Modular Rooftop Building-Integrated Photovoltaic/Thermal Systems for Low-Rise Buildings in India

Olesia Kruglov, Efstratios Rounis, Andreas Athienitis, Bruno Lee, Ashutosh Bagchi, Hua Ge and Theodore Stathopoulos

Concordia University, Montreal (Canada)

Abstract

This study aims to investigate the utilization of the abundant solar resources available in India to provide energy for low-rise mixed use buildings in the city of Chennai. To accomplish this, a modular rooftop building-integrated photovoltaic/thermal (BIPV/T) system is designed, developed and modeled for an archetypical mixed-use building. The BIPV/T system incorporates the production of electricity and useful heat, while considering the building envelope requirements for roof as well as façade applications. These systems can be alternatives to traditional cladding, while retrofitting with BIPV/T can turn unused or semi-conditioned spaces into fully enclosed conditioned spaces. For a roof coverage of 180 m^2 and average summer day conditions in Chennai, a typical system with an efficiency of 15% would have an electrical output of approximately 150 kWh and a thermal output of approximately 230 kWh, which can be used for heating through a heat pump, directly, or for cooling through a thermally driven cooling system. For a climate such as the one in India, a BIPV/T application can utilize heat driven technologies such as absorption cooling systems.

Keywords: Building-integrated photovoltaic/thermal, modular roofing, building typologies

1. Introduction

India is one of the top energy consuming countries in the world, after China, the United States and Russia. However, the country's per capita electricity consumption is less than one third of the world average. In acknowledgement of this as well as the rapid rise of technologies used to harness solar energy, the Indian government has recently initiated policies to encourage the use of photovoltaic (PV) and building-integrated photovoltaic (BIPV) systems for local energy production. While the country does get as many as 300 days of sunshine a year, it is densely populated with little land available for solar parks. Because of this limited land availability and largely accessible unused roof space, rooftop PV systems are especially garnering attention (Shukla et al., 2018).

The Indian government has set goals to produce 100 GW of solar energy by the year 2022, and 40% of this will come from rooftops, which is now the fastest growing technology in the clean energy sector, and is cheaper than commercial and industrial power in India ("India Transforms Market for Rooftop Solar," n.d.). The current issue is that while the rooftop projects for commercial buildings are rapidly advancing, solar for residential buildings is falling behind due to large upfront costs and net-metering programs ("Rooftop solar is the fastest-growing segment in India's renewables market — Quartz," n.d.).

This IC-Impacts collaborative project aims to develop novel of rooftop solar concepts for the residential sector. The India-Canada Centre for Innovative Multidisciplinary Partnerships to Accelerate Community Transformation and Sustainability (IC-Impacts) is a center of excellence which focuses on research to improve sustainability within Canadian and Indian communities. The goal of this particular research is to identify optimal configurations of building technologies suitable for the local climate and to aim for the design of a net-zero energy building by utilizing local energy generation from renewable sources. Specifically, the project involves the design and modeling of a low-rise residential building in the city of Chennai, India.

The project conceptualizes a building-integrated photovoltaic/thermal (BIPV/T) cladding for the building which is more efficient than a typical rooftop system and replaces some of the building cladding components, lowering

doi:10.18086/eurosun2018.06.12 Available at http://proceedings.ises.org

the critical up-front cost of material and installation. Since India is one of the leading producers of aluminum, it would be acceptable to use aluminum curtain wall framing to contain the PV panels and enclose the rooftop, converting it into a semi-conditioned space and reducing the solar heating of the roof, which in turn would reduce the energy needed to cool the building.

1.1 BIPV/T Technology

Current practices for utilizing PV panels on rooftops mainly include racked systems. BIPV and BIPV/T technologies can be used as alternative to traditional claddings on both roofs and facades. Retrofits with these systems can turn unused spaces into semi-conditioned or fully enclosed spaces.

A BIPV system serves a dual purpose. The PV components not only produce electrical energy but also serve as the exterior cladding of a building envelope, replacing the outer materials that function as walls and roofs. There are many types of BIPV systems, including facades, roofs, fenestration, and sunshades. One way in which the BIPV technology has advanced is the harvesting of excess heat produced by the PV cells and transferring it to a medium for useful energy, further benefitting the electrical production of the system by maintaining lower PV cell temperatures. This variation on the BIPV design is called a building-integrated photovoltaic/thermal (BIPV/T) system and many improvements to this technology have been studied and documented (Yang and Athienitis, 2016). This study focuses on the application of BIPV/T systems (Figure 1) on rooftops.

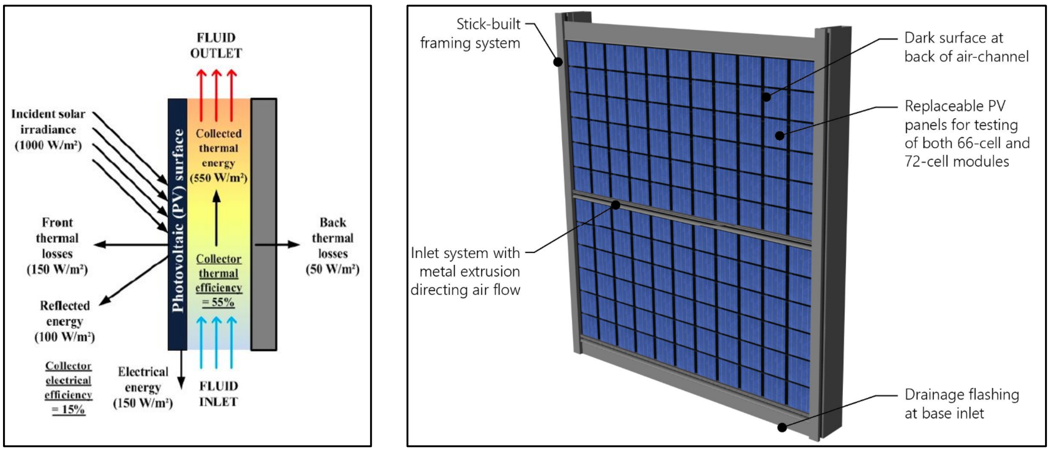

Fig. 1: BIPV/T energy distribution diagram (left) and curtain wall framing design for BIPV/T (right) (Bambara, 2012)

Two examples of built BIPV/T assemblies are shown in Figure 2. The left image shows a modular BIPV/T system assembled with several components. This was used as the roof structure of the Team MTL house for the Solar Decathlon competition in summer of 2018 in Dezhou, China. The image on the right shows a fully integrated BIPV system as the roof of a library building in Quebec. The area of the system is 711 m² and 173 m² of this is BIPV/T, producing 220 kWh of solar heat on a cold, sunny day. The slope of this building is 30° due to the northern latitude, but an even higher slope would have been ideal to prevent snow accumulation.

Fig. 2: Modular BIPV/T prototype for the Solar Decathlon (left) and BIPV/T roof on the Varennes library in Quebec, Canada (right)

2. Location Analysis: Chennai, India

Chennai is located in the southern part of India, in the state of Tamil Nadu. At the geographical coordinates 13°N, 90°E, this coastal city is close to the equator and has a warm-humid climate. As shown in Figure 3, the annual global horizontal irradiation (GHI) is 1,957 kWh/m², while the average air temperature is over 28°C. The annual direct normal irradiation is 1,377 kWh/m² and the annual diffuse horizontal irradiation is 935 kWh/m².

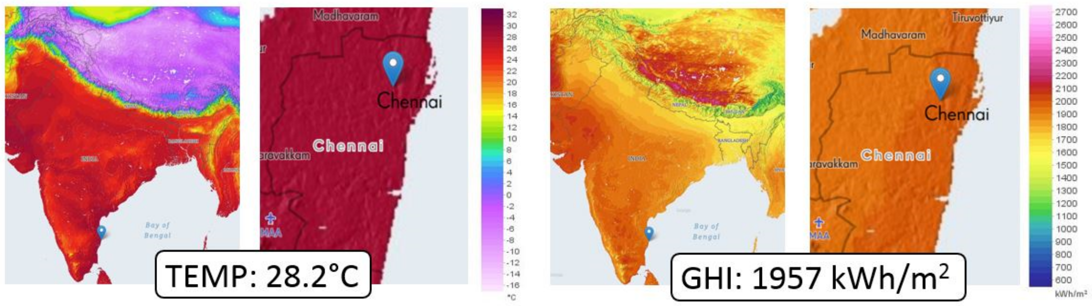

Fig. 3: Radiation and temperature maps of Chennai, India ("Global Solar Atlas," n.d.)

Average air temperatures for Chennai vary between 24°C in the winter months and up to 32°C in the summer, making this a cooling dominated climate (Figure 4).

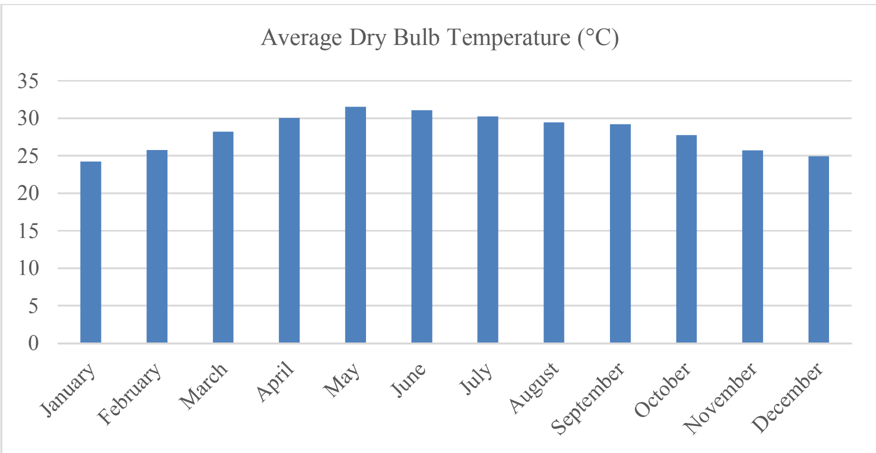

Fig. 4: Monthly averages for air temperatures in Chennai, India

For a location such as Chennai, a PV system would need a low slope to maximize incident radiation. A 13° slope is favorable, but a lower slope would also be beneficial, due to dominating diffuse radiation. This is due to higher cloud cover in the summer months during the monsoon season. The global horizontal irradiation (GHI) follows a typical pattern throughout the year (Figure 5).

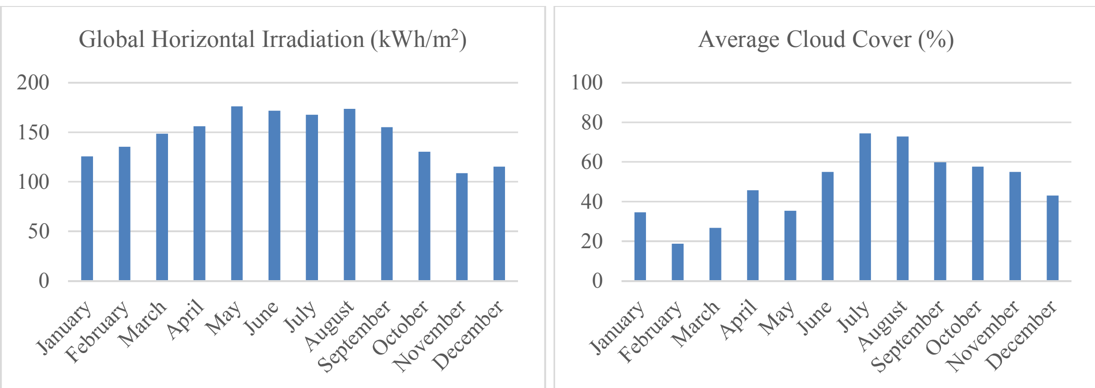

Fig. 5: Monthly total for GHI (left) and percentage of sky covered by clouds (right)

2.1 Building Typologies

Building typologies of the state of Tamil Nadu were studied for patterns in existing residential structures. Among the most common are reinforced concrete structures with non-bearing masonry infill walls. The buildings are often aligned at the front street facade and have narrow plots on which they sit. Several representative buildings are shown in Figure 6.

Fig. 6: Building typologies in the state of Tamil Nadu (National Disaster Management Authority, 2013)

A typical reinforced concrete building frame is shown below (Figure 7). This type of structure requires a lightweight BIPV/T framing system with simple attachment methods at the roof.

Fig. 7: Reinforced concrete framed building construction ("Reinforced concrete portal frame / prestressed concrete - Pujol," n.d.)

3. Case Study

Initially for the study, 4 apartments were selected as representative samples from both Nagpur, which has a composite climate, and Mumbai, which has a warm and humid climate. Specific to the city of Chennai, India, two types of building typologies were reviewed. One is a typical low-rise, 4-story building consisting of 4 apartments and retail or parking spaces on the ground level. Each floor is 55 m^2 by 45 m^2. The second typology is a 3-story single family home with parking on the ground floor. An energy analysis was performed on the first typology. The building envelope properties for energy analysis were selected based on BEEP (2016) *Design Guidelines for Energy-Efficient Multi-Story Residential Buildings: Warm-Humid Climate* (Table 1). Results show an average annual energy use intensity of 156 kWh/m^2. It is important to note that at this stage, only a base case has been modeled. Improved insulation and an airtight building design will significantly lower the energy use. The energy model is based on ideal control with an assumed constant cooling coefficient of performance (COP) of 2.5 for the heat pump.

Tab. 1: Building envelope properties for base case

Design Parameters	Default Input Values
Roof U-value (W/m^2-K)	3.0
External wall U-value (W/m^2-K)	2.0
Intermediate floor U-value (W/m^2-K)	3.4
Window SHGC, VLT	0.8, 0.85
Window overhang projection factor	0.6

The available rooftop area is 220 m^2 and the western half of the south wall has no windows. For this building design, the application of BIPV/T could extend not just across the roof but also over 97 m^2 of the south wall (Figure 8).

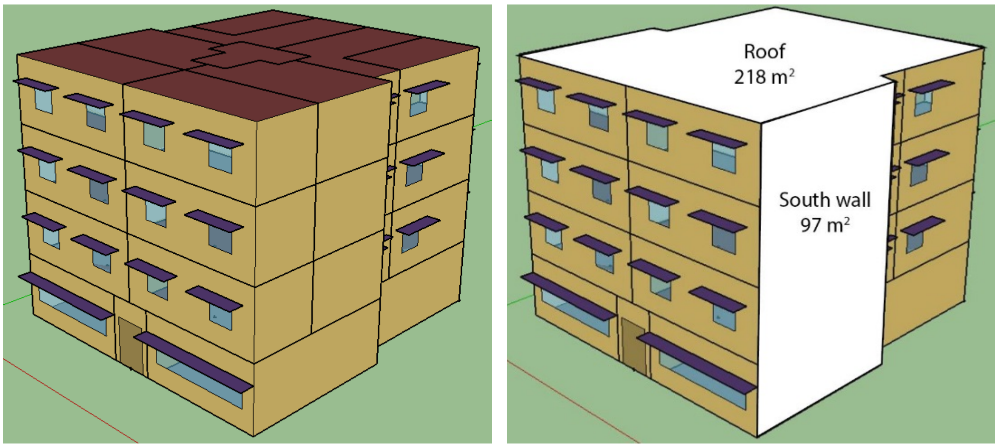

Fig. 8: Building schematic (left) and roof and wall areas available for PV coverage (right)

3.1 BIPV/T Roof Design

Different layouts were studied for rooftop PV applications (Figure 9). The first two layouts (left and center) are sawtooth configurations and commonly used, but the BIPV/T layout was determined to not only have maximum area but also receive the most annual radiation, as shown in the radiation maps below each layout.

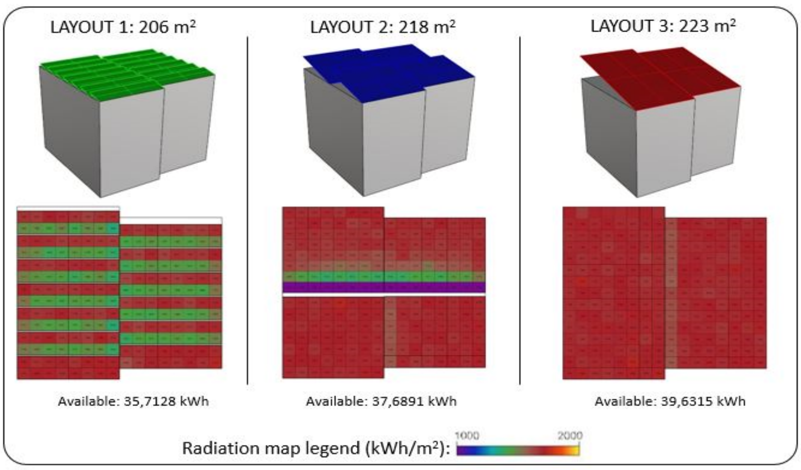

Fig. 9: Rooftop PV configurations and their radiation maps

Preliminary calculations showed that for the design shown in the bottom right of Figure 9, the annual AC energy production would be approximately 46,781 kWh for a system sloped at 13°. However, it was decided to use only the roof portion available for BIPV/T system.

The project will feature a low-sloped BIPV/T roof of approximately 13° which is optimal for near equatorial latitudes. The system is based on a prototype developed and constructed in collaboration with curtain wall framing manufacturers. The prototype was assembled with aluminum framing and has been tested for base characterization in the Solar Simulator at Concordia University (Kruglov et al., 2017; Rounis et al., 2017). The design will include an insulated air channel, allowing air to flow through it and cool the PV panels, which serve as the outer layer of the cladding. A manifold will collect the preheated air from the air channel(s) which will then be utilized depending on the coupling with the HVAC system. With a focus on common building practices and the use of local materials for framing design, the potential for modular and unitized rooftop systems to achieve energy savings is even greater for large scale applications. Figure 10 shows the layout and capacity of the designed BIPV/T system.

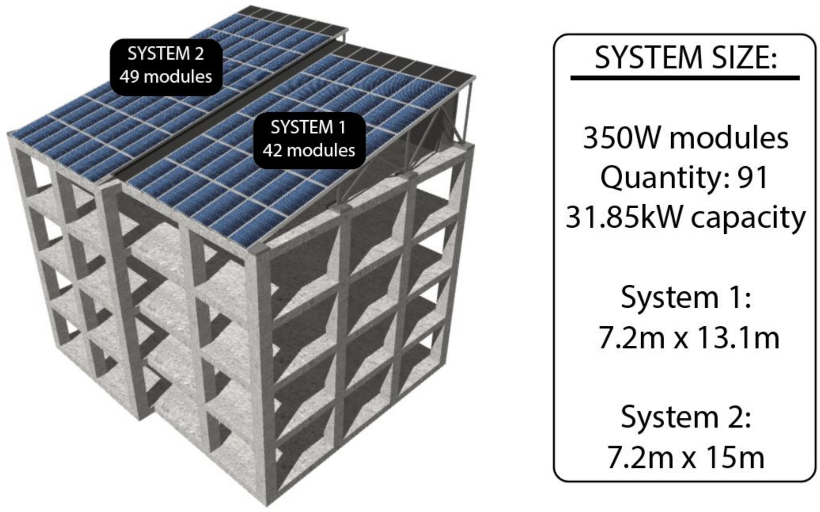

Fig. 10: Size of BIPV/T rooftop system

The focus of this design is on common building practices and previous lack of true integration between façade and PV/T systems. The design offers the potential for modular and unitized designs, primarily for large scale applications, as well as architectural and visual continuity. The mechanical equipment sizing is ongoing, so available area for this was determined under the system (Figure 11).

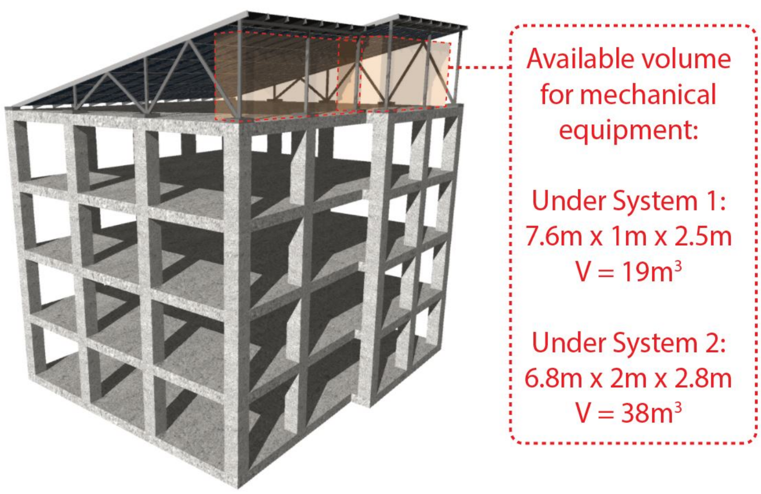

Fig. 11: Available area under BIPV/T system for mechanical equipment

Figure 12 shows an architectural section through the BIPV/T roof, indicating a simple framing attachment to the reinforced concrete building frame. The sides of the system would be open to allow for some air movement as closing this space with paneling would increase the temperatures between the BIPV/T system and the roof.

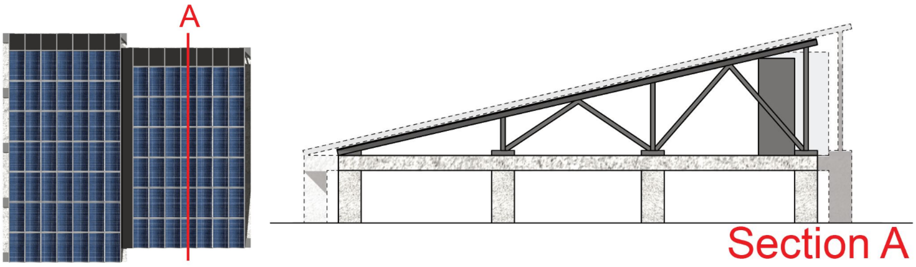

Fig. 12: BIPV/T Plan view (left) and section through the system, framing and building structure (right)

4. Modeling and Results

Preliminary performance calculations were performed based on a model validated with the experimental results of prototype testing. For a roof coverage of 180 m^2 and average summer day conditions in Chennai, India, a typical system would have an electrical output of 147 kWh and a thermal output of 228 kWh. Figure 13 shows the total monthly values of electrical output, with a conservative inverter efficiency of 85%. Maximum outlet temperatures of the air passing through the air channel would be over 60°C for more than 5 hours throughout the day. A glazed solar thermal collector added to the end (top) of system could further boost air temperatures to over 70°C, at which point the air can be used for an absorption cooling system. These values were based on a design that included 9 strings of 10 PV modules each and which had a capacity of 27 kWp, less than the final design shown in the previous section.

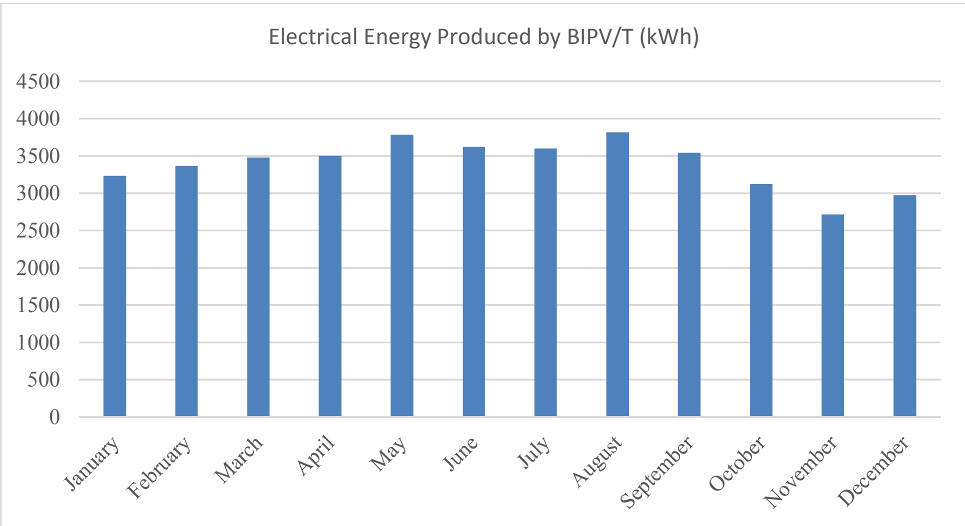

Fig. 13: Monthly electrical production (AC) of the BIPV/T system ("PVWatts Calculator," n.d.)

Figure 14 shows the PV electrical production offset from the initial energy demand of the building. The values shown are for a base case scenario, without improved insulation, fenestration, airtight design, and a properly controlled cooling system. As the project progresses, passive design strategies will be implemented prior to the BIPV/T system.

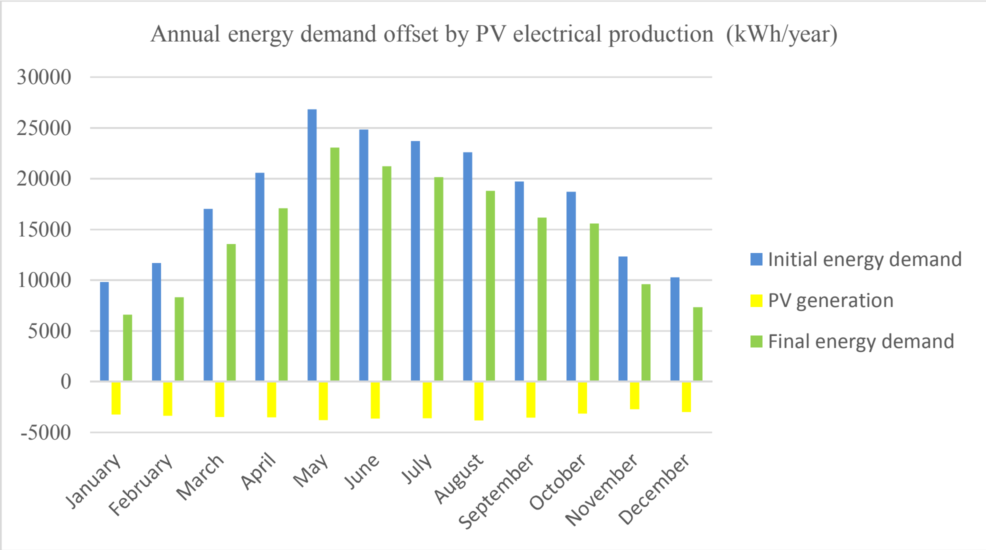

Fig. 14: Monthly totals of building energy demand before (blue) and after (green) addition of BIPV/T electrical energy production (yellow)

5. Conclusion and Future Work

A lightweight BIPV/T system has been introduced as a solution to provide local, affordable energy for low-rise, mixed-use buildings in India. A system covering a roof of approximately 180 m^2 can produce up to 147 kWh of electrical energy and 228 kWh of thermal energy on a typical summer day. The heat extracted can be used in a thermally driven cooling system. However, it is important to reduce building energy loads by passive design strategies prior to implementing energy generating technologies such as BIPV/T.

The next step for this project is to calculate the annual electrical and thermal performances of the system if it were characterized as a BIPV/T system. The water storage tank (which takes up approximately 20% of the rooftop), air collecting manifold and heat exchanger must all be positioned in a way that it does not interfere with the continuity of the BIPV/T system. Due to the hot climate, any resulting hot air from the system will best be used in a vapor absorption refrigeration system since the building needs to be cooled far more than heated. Additionally, using preheated air directly in the HVAC system would not work for cooling and would raise the indoor relative humidity. Other heat driven cooling systems are currently being researched.

6. References

Bambara, J., 2012. Experimental Study of a Façade-integrated Photovoltaic/thermal System with Unglazed Transpired Collector. Concordia University.

Global Solar Atlas [WWW Document], n.d. URL http://globalsolaratlas.info/?c=19.890723,81.452637,5&s=13.09,80.27&m=sg:ghi (accessed 4.3.18).

India Transforms Market for Rooftop Solar [WWW Document], n.d. URL http://www.worldbank.org/en/news/feature/2017/12/07/india-transforms-market-for-rooftop-solar (accessed 4.3.18).

Kruglov, O., Rounis, E.D., Athienitis, A.K., Ge, H., 2017. Experimental investigation and implementation of a multiple-inlet BIPV/T system in a curtain wall, in: Proceedings of the 15th Canadian Conference on Building Science and Technology. Vancouver.

National Disaster Management Authority, 2013. Seismic Vulnerability Assessment of Building Types in India.

PVWatts Calculator [WWW Document], n.d. . U.S. Dep. Energy, Off. Energy Effic. Renew. Energy. URL https://pvwatts.nrel.gov/ (accessed 9.7.18).

Reinforced concrete portal frame / prestressed concrete - Pujol [WWW Document], n.d. URL http://www.archiexpo.com/prod/pujol/product-89366-1447649.html (accessed 9.7.18).

Rooftop solar is the fastest-growing segment in India's renewables market — Quartz [WWW Document], n.d. URL https://qz.com/1148332/rooftop-solar-is-the-fastest-growing-segment-in-indias-renewables-market/ (accessed 4.3.18).

Rounis, E.D., Kruglov, O., Ioannidis, Z., Athienitis, A.K., Stathopoulos, T., 2017. Experimental investigation of BIPV/T envelope system with thermal enhancements for roof and curtain wall applications, in: Proceedings of the 34th European PV Solar Energy Conference. Amsterdam. DOI 10.4229/EUPVSEC20172017-6BV.3.50.

Shukla, A.K., Sudhakar, K., Baredar, P., Mamat, R., 2018. Solar PV and BIPV system: Barrier, challenges and policy recommendation in India. Renew. Sustain. Energy Rev. 82, 3314–3322. DOI: 10.1016/j.rser.2017.10.013.

Yang, T., Athienitis, A.K., 2016. A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. Renew. Sustain. Energy Rev. 66, 886–912. https://doi.org/10.1016/j.rser.2016.07.011. DOI: 10.1016/j.rser.2016.07.011.