DESIGN AND PERFORMANCE EVALUATION OF A COLORED BIPV/T SYSTEM FOR SLOPED WOOD-FRAMED ROOFS

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ABSTRACT

Building Integrated Photovoltaic Thermal (BIPV/T) systems produce both electricity and heat on-site while also achieving high architectural integration making them a great solution for increasing renewable energy capacity within urban environments. However, BIPV/T systems are still not widely used as only recently have BIPV products of different colors and easier integration become available, but are still expensive, and the heat recovery requires integration with the building heating system, as well as the envelope design. This paper presents the design development of a colored BIPV/T system for sloped roof integration and its application to different climatic conditions. A case study is conducted to demonstrate the performance and applicability of the proposed system in two different locations, namely Montreal and Athens, while also assessing the effect of weather and electricity prices in each location. The BIPV/T system achieved increased energy savings during winter for Montreal due to higher electricity demand. The COP of the solar assisted heat pump connected to the BIPV/T increased by 4.24% in Montreal and 2.8% in Athens during winter. Finally, the economic analysis highlighted the importance of net metering in both locations as it significantly reduced payback periods, making the BIPV/T system more financially attractive.

1 INTRODUCTION

More than half of the world's population is living in cities accounting for 75% of the global energy consumption and 70% of global CO_2 emissions (United Nations, 2023),(International Energy Agency, 2021) highlighting the need to increase distributed renewable energy generation within urban environments. The required acceleration of renewable energy deployment coupled with the increasing electrification of buildings stresses the importance for a profound and systemic transformation of the Architecture, Engineering and Construction (AEC) sector. Buildings need to become smart, interconnected, highly energy efficient, and powered and heated or cooled predominantly by renewable energy (Renewable Energy Agency, 2023).

With the integration of renewable energy technologies into the building envelope, buildings can become active components of the energy network by consuming, producing, storing, and supplying energy and thus play a key role in achieving distributed renewable energy generation within urban environments. As photovoltaic (PV) technologies have reached grid parity, solar building envelopes can provide a cost-effective solution to transform buildings from consumers to prosumers. Building integrated photovoltaic (BIPV) systems are part of the building envelope itself replacing conventional building materials such as cladding, roof tiles and curtain walls. However, the vast majority of BIPV installations are roofs due to the better sun exposure which can optimize energy production. By adding thermal recovery to BIPV systems, heat can also be collected and used, increasing the overall efficiency. These systems are commonly referred to as building integrated photovoltaic / thermal (BIPV/T) systems and can be coupled with the building HVAC where the collected heat can be used for pre-heated ventilation air, at the source side of a heat pump, for domestic hot water and for thermal storage charging amongst others.

https://doi.org/10.52202/077185-0052

Compared with conventional PV panels, BIPV/Ts exhibit several advantages including (Pillai et al., 2022):

- serving dual functions as both building envelope components and renewable energy generators,
- achieving higher architectural and aesthetic value,
- provide large areas for installation in dense urban environments,
- reduce electricity transmission losses by producing and utilizing energy on-site,
- reduce capital costs by replacing conventional building materials.
- producing more energy (electricity & heat) per m^2

As BIPV is primarily installed in urban environments it is important they are well integrated technically as well as aesthetically to achieve broader social acceptance. The recent progress in the BIPV field has allowed for a wide array of customization options regarding the appearance of the BIPV products to become available such as colored or transparent BIPV. This gives greater flexibility in the design of solar envelopes, which is especially important in sensitive urban areas or in the case of protected heritage buildings. Different coloring techniques can be used to hide the PV cells and alter the appearance of the BIPV module. However, this commonly involves adding a type of colored layer or print in front of the PV cells thus reducing the irradiance that reaches the cells and decreasing the electricity production. The reduction depends on the coloring technology used (Eder et al., 2019). Different coloring techniques include (Eder et al., 2019):

a. *Anti-reflection coatings on solar cells:* As bare crystalline silicon (c-Si) presents high reflectance values (around 30 %), an antireflective coating is added on their surfaces. By varying the antireflective coating thickness a shift in color can be achieved.
b. *Coloured and/or semi-transparent PV-active layers*: Semi-transparency of the PV cells themselves can be achieved with some PV cell technologies such as amorphous silicon PV modules (a-Si) or cadmium telluride (CdTe) technology.
c. *Interlayers with colours:* A cost-effective solution involves laminating an interlayer with a specific color or pattern within the module as an extra encapsulant sheet or coloring the encapsulant or backsheet itself.
d. *Coloured polymeric encapsulant films:* The combination of a-Si technology with coloured polyvinyl butyral as the back encapsulant can result to a coloured PV glass with different levels of transparency. As the coloured back encapsulant is added in back of the PV layer the energy output is not affected.
e. *Front glass surface techniques:* Different surface treatments can be applied to the front glass cover to achieve different colors or patterns. Different methods include i) Spectrally selective coating, ii) Coloured enamelled (or fritted) glass, iii) Sandblasting, iv) Digital glass printing.

As BIPV/T is an active element of the building by generating energy on-site, an important element to consider during the design is the management of the produced electricity and heat HVAC integration applications. Air-source heat pumps play an important role in the electrification and decarbonization of the heating sector, however their usage is restricted in cold climates due to reduced heating performance. During the winter months when exterior temperatures drop below 0°C the heat pump capacity and coefficient of performance (COP) can be significantly decreased. Solar-assisted heat pumps have gained popularity as they mitigate the risk of freezing and achieve a higher COP by attaining warmer source-side temperatures (Dumoulin et al., 2021; Kamel & Fung, 2014; Tardif et al., 2017).

A significant barrier to widespread adoption of BIPV/T systems is the lack of an appropriate business case which can convince an investor or client that BIPV/T is an attractive investment (Eiffert & Thompson, 2000; PVPS, 2020). Besides the direct economic impacts, a BIPV/T can produce such as reducing the constriction material costs and electricity costs there are numerous other indirect economic impacts such as increase property resell value or tax benefits due to environmental emissions reduction which are commonly not included in the investment analysis (Eiffert & Thompson, 2000; PVPS, 2020).

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Different economic indicators are used to assess the life cycle cost including Net Present Value (NPV), Levelized Cost of Energy (LCOE), Discounted payback period (DPB) (Amoruso & Schuetze, 2022),(Li et al., 2023),(Rad et al., 2021).

This paper presents the design development of a colored BIPV/T system for sloped roof integration and its application to different climatic conditions. Through this research the authors aim to evaluate the application of colored PV panels for BIPV/T systems and develop a unified system tailored for sloped wood-framed roofs. A case study is conducted to demonstrate the performance and applicability of the proposed system in two locations while assessing the effect of weather and electricity prices and sources in each location.

2 SYSTEM DESIGN & MODEL DEVELOPMENT

This section describes the design process of the colored BIPV/T system as well as the energy model development and validation against experimental data.

2.1 System Design

For this BIPV/T system colored PV panels were selected which are connected to a framing system targeted towards building integration. This system transforms frameless standard PV modules into solar tiles for sloping roofs. The system allows for an overlapping between the panels which prevents water penetration within the roof structure but at the same time can allow some air to pass through creating a multi-inlet BIPV/T system which can achieve higher thermal efficiency (Yang & Athienitis, 2015). Furthermore, the system is designed to withstand heavy snow loads. A dark red brown (terracotta) color was selected to be used for the PV panels. The color is achieved from ceramic pigments that are fused into the front glass of the PV. The final appearance of the system is aimed to resemble traditional clay tile roofs which can broaden the application of BIPV/T systems to heritage buildings without compromising their architectural value.

A custom wood framed mounting system was developed to represent the roof structure in which the PV panels will be placed on. With this design a continuous mechanically ventilated air channel is placed right under the panels which serves two purposes: a) Ventilates the PV panels. Circulating air behind the PV modules enables the extraction of heat, and effectively cools the PV surface. This can enhance electrical performance and prolong the life expectancy of the PV system. b) Collects the heated air. The heated air from BIPV/T systems can be used for various thermal applications including preheated ventilation air, source for an air-source heat pump or thermal storage charging.
Figure 1 illustrates the manufactured experimental prototype of the system as well as a schematic of a full-scale system.

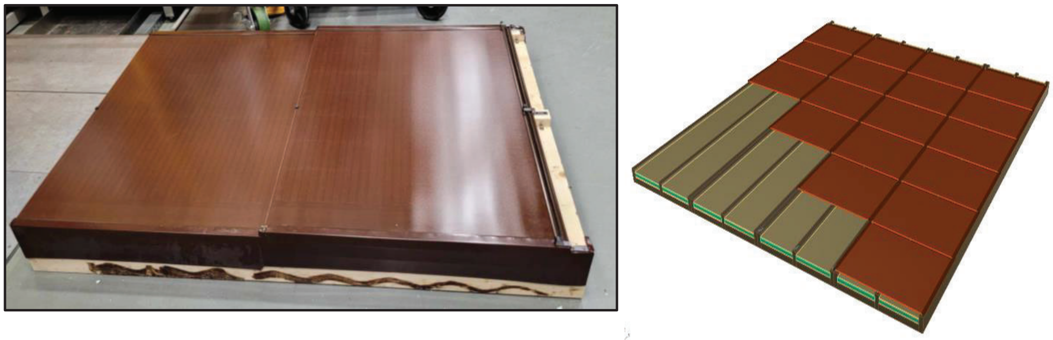

Figure 1: Experimental prototype (left), Schematic of full-scale system (right)

Optimal coupling of BIPV/T with the building energy system can effectively increase their energy efficiency and thus, also impact their cost-effectiveness, highlighting the importance of considering BIPV/T-HVAC integration in the early design stages. The most common applications for the heated air

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include coupling with an Energy Recovery Ventilator (ERV) or an air-source heat pump. BIPV/T-ERV applications can help decrease the consumed energy required for heating the ventilation air. However, as the efficiency of commercially available ERV units is already quite high this option often does not achieve high energy reductions. Additionally, if the airflow sent to the ERV is not optimally controlled it can lead to overheating of the air which can ultimately have adverse effects by increasing the energy consumption for cooling. In this study the BIPV/T is connected to an air-source heat pump to reach a higher COP by achieving warmer source side temperatures.

2.1 Model Development and Validation

Air-based BIPV/T systems consist of the PV layer, an air-channel where the air circulates and extracts heat from the PV modules and the back layer which is part of the building envelope (exterior wall or roof with insulation). A steady-state BIPV/T model is developed for this study using the thermal network method with finite control volumes. In order to simplify the BIPV/T thermal modeling the following assumptions were made: 1) The temperatures of the surfaces are assumed to be uniform inside the control volume, 2) The temperatures of the solar cells, the air within the channel and the insulation vary only in the direction of flow of the air (1-D simulation within the control volume), 3) The fluid medium is assumed to have a uniform velocity profile and an average fluid velocity throughout the channel, 4) The heat loss from the sides of the system is negligible. Figure 2 illustrates a 3D model of the BIPV/T system as well as a 1-D schematic representing the energy balance of a control volume of the BIPV/T system. Further details on the BIPV/T model development method can be found in (Sigounis et al., 2023).

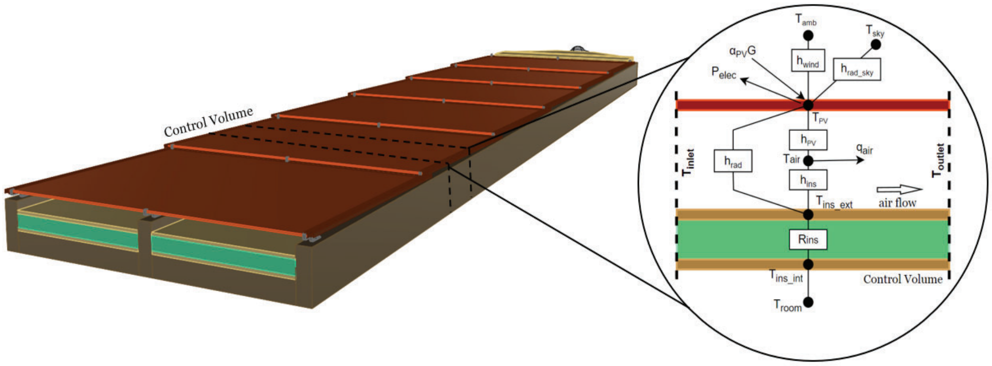

Figure 2: 3D model with 1D schematic of the energy balance of a control volume

The model is validated using experimental data from a series of experiments conducted for a multi-inlet BIPV/T system in the Solar Simulator and Environmental Chamber (SSEC) laboratory at Concordia University by Yang and Athienitis (Yang & Athienitis, 2015). The error between the model outputs and experimental data, is quantified by the Normalized Root Mean Square Error (NRMSE) formulated as:

$$NRMSE = \frac{\sqrt{\sum_{i=1}^{n}\frac{(\hat{T}_{outlet_i}-T_{outlet_i})^2}{n}}}{T_{outlet_{max}}-T_{outlet_{min}}} \tag{1}$$

where, $\hat{T}_{outlet}$ is the predicted outlet temperature, T_{outlet} is the measured outlet temperature, and T_{outlet_max} T_{outlet_min} are the maximum and minimum measured temperatures respectively.

The validation resulted in a NRMSE = 0.085 for the outlet temperature of the system indicating a good fit between the predicted and actual values.

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3 CASE STUDY

To demonstrate the potential application of this system in diverse geographic locations, a case study is conducted. The system is implemented in two distinct locations, and an analysis is performed to assess its energy efficiency and economic viability of the system at each location.

3.1 Climatic Conditions and Building Characteristics

The simulations for the case study were run for one year with climatic data for Montreal, Quebec, Canada and for Athens, Greece. Table 1 shows some climatic and geographic characteristics for each location.

Table 1: Climatic characteristics for each location, (ASHRAE, 2020; Solargis, n.d.)

Parameter	Montreal	Athens
Lat/Long	45.467/ -73.75	37.936/ 23.944
Annual Global Horizontal Irradiance (kWh/m^2)	1350	1700
Annual Avg. dry bulb temperature (°C)	7.5	17.5
HDD18.3	4257	1259
CDD10	1387	2876
Climate Zone (ASHRAE)	6A	3A

The reference building used in this paper is a two-story residential building with a south-facing sloped wood-framed roof. The building was modelled in the Rhinoceros environment using Grasshopper, while the plug-in Honeybee which uses the EnergyPlus engine, was used for the energy calculations. Table 2 provides the key properties of the building envelope and technical systems for each location.

Table 2: Characteristics of the building model and building equipment

Parameter	Montreal	Athens
Floor area (m^2)/storey	60	60
U-value external wall (W/m^{2}K)	0.25	0.39
U-value roof (W/m^{2}K)	0.19	0.38
U-value window (W/m^{2}K)	2.12	2.52
WWR (%)	S: 40, W & E: 20, N: 10	S: 40, W & E: 20, N: 10
Heating COP	$0.0007 \cdot {T_{supply_{air}}}^2 + 0.0956 \cdot T_{supply_{air}} + 3.842$	$0.0007 \cdot {T_{supply_{air}}}^2 + 0.0956 \cdot T_{supply_{air}} + 3.842$
Cooling COP	3.5	3.5
Heating setpoint/ Setback (°C)	21/18	21/18
Cooling setpoint	23	23
Schedule (occupancy)	00:00-06:00 & 17:00-00:00	00:00-06:00 & 17:00-00:00
Occupant density (m^2/person)	30	30
Plug loads (W/m^2)	10	10
Electric lighting (W/m^2)	7	7

A data-based model of an air-to-water heat pump using performance data available from the manufacturer was developed (Dumoulin et al., 2021). For this work the HP requires an air flow rate of 0.83 kg/s, has a reference COP of 2.75 and heating capacity (HC) 11.5 kW for air and water temperature 0°C and 40°C respectively. The equation of the COP for the heat pump is given in Table 2. The supply air is provided from the BIPV/T during winter. In summer, the BIPV/T is used only for electricity production while the circulating air serves solely to cool the PV modules and is then discarded. For cooling a different heat pump is assumed with a steady COP of 3.5.

3.2 BIPV/T system

The BIPV/T system covers the whole south-facing part of the roof. The dimensions and specifications of the BIPV/T system for each location are shown in Table 3.

Table 3: Characteristics of the building model and building equipment

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Parameter	Montreal	Athens
South-facing roof dimensions (m)	5.5 x 10	5.1 x 10
South-facing roof inclination	40°	35°
BIPV/T channel depth (m)	0.04	0.04
PV cell technology	mono c-Si	mono c-Si
PV nominal electrical efficiency (%)	18	18
Power Peak (Wp)	210	210
Voc (V)	33.97	33.97
Isc (A)	8.68	8.68

It should be noted that due to the colorization of the modules less incident irradiation reaches the PV cells which leads to decreased electrical performance compared to traditional PV modules. The decrease in electrical performance for the PV module used in this study was evaluated at 18%. Additionally, colored PV modules typically incur higher costs than traditional modules, thereby potentially impacting the overall life cycle cost of the system. On the other hand, colored PV can be applied to a wider range of building types and surfaces providing greater flexibility for PV integration in the built environment while still achieving high energy generation. A comparative analysis between traditional and colored PV modules in terms of both energy performance and life cycle cost is beyond the scope of this study, however, is part of future planned work.

3.3 Key Performance Indicators

Energy Savings

The total energy consumption of the building is calculated using the following equation:

$$E_{net} = \left(\frac{Q_{heat}}{COP_h} + \frac{Q_{cool}}{COP_c} + Q_{light} + Q_{plug}\right) - E_{PV} \tag{2}$$

where, Q_{heat}, Q_{cool} are the heating and cooling demands, E_{light} and E_{plug} are the lighting and plug loads, E_{PV} the produced electricity from the PV panels and COP_h, COP_c are the coefficients of performance for the heat pumps.

The energy savings are then quantified by subtracting E_{net} from the energy consumption of a refence case scenario for each location. The reference case consists of the same building but without the addition of the BIPV/T system. The energy savings thus will be given by:

$$E_{savings} = E_{net\_ref} - E_{net\_bipvt} \tag{3}$$

where, E_{net_ref} is the total energy consumption for the reference house without the BIPV/T and E_{net_bipvt} is the house with the BIPV/T.

Load Matching

One of the ongoing challenges of solar systems is the mismatch between generated energy and energy demand. Besides energy saving potential the load matching between the BIPV/T generation and consumption profile of the building is also assessed through the calculation of the load matching time (%). The indicators used for this purpose include a) self-consumption rate (Sc) which indicates the share of the total BIPV/T energy which is consumed locally and b) self-sufficiency rate (Ss) which indicates the average hourly contribution of the BIPV/T system on the building loads (Skandalos & Karamanis, 2021).

$$S_c(\%) = 100 \cdot \left(\frac{E_{BIPV/T\_consumed}}{E_{BIPV/T}}\right) \tag{4}$$

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$$S_s(\%) = 100 \cdot \left(\frac{E_{BIPV/T\_consumed}}{E_{building}}\right) \tag{5}$$

where, $E_{BIPV/T\_consumed}$ is the amount of electricity generated by the BIPV/T system that is consumed on-site, $E_{BIPV/T}$ is the total amount of electricity generated by the BIPV system and $E_{building}$ is the total energy demand of the building.

In Quebec, Canada, where heating is predominantly electric, peak periods of electricity demand occur during very cold days from December until March 6 to 9am in the morning and in the evenings from 4 to 8 pm. This highlights the importance of reducing electricity demand during these hours. As efforts progress towards decarbonizing the heating sector through electrification, similar patterns are expected to emerge in other regions globally. In this study the effect of BIPV/T on the flexibility potential of the building for these peak demand periods is also evaluated. However, optimal results for harvesting the energy flexibility of buildings are expected with the combined use of BIPV(/T), energy storage and optimal control strategies.

Life Cycle Cost Analysis

The evaluation of the investment cost for the BIPV/T system is conducted by determining the Net Present Value (NPV). If NPV > 0 the BIPV/T project is economically feasible; the total cost is recovered within the life cycle of the BIPV/T project. However, if NPV<0 the BIPV/T project will not generate sufficient income to recover its costs within the project's life cycle. The NPV is given by:

$$NPV = I_c + \sum_{t=1}^{N} \frac{F(t)}{(1+r)^t} \tag{6}$$

where Ic is the initial investment cost (€), F(t) is the annual generated income for each year (€/year), N is the lifetime of the BIPV system and r is the real rate of interest for each location.

Table 4 lists the key parameters considered in the financial assessment of the BIPV/T systems. This study primarily focused on the preliminary and feasibility stages of the project thus maintenance costs were limited to the replacement of the inverter every 10 years, given its prominence as the most significant operational and maintenance expense over the BIPV/T lifecycle.

Table 4: Parameters for BIPV/T financial assessment

Parameter	Montreal	Athens
PV self-consumption (%)	40	38.4
Electricity savings (kWh)	207	724
Average BIPV/T cost (€/m^2)	346	346
Average cost of conventional ceramic tiles (€/m^2)	65 € (Gholami & Røstvik, 2020)	65 € (Gholami & Røstvik, 2020)
Inverter replacement cost	10% (Skandalos & Karamanis, 2021)	10% (Skandalos & Karamanis, 2021)
Inverter lifecycle (years)	10	10
Electricity tariff (€/kWh)	Rate D: first-tier rate (up to 40kWh): 0.0443 second-tier rate (rest): 0.068 (Hydro Quebec, n.d.-b)	0.179 (ΔEH, n.d.)
Electricity tariff inflation rate	1.82 (Hydro Quebec, n.d.-a)	1.8 (Gholami & Røstvik, 2020)
Real interest rate (%)	2.1 (TradingEconomics, n.d.)	1.6 (TradingEconomics, n.d.)
BIPV/T lifecycle (years)	30	30

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4 RESULTS & DISCUSSION

This section presents the key findings of the analysis as well as a thorough discussion.

4.1 Energy Savings

Figure 3 illustrates the monthly energy savings attributed to the BIPV/T addition for each location. A notable observation is that in Montreal, a heating dominated climate, the energy savings exhibit pronounced peaks during the winter months in contrast to Athens. Nonetheless, in both cities, energy savings remain considerable during the summer period owing to increased sunlight availability, leading to enhanced electricity generation from the BIPV system. In regard to the thermal production of the BIPV/T specifically, the solar assisted heat pump exhibited an average increase of 4.24% in Montreal and 2.8% increase in Athens during the winter months.

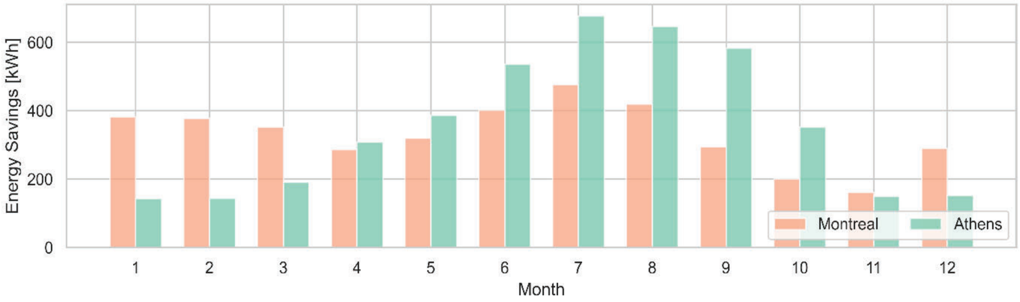

Figure 3: Monthly Energy Savings

4.2 Load Matching

Figure 4 shows the monthly self-consumption and self-sufficiency rate for both cities. The self-consumption rate indicates the proportion of the energy generated by the BIPV/T system which is consumed on-site while the self-sufficiency refers to the degree to which the BIPV/T system could meet the building energy demands. In Montreal both the self-consumption and self-sufficiency are higher during the winter months compared to Athens which indicates the higher energy demand during those months. Regarding the seasonal variation, in Montreal, high PV generation in combination with lower electric needs led to a surplus of energy, decreasing the PV- self consumption during shoulder seasons. However, due to the increased need for cooling in Athens self-consumption is increased during summer. In both cities the self-sufficiency rate is higher during the summer months which could be attributed to increased daylight hours and solar energy generation during the summer.

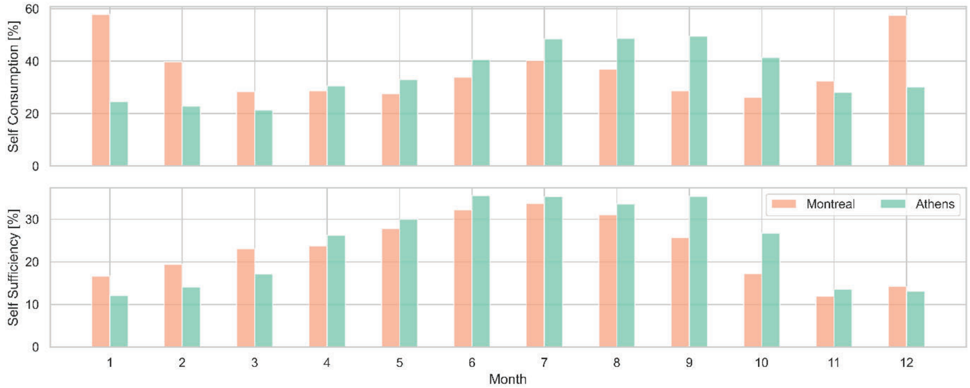

Figure 4: Monthly Self Consumption and Self Sufficiency

Figure 5 and Figure 6 illustrate the daily average PV generation and electricity consumption (heating/cooling/lighting) profiles for the two studied cities. The electricity consumption profile of the

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building closely follows the building occupancy. Electricity needs are higher in winter compared to summer months in Montreal. Peak load occurs in the morning and evening, while heating is necessary even outside occupancy hours in winter. Highlighted with green are the peak demand hours for which it is important to reduce electricity demand as previously described in section 3.3. With the addition of the BIPV/T the demand was reduced by 26% during the morning peak and by 3.5% during the evening peak for Montreal while for Athens the 17% and 1.3% respectively. Utilizing advanced control strategies such as Model Predictive Control (MPC) and integrating electric and thermal storage solutions into the building's design can help maximize the energy flexibility potential, especially during the evening peak period when the effectiveness of the BIPV/T is reduced due to sunset.

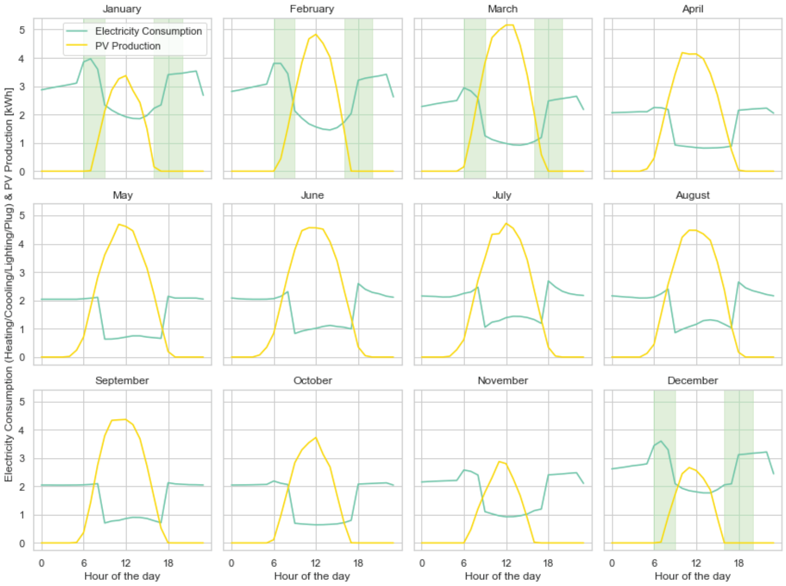

Figure 5: Daily average generation profiles of the BIPV/T system and comparison with the average building electricity consumption (Montreal)

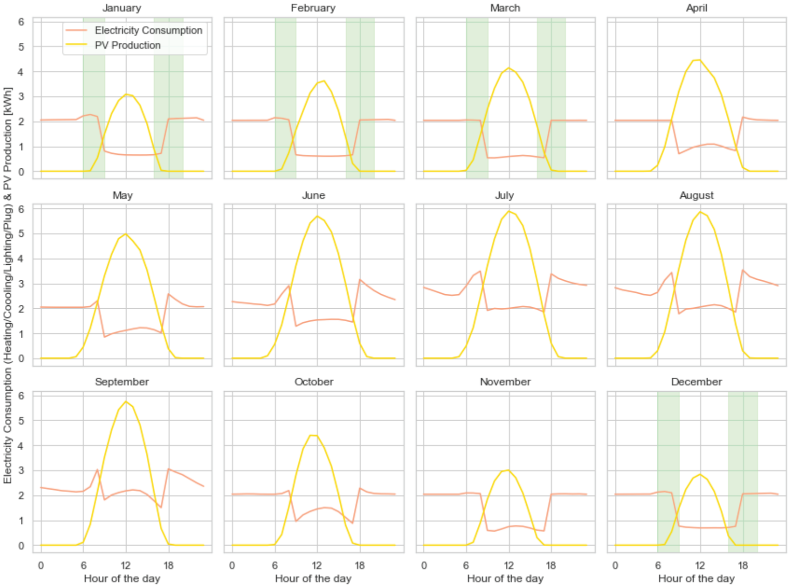

Figure 6: Daily average generation profiles of the BIPV/T system and comparison with the average building electricity consumption (Athens)

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4.3 Economic Analysis

The cumulative sum of anticipated cash inflows (benefits) and outflows (expenditures) throughout the projected lifespan of the investment (expected to be 30 years) was assessed and utilized to compute the Net Present Value (NPV) index. Figure 7 shows the cumulative NPV throughout the BIPV/T lifespan for both cities both with and without the net metering option. Net metering is a billing arrangement used by utilities that allows owners of PV systems to receive credit for the electricity they generate and feed back into the grid. This is especially beneficial when a mismatch between energy production and building loads occurs as the excess electricity is exported to the grid and is given back to the customer in the form of credits.

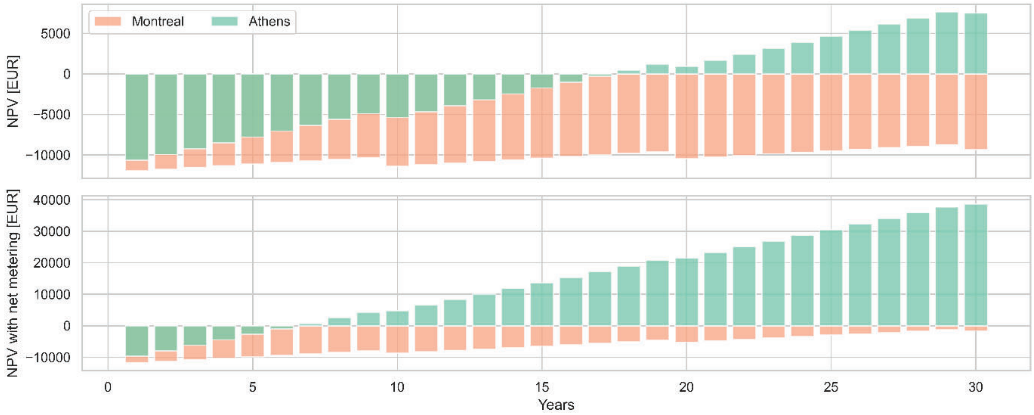

Figure 7: Net Present Value (NPV) associated with the investment of the BIPV/T

As can be seen in Figure 7 net metering can play a significant role in the economic feasibility of BIPV systems. For Athens without net metering the BIPV/T payback period occurs in year 18, however with net metering this drops to year 7. Similarly, the net metering option significantly increases the NPV for the BIPV/T in Montreal. However, the NPV in Montreal remained negative mostly due to the significantly lower electricity prices. Nevertheless, indirect savings which are not considered in this study such as increased property resell value, tax benefits due to environmental emissions reduction and reduction of transmission losses could make BIPV/T systems an attractive investment. Additionally, the resilience provided by energy self-production should be acknowledged as a significant benefit, particularly in light of current and anticipated climate shocks and disasters.

5 CONCLUSIONS

The transformation of buildings to solar generation systems can aid the evolution of the energy sector towards a decentralized and environmentally sustainable system with BIPV playing an essential role in meeting the increasing demand for zero-energy and zero-carbon buildings. In this study the design development of a colored BIPV/T system for sloped roof integration and its application to different climatic conditions was presented. As BIPV is primarily installed in urban environments the addition of color can give greater flexibility in the design and broaden the surfaces where BIPV can be applied to. A case study where the developed system is applied to different climatic conditions was conducted to demonstrate the performance and applicability of the proposed system in different locations which exhibit distinct weather conditions, diverse sources of electricity, and differing electricity prices, allowing for a comprehensive analysis across varied environmental and economic conditions.

The BIPV/T system offered increased energy savings during the winter months for Montreal due to higher electricity demand while both cities exhibited considerable energy savings during summer. The heated air from the BIPV/T increased the heat pump COP by 4.24% and 2.8% in Montreal and Athens respectively. The higher COP increase in Montreal can be attributed to the lower outdoor temperatures and a higher ΔT achieved by the BIPV/T during winter.

The load matching analysis reveals the importance of considering self-consumption and self-sufficiency rates, which vary seasonally and between cities. Higher self-consumption rates are observed during

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winter months in Montreal while Athens exhibits increased self-consumption during summer due to higher cooling demands. Advanced control strategies, such as Model Predictive Control (MPC), and the integration of storage can maximize the energy flexibility potential of buildings, particularly during peak demand periods.

The economic analysis underscores the importance of net metering in enhancing the economic feasibility of BIPV/T systems. Notably, net metering significantly reduced payback periods and increases the NPV, making BIPV/T systems more financially attractive. However, indirect savings, such as increased property resell value, environmental benefits, and resiliency, should also be factored into investment decisions.

NOMENCLATURE

a-Si	Amorphous Silicon	Q_{heat}	Heating loads (kWh)
BIPV	Building Integrated Photovoltaic	Q_{light}	Lighting loads (kWh)
BIPV/T	Building Integrated Photovoltaic Thermal	Q_{plug}	Plug loads (kWh)
CdTe	Cadmium Telluride	$E_{savings}$	Energy savings (kWh)
CIGS/CIS	Copper Indium Gallium Selenide	E_{net_ref}	Energy consumption reference case (kWh)
COP	Coefficient of Performance	E_{net_bipvt}	Energy consumption bipvt case (kWh)
c-Si	Crystalline Silicon	S_c	PV self consumption (%)
DPB	Discounted Payback Period	E_{PV}	PV produced electricity (kWh)
ERV	Energy Recovery Ventilator	NPV	Net Present Value (€)
HP	Heat Pump	μ-Si	Micromorph Silicon
HVAC	Heating Ventilation and Air Conditioning	LCOE	Levelized Cost of Energy
LCCA	Life Cycle Cost Analysis	Q_{cool}	Cooling loads (kWh)
PV	Photovoltaic	S_s	PV self sufficiency (%)
WWR	Window to Wall Ratio	QTO	Quantity Take Off

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ACKNOWLEDGEMENT

This work was supported by a NSERC/Hydro Quebec Industrial Research Chair. Anna-Maria Sigounis would like to acknowledge the financial support received though an NSERC Postgraduate Scholarship-Doctoral (PGS D) and through a Doctoral Research Scholarship from Fonds de recherche du Québec - Nature et Technologies.

https://doi.org/10.52202/077185-0052