector of the country. Considering the fact that integration of PV in the building sector provides a huge potential to tap for the Indian energy sector, the Grid Connected Solar Rooftop Scheme has been greatly promoted by GoI in the second phase of JNNSM. By this programme, it is targeted a cumulative capacity of 40 GW Rooftop Solar (RTS) installations by 2022. As reported by DISCOMs, an overall of 3.7 GW capacity of grid connected rooftop solar plants has been installed in the country by December 2020, and was extended to 6.1 till November 2021 [12] [25]. As of now, the Solar Rooftop Scheme remains the only programme promoting solar PV in the building sector, and discussions are based on the programme.

Main RTS program actors

Solar Energy Corporation of India (SECI)

SECI is a CPSU under the administrative control of MNRE, set up to facilitate the implementation of solar plants under the JNNSM. SECI plans of the targets of RTS installations in the country and decides on the allotted capacity following the competitive bidding process.

State Nodal Agencies (SNAs)

Under MNRE, SNAs have been established in the states and UTs for the promotion, coordination, finance and development of renewable energy projects in their state/UT. For the RTS program, the SNAs prepare targets as sanctioned by MNRE and select channel partners/installers through tendering with the rate contracts. SNA are also involved with the monitoring and inspection of the RTS installations.

Distribution Company (DISCOM)

Various public and private DISCOMs are concerned with the interpretation and implementation of the policies and regulations provided by both the Central Government and Governments of individual states. The overall technical feasibility study, evaluation of design and installation parameters for grid connected RTS system, installing metering arrangements have been carried out by the DISCOMs.

Chief Electrical Inspector to Government

The Chief Electrical Inspector (CEIG) ensures safety compliance and operations of RTS system. They involve in the approval of design and drawings, the pre-commissioning inspection and issuing of Charging Certificate.

Channel Partners

Channel Partners are the agencies associated with the sourcing of equipment/ solar components, or the implementation of RTS system for the clients, being empanelled by MNRE. The Channel Partners could include the solar Renewable Energy Service Companies (RESCO), vendors/ suppliers of solar equipment, project developers, manufacturer of solar components/ equipment, solar ambassadors etc. The empanelment with MNRE is based on certificate from a rating agency in the country for technical and financial strength. SNAs and DISCOMs have to undertake competitive bidding for selection of developers for RTS plants with the claim for Central Financial Assistance (CFA)/ subsidy. The channel partners submit the proposal to the clients (rooftop owners), sign the EPC/Power Purchase Agreement (PPA) agreement with clients and submits for the metering arrangement (to DISCOM) and subsidy (to SNA).

Financial Institutions/Banks

The financial Institutions and financial Integrators like NABARD, National Housing Banks, other Banks, IREDA, etc. are also eligible for implementing the RTS program. They may source funds from MNRE, their own resources or any other sources i.e., carbon credits, National Clean Energy Fund, funds from States, beneficiary contribution, CSR sources etc. Other Govt. Departments/ Agencies i.e., Railways, Defense/ Para Military Forces, Local Government Bodies including Municipal Corporations/ Municipalities, State Departments, etc. interested in directly implementing the program are also encouraged [26] [27] [28] [29].

Boundary conditions for PV in relation to building typologies (based on RTS scheme)

This section presents an overview of the different boundary conditions for the present state of solar PV adoption in Indian buildings. Financial relaxations for the different building typologies (residential, commercial and industrial) according to the benchmark cost provided under the RTS scheme establish the investment of solar installations in building. The cost of electricity and the levelized cost of electricity (LCOE) lays the foundations for an accurate cost analysis for solar installations. The analysis of electricity costs, the benchmark cost and financial relaxations will help to understand the framework and the strategies adopted for the RTS consumers in the country. The electricity costs within the different building typologies, the metering methods and available business model form the basis of attractiveness of RTS scheme in India. The different boundary conditions of Indian RTS scheme are discussed below.

1. Financial relaxations and benchmark cost

For residential buildings

Under Phase II of Grid Connected Rooftop Solar, the CFA has been approved for the beneficiaries until 31st December 2022. Under the scheme, only domestic manufactured modules and solar cells have to be used and the CFA shall be on percentage of benchmark cost of MNRE for the state/ UT or lowest of the costs discovered in the tenders for that state/ UT in that year, whichever is lower. For the residential sector, the CFA is 40% for capacity up to 3 kWp, 20% for capacity beyond 3 kWp and up to 10 kWp, and 20% for Group Housing Society (GHS) / Residential Welfare Association (RWA) capacity up to 500 kWp (limited to 10 kWp per house). The scheme is to be implemented through Power Distributing companies (DISCOMs), and for the residential consumer the CFA can be availed by operating through the DISCOMs [30]. The benchmark costs for Grid-connected Rooftop Installation under Phase II for the financial year 2020-21, decided by MNRE as presented in the **Tab. 1.1** and **Tab. 1.2**. Cost are referred to turnkey PV plants (including installation and put in operation) for conventional PV plants (e.g. BAPV on-roof systems). The benchmark cost includes the cost of PV panels, inverter, balance of system (cable, switches/ circuit breaker/ connectors/ junction box, mounting structure), earthing, lightning arrester, Comprehensive Maintenance Contract (CMC) for 5 years, transportation, insurance, applicable taxes, etc. The cost for metering and battery backup are not included [31] [32] [33].

For other buildings

In the Phase II of RTS scheme, institutional, educational, social, government, commercial and industrial sectors are excluded from availing CFAs, as the beneficiaries of these sectors are advantaged without CFA, since they are mostly high tariff paying consumers. However, for the penetration of solar systems in these sectors for the implementation of 40 GW rooftop solar installation target, acceleration depreciation (AD) benefits and Viability Gap Funding (VGF) is provided by the GoI under JNNSM Scheme [34] [35].

For the DISCOMs

For DISCOMs progressive incentives provided by the government are based on achievement levels, calculated above baseline, i.e. the cumulative rooftop capacity achieved at the end of previous financial year. For capacity addition up to 10%, there is no incentive. For 10%-15% capacity addition there is 5% incentive, and for above 15% capacity addition 10% incentive is provided. The incentives are limited to the initial 18 GW capacity [30].

System capacity range	< 1 kWp	1-2 kWp	2-3 kWp	3-10 kWp	10-100 kWp	100-500 kWp
Benchmark cost (Rs/kW)	46,932	43,140	42,020	40,991	38,236	35,886
Benchmark cost (2021 €/kW)	554	509	496	484	451	424

Tab. 1.1 Benchmark costs for grid-connected rooftop installation under Phase II for the financial year 2020-21 for general category states/UTs (currency conversion 17/01/2022). Source: MNRE.

System capacity range	< 1 kWp	1-2 kWp	2-3 kWp	3-10 kWp	10-100 kWp	100-500 kWp
Benchmark cost (Rs/kW)	51,616	47,447	46,216	45,087	42,056	39,467
Benchmark cost (2021 €/kW)	609	560	545	532	496	466

Tab. 1.2 Benchmark costs for grid-connected rooftop installation under Phase II for the financial year 2020-21 for special category states/UTs: North eastern states like Sikkim, Himachal Pradesh, Uttarakhand, Jammu and Kashmir, Ladakh, Andaman and Nicobar and Lakshadweep islands (currency conversion 17/01/2022). Source: MNRE.

2. Billing mechanism and RTS considerations

The type of metering greatly influences the growth of the PV sector, as it directly affects both the consumer economy and the energy sector. The types of metering are detailed below.

Net Metering

In net metering systems, a bi-directional meter is used to measure the difference in energy consumption from the grid and energy export to the grid. Consumers are provided with the opportunity to offset their electricity bills accordingly. Surplus injection compensation may or may not be provided (depends on state regulations) for the excess energy supplied to the grid.

Gross Metering

In gross metering or feed-in metering, all the energy generated from the system is exported to the grid and is separately recorded through a different 'feed-in meter'. In this case, the third-party investors/RESCO developers enter into a long-term PPA with the utility. The developer exports the solar energy to the utility at a predetermined feed-in-tariff (FiT) approved by the regulator. The model is particularly aimed at rooftop owners/third party investors who would like to sell energy to the DISCOM.

According to the latest amendment by the Ministry of Power, every consumer can avail net metering system for RTS installation below 500 kWp [36]. Further, any state government can extend the limit according to their regulations for any solar installations. The net metering regulations for commercial and industrial buildings, the electricity retail tariff, feed-in-tariff for gross metering and the surplus injection compensation for consumers who supply excess energy to the grid (in the case of net metering) for the different building typologies are determined by the state commissions and the DISCOMs. These state regulations greatly determine state's friendliness for the RTS scheme and other solar PV integration in residential, commercial and industrial buildings [37].

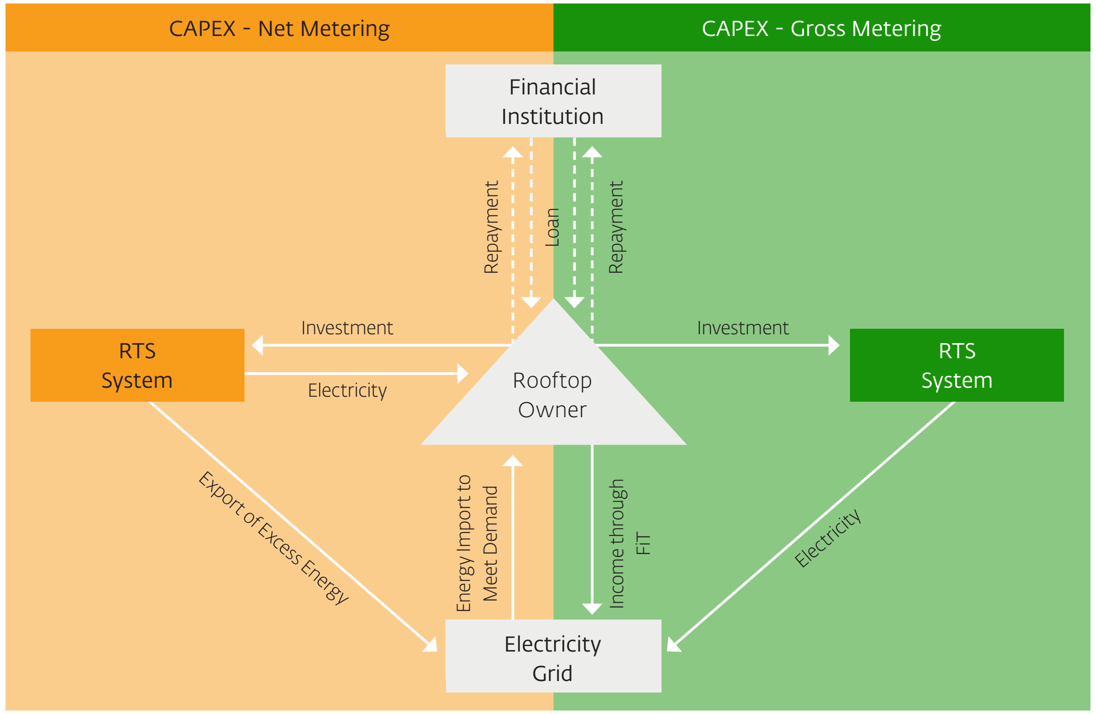
Appropriate business is always necessary to have a satisfactory revenue model for the stakeholders under consideration. In particular, it permits to the investor to understand the value of the investment in solar installations and to optimize the strategies of investment in solar systems. CAPEX model is considered as the first-generation model, which is a consumer self-owned model. RESCO model is the second-generation business model revolved around third party ownership and operation. Currently, these two models are majorly prevailing in India for PV building installations, the policies for each are according to DISCOMS and state government regulations. The third-generation, utility ownership driven model is considered as a future scope in global solar energy sector, but it is only emerging in Indian solar rooftop/ solar building scenario. Within these paragraphs, the two most popular business models in India for grid connected solar rooftops are elaborated. For other BIPV systems, CAPEX models are considered unchallenging, because of the ownership provision; other dedicated business models are necessary for the sector in future. CAPEX model is the most common business model for rooftop solar deployment in India. In this model, the consumer (rooftop owner) owns the system (expenses include the installation cost, O&M cost), by upfront payment or with other financial aid, often through a bank. These expenses include the cost to set up, maintain and operate the system. The power is either consumed or injected to the grid with a Feed-in-Tariff (gross metering) or net metering, as shown in **Fig. 1.17**. CAPEX models are well suited for consumers that can bring the investment upfront, and has a stake on the building.

In RESCO model, third party (RESCO) involves in financing and development of solar rooftop systems. Third party may rent rooftop space from rooftop owner and sell the electricity generated to the grid or the rooftop owner through a PPA, or may also lease out the PV system to the rooftop owner who may utilize the power from the system. For consumers who does not have a stake on the building, such as government building, public educational institutions, leased building, etc., or consumers who cannot bring the investment upfront, the RESCO operation models are best suited. The possible models upon different agreements are described and represented in **Fig. 1.18** and **Fig. 1.19**.

Solar system leasing

In this, third party investor leases the PV system to rooftop owner who makes payments as per the agreement for the consumption of the electricity generated. The third-party investor earns month-to-month lease payment. The savings from the generated electricity is the source of revenue for the rooftop owner.

Fig. 1.17 Financial schema: CAPEX net and gross metering. Source: NIIST.



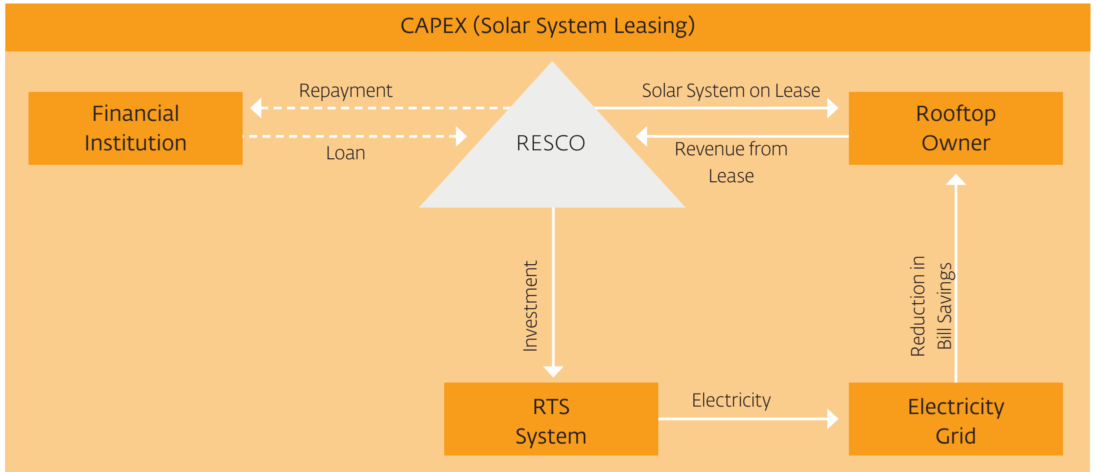


Fig. 1.18 Financial schema: CAPEX solar system leasing. Source: NIIST.

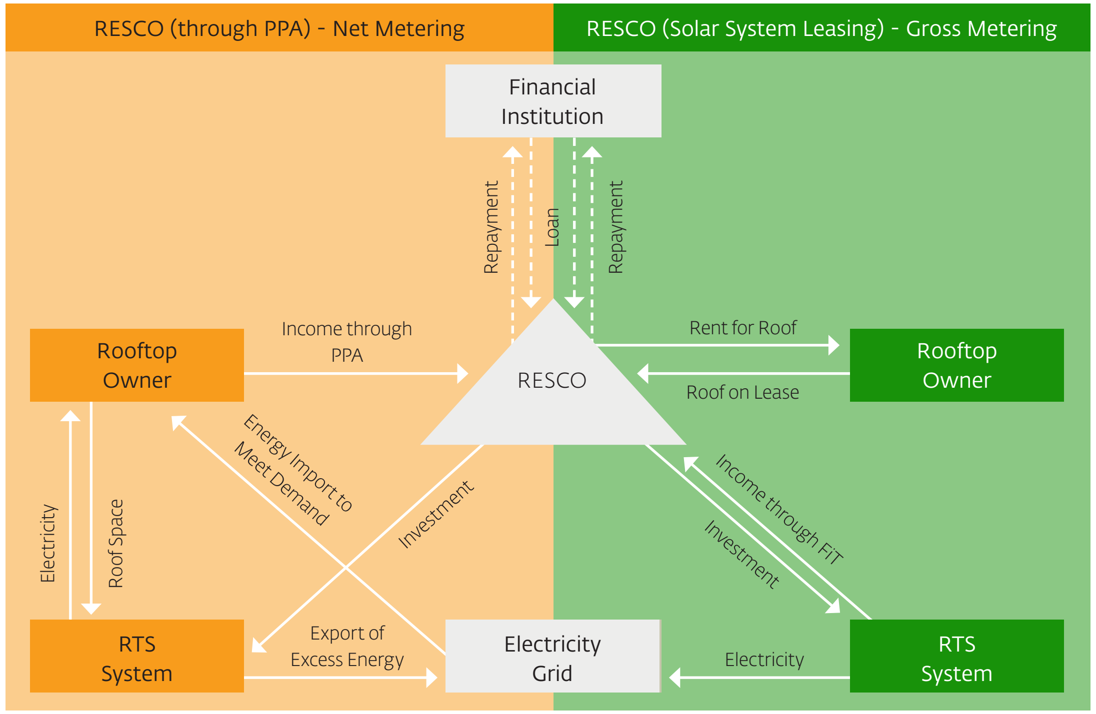
Rooftop Leasing (Under Gross Metering)

In this third party leases the rooftop and pays lease/ rent to the building owner in the lease period. The RESCO developer exports the generated power to the utility at a predetermined FiT approved by the regulator.

PPA (Under net metering)

In this, the third party invests in the solar system, and sells the generated power to the rooftop owner in with a lower solar power tariff compared to the grid tariff and the export of excess power through net metering makes savings for the rooftop owner.

Fig. 1.19 Financial schema: RESCO net and gross metering. Source: NIIST.



3. State-wise attractiveness of RTS scheme

Indian PV scenario has not achieved uniformity regarding the attractiveness of solar programmes, especially RTS installations. Many state-wise physical, technical, political, social, institutional, and economic factors such as solar policies, incentives, metering regulations and rooftop availability, electricity tariffs, distribution infrastructure differ the sector in each state. An ambiguous situation is thus prevailing for the stakeholders associated with the solar sector in India, especially for the renewable energy companies, entrepreneurs, developers, financial institutions, as well as government in policy making. Thus, it is critical to have a platform at national level for the evaluation of states' support level for the RTS programme.

Considering this, State Rooftop Solar Attractiveness Index (SARAL ranking) has been designed by MNRE in collaboration with Shakti Sustainable Energy Foundation (SSEF), Associated Chambers of Commerce and Industry of India (ASSOCHAM) and Ernst & Young (EY) for ranking the overall attractiveness of RTS programme in different Indian states with a dedicated evaluation method. The aspects considered for the evaluation are:

- Comprehensiveness/robustness of policy framework (Level of policy support, Covenants, Billing mechanism)
- Ease of implementation/effectiveness of policy support (Ease of application, Power offtake attractiveness, State of affairs of DISCOMs, Impact of Policy)
- Investment climate for the rooftop solar sector (Driver for rooftop solar uptake, Ease of financing, Maturity of market)
- Consumer experience (Pre-installation consideration, During installation, post-installation experience/costs)
- Business ecosystem (Business Enablers, Fiscal and Regulatory environment, Economic outlook)

The detailed evaluation mechanism is explained in SARAL reports. According to the 2018-19 report Karanataka, Telangana, Gujarat, Andhra Pradesh scored the first four positions in the ranking [38].

4. Electricity cost & Levelized Cost Of Electricity

The electricity cost in India is calculated under consumption slab basis, i.e., the final cost is determined by the range of total energy consumption. The average electricity cost for residential building in India is around 4.2 INR/kWh to 6.7 INR/kWh, which varies according to the state, the DISCOM, and the amount of unit (in kWh) consumed. For commercial buildings, it is coming around 7.5 INR/kWh to 8.6 INR/kWh, and for industries it is around 6.6 INR/kWh to 7.6 INR/kWh. The determination of average electricity cost does not clearly indicate the overall scenario and unevenness of electricity cost in India, which changes with the electricity policies adopted by different state governments and DISCOMs. As for example, the electricity cost in residential sector varies from 0.85 INR/kWh in Tamil Nadu to 7.38 INR/kWh in Rajasthan up to 100 kWh slab, and the maximum rate of 13.4 INR/kWh can be seen in Maharashtra for up to 1000 units' slab. CEA has published the electricity tariff across India for the different building sectors [39].

The price of electricity influences the economic payback of solar systems. The revenues, which consist in savings on the yearly electricity bill, are also associated to the self-consumed electricity. For each kWh that is self-consumed, a saving up to the amount of the compensable retail electricity price can be made in the case of net metering arrangement. In this sense, consumers (rooftop owners) have a better payback rate for states having higher electricity cost. However, the revenues coming from building integrated solar systems includes the excess electricity that is fed-back to the grid and also from the multifunctionality of any Building Integrated Photovoltaic (BIPV) systems that can be considered as a replaceable element for conventional construction materials and power generators [40].

LCOE can be considered as the best measure of an electricity generating system in an economic perspective. It denotes the average net present cost (including the fixed and variable cost) of generating electricity from a system in its lifetime to break even. Lower the LCOE value denotes better economics from the consumer point of view.

A recent study conducted by Siddharth Joshi et.al., for evaluating the potential of rooftop solar PV installations across the globe (with building footprints, solar radiation mapping with seasonal variability, and technology-specific information like panel size, conversion efficiency, and system losses) showed the potential competency of Indian conditions. The study concluded that, India is one of the countries with least LCOE value of 66 $/MWh for attaining the country-specific potential of 1,815 TWh/yr. The global map generated in the study for the assessed LCOE value is shown in **Fig. 1.20**.

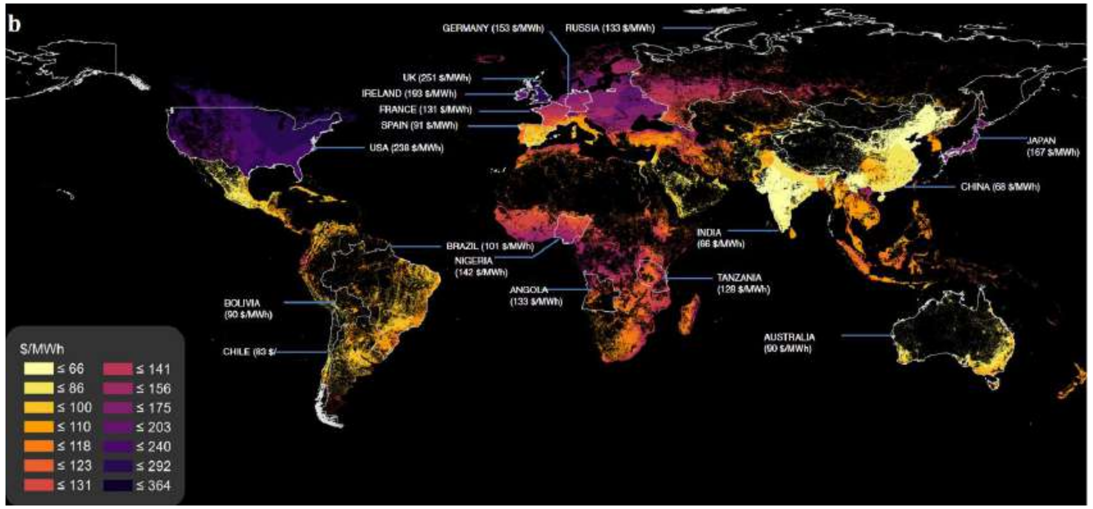


Fig. 1.20 Global Distribution of RTS technical potential and LCOE values. Source: [41].

Chapter 2
Solar constructions

2.1 Green building revolution and role of BIPV

The real estate sector in India is the second-highest employment generator in India after the agriculture sector. In the coming years, rapid growth in the construction market and the adoption of state-of-the-art construction technologies are expected in India. More specifically, by 2024, the real estate market will grow to about 9 US$ billion, with a high Compound Annual Growth Rate (CAGR) of 19.5% from 2017-2028 is expected [1]. The current housing shortage in India's urban areas is estimated to be about 10 million units; thus an additional 25 million units of affordable housing are required by 2030 to meet the demand of growing urban population [2].

Worldwide, buildings account for nearly 39% of annual CO2 emissions, among this 28% is related to building operations and 11% to building materials and construction [3]. The high energetic footprint of the construction sector emphasises the need for introducing strategies to reduce the energy impact on buildings. To address these issues, the World Green Building Council has launched 'Advancing Net Zero' worldwide to promote and accelerate the growth of net-zero carbon buildings to 100% by 2050. According to the World Green Building Trends 2021 report by Dodge Data and Analytics, India is expected to raise the green building sector from 12% in 2021 to 25% by 2025 (survey conducted within respondents having more than 60% green projects) [4]. However, according to the report, the Indian green building sector is driven mainly by the country's environmental regulations rather than the market or public awareness. The lack of trained/educated green building professionals and unaffordability in every building sector constitute the major hindrances in the Indian green building sector. Currently, the market of green buildings in India has been concentrated in new commercial, institutional and large residential spaces.

Different green building rating systems have been introduced worldwide to promote net-zero building strategies with certificates, incentives and financial assistance. Three rating systems are predominantly existing in India: 1) Globally framed Leadership in Energy and Environmental Design (LEED), 2) rating system of Indian Green Building Council (IGBC), and 3) Green Rating for Integrated Habitat Assessment (GRIHA) of MNRE. The IGBC was formed in 2001 under the Confederation of Indian Industry (CII), which was one of the initial revolutionary course. Through the years IGBC promoted green revolution ranging from buildings, industries, cities and other habitats with individual ratings (with the involvement of key stakeholders including architects, builders, consultants, developers, owners, institutions, manufacturers and industry representatives), certification, training programs and green energy building conferences.

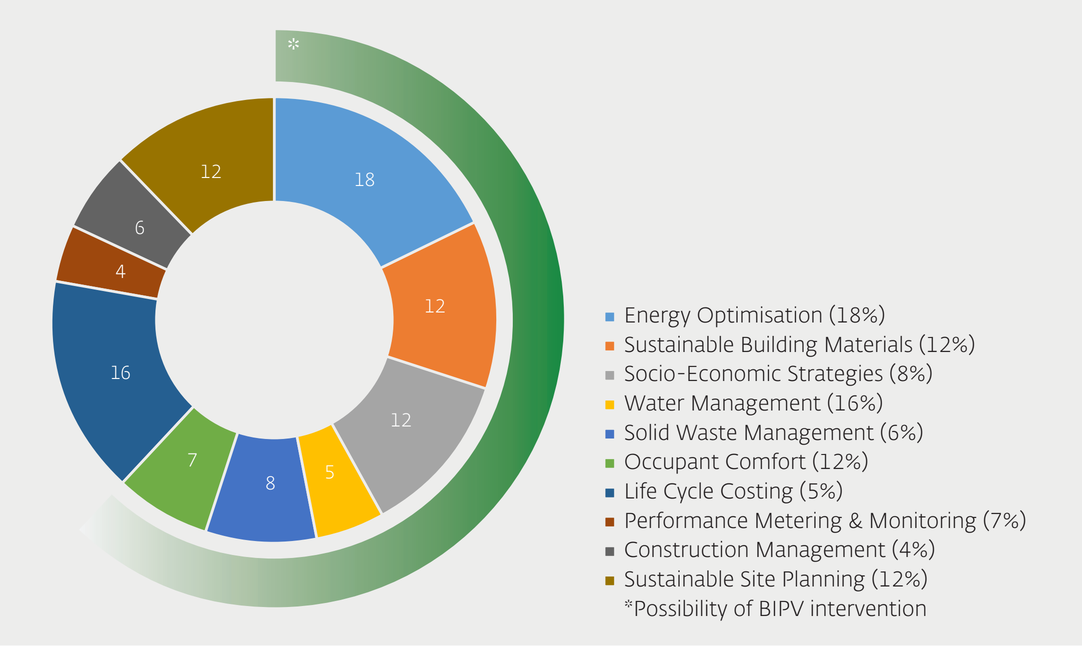
Also, MNRE has been widely promoting programmes and regulations for energy efficiency in the building environment to advocate the concept of self-sustenance, both in resources and energy, in the country. The national rating system GRIHA was developed by The Energy and Resources Institute (TERI) and endorsed by the ministry in 2007 with modifications as suggested by a panel of architects, builders, renewable energy and sustainability experts. GRIHA has been developed to rate commercial, institutional and residential buildings in India emphasising national environmental concerns, regional climatic conditions (building design considerations are done based on the six climatic zones, according to a study conducted by IIT Delhi, and adopted by MNRE), and indigenous solutions. It is a more holistic and life-cycle approach (from site selection to planning, construction and demolition) with an objective to reduce resource consumption, reduce greenhouse gas emissions and promote the use of renewable and recycled resources in buildings to rate the "greenness" of a building. It integrates all relevant Indian building codes (National Building Code 2005; the Energy Conservation Building Code (ECBC) 2007 announced by Bureau of Energy Efficiency (BEE), and other Indian Standards [5].

GRIHA has a 5-star rating system, evaluated with a set of criteria included for aspects of design, construction and operation of a green building. The pre-assigned points for each criterion are calculated with benchmark performance goals and added up to obtain the star rating. GRIHA rating is applicable for all newly constructing habitable building typologies (Residential, Healthcare, Hospitality, Institution, Office, Retail, Transit Terminals, etc.) with a minimum built-up area of 2,500 m2. Other GRIHA ratings are adopted for less built-up area buildings (Simple Versatile Affordable GRIHA), existing buildings, existing schools, large developments, etc. According to the rating directives of GRIHA [6] around 42% of point share is dedicated to Energy Optimisation (18%), Occupant Comfort (12%) and Sustainable Building Materials categories (12%). Thus, the GRIHA rating can be considered as a technical tool for green building development in India. Even though renewable energy utilization constitutes 5% of it, BIPV integration has enumerate possibilities and advantages in the mentioned categories, other than energy generation, such as:

- Passive solar construction techniques including material, architectural design and product design interventions through BIPV products
- Energy savings through PV integrated daylighting systems
- Energy conservation through thermally insulated BIPV roof and facade
- BIPV products that can offer both visual, thermal and acoustic comfort as per Indian standards
- Utilisation of alternative materials in building using BIPV, prefabrication and modular construction: Offsite construction of building components and its onsite assembly is an upcoming approach for green building construction. Prefabricated structural construction and modular assembly can be greatly congruent with BIPV elements such as building skin as façades, glazing, external roofing, etc. It greatly reduces the material consumption of conventional building construction, reduces its wastage, induce safer working conditions, reduces the time of construction, and can provide better energy and comfort performance in line with the BIPV product specifications, expanding provision for higher GRIHA rating.

Other possibilities of BIPV interventions in the GRIHA rating system includes the sections of Life Cycle Costing, Socio-Economic Strategies, and Performance Metering and Monitoring. The various sections of GRIHA rating and potential areas for BIPV interventions are briefed in **Fig. 2.1**.

Fig. 2.1 Pie chart representing different shares for GRIHA rating in percentage and potential share for BIPV interventions. Source: [2].



2.2 Building Integrated Photovoltaic systems

If the necessity to improve the energetic performance of buildings induces the stakeholders of the construction sector to use solar systems, the rapidly growing construction market in India requires introducing new ideas and technologies. The installation of solar systems as building envelopes not only permits to transform buildings into solar power plants but also to integrate multifunctional properties of the construction system, replacement of building cladding materials and improving aesthetics considering the architectural image. The integration of solar energy systems in the buildings is well recognised with the acronym BIPV (Building Integrated Photovoltaic) as defined within the solar community. For example, now the BIPV products are available in different colours and sizes [7]. The reported market overview for state-of-the-art coloured BIPV products clearly reveals that, for all parts of a BIPV module, there are technical solutions available for colouring and customisation. Pilot projects utilising coloured BIPV products have been built in numerous (mainly European) cities, clearly demonstrating the maturity of these solutions. Besides the colour perception of the BIPV elements under solar irradiation, which is essential for the acceptance of the exterior appearance of a building, also the transparency and inside visual comfort of BIPV sells itself as essential window and façade elements for the users [8].

Since the building envelope normally cannot be produced in one piece, it is necessary to break it down into individual parts. For many years, the BIPV community did not reach a consensus about a reference categorisation of BIPV applications in the building skin. In this chapter, the definition of BIPV is provided on the basis of the specifics promoted by the IEA PVPS Task 15 [9]. The categorisation is based on three levels that include the i) application category, ii) system, and iii) cladding properties.

A definition of BIPV

IEC 63092-1:2020 [10] specifies BIPV module requirements and applies to photovoltaic modules used as building products. It focuses on the properties of these photovoltaic modules relevant to basic building requirements and the applicable electro-technical requirements. This document addresses requirements on the BIPV modules in the specific ways they are intended to be mounted but not the mounting structure itself, which is within the scope of IEC 63092-2. This document is based on EN 50583-1 [11]. The basic requirements for construction works are:

- Mechanical resistance and stability
- Safety in the case of fire
- Hygiene, health and the environment
- Safety and accessibility in use
- Protection against noise
- Energy economy and heat retention
- Sustainable use of natural resources

As already mentioned, the BIPV module is a prerequisite for the integrity of the building's functionality. If the integrated PV module is dismounted (in the case of structurally bonded modules, dismounting includes the adjacent construction product), the PV module would have to be replaced by an appropriate construction product. Inherent electro-technical properties of PV alone do not qualify PV modules as to be building-integrated.

Referring to the above-mentioned references, a definition of a BIPV module is exposed [12]:

A BIPV module is a PV module and a construction product together, designed to be a component of the building. A BIPV product is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system that retains building-related functionality. If the BIPV product is dismounted, it would have to be replaced by an appropriate construction product.

A BIPV system is a photovoltaic system in which the PV modules satisfy the definition above for BIPV products. It includes the electrical components needed to connect the PV modules to external AC or DC circuits and the mechanical mounting systems needed to integrate the BIPV products into the building.

amended building bye-laws have been passed by the Ministry of Urban Development (MoUD) and the introduction of concepts of "Smart City" [2] and "Solar City" [3] has been made by the government, yet the developments focussed only on RTS installations in buildings. However, exclusive BIPV policies connecting comprehensive decentralised distributed renewable energy, building energy conservation, individual building and city infrastructural planning, BIPV analysis, extended energy policies like for electric vehicles (EVs), etc., are essential. Regulations should also support solar investment within a community or nearby locales for BIPV specific building projects leading to the creation of green energy communities.

Regulations for stakeholder harmonization in solar and construction sectors

A balanced environment between the stakeholders is essential in the coming decades of solar avalanche, especially for solar power acquirement from buildings. With the better performance of the country in solar energy sector, India may need to shift the policies and regulations to favour both building owners and Distribution Companies (DISCOMs). Even though the current scenario with the RTS programme of JNNSM Phase II favours building owners, especially of the residential sector, by CFA allowance and increased cap of net-metering limits, there is a need to accommodate DISCOMs in the future. The charges compensated/ paid under the RTS scheme, which follows net-metering, aroused a considerable revenue impact for the DISCOMs. However, shifting from net-metering to gross-metering with a passable feed-in-tariff can be foreseen as an obstruction to the extensivity of the existing building rooftop model, especially in small scale and residential sector, as it increases the system payback period. The PV scenario in Europe supports the same, as they have encountered a market declination after the introduction of feed-in-tariff. However, this represented a great opportunity for the growth of the BIPV sector with the concepts of multifunctional, aesthetic, innovative products with new technologies and cost reduction potentials from both renewable energy and building (construction and architectural point) of view. Thus, state and central regulations should be revisited and modified regularly (with the PPA) in the future to create a balanced environment.
Considering these factors, BIPV could centre on the aspect of building elemental replacement and multi-functionalities, to create an impact on the building renewable energy and construction market in the near future. Further, with the end of the current phase of JNNSM by 2022, the extensivity of building solar programmes should be ramped up from RTS to more innovative schemes for BIPV/ BAPV interventions. However, rather than focusing completely on energy regulations and government financial assistance, new business models could be evolved that caters for the financial concerns of both the building owners for large scale deployments and the DISCOMs. Utility-driven models can be adopted as one of the trade-off approaches for the concerns. Central and state governments could implement different adoptable business model-based regulations, financial relaxations and policies within communities, or locations, or states for BIPV. These location-based implementation strategies could be adopted with proper consumer evaluation, technical assessment, and feasibility studies.

Business model revision for BIPV [4] [5]

The following factors majorly hinder the implementation and expansion of existing business models for BIPV in India

1. Existing net metering billing system can lead to substantial financial concerns for DISCOMs
2. Lack of technological and financial awareness among the building owners and project developers leading to scepticism among the owners regarding the implementation and financial benefits
3. Inability of consumers to invest upfront costs for the BIPV system
4. Uneven implementation feasibility (due to factors like shading, building typology, building orientation, etc.) among a community/locale can lead to a lack of enthusiasm within building owners

Some of the proposed business models for the cause are below:

- On-billing financial model: The model is useful when the individual building owner cannot make the investment upfront. Herein, a third party or DISCOM lends the money as a loan and own the system up to the loan repayment. Monthly instalments make the loan repayment to the DISCOM along with the net electricity billing (or signing PPA with DISCOM), and consumers can receive benefits of reduced grid electricity consumption (or monetary benefits of selling electricity to the grid). After the loan repayment, ownership is transferred to the building owner. Unlike normal rooftop installation, the model is very convenient from the consumer point of view, as there is a great necessity to own the BIPV system as part of the building, but cannot afford the investment cost initially.
- Solar partner model: The model is well suited for building spaces like that of multiple villas where individuals have access to the space. The model is driven by DISCOMs, which aggregates both the supply and demand sides. DISCOM aggregates the building skin owners in its locale and identifies developers for the installation through competitive bidding. Developers conduct the feasibility studies, project installation and own the system. Rooftop/facade owners are benefited either from monthly rent for their building space or a credit on their electricity bill with metering and solar subscription. DISCOM signs PPA with the developers for the period of the system's lifetime
- Utility driven community model: Utility driven community model is one of the straightforward approaches that can enable faster implementation of BIPV in a community, where DISCOM will lead the project and aggregate the consumers. Herein, consumers who do not own a BIPV feasible building space can also access solar electricity by sharing space of a common building like high rise multi-unit buildings or from a public or privately owned building spaces elsewhere. It also allows sharing the most favourable building surfaces with higher solar potential independently by single owners and local public/ private ownerships. The consumer can access the electricity by paying the system installation cost upfront or by paying a regular subscription fee. The model will be very advantageous for tenants living in a multi-storey building, and also suits for solar electricity distribution from a public/private owned institution. The model eliminates the ambiguity for the consumers, as they don't need to be involved in the BIPV project directly or create a long term agreement with DISCOM, but need to have only a one-stop contact with the DISCOMs directly.

(2) Opportunities: Practical tips for cost reduction

Multifunctionality as key for faster BIPV penetration

The multifunctionality of BIPV products could bring some advantages if compared with conventional building envelope solutions and non-integrated PV systems together, especially in terms of better aesthetic integration, cost-effectiveness, technological performance, environmental and social impact, etc. [6]. In recent years, all these advantages have aroused a growing worldwide interest in BIPV products and dynamic market trend for the replacement of less offering conventional building materials/ construction **(Fig. 3.1)**. However, one of the main challenges and needs of the market is to improve the energy performance of the facade to produce renewable electricity or solar thermal energy. Numerous studies and projects demonstrate that PV is the most straightforward technology to integrate into façades, suitable for meeting the net goal of zero energy buildings. While incorporated into the building envelope, photovoltaic solar cells can reduce their energy performance levels not only due to suboptimal working conditions (such as higher temperatures) but also suboptimal orientations (mainly due to building design and surfaces

Fig. 3.1 A multifunctional BIPV building in Pregassona, in addition to the home for the elderly, this multifunctional centre in Pregassona houses a kindergarten. Photo credits: Chiara Zocchetti – CdT.

available) and also to aesthetic needs. As demonstrated in several studies [7], the treatments of the front glass to hide the photovoltaic solar cells, providing the colours to the BIPV module, can lead to relative efficiency losses from 10% up to 60%. However, this trend defined as "camouflaged" and "customised" PV with the aim of combining high solar energy production with a appealing aesthetic of its visual design (Fig. 3.2). This is based on the use of glass as a key material, not in its standard form of transparent and this dematerialised skin is the result of the joint efforts between the glass and the PV industry. Where, no technical limit seems to be conditioning for the revolutionary design flexibility of the glass on which disparate customisation techniques are applicable, even including intermediate sheets and photovoltaic cells [8].

As implemented in different Swiss and European cases, various designs can be achieved by treating the outer surface of the glass (e.g., by sandblasting) which, in turn, can be combined with a colour of the glass to conceal the solar cells behind it. A design or colour on the front glass can be achieved with a screen-printing process that deposits a special ink on the surface of the glass, such as ceramic-based digital printing or, alternatively, by stabilising the colour at high temperature with monochromatic or multi-chromatic scales used to obtain high-resolution images or prints. By combining the satin finish on the outer surface of the glass with screen printing on the inner side, a resulting coloured matte surface can make the glass opaque and active. Nanotechnology-based solutions have been developed for selective filters that can be added as internal sheets to reflect and diffuse the visible spectrum, thus providing a colourful appearance without much losses in the PV efficiency. All these techniques are in progressive development to find the best compromise between visual effect and efficiency of photovoltaic production, and represent a dynamic branch of the "active glass" industry as the current frontier of BIPV for the next few years. This innovative trend aims to facilitate the transition to active buildings while providing infinite possibilities for aesthetic variation and for rethinking the concept of building skin [9].

Innovative approaches like Rooftop Agrivoltaics

With the continual trend in urbanisation across the globe, the possibilities of farming have been very much reduced to building rooftops in urban areas. Thus, any technology interventions that endow building skin potential for both energy generation and food production will have huge business potential and a breakthrough for faster PV adoption. Further, considering the difficulties of water resource management and temperature control in urban rooftop farming under tropical climatic conditions, the integration of rooftop PV systems with agriculture practices can be a promising BIPV approach. Rooftop Agrivoltaics (RAV) can replace conventional metal/polymer/ceramic external roofing systems for building protection or for reducing cooling load, it also supports agricultural/gardening practises in open building spaces. The solution will be multidimensional, offering synergetic subsidy benefits of PV integration and rooftop farming, as supported by various state governments of India. Hence, RAV technology makes an attractive business model for faster BIPV penetration in India, as it benefits the building owner with solar energy, farming space and also eliminates the "Heat Island Effect (HIE). However, the technical maturation of RAV systems is very limited with the installation of intermittent solar PV installation. To develop as a BIPV roofing solution, technical innovation-related improvements, especially in solar light

Fig. 3.2 Office for Environment and Energy (AUE), Basel. Source: solarchitecture.ch.

management, have a maximal potential impact than market maturation improvements, both on the end-user cost and on competitiveness. (Fig. 3.3).

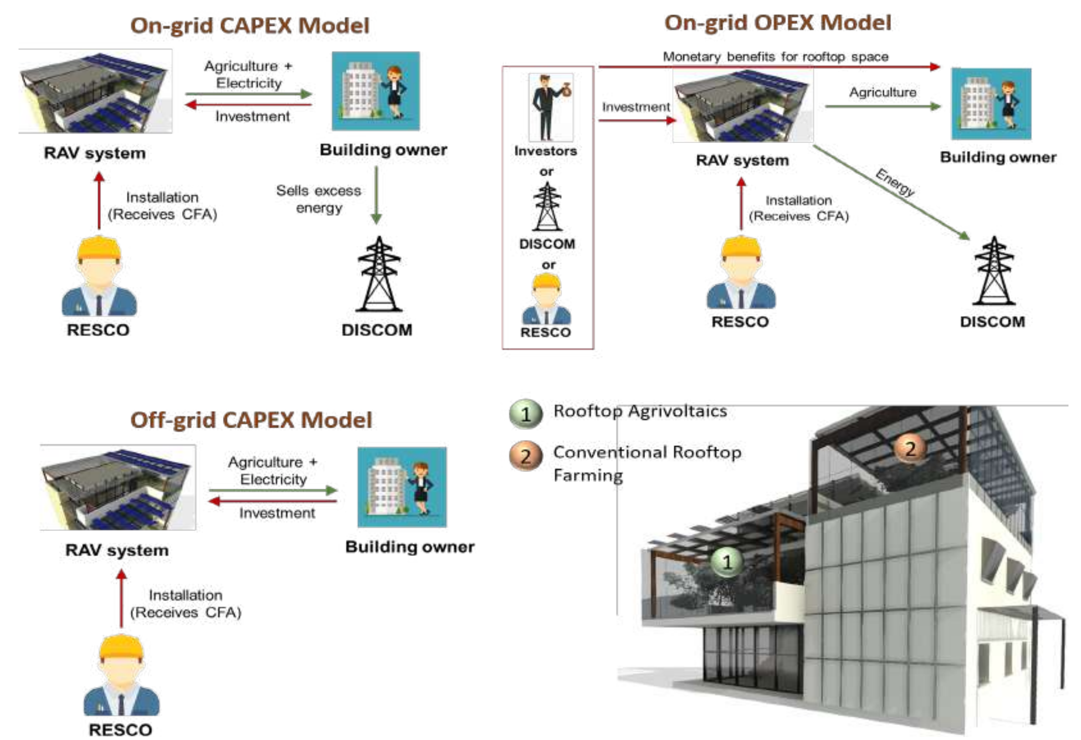
Prefabricated (Prefab) building construction and modularity

Prefabricated and modular active solar building envelopes are one of the key-strategies for reducing costs in the construction industry, thanks to product and process optimisation against the conventional building approaches. Also, in the BIPV sector, they're proposed as one of the cost reduction strategies, such as the one adopted by BIPVBOOST (www.bipvboost.eu), to accelerate the global uptake of BIPV. Majorly, the current Indian construction sector relies on the conventional construction method of "brick and cement". The reason is the less popularity of Prefab, and modular building construction solutions, though many solution providers are available with customised offerings. It basically involves manufacturing the building structural elements and envelope modules in an off-site manufacturing plant. The method is considered a more convenient and sustainable way of building construction and more advantaged with reduced material wastage, fast on-site assembly and dismantling, and compatible reuse. Apart from that, it has considerable cost reduction potential for the consumers, by reducing the labour cost, transportation cost, etc., with additional benefits of reduced construction time and higher quality, thanks to off-site integrated operations. A lower dependency on weather conditions, which can cause delays, is a benefit that can also be mentioned. Integrating BIPV installation with prefab construction can eliminate the need for other building elements like wooden panels, glasses, etc., further reducing the investment. Further, the installation of BIPV modules will become easier, compared to other conventional building construction methods. With the evolution of BIPV products in the future, which can fulfil and replace conventional building elements in every aspect, prefab construction may be more oriented towards it, with more convenient fastening and assembly of BIPV elements.

Lightweight and easy mounting systems

The most adopted PV technology among BIPV products is crystalline silicon based, representing a 90% and 44% market share for roof and facade applications, respectively. In the BIPV sector, they're typically realised

Fig. 3.3 The scheme describes potential business models for rooftop agrivoltaics (1) and its opportunities when compared with conventional rooftop farming (2) solution. Source SUPSI, NIIST.



in glazed panes such as laminated glasses [10]. However, in the recent years, thin-film based PV technologies have been developed to ensure flexibility, bendability and lightness in BIPV products. These technological alternatives consist of a PV active layer (CIS, CIGS, etc.) encapsulated in glass, metal or polymers. Thin-film based BIPV components have been demonstrated to be versatile and adaptable to different building applications in order to satisfy both the aesthetic and technological requirements. In many cases, the system results in a lightweight BIPV module on which the lower transportation, installation and labour cost can be further the key drivers for the cost reduction and the attractiveness on the market. For example, a typical product consists of a CIGS module on metal, which best suits industrial rooftop buildings and large surfaces. The use of easy mounting structures represents a cost reduction strategy to lower installation time related to assembly and the installation on site. Even though the above-mentioned solutions represent a clear strategy to directly reduce the costs of BIPV installations, their availability on the market is still a question, since only a few manufacturers offers market ready solutions.

(3) BIPV Industrial Sphere: Technology readiness, Supply chain and Certification

Enabling faster Technology Readiness among research and industry

To facilitate a faster route for the BIPV (or) BAPV innovations to market, country need to build the right ecosystem for R&D that will expedite the timeline for prototyping, benchmarking, and commercialisation. On the one hand, it is important to financially support science-based innovation projects conducted by industrial partners and private and public institutions jointly, with research partners in all subject areas to develop new types of products, services or processes together. This is crucial, not only for innovative product development but also for product modifications and corrections. On the other hand, it also helps to promote the development and testing of new technologies, solutions and concepts relating to the economic and ecological use of energy. Pilot scale demonstration programs act as a key interface between research and the market to improve the status of the development of new technologies so that they can ultimately be brought into the market. In this context, demonstration activities in BIPV are an important part of research for enabling its market exposure. For example, SUPSI activity across many years through BIPV national and international projects, translated it in the form of an applied research approach focusing on the BIPV product validation between indoor testing (Technology Readiness level - TRL 5), small-scale outdoor mock-ups (TRL 6) and demonstration in a real building environment (TRL 7/8). Hence for India, real-scale and modular testbeds are also necessary for innovative product development. They can act as a Research and Industrialisation hub housing R&D turnkey lines for BIPV module innovation, prototyping facilities for new product development, testing and certification facilities. To facilitate a faster route for the technology innovation to market, this concept of research and innovation testbed can be implemented at varies locations of the country with international exchanges and operate in synergy with market stakeholders.

Product customisation and supply chain management

Rather than a renewable energy technology, BIPV has been predominantly promoted worldwide as building materials in the last decade, because of its multifunctional categorisation [6]. With the contemporary building architectural and aesthetic inclinations, elemental building designs (size, shape, structure and external envelope designs) have been unrestricted with new construction technologies, innovative building products, and implied with local building codes and regulations. The perspective has extensively demanded building materials to add functional values, aesthetic appeal with customisation opportunities, especially for facade application. Hence, customisable BIPV module production, with the aspect of size, shape, texture, colour and functional properties, is a need of the hour. The manufacturing facilities could cater for these requisites, especially at the early stage of BIPV evolution.

The extent of the local supply chain strongly determines these customisations, product quality and reliability. Within the function of visible light transmission, selective light reflection, textural appearance, the importance of laminating glass and laminating polymer layer can be accounted to overall BIPV building aesthetics and functionalities. The connecting glass sector market can include solar clear glass, coloured glass, anti-reflective glass, insulated glass units, active shadings and blinds, textural and printed glass, etc. Considering the Indian context, the material supplying companies are scattered and lacks awareness regarding BIPV market possibilities. Creating awareness among these stakeholders and enabling a common material data information repository can deal the problem much effectively.

Designing and engineering BIPV products and their manufacturing is also crucial for the product performance, aesthetics, and final cost. For example, efficiently utilisable design considerations can be implied with textural/ coloured glass, where intermitted spaces can be used for PV integration, enhancing the aesthetics and reducing the material cost. Frameless glass-to-glass solar panels as rooftop shingles and canopy are comparatively the latest strike in the Indian BIPV market. Apart from that, BIPV product innovation can also be achieved with non-silicon photovoltaic technologies like thin-film solar cells (CIGS, GaAs, CdTe), coloured solar cells, organic solar cells, dye-sensitised solar cells (DSSC), that have varied optical transmission, colour, and flexibility. The technological and economic competitiveness are yet to be attained with these types of PV materials, when compared to silicon PV.

Need for exclusive standards and comprehensive ratings

Integrating PV in building skin today requires an accurate performance assessment in accordance with construction norms and PV standards, depending on the type of use and functions. The topic of BIPV as a multi-functional product, more than many other construction products placed on the market, deals with harmonising performance information by finding the right approaches considering its dual function as an energy and construction component, and the growing customisation of technologies. The current complexity of the normative assets, as it is today, is still considered a practical barrier for market implementation, and innovators often struggle between interpretation and experience. However, new testing approaches ensuring product quality, cost reduction and more substantial penetration of BIPV in the market are under investigation and development in current projects. With the expansion, up-gradation and development of PV technologies, there is a bigger concern of product performance and reliability. With the introduction of BIPV, development and regular amendments of individual product standards/testing with the application is getting crucial. Also, their testing and certification should be conducted in time for the industries and be standardised with reliability for the consumers. Thus, a proper standardisation, testing and certification of BIPV products helps in the regulation of costs, thereby increasing the market. In India, the National Institute of Solar Energy (NISE) has been the apex institute for the testing and certification of PV devices and components (NISE, together with the National Institute of Wind Energy (NIWE) and the National Institute of Bio-Energy (NIBE) acts as the primary test labs for the whole renewable energy sector). In addition to that, three testing labs in R&D organisations, supported by MNRE and two private-sector labs (UL India Pvt. Ltd., and TUV Rheinland), are involved in testing and certification of solar PV programmes in India (according to MNRE data (2017) published in website). With the demand of testing centres, MNRE is trying to expand their reach to the Council of Scientific and Industrial Research (CSIRs), Indian Institutes of Technology (IITs) and National Institutes of Technology (NITs) for their assistance. All the test labs should have a National Accreditation Board for Testing and Calibration Laboratories (NABL) accreditation and be approved by the Bureau of Indian Standards (BIS). These centres will act as secondary labs, for result comparison and calibration practises for quality assurance. In India, manufacturers and solar modules approved by BIS and MNRE, and are published in the Approved List of Modules and Manufacturers (ALMM) will be eligible for the government's solar schemes. The detailed guidelines for certification and Indian Standards for the modules and components have been published by MNRE [11]. For testing a new product, the sub-SQCC initially checks the applicability of existing standards. A new procedure will be developed based on the requirements and product properties. Testing will be conducted in three different labs with the same procedures, and the results will be validated with errors and uncertainties. The method will be reviewed with the consultation of other test labs and finally decided by MNRE. The Standards, Test and Quality Control Committee (STQCC) is organised with Secretary, MNRE as Chairman, subject experts including from NABL and BIS as members, and adviser as Member Secretary to oversee and coordinate the standardisation and testing of the renewable energy system, components, and devices. Sub-SQTCC are formed in each of the three primary labs with experts from R&D/ academic institutes and industries to develop and update standards and testing protocols for the respective product area.

With the expecting and upcoming phase of BIPV, and the possibility of utilisation and flexibility of it in building elemental replacement, will create huge stress on the area of standardisation, testing policies and protocols of the products, components and systems, especially for the vast Indian geography and market. Since additional testing and standardisation of different product performances are required for BIPV systems, a vigorous involvement of experts from different fields, including architects, subject experts from R&D institutes, experts from building construction, and members from solar industries, are required in prior for the development. More BIPV exclusive testing centres could be formed across India in different zones, and a specific pattern of testing protocols could be considered according to the different regional climatic conditions. In the H2020 BIPVBOOST project (www.bipvboost.eu - European Union's Horizon 2020 reasearch and innovation programme under grant agreement No 817991), a first effort for developing new BIPV test procedures has been made as reference for the BIPV community with the goal of supporting the sector overcoming the current missing gap among construction and PV performance assessment and also addressing the cost reduction targets [12], [13]. Hence, as a recommendation, a comprehensive and easily understandable BIPV rating system could also be considered for the better penetration of BIPV products in the Indian market. The rating system could be standardised with controls and exclusive testing protocols for each of the property evaluations, which could be classified for mandatory and non-mandatory tests based on the application.

(4) Innovation landscape

Research Projects

In India, the R&D for BIPV specific technology and products development is at a nascent stage. However, fundamental research of interdisciplinary nature is being carried out by both academic and research institutes leading to high-quality publications, facilities and patents required for the BIPV technology development and deployment. On the basic R&D front, the efforts majorly concern newer topics for energy generation and efficiency, such as functional materials for energy-efficient devices, , sensitisers, photo/thermo/electrochromic materials, third-generation PV technologies etc. One risk of basic research is not to have immediate commercial objectives or that it may not necessarily result in a solution to a practical problem in the form of products, procedures or services which are ready for the market. Apart from fundamental research of interdisciplinary nature, technology-based interventions have been greatly carried out in the last decade, especially in the field of solar energy. This includes innovative solar energy management technologies like planar light concentrators, dynamic power windows, organic and inorganic hybrid solar cells, rooftop agrivoltaics etc., which can be mentioned as a few in the BIPV headway. In this framework, the applied research methodology is a complementary discipline to solve specific, practical problems bridging scientific aspects with the industrial, market and stakeholder's needs and challenges. India needs to develop expertise in manufacturing production equipment for PV/BIPV technologies since the country had been depending on technologies elsewhere and was importing them at a high cost. With the indigenisation of technology, it is possible to achieve a very impacting cost reduction compared to the existing ones in the international market, which could help with large scale deployment for various BIPV sectors in the near future.

A key point will be the interdisciplinary and quality of the research projects, together with the territorial and academic networks' efficacy in both quantitative and qualitative terms. Along with a wide research portfolio, ranges from sensitisation and education, to technological developments with industrial partners, including testing and validation in real scenarios, Pilot & Demonstration projects in collaboration with industries, architecture/engineering offices, installers and other authorities and real players will have to be one main focus. This will bring down the over cost of multifunctional BIPV systems, limiting the over cost concerning traditional, non-PV, construction solutions and non-integrated PV modules, towards the mass realisation of nearly Zero Energy Buildings. The strong complementarity and synergy between the levels of maturity of technologies, which are ranging from TRL1 to 4 (technology Laboratory Validated) for fundamental research and between TRL5 and 7/8 (System prototype demonstration in operational environment/System complete and qualified) for applied research will be a key-point. This opens for potential joint programs in planning, managing, and assessing a successful technology transition for the Indian research sector through a core set of activities that can support pushing towards the mature products with a greater degree of readiness, including systems re-engineering that are tailored to the BIPV technology development for the Indian market and local goals.

Engagement of international communities

BIPV has achieved a high level of technology maturity globally, especially in Europe with multiple live demonstration projects. Engagement of PV industries and constructions sectors has taken the EU BIPV sector towards higher Commercial Readiness Levels (CRL). Currently, realising the involvement of multiple stakeholders, the BIPV Capacity Building programme is structured through the involvement of R&D institutions and industries to bridge the knowledge gap within the PV and construction sector stakeholders, thereby meeting UN SDG's 4, 9 and 11. With its wide demography, a country like India can consider developing BIPV specific capacity building programme jointly with international partners, which will, in turn, accelerate the CRL of the BIPV industry in the country by generating the know-how about the state-of-the-art in the BIPV industry. Hence, it is of utmost importance to formulate a dynamic, evidence-informed and proactive international S&T engagement strategy for India's BIPV sector to keep pace with the global benchmarks. Under the aegis of the Ministry of Science and Technology, GoI; DST has come up with a draft Science, Technology, and Innovation Policy (STIP) that supports international engagement to address global challenges, thereby supporting UN SDG's. The draft STIP has multiple objectives, such as *"addressing some fundamental issues in science by participating in international collaborative research, establishing scientific facilities of international standard in India, developing cutting edge technologies, training of researchers, engineers and industry professionals, design and delivery of major precision equipment for these and utilising spin-off technologies emanating from them towards societal benefits*" [14]. Thus, it is expected that the new STIP policies will ensure cohesive and transparent evaluation of all kinds of research and innovation, with global partners. This will enable the Indian BIPV sector to develop a standardised research and innovation excellence framework in collaboration with international communities. Further, the engagement of the Indian BIPV sector with global industries, R&D institutes, and academia will enable global R&D progress indicators, know-how for state-of-the-art technologies and products, patents, and other critical knowledge required for faster diffusion of BIPV. Further, such frameworks will also act as a fertile innovation landscape for BIPV specific innovation and indigenous product development in the country.

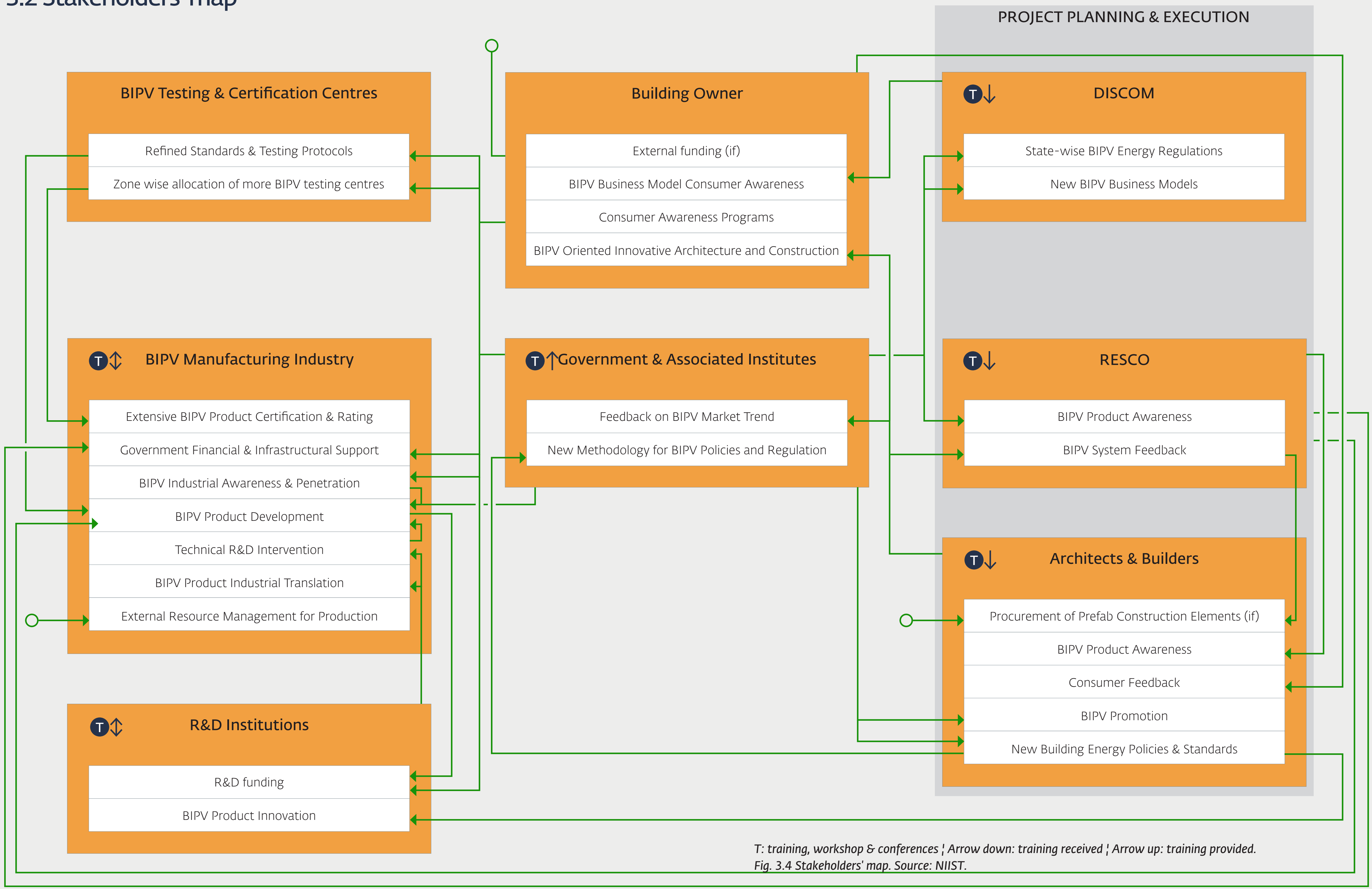
(5) Defining stakeholder involvement: Need for stakeholder awareness, extensive project planning & execution

As per the discussion in the previous sections, the stakeholder involvement mapping (as shown in the **Fig. 3.4**) is essential for the evolution of the BIPV sector in India. Considering the project implementation of Rooftop Solar installation in India, the stakeholder involvement is majorly limited to the DISCOM and RESCOs for the project development phase. The involvement of architects and builders are almost zero in this regard, as less project design or solar architecture is involved in this. However, for BIPV installations, the synergetic involvement and collaboration of architectures, builders, DISCOMs, and RESCO is necessary at different project execution levels. Herein, some of the foreseen project implementation concerns and directions to defy them are described.

For easy BIPV sector expansion as augmented marketing technology, the product, system implementation, technical, and technological awareness growth could always be prerequisites for the consumers. Unlike normal PV systems, these multiple layers of awareness should always follow the proper channels, making it a complicated framework to develop. Products, system and economic knowledge is always a primary concern for every stakeholder in project implementation, including the consumer, architects, builders, RESCO and DISCOM. Certified BIPV products of different companies could be conveniently enlisted and exhibited in a decentralised common platform for better product knowledge and technical awareness.

At the time of project initiation, architects, being the centre of planning, could collaborate with RESCO for developing innovative building plans with BIPV integration possibilities. Unlike normal rooftop PV systems, better knowledge of solar architecture for RESCO could be acquired with proper training. Architects could be oriented with Building Information Modelling software which are BIPV product oriented can be very helpful for parametrising and optimising building design features. For example, computational models for different building typology, exhibiting all the visual and functional aspects of BIPV elements, can attract the consumers better and shows better execution plans. Government regulations and financial relaxations could be published by DISCOM for the awareness of architects and consumers thereby realising more renewable energy integrated building plans. A detailed proposal with the energy capacity, proposed yearly energy generation, building codes, energy conservation features, etc., could be submitted to the DISCOM for evaluation and approval for financial relaxations, if any. Any other building investment allocation approval from the government, if any, could be submitted separate by the consumer. At the time of commencement, the involvement of builders with structural engineering and RESCO is extremely important for a BIPV specific building design. For a prefab building, the structural parts are designed and acquired from the prefab companies, according to the BIPV module specifications. Strong interaction of architects, builders and prefab companies are thus required even from the early stage of deployment. Innovative structural design, assembly design and methods, tend to build on the BIPV outlook. Lack of interaction and knowledge sharing between RESCO, and the building industry tend to fade the project standards and timely execution. Easiness and timely planning and execution can be regarded as one of the indicants of better market penetration and business model evaluation of BIPV. Rigorous and coordinated training is necessary for stakeholders directly involved in the project planning and execution. Government, SNAs, R&D Institutes, BIPV manufacturing companies could conduct stakeholder-oriented workshops, conferences and training programmes, for better understanding of the technical and non-technical aspects of BIPV sector. Training on systematic design tools and geographic data acquirement could be provided for RESCO and architects from R&D and other Government institutes. BIPV manufacturing companies could conduct regular marketing programmes with absolute technical and economic evaluation, followed by building economic evaluation of BIPV from architects and builders. Regular interaction and market feedback from consumers, architects, and RESCO

3.2 Stakeholders' map



T: training, workshop & conferences ¦ Arrow down: training received ¦ Arrow up: training provided.
Fig. 3.4 Stakeholders' map. Source: NIIST.

Strength

High Solar attractiveness: According to EY May 2021 report, the Renewable Energy Country Attractiveness Index (RECAI) ranking of India has raised from fourth to third rank globally, in the renewable energy investment and deployment opportunities, and scored first in the Solar PV category [15].

Lower Levelized Cost of Electricity (LCOE): With the increasing exploitation of the vast solar potential and lower benchmark cost of Rooftop Solar (RTS) systems, India has the least LCOE for RTS systems across the globe. Compared to countries like the USA (238 $/MWh) and Spain, the lowest in Europe (90 $/MWh), the LCOE is very low in India (66$/MWh) [16]. The trend is expected to favour the BIPV sector in India too.

Consumers attractiveness with net metering regulations: As per MNRE OM dated 2021, GoI has extended the limit of net metering RTS installations from 10kW to 500kW. Also, many individual states have been promoting PV building integration with state regulations and policies with DISCOMs for residential, commercial, institutional and industrial sectors, widely influencing the consumers [17].

GoI's initiative to promote Indian solar industry: Currently, India has a domestic module manufacturing capacity of 15 GW/year and a cell manufacturing capacity of 3 GW/year [18] and heavily depends on countries like China, Taiwan, etc. for solar equipment, components and sub-systems. To enhance the growth of solar industry in India, there is a considerable need to develop solar associated products and elements domestically. With the GoI's Atma Nirbhar Bharat strategy, the Department for Promotion of Industry and Internal Trade (DPIIT) produced an order to give preference to local suppliers for purchases. MNRE also imparted an order to promote Class-I local suppliers (local content <50%) for products having sufficient local capacity and competition. Other schemes like special incentive package scheme (M-SIPS), Production Linked Incentive (PLI) Scheme and policies like discontinuation of customs duty concession and imposing duty on imported PV modules and cell are some measures taken by GoI for the cause.

Opportunities

Growth of Indian building construction sector: As mentioned, the Indian construction sector is expected to grow with an impressive trend, with a projection of ~45 billion square metres in floor area additions by 2060.

Era of electrification in transport sector: The GoI aims to penetrate the transportation sector by electric vehicles for 30% of private cars, 70% for commercial vehicles and 80% for two- and three-wheelers by 2030. Even though this can constitute around 2% of national electricity demand, the distribution and charging of Electric Vehicles (EVs) are expected to contribute more from building energy than public distribution systems [19].

Building energy demand rise: By 2050, the building energy demand is expected to rise 10 times from that of 2020, with stable GDP growth, baseline cooling, and home EV charging [20].

Prefabricated and cost-effective construction: As discussed in this chapter, BIPV implementation can have a strong economic impact and implementation potential when allied with prefab modular construction.

BIPV as a disruptive technology: BIPV's selling point is always marked as a multifunctional renewable energy technology that can replace conventional building elements. However, sector maturation is not yet achieved in the Indian context. With product and construction standardisation, and better economic awareness and feasibility, BIPV technology can have a rapid disruptive growth in the building construction sector in the coming decades.

Weakness

BIPV Product certification: As it is an emerging technology in the country, the product standards and building codes have not yet been established for BIPV systems. Apart from basic energy certifications, the requirement of explicit functional, safety and performance standards are necessary.

GoI subsidy limitation across states: As the Indian building solar sector is concentrated on rooftop solar systems, the regulations are specified and followed under this category. Thus, for BIPV system, the lower capping of subsidy limits (as for residential buildings, it is 10kW; subsidies are not allowed for other sectors) will hinder the growth of the BIPV sector with the current business plans.

Extensive administrative procedures: Majorly centred with DISCOM, the need for standardisation and simplification of installation procedures is required to implement fast processing and implementation, and also to decrease the administrative burden on DISCOMs. Recently, regulations have been announced to conduct vendor selection and submission of the application directly from consumers for RTS installations. However, for proper conduction of this, reduced number of interactions, complex paperwork and process duration, along with consumer awareness on procedures and techno-economics, are requisite.

Lack of manufacturing industries & awareness: On May 2020, India had a module manufacturing capacity of only 10 GW, which hampers the growth of innovative solar technologies and solar energy growth of India [18]. The existing stakeholder community has less awareness and knowledge of BIPV products/ BIPV building constructions. Regarding project planning and execution of BIPV projects, multiple stakeholders, their awareness, effective interaction and collaboration is necessary. The involvement of architects and builders are meagre with the current rooftop solar business models.

Unevenness of solar policies and regulations in India: State-wise policies and regulations are uneven in India, which effects the reach and growth of RESCOs in a zone.

BIPV demonstrations in India: Not many BIPV demonstrations with benchmarking, energy and performance evaluation has been carried out in India, which can upshot less confidence within stakeholder community & investors.

Threats

Regulation imbalance: For the expansion of the BIPV sector in India, there is a greater need for a balanced obligation in regulations and business plans between consumers and DISCOMs. The mostly adopted CAPEX-net metering solar building business plan will create more financial plight for the DISCOMs on the long course.

Possibility of pseudo and inferior BIPV products/installations: India is yet to have the verge of expansion in the BIPV sector. Further, the regulations, standardisation and certification of BIPV products and deployment are indeed lacking. If a sudden market urge evolves in the coming years, there will be a significant threat of sub-standard and pseudo BIPV products penetration in the market.

Lack of coordination and awareness leading to uninspired project demonstrations: As mentioned, BIPV project planning requires rigorous coordination and execution from architects, builders, RESCO and DISCOM. Lack of BIPV products and building design awareness can cause insignificant models in the market.

Elevating import duty: India is a country that majorly depends on imported raw materials, from solar cells to modules. India is planning to set basic customs duty of 40% on solar modules and 25% on solar cells from April 1, 2022. Even though it promotes local manufacturing of solar modules for utility farms and rooftop installations, it may contradictorily affect the not yet evolved BIPV sector by hampering its growth or elevating the price.

Operation and maintenance: Operation and maintenance of BIPV installed buildings can also be a major concern in the future, as it is prevailing now with the poor air quality in India [21].

Application categories

As mentioned in the previous paragraphs, the draft of the standard IEC 63092 [10] classified the BIPV applications into five main categories listed as "Application Categories" **(Tab. 2.1)**. It is applicable to different types of BIPV modules, and it is a classification according to the type of integration, slope and accessibility criteria, in particular:

- Integrated into the building envelope: yes/no
- Accessible from within the building: yes/no
- Sloped: yes/no

"Not accessible from within the building" means that another construction product still provides protection against mechanical impact within the building, even if the PV module has been damaged or removed. These categories are developed considering glass as a main substrate and material of the BIPV module retaining most of the mechanical properties.

System Categories

The classes of building skin systems can be identified as specialised construction units, and the categorisation is based on the main technological systems available for building envelopes. In conventional constructions, the definition of the main building skin construction systems can be grouped in:

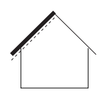
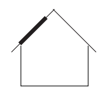
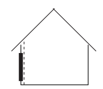
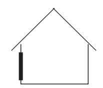
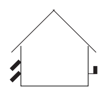
- *Roof*: A roof, in a traditional building construction with a top distinguishable by the facade, is the top covering providing protection and separating indoor and outdoor environments (application categories A and B).
- *Façade*: A façade, in a traditional building construction with parietal walls distinguishable by the roof, is the vertical (or tilted) exterior surface, which is the architectural showcase and separates indoor and outdoor environments. (Application categories C and D).
- *External integrated device*: Elements and systems of the building skin which are in contact only with the outdoor environment (application category E).

These groups can be categorised in sub-systems as shown in the following figures **Fig. 2.2** [9].

A specific definition of the sub-systems based on the IEA PVPS T15 [9] is presented below:

- *Discontinuous roof*: A "discontinuous roof" is typically a pitched/sloped opaque envelope part consisting of small elements (tiles, slates, shingles, etc.) with the primary function of water drainage. It is the part of the building envelope, where the PV transfer had its first successes due to the advantages of optimal orientation of pitches and the simplicity of installation. BIPV is typically part of the discrete elements composing the roof tiling, which form part of the roofing layer.
- *Continuous roof*: A "continuous roof", a flat or curved roof, is characterised by a large uninterrupted layer with the primary function of being water-resistant. Usually, membranes are used as a water barrier. In the first applications in time, the PV was mainly placed on top of the roof (BAPV). Lightweight and self-bearing systems represent the second generation of PV applications (BIPV). Flexible membranes, solar flooring and other solutions can be used for integrating PV as a multifunctional part of the building envelope.
- *Skylight*: These are light-transmitting building elements that cover all or a part of the roof. They are typically (semi)transparent for daylighting purposes, with additional thermal, acoustic and/or waterproofing functions when protecting an indoor environment. Alternatively, they serve mainly as a shelter if protecting outdoor (non-heated) areas (atriums). They can be fixed or openable, and retractable. PV is typically part of the glazed layer, applying both crystalline or thin-film PV technologies, and with various possibilities for transparency degrees and visual appearance.
- *Curtain wall*: It is an external and continuous building skin fenestration system, totally or partially glazed, composed of panels supported by a substructure in which the outer components are non-structural. A curtain wall refers to its construction, since façade is hanging (just as a curtain) from the top perimeter of the building and is locally fixed to resist air and water infiltration, and is typically designed with extruded aluminium frames (but also steel, wood, etc.) filled with glass panes. The façade should satisfy multiple requirements, such as a load-bearing function, acoustic and thermal insulation, light transmission, waterproofing, etc. E.g., in the configuration of "warm façade" it directly divides, as a skin layer, outdoor and indoor environments. It can be realised according to different construction systems such as stick-system, unitised curtain wall, Structural Sealant Glazing (SSG), point-fixed or suspended façade. In their most basic form, they are windows, while in more complicated forms, they can be used to realise complex skin façades. PV is typically part of the outer cladding layer, in the form of glass-glass elements, with crystalline or thin-film technologies and various transparency

Tab. 2.1 List of Application Categories. Source: IEA.

Category A:	Sloping, roof-integrated, not accessible from within the building The BIPV modules are installed at a tilt angle between 0° and 75° from the horizontal plane [0°, 75°], with another building product installed underneath	
Category B:	Sloping, roof-integrated, accessible from within the building The BIPV modules are installed at a til angle between 0° and 75° from the horizontal plane [0°, 75°]	
Category C:	Non-sloping (vertically) envelope-integrated, not accessible from within the building The BIPV modules are installed at a tilt angle between 75° and 90° from the horizontal plane [75°, 90°], with another building product installed behind.	
Category D:	Non-sloping (vertically), envelope-integrated, accessible from within the building The BIPV modules are installed at a tilt angle between 75° and 90° from the horizontal plane [75°, 90°]	
Category E:	Externally-integrated, accessible or not accessible from within the building The BIPV modules are installed to from an additional functional layer that provides a building requirement. E.g. balcony balustrades, shutters, awnings, louvres, brise soleil, etc.	

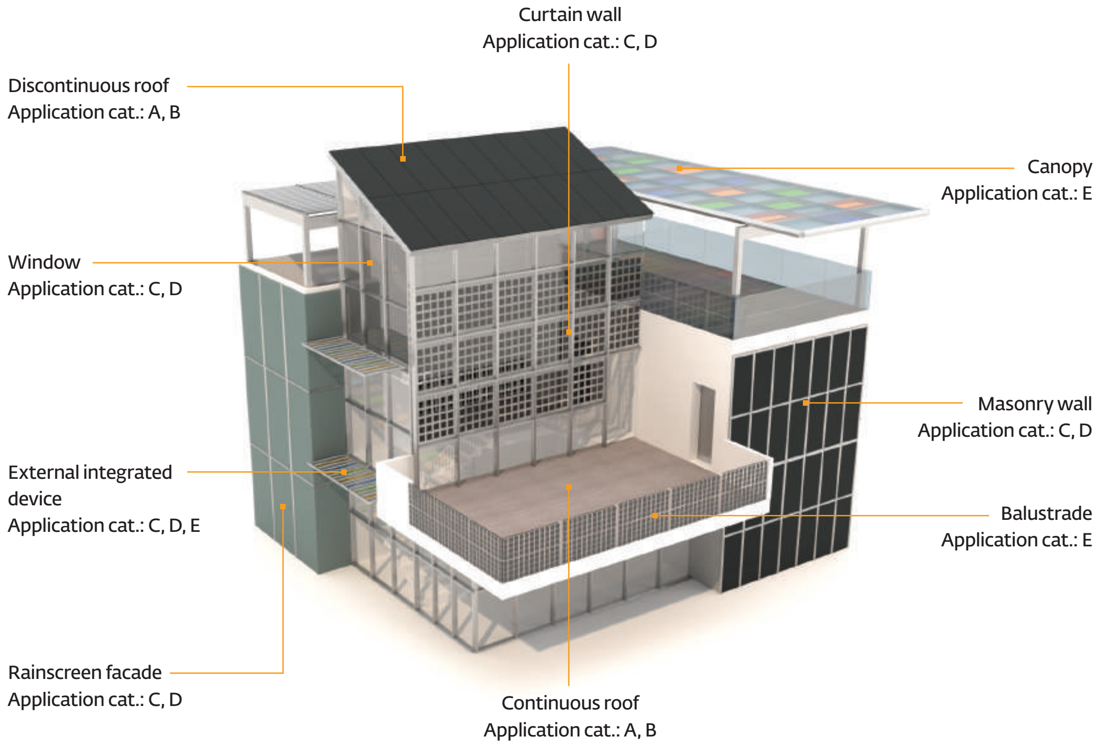


Fig. 2.2 System categories. Source: SUPSI.

degrees and visual appearance possibilities. Usually, the glass is an IGU (double or triple glazing) to ensure adequate thermal and acoustic insulation.

- *Rainscreen*: Well known as a "cold" or ventilated façade, it consists of a load-bearing substructure, an air gap and a cladding. In summer, heat from the sun is dissipated, thanks to the cavity that usually is naturally ventilated through bottom and top openings. A rainscreen is ideal for enhancing rear ventilation. It is typically categorised as "vented" with openings at the bottom; "ventilated" openings at both the bottom and top; and "pressure equalised" rainscreen with compartmentalisation in the air cavity. Many construction models and technological solutions are available on the market, also with various joints and fixing options. Usually, PV elements are integrated similarly to opaque, non-active building cladding panels and can assume many aesthetic configurations, especially through glass customisation (colours, textures, sizes, etc.).
- *Double skin façade*: It consists of two layers, usually two glazing elements wherein air flows through the intermediate cavity. This space (which can vary from 20 cm to a few meters) acts as insulation against extreme temperatures, winds, and sound, improving the building's thermal efficiency for both high and low temperatures. PV is applied similarly to a curtain wall even though the outer façade, in this case, does not require thermal insulation. Thus, it is often a glass laminate rather than an insulated glazing unit (IGU).
- *Window*: A window is a glazed wall opening to admit light and often air into the structure and to allow outside views. Windows, as a very ancient invention probably coincident with the development of fixed and enclosed constructions, are also strongly related with the building architecture, the space design, climatic conditions, functions, technologies and performance, etc. PV can be integrated into conventional PV glazing or also into some innovative applications.
- *Masonry wall*: A "barrier wall" or "mass wall" is an exterior wall assembly of bricks, stones or concrete that relies principally upon the weather-tight integrity of the outermost exterior wall surfaces and construction joints to resist bulk rainwater penetration and/or moisture ingress (e.g. precast concrete walls, exterior insulation and finish systems EIFS, etc.) or upon a combination of wall thickness, storage capacity, and (in masonry construction) bond intimacy between masonry units and mortar to effectively resist bulk rainwater penetration.
- *External integrated device*: These include 1) Transparent or opaque multi-functional and photovoltaic solar shading devices (Louvres or embedded venetian blinds) for façades or balustrades with the role of "fall protection" that are necessary for the safety of the building (e.g., in balconies, loggias, parapets);2) Transparent or opaque shading devices for roofs aimed to select the solar radiation; 3) Integrated canopies, greenhouses and veranda.
- *Canopy*: A canopy is an unenclosed roof or a structure over which a covering is attached, providing shade or shelter from weather conditions. Such canopies are supported by the building to which they are attached or also by a ground-mounting or stand-alone structure, such as a fabric-covered gazebo.

BIPV cladding properties

Cladding is referred to the external part of the technological system layering (e.g., façade cladding or roof tiling) together with the associated technological requirements (e.g., building covering, weather protection, safety, etc.). Today, BIPV claddings, namely the BIPV modules, can be tailored for almost every kind of building envelope resulting in a performing and high aesthetic solution. The customisation aspect includes colour, dimension, shape, thermal properties, material, etc. A categorisation of BIPV cladding, based on their properties and application, as defined in the framework of report D1.3 of the project H2020 BIPVBOOST project [13] is reported in Tab. 2.2. It offers to architects, building owners and other stakeholders of the BIPV value chain an overview of the possibilities offered by BIPV products:

Tab. 2.2 BIPV cladding properties. Source: IEA.

CLADDING	DESCRIPTION	SOURCE
MATERIAL	It represents the main material/s in which the solar cells are integrated or encapsulated in order to form the end BIPV product. Today, the most common material is glass, used as module backsheet and/or frontsheet. Glazed solution is suitable for semi-transparent and opaque solutions. Other supporting materials adopted for BIPV installations include polymer, metal, and cement-based materials. The features of the material establish the thermal, architectural and technical properties of the building envelope.	BIPVBOOST [13]
TRANSPARENCY	It permits to distinguish semi-transparent and opaque solutions. Semi-transparent solutions are suitable for curtain walls, double skin façades, warm façades, skylights, canopies, etc. The transparency value of BIPV modules allows architects and designers to increase the building's user comfort and energetic performance. The assessment of daylighting, glare and view out are additional parameters that can be set by adjusting the transparency performance of semi-transparent surfaces. Opaque solutions do not permit the light to pass through the building envelope. These solutions are suitable for rainscreen, prefab roof/façade, railings, louvres, curtain wall, flat or pitched roof solutions.	BIPVBOOST [13] IEA PVPS Task15 [9]
THERMAL INSULATION	It is referred to the module's thermal transmittance (U value). The thermal protection of the building is given by the materials that form the building skin. The minimum value required to overcome the energetic standard depends on the local regulations. The following solutions give the thermal insulation for the claddings: • Insulated glazed unit: Glazed solution normally used when thermal protection between two spaces is required (insulated glass unit, curtain walls or skylights, etc.); • Prefab solution: Composite solution where the cladding is one single element composed of a front-sheet, photovoltaic layer and a substrate. The front-sheet could be either glazed or not glazed. The substrate could be composed by different functional materials such as for thermal/acoustic or fire protective layers.	BIPVBOOST [13] IEA PVPS Task15 [9]
COLOURING	This framework represents one of the possible ways to customise and boost architecture. Today, several manufacturers offer coloured solutions, and the implementation of coloured modules is growing fast. In such a way, for example, PV cells can be camouflaged behind coloured patterns that completely dissimulate the original visuality of the PV cells. A shortlist of the colouring possibilities available in the today's market is presented below: • Products with coloured/patterned interlayers and/or with special solar filters • Products with coloured and/or semi-transparent PV-active layers (thin film, OPV) • Products with coloured polymer films (encapsulant, backsheet) • Products with coated, printed, specially finished or coloured front glass covers • Products with coloured anti-reflective coatings on solar cells (c-Si)	BIPV Status Report 2020 [7] IEA PVPS Task15 [8]
SIZE	The size parameter are distinguished as i) Large modules, when they exceed 2.6 m in any dimension or 2.1 m in both dimensions, ii) Less than 0.9 m in both dimensions for shingle, iii) Regular modules, when they do not fall under the categories of large or shingle [14].	IEA PVPS Task15 [9]

2.3 BIPV potential for buildings

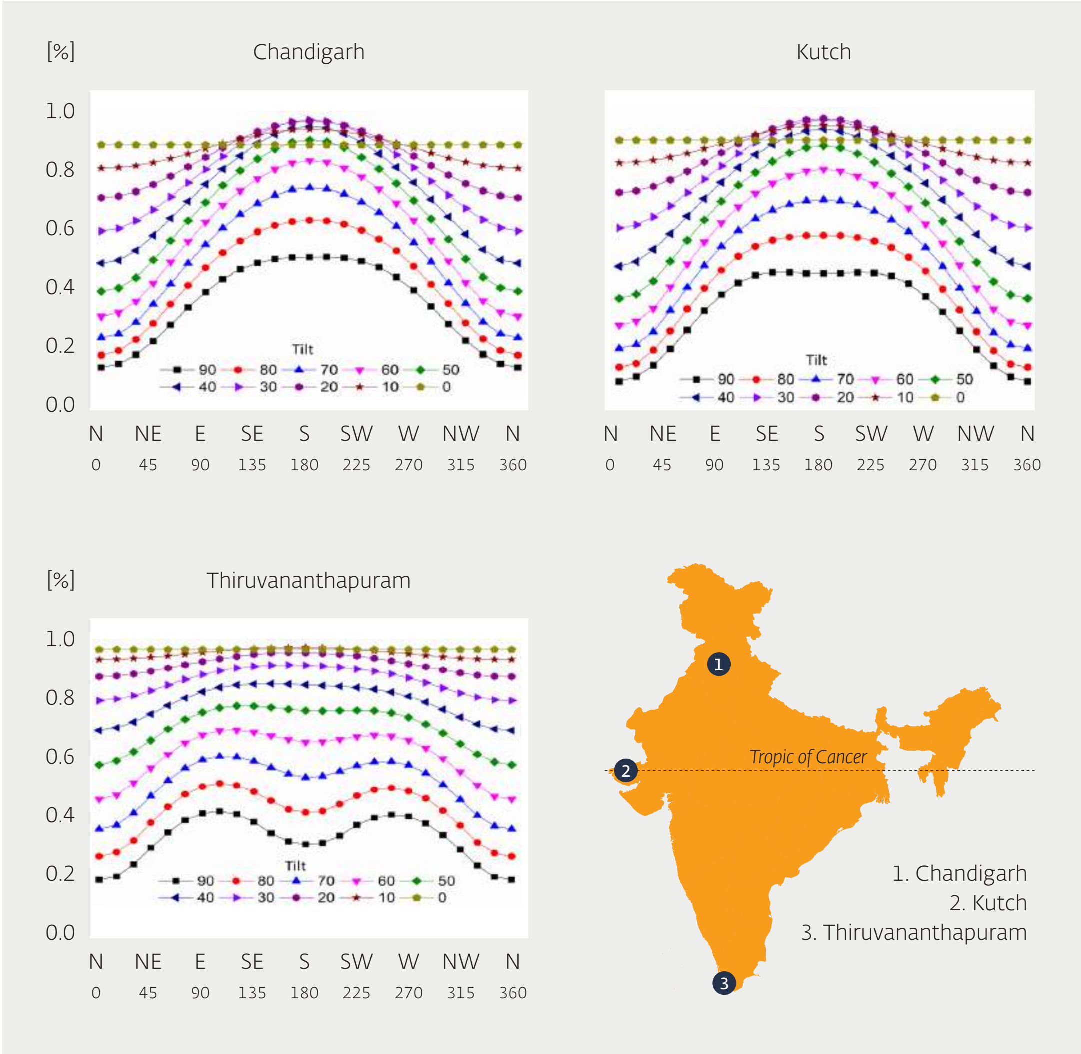
To optimise the energy production from solar panels, one of the most investigated aspects is the relation between solar yield with orientation and inclination. The optimal inclination to exploit the maximum solar irradiation is mainly a matter of solar geometry; i.e., it depends on the location's latitude. However, for BIPV, the orientation possibilities need to be defined from the building design stage itself.

India has an extend of land from 8°4' to 37°6' North latitude and 68°7' to 97°25' East compiling 29 states and 6 union territories. In India, the Tropic of Cancer passes through eight states: Gujarat, Rajasthan, Madhya Pradesh, Chhattisgarh, Jharkhand, West Bengal, Tripura and Mizoram. This specific feature of India does so that for locations to the north of Tropic of Cancer, solar radiations at peak time occur to be from South directions only for all the seasons. Moving from south to north of India, the optimal PV tilt angle for maximum energy generation, increases due to the decreased solar height. However, for the evaluation of BIPV potential based on application category in the Indian scenario, we need to consider the solar exploitation potential for different PV orientation and tilt angles. Herein, we have considered three locations in India for the study: 1. Thiruvananthapuram (Latitude 8.470865°; Longitude 76.991872°; Annual global irradiation on the horizontal plane 1945.3 kWh/m²); 2. Kutch ((Latitude 23.527348°; Longitude 70.785662°; Annual global irradiation 2050.5 kWh/m²); 3. Chandigarh (Latitude 30.7334421°; Longitude 76.7797143°; Annual global irradiation 1788.5 kWh/m²) (Irradiation data acquired from PV*SOL online tool). The locations are selected for the general solar pattern typology in India; Thiruvananthapuram for location south of Tropic of Cancer, Kutch for location passing through Tropic of Cancer, and Chandigarh for location north to Tropic of Cancer. The distinction in solar path of the three places is evident from the figure that for the southern location (Thiruvananthapuram) solar irradiation is coming from the North direction alone for more than one-third of the year, which will be reduced when moving towards north. The pattern will be evident up to the places of Tropic of Cancer (like Kutch), further moving towards north (like Chandigarh) will reduce the share of northern irradiation, particularly at the solar peak of a day.

To unlock the solar energy integration in the built environment, the assessment of the BIPV potential for existing urban areas represents a preliminary fundamental step. In fact, by knowing the BIPV potential, urban decision-makers can support the integration of PV in the urban environment with appropriate policies to achieve energy transition goals. Specifically, to assess the urban BIPV potential of façades, not only solar radiation analysis is required but also the identification of construction façade characteristics, which significantly affect the real BIPV exploitability. Many current urban BIPV façade cadastres generally do not consider specific building characteristics since the majority of them are based on 3D city models (e.g. LOD200-schematic design), meaning that the influence of architectural elements (such as windows, balconies, etc.) is not evaluated. Therefore, it is crucial to have a calculation method capable of matching existing solar radiation analysis with architectural characteristics of façades, through building typological indicators, in order to better estimate the urban BIPV potential, especially for façades, to improve the current estimations and create the framework to properly evaluate BIPV potential from the early design phases [15].

The following paragraphs present an in-depth analysis of the sun position in India and the related solar irradiation of the building envelope.
The solar potential study involved the data acquisition of energy generation from PV at the intended locations for different tilt and orientation of PV using PV*SOL online tool (Assumptions: Calculated for roof-mounted 300 Wp Si monocrystalline PV modules (18.1% efficiency) with zero considerations of diffuse light, shadowing and soiling loss). The data generated are used for a comparative study of the optimum tilt and orientation of PV at the specific locations, thus normalising the factor of annual global irradiance and the assumptions taken. The PV Energy Factor (ratio of energy that can be generated yearly for the specific tilt and orientation to the maximum possible energy generated at the optimum tilt and orientation for the same system at a specific location) of the location is plotted for the three locations with different tilt and orientations.
The optimum orientation is south for India, the tilt being higher in northern regions, as shown in the **Fig. 2.3** for Kutch and Chandigarh. This is due to the lower solar azimuth angle for northern regions compared to south. The optimum angle for Thiruvananthapuram, Kutch and Chandigarh is 8˚, 23˚ and 26˚ respectively. The condition of southern states is thus more suitable for collecting irradiation with horizontally flat or small pitched PV systems (<10˚). Compared to Kutch and Chandigarh, the south state, Thiruvananthapuram shows a peculiar pattern of maximum energy factor around E-SE and W-SW orientations for vertically tilted PV systems. The formation of this pattern is due to the availability of irradiation from north for a considerable number of days in the southern locations. The pattern tends to diminish by decreasing the PV tilt. Also, the influence of irradiation from the north will reduce much when we travel from south to north of India, diminishing the pattern, thus the placement of vertical PV systems seems liberal in the northern region. As shown in the figure, Kutch and Chandigarh can utilise E-S-W orientations for vertical PV systems, offering a liberal vertical PV positioning.

Fig. 2.3 i) Top left: PV Energy Factor for Trivandrum; ii) Top right: PV Energy Factor for Kutch; iii) Bottom left: PV Energy Factor for Chandigarh. iv) Bottom right: Marking of selected locations in India. Source: NIIST.



For designing BIPV/BAPV integration in new or existing buildings, the necessity of mapping and valuing the solar potential of that building is crucial for efficient energy and economic optimisations. The BIPV potential of a building is associated with the factors like location, orientation and tilt of potential building surfaces, and other external factors (not considered here) like shading loss, soiling loss, hail loss, clouding loss, atmospheric pollution loss, etc. Herein, as an example, the representation for BIPV potential score (PV energy factor converted as score in 100 for easy adoption) is shown Fig. 2.4 indicatively for the three selected locations, and applicable for categories:

1. Sloping roof integrated (category A and B): Discontinuous and continuous roof, skylight, canopy. The BIPV score has been calculated with a minimum tilt angle of 0°.
2. Sloping roof integrated (category A and B): Discontinuous and continuous roof, skylight, canopy. The BIPV score has been calculated with a maximum tilt angle of 15°.
3. External integrated (category E): External integrated device and canopy. The BIPV score has been calculated with a tilt angle of 75°;
4. Non-sloping (vertically) envelope-integrated (category C and D): Rainscreen, curtain wall, double skin, window and masonry wall. The BIPV score has been calculated with a minimum tilt angle of 75°.
5. Non-sloping (vertically) envelope-integrated (category C and D): Rainscreen, curtain wall, double skin, window and masonry wall. The BIPV score has been calculated with a maximum tilt angle of 90° (refer BIPV application category).

In conclusion, the mapping of solar potential score for buildings (including the external losses) helps in identifying the utilisable surfaces and solutions for BIPV/BAPV integration for efficient investment. For new buildings, a score mapping according to the building design (including shade and utilisable surface analysis) can support the generation and modification of BIPV innovative designs for better energy and economic optimisation with efficient material utilisations.

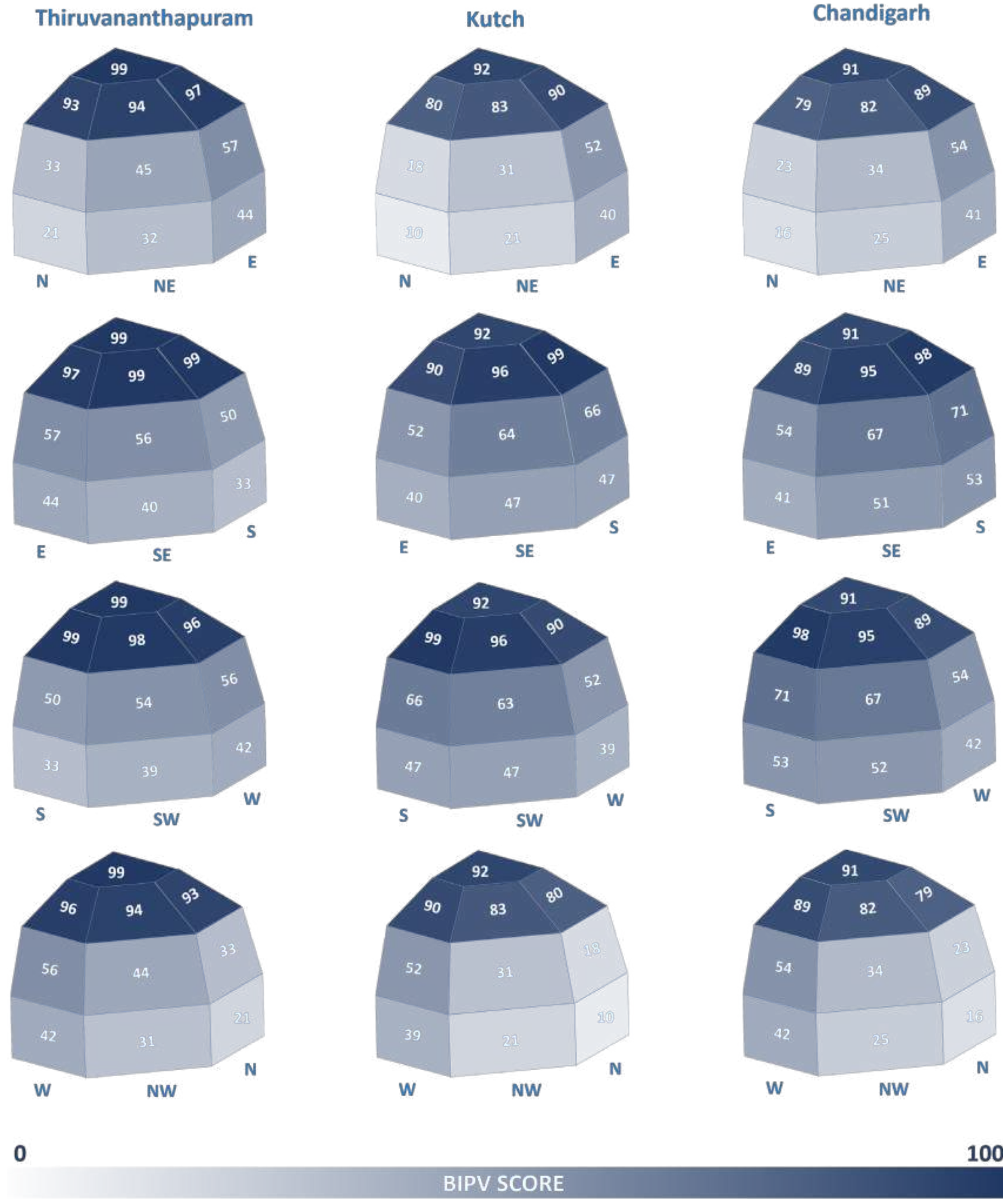


Fig. 2.4 BIPV Score: PV energy factor converted as score in 100 for easy adoption. Source: NIIST.

Sponsored content

Aelius Turbina

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Introduction

Aelius Turbina was conceived in 2020 with a purpose of bringing green energy to the masses & trying to achieve the NetZero dream. We have won the **Best Green Energy Start-ups 2021** award and have been invited by the **Indian Consulate** to represent Innovation in the Solar sector for **Dubai Expo 2020.**
Aelius Turbina are the thought leaders, innovators & implementers of **BIPV** technology in India.

Our Innovation & USP:
- Our ultimate goal is to create a NetZero Carbon Building consisting of Aelius Turbina's innovative BIPVproducts.
- These BIPV products are a direct replacement of traditional building surfaces to maximise the potential of the Solar energy generation.
- While these BIPV products are independent solar energy products, they can be combined together to fulfil the energy requirements of any structure - flat to factories.
- Most of our BIPV Products have a ROI between 3-4 years*

a. Aelius BIPV roof (Roofing BIPV product)
The key features are:
- The Aelius BIPV Roof is a 5 in 1 integrated roof - shade, solar power, daylight, waterproofing and rainwater harvesting.
- There is no need for separate roofing costs. The Solar panels are the roof.
- Any solar panel can be converted into Aelius BIPV Roof. The BIPV roofing system is highly customizable.
- Economical than Metal Roofing + Solar.
- Accelerated depreciation benefits.
- Eligible Input Tax Credit.

Applicable for: Warehouses, Factories, Production Set-up, Manufacturing Plants, IT Parks, Hospitals, Hotel Chains, Bungalows, Houses/Flats.

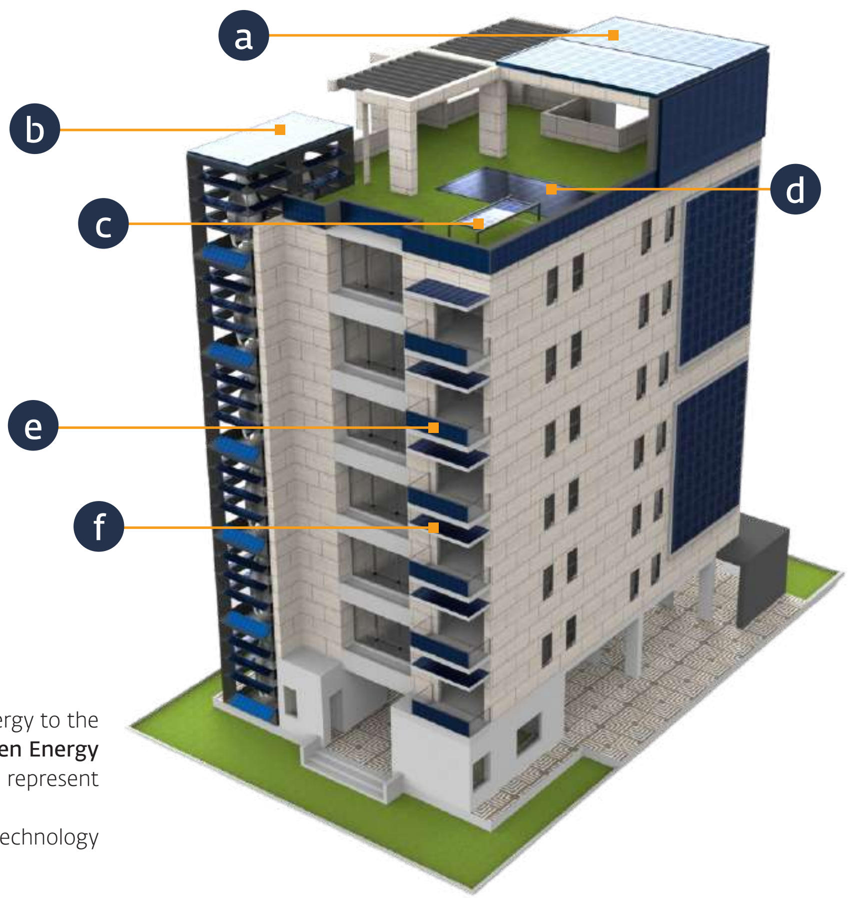


Fig. Aelius Turbina - BIPV Products & Services

b. Aelius Insulated Roof (Roofing BIPV product)
The key features are:
- This unique Roofing Panel is a combination of Metal Roof + Insulation + High SRI Cooling + Solar Panel all embedded into a single homogenous product.
- Perfect for factories and warehouses where high temperature is an issue.
- Provides Waterproofing as well.
- No separate installation mechanism.
- Modular, lightweight & durable.

Applicable for: High Temperature Regions - Warehouses, Factories, Production Set-up, Manufacturing Plants, Houses/Flats.

c. Aelius Solar Coffee Table (NetZero Individual product)
The key features are:
- Aelius Coffee Table is an aesthetically appealing, Solar Smart Table that allows you to charge your devices while enjoying your choice of drink.
- It is an all weather, outdoor friendly & light weight coffee table.
- It is equipped with 2 fast USB charging devices, ambient light, battery indicator & a 12AH battery backup that allows the table to be used even during the night.

Applicable for: Individual Home/Flat Owners, Hotel Chains, Cafes, Bungalow owners, Parks.

d. Aelius Solar Pavers (Building oriented BIPV)
The key features are:
- Single, modular solar pavers can be combined together.
- Direct replacement of tiles and multiple pavers.
- Waterproof, leakproof, tamper-proof, heat resistant & walk friendly.
- Easy maintenance.
- High energy yield.

Applicable for: IT Parks, Hospitals, Hotel Chains, Gardens, Pavements, Parks, Bungalows, Open public areas.

e. Aelius Solar Railings (Building oriented BIPV)
The key features are:
- A smart balcony railing that generates power from the sun.
- An aesthetically pleasing alternative to conventional glass panel railings.
- Seamless solar cell integration results in limitless design and colour options.
- Same sturdiness and protection of a traditional glass railing.

Applicable for: Architects, Builders, Houses/Flats, Hotel Chains, Residential Buildings.

f. Aelius Solar Awnings (Building oriented BIPV)
The key features are:
- Aelius Awnings acts as solar protection during the day thereby reducing the heat while generating energy for usage.
- Simple to set up, can be placed on the openings of the rooms or commercial premises as a single module or in series.
- Can be connected to an off-grid or on-grid stem, typically used for self-consumption.
- Modular, light-weight, easy to maintain.

Applicable for: Architects, Builders, Houses/Flats, Hotel Chains, Residential Buildings, Cafes.

Chapter 3
Indian BIPV roadmap

3.1 Roadmap for BIPV implementation

Unlike standalone PV utility systems and rooftop solar systems, the penetration of the BIPV sector in the market requires direct renewable energy policies integrated with other uninitiated policies and regulations in building energy and construction sectors. Building a roadmap for the Indian BIPV sector is challenging at the current state of non-uniform and expansive market, demographic distinction, stakeholder value and hierarchy, industrial inflexibility with the present state of affairs, and severe lack of awareness within every stakeholder level. To initiate and define a collective and concrete roadmap for BIPV implementation in India, this report focuses on five main factual contemplation levels;

1. Perspective: Government policies, Initiatives and Business models
2. Opportunities: Multifunctionality and cost reduction
3. BIPV Industrial Sphere: Technology readiness, Supply chain and Certification
4. Innovation landscape: Research projects & Engagement of international communities
5. Defining stakeholder involvement: Need for stakeholder awareness, extensive project planning & execution

(1) Perspective: Government policies, Initiatives and Business models

Scenario

Indian construction sector is expected to grow with an impressive trend, with a projection of ~45 billion square metres in floor area additions by 2060; among this, more than 80% of floor area accounts for residential buildings [1]. In this purview, India has a huge opportunity to build new renewable energy infrastructure in a more decentralised manner via the integration of solar energy systems in the built environment and also with the new building designs. To support sustainable renewable energy adoption, the Government of India (GoI) has developed many policies and initiated international alliances in the energy sector; this includes the handholding with International Solar Alliance for large scale solar adoption. Further, GoI has initiated many bilateral programs for attaining energy efficiency in the built environment, such as Indo-Swiss and Indo-US Building Energy Efficiency Projects (BEEP). In the similar line, national mission mode programs such as Smart Cities Mission and National Mission on Sustainable Habitat were initiated, where share for renewables is a major focus. Recently, GoI had released its National Action Plan on Climate Change, this is in line with the United Nations Sustainable Development Goals (UN SDG) and Mission Innovation (MI) launched during COP21. The MI is a global platform to foster and promote R&D for accelerated and affordable clean energy innovation, India and the EU are certain key members for this global initiative.

How can BIPV directly influence policies & regulations?

Replacing surfaces of building roofs and façades with active claddings, BIPV is a unique way to reduce the energetic impact of buildings, transforming them to nearly-zero energy or plus energy. Indeed, the multifunctionality of BIPV installations allows to produce on-site renewable electricity and to act for the performance as building skin with added functions of a building construction system. Moreover, as previously discussed, technology can be flexibly used for customising the architectural design of contemporary buildings. However, faster adoption of BIPV into the Indian building sector requires substantial efforts at the policy level. In this regard, Governments can pull two main levers: support the cost-effectiveness of BIPV products through the implementation of subsidies (similar to rooftop PV discussed in Chapter 1) or charge for the hidden costs of pollution and CO2 emissions in buildings. Ideally, any plan to address climate change via decentralised energy generation in buildings needs both. Implementing the right policies at the right time, especially in the construction sector, will open the possibilities to tap our most promising and sustainable landscape for sustainable design and decentralised renewable generation, extracted as "The building as energy generation nodes". To make this possible in the construction sector, Government could ensure that at least some of these carbon costs are paid by whoever is obligated and reduce the green premium, especially for multifunctional products that offer renewable integration into the buildings by exploiting already built surfaces. This would, in turn, create an incentive for building product manufacturers to come up with carbon-free alternatives, for example, building construction/ materials leading to sustainable solutions such as innovative BIPV products and their faster adoption in the construction sector.

Aside from that, governments, policy advisers and policymakers need to introduce new building energy policies and energy-efficient city planning. Even though

Chapter 4
Case studies

Case study: Malabar HQ, Kozhikode. 2017

The project constituted of more than 180 highest quality PERC solar panels installed as canopy over the building. The solar power plant installed at the site helps to produce about 89,000 kWh per year and thus annually saving around Rs 7,12,480. The solar power plant helps to reduce around 44 tons of carbon dioxide and also helps to save around 2,013 trees. The installation of the solar power plant required a completion time of two weeks.

Fig. 4.14 General view. Source: Sunsenz.

Tab. 4.16 System features.

Building typology	-	Administrative
Technological system	-	Canopy
Active cladding surface	ft^2	4,500
Orientation	°	South
Tilt	°	8
Nominal power	kWp	60
System power density	Wp/ft^2	13.3

Tab. 4.17 Product features.

BIPV technology	-	Semi-transparent glass/glass modules (325Wp per module)
PV technology	-	PERC, bifacial modules
Degradation rate yr 0	%	0.70
Degradation rate yr >0	%	0.70
Customization in size	-	No
Customization in colour	-	No

Tab. 4.18 Energetic features.

Energy production	kWh/yr	89,060
Average yearly yield	kWh/kWp	1,460
Self-consumption	%	NA
Self-sufficiency	%	NA
Business model	-	NA
Subsidies	-	No
Payback time	Year	NA

Fig. 4.15 Canopy, interior view. Source: Stapati.

Case study: Sierra E-Facility HQ, Coimbatore. 2018

The facade of the building in Coimbatore is fitted with amorphous silicon BIPV modules that produce solar power energy in conditions of low light. The curtain wall facade combines transparent photovoltaic glass with conventional glass, achieving an aesthetic and functional result. Has been calculated that the yearly energy production is about 1,200 kWh. The PV glazing solution is a laminated safety glass with modules used in standard size (4.1x6.1ft^2) with medium transparency. The solar capacity of the building has been completed with further PV installation in the roof. The Sierra E-Facility uses environmentally friendly building materials and high-performance glass. It scored 103 points in the LEED-NC rating system.

Tab. 4.1 System features. Source: Onyx Solar.

Building typology	-	Commercial
Technological system	-	Curtain wall
Active cladding surface	ft^2	580
Orientation	°	East
Tilt	°	90
Nominal power	kWp	4.3
System power density	Wp/ft^2	7.4

Fig. 4.1 Curtain wall. Source: Onyx Solar.

Tab. 4.2 Product features. Source: Onyx Solar.

BIPV technology	-	Transparent glass modules (medium transparency)
PV technology	-	a-Si PV
Degradation rate yr 0	%	NA
Degradation rate yr >0	%	NA
Customization rate	-	100% customized in shape, thickness, colour, transparency-degree, size and finishes

Tab. 4.3 Energetic features. Source: Onyx Solar.

Energy production	kWh/yr	1,476
Average yearly yield	kWh/kWp	343
Self-consumption	%	100
Self-sufficiency	%	NA
Business model	-	NA
Subsidies	-	NA
Payback time	Year	<16

Fig. 4.2 a-Si BIPV glazed facade. Source: Onyx Solar.

Case study: Desai Brothers Ltd, Sahakarnagar. 2019

Discontinuous roof covered by BIPV tiles. The solar roof of the following commercial activity produces about 6,000 kWh per year being oriented towards South, West, East, Southwest and Southeast. The installation of the tile is very simple and doesn't require the use of sealant. In the following case study, the shading losses are lowered due to the installation of bypass diodes for each tile. The rooftop is installed in Sahakarnagar, Bangalore and the payback time of the solar investment is assessed in 5-6 years.

Tab. 4.13 System features.

Building typology	-	Commercial
Technological system	-	Discontinuous roof
Active cladding surface	ft^2	387
Orientation	°	S, W, E, SW, SE
Tilt	°	25
Nominal power	kWp	5
System power density	Wp/ft^2	12.9

Fig. 4.12 Rooftop installation. Source: Anu Solar Power.

Tab. 4.14 Product features.

BIPV technology	-	BIPV roof tiles
PV technology	-	c-Si
Degradation rate yr 0	%	0.7
Degradation rate yr >0	%	0.7
Customization rate	-	Flexible and easy installation. No need of sealant application

Tab. 4.15 Energetic features.

Energy production	kWh/yr	6,300
Average yearly yield	kWh/kWp	1,260
Self-consumption	%	NA
Self-sufficiency	%	NA
Business model	-	CAPEX
Subsidies	-	40% tax depreciation
Payback time	Year	5-6

Fig. 4.13 Rooftop detail. Source: Anu Solar Power.

Case study: CTRLS Datacenter, Maharashtra. 2020

The CTRLS Datacenter was renewed in 2020 with the installation of BIPV glazed modules installed on all four facades. The installation is realized by U-Solar, a Clean Energy Eneterprise with PAN India and neighboring country installations. The center located in Mumbai is the largest building integrated vertical solar PV system in India. The solar installation allowed to transform the building in a solar power plant and drastically reduced its energetic impact. The mono c-Si PV frameless modules cover a vertical surface of about 51,505 ft² with a system capacity of 863 kWp. The active facade area is about 7-8 times of that available on the roof (this is assuming all the roof is empty - which is not).

The glazed PV modules have been installed on the top of the previous opaque facade, by creating a ventilated airgap between the thermal insulation and the PV panels. Indeed, the technological system is rainscreen.

The solar system is configured accordingly to four orientations: NW (252 kWp), SW (261 kWp), SE (290 kWp) and NE (60 kWp). The PV modules utilized are 2,466 per 350 Wp.

The energy production has been measured in more than 590 MWh per year, corresponding with an average yield of almost 700 kWh/kWp. The actual energy production corresponds with an increase by 7% of those expected.

Considering the high energy demand of the datacenter, the self-consumption rate is 100%, which means that the total amount of energy produced by the solar system is used outright. However, only 2% of the energy demand is supplied with renewable energy.

Building typology	-	Commercial
Technological system	-	Rainscreen
Active cladding surface	ft²	51,505
Orientation	°	NW, SW, SE, NE
Tilt	°	90
Nominal power	kWp	863
System power density	Wp/ ft²	17

Tab. 4.4 System features.

BIPV technology	-	Opaque glazed BIPV solution without thermal properties
PV technology	-	Mono c-Si
Degradation rate yr 0	%	0.70
Degradation rate yr >0	%	0.70
Customization in size	-	No
Customization in colour	-	No

Tab. 4.5 Product features.

Fig. 4.3 CTRLS during the BIPV facade construction phase. Source: U-Solar.

Energetic and economic evaluation

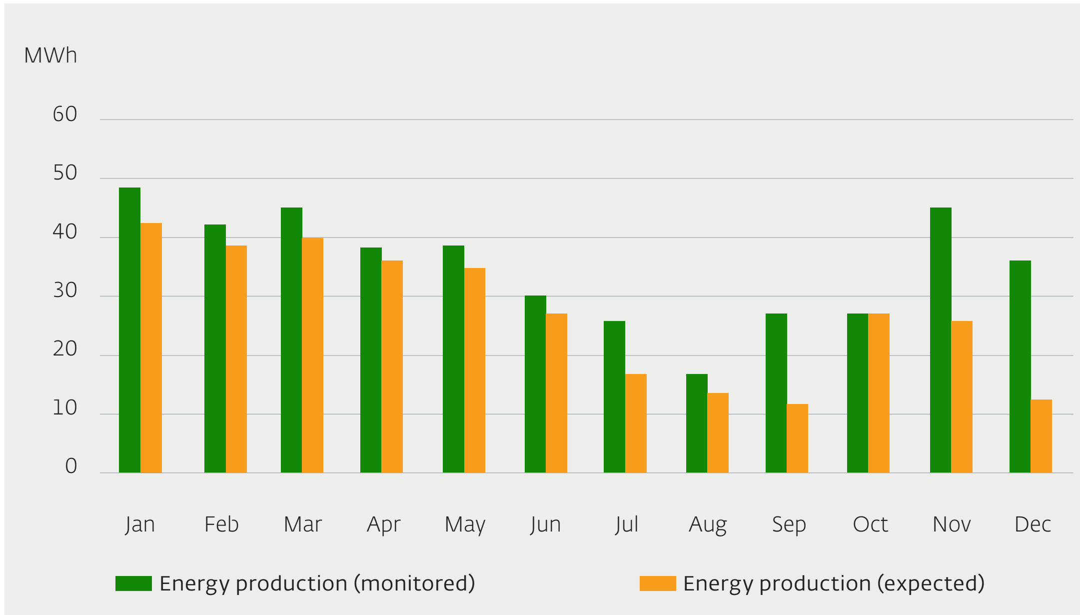
Energy production	kWh/yr	593,014
Average yearly yield	kWh/kWp	687
Self-consumption	%	100
Self-sufficiency	%	2
Business model	-	CAPEX
Subsidies	-	40% tax depreciation
Payback time	Year	4.3

Tab. 4.6 Energetic features.

The system energy payback time, calculated by U-Solar, is less than 5 years by assuming a total cost of about 650 Rs/ft², subsidies corresponding with a 40% accelerated tax depreciation. The business model is CAPEX.

Fig. 4.4 CTRLS BPV facade. Source: U-Solar.

Fig. 4.5 Energy production (expected vs monitored-2020), variation over the year due to weather. Source: U-Solar.



Case study: Ponnore Group (Aqua Star), Kerala. 2020

This administrative building is covered with high efficiency mono PERC double glass semi-transparent BIPV facade facing the south and west orientation. The solar power plant transforms the Ponnore Group Construction in a low energy building. Indeed, the energy production, estimated in about 17,000 kWh/yr, generates 50% of the energy requirement of the building. Considering the high yearly solar horizontal irradiation of the location (about 2,000 kWh/m²/yr) and according with the calculation of the facade manufacturer, the payback time of the investment in the solar power plant is only 4.3 years by including a 40% tax depreciation.

Tab. 4.10 System features.

Building typology	-	Administrative
Technological system	-	Curtain wall
Active cladding surface	ft²	1,000
Orientation	°	S, E
Tilt	°	90
Nominal power	kWp	12.2
System power density	Wp/ft²	12.2

Fig. 4.10 Rendering of the curtain wall. Source: TopSun.

Tab. 4.11 Product features.

BIPV technology	-	Semi-transparent BIPV laminated glazing
PV technology	-	Mono PERC
Degradation rate yr 0	%	0.70
Degradation rate yr >0	%	0.70
Customization in size	-	No
Customization in colour	-	No

Tab. 4.12 Energetic features.

Energy production	kWh/yr	17,000
Average yearly yield	kWh/kWp	1,398
Self-consumption	%	NA
Self-sufficiency	%	50
Business model	-	CAPEX
Subsidies	-	40% tax depreciation
Payback time	Year	4.3

Fig. 4.11 Curtain wall under construction. Source: TopSun

Case study: BIPV Rupa Renaissance, Mumbai. 2021

Aelius Turbina is proud to have commissioned one of India's Highest Rooftop BIPV Solar Installation at Rupa Renaissance, Mumbai - an A+ grade commercial office campus.
This 300 KW Solar plant has been installed with Mono PERC cells that offer 21.2% high efficiency resulting in more energy generation and the space below the plant continues to be utilised fully.
Key Benefits & Features:

- 40% extra energy yield in the same space.
- Solar panel as a Roof. Savings on Metal Roofing.
- Integrated roofing with daylighting.
- More economical than metal roofing + solar.
- Savings on Solar module mounting structure.
- Eligible for GST Input Tax Credit

Tab. 4.19 System features.

Building typology	-	Commercial
Technological system	-	Canopy
Active cladding surface	ft²	15,400
Orientation	°	East, West
Tilt	°	3
Nominal power	kWp	300
System power density	Wp/ft²	19.5

Fig. 4.16 Building view. Source: Aelius Turbina.

Tab. 4.20 Product features.

BIPV technology	-	BIPV roof
PV technology	-	540 Wp Mono PERC
Degradation rate yr 0	%	2
Degradation rate yr >0	%	0.55
Customization in size	-	No
Customization in colour	-	No

Tab. 4.21 Energetic features.

Energy production	kWh/yr	405,000
Average yearly yield	kWh/kWp	1,350
Self-consumption	%	100
Self-sufficiency	%	5
Business model	-	CAPEX
Subsidies	-	40% tax depreciation
Payback time	Year	3

Fig. 4.17 Canopy. Source: Aelius Turbina.

Case study: Residential villa project, Bengaluru. 2022

Renewable energy pioneer SunEdison launched their new integrated solar roofing range, called the 'ARKA collection', developed in partnership with ARKA Energy, a Silicon Valley-based startup. The ARKA collection consists of aesthetic BIPV solutions with Mono-PERC dual glass PV tiles as the base along with a false ceiling and the option of a gazebo structure.
The case study is a duplex villa in a luxury complex project in an upcoming locality in Bengaluru. The rooftop area was already fitted with a 280 ft^2 hexagonal metal gazebo structure with a fibrocement board, meant to be used as a recreational or garden space. SunEdison saw this opportunity to install the ARKA PowerRoof – which consisted of a BIPV solution with a customized false ceiling, an inverter & necessary safety and electrical peripherals. The client wanted the hexagonal structure to remain intact but requested for a wooden finish matching the building architecture. A PowerRoof solution with a DC capacity of 4 kWp was proposed for the location.
The solar tiles used in the solution are homogeneously black and frameless, ensuring a picture-perfect minimalist look from the top. Below the hexagonal structure, one can see the wooden false ceiling fit seamlessly with the gazebo. The perforated metal cage covering the inverter and switchgear is custom made to match the overall structure.
Tested as per BIS / IEC standards, the system can withstand winds of up to 160 km/hr. The customer was given app access allowing the monitoring of system performance.

Building typology	-	Residential
Technological system	-	Canopy
Active cladding surface	ft^2	280
Orientation	°	South
Tilt	°	10
Nominal power	kWp	4
System power density	Wp/ ft^2	14

Tab. 4.7 System features.

BIPV technology	-	Opaque dual glass BIPV solution with false ceiling
PV technology	-	Mono Perc MBB
Degradation rate yr 1-5	%	5.00
Degradation rate yr >5	%	0.60
Customization in size	-	Yes
Customization in colour	-	No

Tab. 4.8 Product features.

Fig. 4.6 Close-up of the PowerRoof. Source: SunEdison

Fig. 4.7 . Aerial view of the PowerRoof. Source: SunEdison

Energetic evaluation

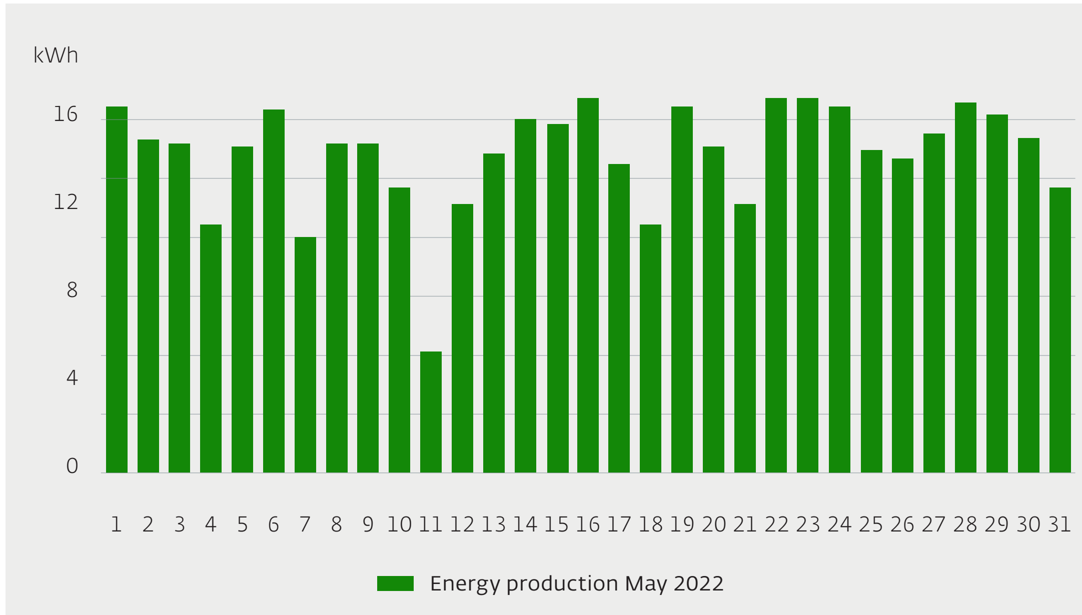
The first aim of the ARKA PowerRoof is to provide an aesthetic, durable & reliable roof that acts as a solar investment for the future. The tiles are wired such that the impact of nearby shadows are minimized, and shaded tiles are isolated in a different string with minimal impact to system performance.
The southern oriented PowerRoof produces a large amount of electricity to satisfy the energy needs during peak summer.
This will continue to produce optimum energy during winter months, where energy generation is boosted by the lower temperatures.
Energy performance on sunny days largely mirrors the performance of regular PV systems; however, the impact of shading and soiling is reduced due to the usage of modular tiles.
The rest of the system is designed from a safety perspective; lightning protection, suitable earthing as per IS standards, and protective equipment on the DC and AC side ensure low downtime.

Fig. 4.8 View of the PowerRoof. Source: SunEdison.

Energy production (May 2022)	kWh	428.31

Tab. 4.9 Energetic features.

Fig. 4.9 PV energy production on May 2022 (monitored).



Summary and Outlook

Within the existing framework of the Indian PV sector, the essentiality of BIPV sectoral evolution is indispensable for the coming decades of the Country's green energy uprisal. However, the Indian BIPV sector needs multi-stakeholder involvement as frontline participants for its growth. Hence, the requirement of awareness of the present state of the Indian BIPV sector is essential to conceptualize the factors and ideas for the future and initialize a roadmap. The " Indian BIPV Report 2022: Status and Roadmap" essentially conducts the same in consideration with the future of the Indian BIPV sector. The Indian solar market potential, perspectives, and financial schemes presented in the first chapter draw the main traits for penetration (BI)PV in the Country. The chapter also documents and exhibits the historical development of the Indian PV sector with the recollection of government policies and regulations and landmarks architectures developed in the Country. The financial schemes that support conventional solar installations in India need to find the jumping-off point to create specific support for BIPV, which represents a building component combining energy production, multifunctionality and aesthetics. The second chapter focuses on the technical aspects of BIPV as a building element and its potential in Indian demography. The chapter also provides a precise cut categorization of BIPV products, as it is currently needed, especially for India, where the ambiguity on BIPV definition prevails. The Indian BIPV roadmap, analysed in the last chapter, is presented as a discussion through five factual contemplation levels that represent the resume of the report and are aimed at opening future actions. From a roadmap perspective, the last chapter is expected to encourage actions among the various stakeholders of the Indian BIPV scenario towards collaboration among the construction and solar sectors for solid and prosperous development.

In the coming years, India will be called upon to make a great effort to implement the development strategies according to the international agreements, including COP26. The long-term global goal of limiting the temperature rise to 1.5°C above pre-industrial levels has been reaffirmed. In the pact, the signatories also emphasized the effort to accelerate the energy transition. The prime minister of India announced the climate neutrality goal by 2070, setting a 50% of renewable energy share by 2030. Considering the importance of the goal, India provides an excellent opportunity for contributions to the Country's energy transformation, especially in the expanding building and construction sector.

To date, India is one of the world's nations that appears to be more attractive in terms of solar investments, considering the potential for cost-effectiveness and the high value of solar irradiation. Despite the availability of an extensive real estate portfolio, planned urban growth and very high solar energy potential, BIPV is still in the experimental age in India. This report discussed and presented many opportunities to move in the BIPV direction and have already experimented with globally.

Further, the year 2030 also marked globally for achieving United Nations' Sustainable Development Goals (SDGs), also known as the Global Goals. All United Nations Member States adopts sDGs as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity. In this regard, the global community has committed to fast-track progress for those furthest behind first through the pledge to "Leave No One Behind" by ensuring a time-bounded fulfilment of the SDGs objectives. According to the NITI Aayog's 2020 SDG Index, India has achieved remarkable progress in the SDGs related to clean energy, urban development and health. This shows the Country's commitment to achieving energy security, a prerequisite for socio-economic development, ensuring SDG 7 ("Ensure access to affordable, reliable, sustainable and modern energy for all"). By 2030, the SDG 7 target will be to substantially increase the share of renewable energy in the global energy mix and double the global rate of improvement in energy efficiency.

As reported by IEA India Energy Outlook 2021, over the period to 2040, an estimated 270 million people are likely to be added to India's urban population, the equivalent of adding a new city the size of Los Angeles every year. Most of the buildings in India in 2040 have yet to be built. Urbanization underpins a massive increase in total residential floor space from less than 20 billion square meters today to more than 50 billion in two decades. This prompts enormous growth in demand for energy-intensive building materials. Demand for steel more than doubles to 2040, and demand for cement nearly triples. Urbanization is also a spur for the transition of household energy use away from solid biomass and towards electricity [1]. The SDGs go further toward improving efficiency and the use of low-carbon technologies. The rapid growth in the building stock and other infrastructures will demand a range of construction materials. Also the Indian electricity sector is on a solar-powered revolution with the rise of utility-scale renewable projects. The scope for solar to meet India's energy and building needs, as it can happen in BIPV, is a key challenge to match the construction and solar sectoral growth in the upcoming solar urbanization of the Country. The world's progress in meeting the SDGs largely depends on India's progress. In the battle against climate change, India's optimistic movement supporting green energy will be favourable for future generations to conduct a healthier and more sustainable ecosystem.

We strongly hope that India's sun will shape its buildings for years to come!

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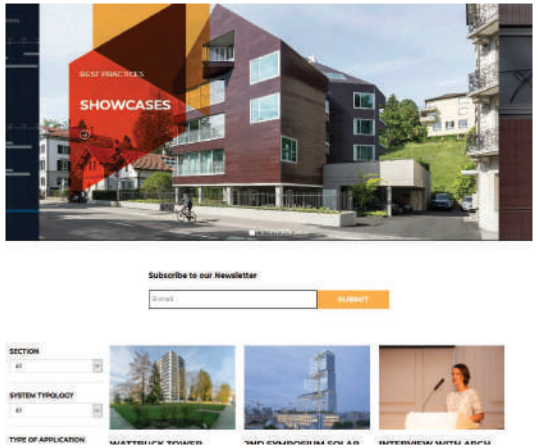

The website www.solarchitecture.ch is one of the communication means of the Swiss BIPV Competence Centre.
Here you find essential information concerning pv technology integration in buildings and different projects realized both in Switzerland and abroad. Moreover, a large database of BIPV modules and fastening systems collecting the main product’s information in a datasheet is available. The website is an active interface opened towards different stakeholders thanks to the possibility to upload and store your BIPV examples (architects, installers, owners, etc.), products (manufacturers, suppliers, installers, etc.) as well as to the technological/client support through the contact info@bipv.ch.

Impressum

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