Optimization of building-integrated photovoltaic/thermal-thermal storage systems for domestic hot water in cold climate

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Abstract

As photovoltaic/thermal collectors are integrated with buildings to reduce net energy consumption, appropriate thermal storage design is essential to maximize their performances. A sensitivity analysis of thermal storage sizing for preheating domestic hot water was applied to a case study building in Mégantic, Canada. The methodology evaluated the performance of the studied system over different seasonal weather conditions to optimize the design for yearly operation. The enhanced storage configuration utilizing a ratio tank volume per solar area of 0.048m was found to improve preheating performance by approximately 28%, electrical generation by 1.8%, and meet over 60% of the weekly domestic hot water load depending on weather conditions.

Introduction

Solar renewable in buildings presents a great opportunity to reduce building energy net demand and achieve net-zero energy. Technologies such as hybrid photovoltaic/thermal (PV/T) collectors can significantly improve the amount of solar energy captured for a similar surface area by generating both electricity and heat. A fluid (typically air or water) is passed behind photovoltaic (PV) cells capturing the not-converted remaining solar energy as heat. The effects can enhance electricity production by cooling the PV cells in addition to significantly improving the overall total efficiency of the solar panels from close to 20% for a typical PV panel to close to 80% for PV/T (Al-Waeli et al., 2017).

Although the amount of energy captured is significantly greater, typically heat is less favorable than electricity since it can mostly be utilized for heating purposes with only a few exceptions. Additionally, yearly incident solar radiation is greater during the summer months where the need for heat is often reduced even in colder climates. In this way, building domestic hot water (DHW) is an ideal candidate to utilize the generated solar heat during the entirety of the year even when space heating needs are low. DHW represents over 14% of buildings' energy consumption in the province of Quebec, Canada (État de l'énergie Au Québec, 2023).

Another consideration of hybrid energy generation is that the heat generated is reduced compared to standard solar collectors with temperature output too low for most heating applications (Herrando et al., 2023). Additionally, PV/T designs such as the glazed and unglazed have significant thermal performance differences. Unglazed PV/T have greater heat losses to the environment from the wind and exterior temperature conditions, while glazed PV/T collector reduces these limitations but can overheat during warmer conditions affecting the electrical efficiency (Kim & Kim, 2012). In this way, optimal PV/T system design consists of increasing the collector's thermal efficiency and heat quality for heating applications without impairing electricity generation.

To meet DHW minimum temperature requirements of 60°C to limit bacteria growth PV/T systems must typically be enhanced with mechanical (heat pump) or auxiliary heating. The solar heat can however be utilized to preheat the water supply significantly reducing the energy needed to heat the DHW. Additionally, preheating minimizes added electrical heating loads and costs by eliminating costly systems. Nonetheless, appropriate dimensioning of the thermal storage is essential since it can have a large impact on the solar thermal efficiency and the final DHW heating load (Çomaklı et al., 2012).

Studies have shown that solar collectors and thermal storage sizing can significantly affect performance. Water tank sizing can vary the electrical energy production of PV/T collectors by as much as 10%, and the annual energy savings by 40% (Cirrincione et al., 2020). In this way, various studies have different optimal ratios of the storage tank volume to the solar collector area from 0.05 up to 0.5 m depending on design, conditions, and studied metrics (Baneshi & Bahreini, 2018; Cirrincione et al., 2020; Çomaklı et al., 2012; Rodríguez-Hidalgo et al., 2012).

This study aims to evaluate the ideal thermal storage design of a PV/T collector system for preheating DHW for an entire year in the Canadian climate. A sensitivity analysis highlights the challenges of maximizing the solar energy captured while maintaining the heat quality for preheating over different seasonal weather conditions.

Methodology

The studied system consists of 40 commercially available PV/T collectors totaling 75 m^2 installed on the roof of a future-planned mixed commercial and residential building in Mégantic, Québec, Canada as shown in Figure 1. The building will consist of 21 residential units, varying in size from 3 ½ up to 5 1/2. The DHW needs are assumed to be mainly for residential purposes.

Figure 1: The studied reference building located in Mégantic, Québec, Canada (Logiaction, n.d.)

The roof-installed PV/T collectors of the reference studied building will be facing 45° South-East with a 20° slope. The low slope is limited by local laws to limit the view of the installation from the streets below. In this study, a 20° slope will be compared to a 45° slope – the ideal for the local latitude – to evaluate the impact on the yearly solar energy output.

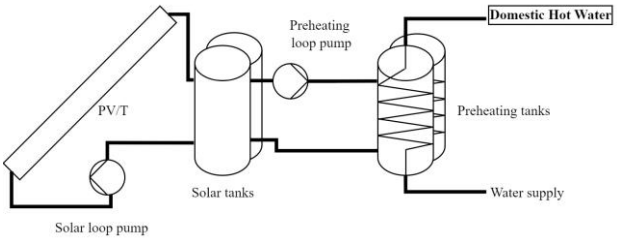

Figure 2: The studied reference PV/T-thermal storage system configuration for DHW preheating

The PV/T collectors' thermal loop is connected to multiple solar tanks without a heat exchanger. These solar tanks are then used to supply preheating tanks that have heat exchangers to preheat the city water supply before reaching the building occupants' individual DHW tanks as shown in Figure 2. The quantity of solar and preheating tanks is varied to optimize the energy and heat quality output. The PV/T collectors, thermal storage, and controls are entirely modeled with Python.

All used weather data was taken from Solcast database at Mégantic city location including the solar radiation, ambient temperature, wind speed, and direction.

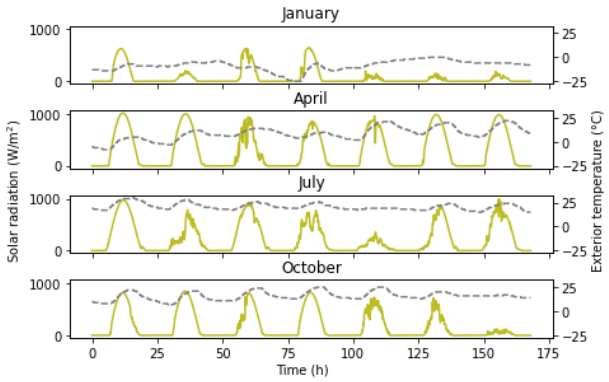

Figure 3: Historic solar radiation and exterior temperature for 1 week in January, April, July, and October 2023

The studied system is evaluated for the 4 different seasons of the year. In each case, the week with the largest amount of sunny days for January, April, July, and October 2023 were chosen from the weather data. A week was selected for the analysis to limit computational time for the sensitivity analysis. Figure 3, shows the solar radiation and irradiance on the PV/T collectors' slope of 20°. Since historical data is utilized, the amount of solar radiation available depending on the season of each of the studied weeks can vary, from 3 sunny days in January up to almost 7 sunny days in April.

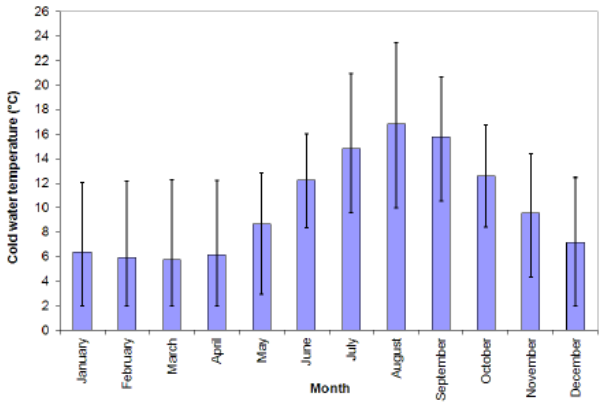

Figure 4: Water supply temperature for DHW based on a field study in Quebec, Canada (Moreau & Laurencelle, 2012)

The city water supply temperature used in the study for each of the evaluated months is based on a field study that was conducted in Quebec, Canada (Moreau & Laurencelle, 2012). Depending on the studied month, the average supply water temperature shown in Figure 4 is used.

PV/T collectors

The PV/T collectors were modelled utilizing a 1st order grey-box thermal network approach represented in Figure 5

(Pelletier-De Koninck et al., 2023). The developed model lumped thermal resistances and capacitances to simplify the collector's physical characteristics. The model was calibrated with experimental data.

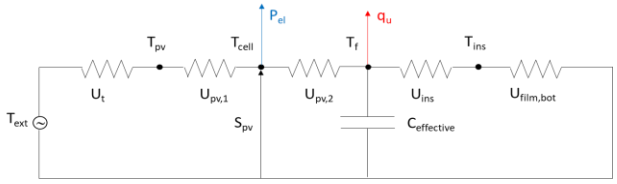

Figure 5: 1st Order thermal network of grey-box PV/T model (Pelletier-De Koninck et al., 2023)

The PV/T model was calibrated and validated from an operational retrofitted façade building-integrated PV/T-thermal storage system in Shawinigan, Quebec, Canada. The PV/T used for the calibration and validation are from the same manufacturer and have identical construction with different dimensions. In this way, the model was calibrated based on the measured electricity generation and the average solar thermal energy stored in the solar tank. The developed model showed high acceptance with the measured achieving an RMSE of 0.53 °C over 3 days in mixed conditions.

Solar tanks

The thermal storage solar tank both in the Shawinigan and the studied system hydronic loop is directly connected from the PV/T collectors to the thermal storage without a heat exchanger. Each tank consists of 450 L and is filled with 50/50 glycol-water mix to minimize potential freezing in the cold Canadian climate. The studied solar tanks are assumed to be in parallel and are charged/discharged simultaneously from the collected solar thermal energy. The tanks are modelled with 5 control volumes to evaluate the impact of stratification on the solar performance of the system. The heat tank loss coefficient was calibrated utilizing the experimental measurements to 3.25 W/m^2-K. The energy balance equation of each node is presented below.

$$C_i \frac{dT_i}{dt} = \dot{m}_1 c_p (T_{i-1} - T_i) - \dot{m}_2 c_p (T_{i+1} - T_i) + U_i A_i (T_{amb} - T_i) \quad (1)$$

Preheating tanks

Differently from the solar tanks, the preheating tanks have heat exchangers that enter the tank near the bottom and exit at the top to transfer the collected and stored solar heat to the water. The preheating tanks are identical in volume with 450 L and are assumed to have a similar heat tank loss coefficient.

The interior heat exchanger was modelled utilizing *Nash et al.* experimentally validated dynamic modelling methodology (Nash et al., 2017). The heat transfer effectiveness between the coil and the tank fluid is assumed to be one. The coil fluid inlet and outlet temperature at each node is determined by a quadratic temperature curve based on empirical measurements. The methodology was adapted to enable heating the coil instead of the coil heating the tank. The approach simplifies heat exchanger modelling utilizing empirical results reducing the need for specific physical characteristics of the heat exchanger. In this way, the energy balance at each node is presented as follows in eq. (2):

$$C_i \frac{dT_i}{dt} = \dot{m}_1 c_p (T_{i-1} - T_i) + \dot{m}_2 c_p (T_{i+1} - T_i) + U_i A_i (T_{amb} - T_i) + \dot{m}_{HX} c_{p,HX} \left(T_{in_{coil},i} - T_{out_{coil},i}\right) \quad (2)$$

To prevent temperature inversion between the nodes, the conductivity coefficient is corrected to enhance mixing between the nodes if the node temperature is lower than the one below or higher than the one above following the *Nash et al.* dynamic modelling methodology (Nash et al., 2017).

Pump controls

The pump of the PV/T loop to the solar tanks is controlled based on the temperature difference in the solar collectors and the solar tanks top node. A temperature difference of 2°C starts the operation, while a 0.5°C temperature difference stops it. The pump flow rate is based on the manufacturer's recommendation of 100kg/h per collector.

Similarly, the pump of the hydronic loop between the solar tanks and the preheating tanks utilizes identical temperature settings for its operation. The pump flow rate is fixed and set at 1800kg/h based on the existing experimental system.

DHW profile

The studied DHW demand profile is based on the average daily profile of 51 hot water withdrawal profiles for Canadian households in Quebec as shown in Figure 6 (Moreau, 2011). The profile DHW sampling was for households of 1 up to 5 occupants. In this way, in this study, the DHW profile is assumed to be constant every day to evaluate the impact of high and low solar radiation and other exterior conditions for constant hot water consumption. The profile was adjusted for the 21 residential units of the studied reference building.

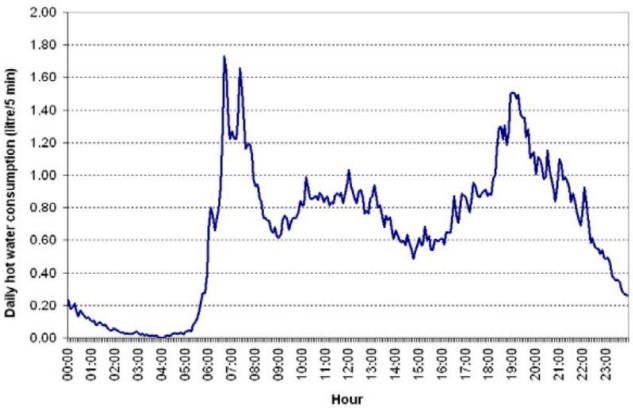

Figure 6: Single household DHW demand profile based on 51 Canadian households in Quebec (Moreau, 2011)

Results

The quantity of solar and preheating tanks where varied in a sensitivity analysis to evaluate the impact on the DHW preheating. The analysis was done both for the sunniest week in summer and winter operations to identify the ideal configuration in these extremely different weather conditions. Figure 7 shows the preheating energy differences during the summer operation.

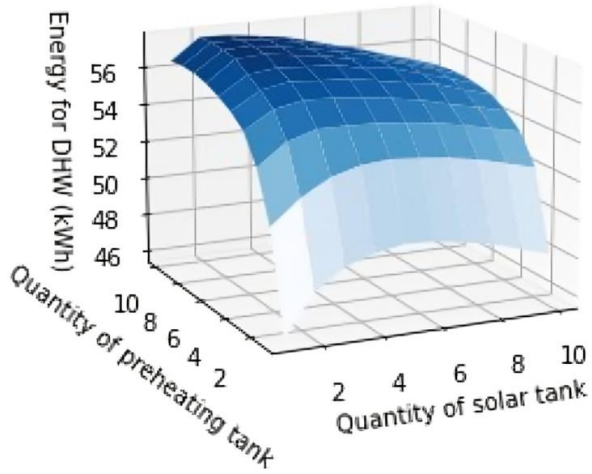

Figure 7: Solar energy used to preheat DHW based on the quantity of solar and preheating tank for a week in July

For the summer operation where there is high solar radiation, high ambient temperature, and high supply water temperature, the increasing the quantity of preheating tanks instead of solar, seems to have the largest performance gains. At 1 preheating tank, increasing the number of solar tanks up to 4 and 5 tanks (1800-2250L) enhances performance by 8.7%. However, utilizing 3 (1350L) preheating tanks with only one solar tank can improve heating performance by 19.2%. In this way, increasing the quantity of preheating tanks keeping a minimum quantity of solar tanks between 2 to 4 (900-1800L), seems to maximize DHW preheating. Nonetheless, since tanks with heat exchangers are typically almost double the cost of standard tanks, it is beneficial to prioritize increasing solar over preheating tanks to minimize costs. Therefore, a configuration of 3 solar, 3 preheating tanks for a total of 2700L and a V/A ratio of 0.048m was found to maximize performance significantly affecting costs.

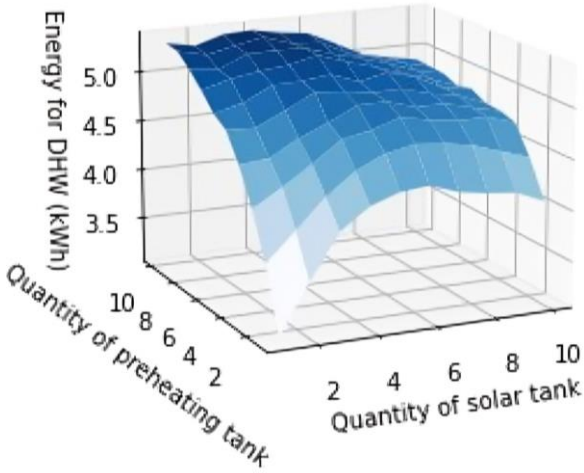

Figure 8: Solar energy used to preheat DHW based on the quantity of solar and preheating tank for a week in January

Figure 8, shows a slightly different trend when applied during winter operation. The total energy that can be used for DHW preheating is significantly reduced with lower solar radiation and exterior temperatures. Nonetheless, adjusting the amount of storage does heavily impact the quantity of stored energy that can be used for preheating. The quantity of solar tanks seems to have a greater effect on performance with 4 up to 6 tanks (1800-2700L) depending on the preheating tank configuration to maximize preheating by up to 28.3%. In the case of the preheating tanks, similarly to the summer scenario, with a minimum of 2 solar tanks (900L), the additional preheating tank improves the energy preheating by an additional 7.9 % gains. An appropriate configuration to maximize performance without affecting cost would be 2 preheating tanks (900L) combined with 4 solar tanks (1800L) for a total volume of 2700L. However, since performance gains in winter are only 1.5 kWh compared to approximately 10 kWh in summer, the optimal configuration in the summer configuration achieves similar performance in winter while improving the summer heat gains. Therefore, the 3 solar and 3 preheating tank configurations are utilized in this study for future analysis.

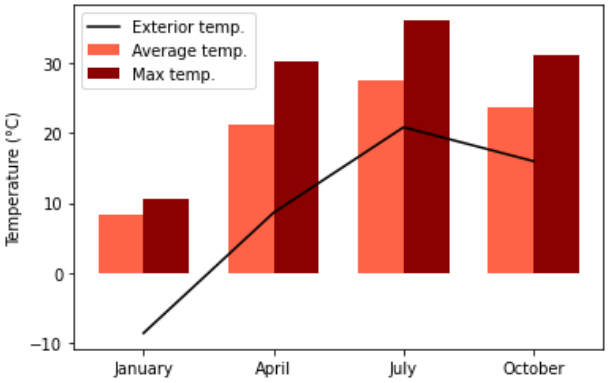

Figure 9: Average and maximum temperature of the preheated DHW based on a 3 solar and 3 preheated tanks configuration for 4 seasonal scenarios

Figure 9, shows the heat quality of the preheated DHW across the 4 seasons for the studied configuration. The maximum temperature that can be achieved with the studied DHW profile water draw is significantly reduced during January when heat generation is minimal. Nonetheless, for the other three seasons, a temperature near 30°C can be achieved with a 20°C average temperature. April presents the most average temperature gains which was enabled by the low supply water temperature as well as high solar radiation. Importantly, the studied week in January had only 3 days of high solar radiation, while the other weeks had between 5 and 7 days of sunny conditions, affecting the final average temperature results.

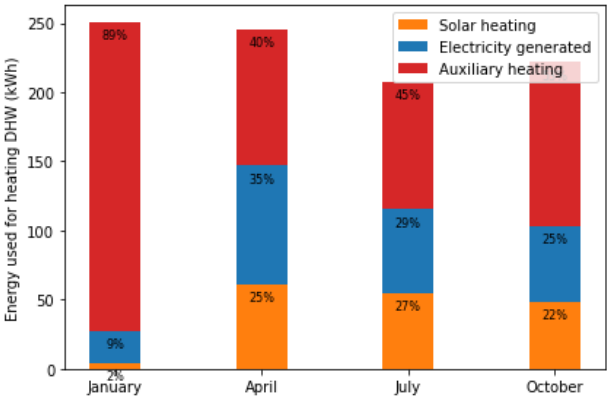

Figure 10: Distribution of the energy sources used for heating DHW based on the solar heat and electricity generated

The total energy generated and stored by the PV/T collectors used for heating DHW through the seasons is shown in Figure 10. The total energy generated by the studied reference system can meet approximately 55% of July and 60% of April DHW water load, while in January it represents only 11%. High city supply temperature lowers the energy needed to meet the heating DHW load for July and October while in April it is the high average solar radiation. The average radiation is affected by the number of sunny days in the studied weeks. The electrical generation was 54% of October and up to 83% of January of the total solar energy generated. In this way, the studied reference system can meet a significant part of the load during most of the year except in winter when the solar gains are significantly reduced.

At an optimized solar slope of 45°, winter solar heat gains can be improved. Table 1, shows the electrical PV and thermal energy generated and used for DHW preheating comparing the PV/T collectors at 20° and 45° slope.

Table 1: Electrical and thermal solar energy generated difference between a 20° and 45° PV/T slope

Month	**20° slope [kWh]**		**45° slope [kWh]**	
	PV	Thermal	PV	Thermal
January	22.44	4.52	27.16 **(+21.1%)**	9.03 **(+99.8%)**
April	86.15	60.79	86.15 **(-)**	60.79 **(-)**
July	60.19	55.04	54.05 **(-10.2%)**	50.17 **(-13.3%)**
October	54.82	48.58	54.82 **(-)**	48.58 **(-)**

Increasing the slope of the collectors does increase the winter solar generation, the electrical is increased by 21.1% and the thermal energy produced is nearly doubled compared to the reference configuration. Nonetheless, these gains represent an increase of a net 1.8% each of the total energy needed for DHW heating for both electrical and thermal increasing the winter total energy production by 3.6% or 9.24 kWh. However, the 45° slope also reduces summer energy production by 10.2% for the electrical generation and 13.3% for the thermal, which represents a total of 5.14% or 11.27 kWh of the summer weekly preheating load.

Table 2: Electrical and thermal solar energy generated and their total percentage of the total DHW heating load for a 45° and 80 PV/T configuration

Month	**45° slope and 80 PV/T (150 m^2)**		
	PV	Thermal	**Percentage of total load**
January	54.32 *(21.7%)*	16.52 *(6.6%)*	**28.3%**
April	170.40 *(69.6%)*	87.60 *(35.8)*	**105.4%**
July	106.91 *(51.5%)*	76.17 *(36.7%)*	**88.2%**
October	108.31 *(48.9%)*	74.79 *(33.8%)*	**88.7%**

Table 2, shows the impact of doubling the PV/T area from 40 (75 m^2) to 80 PV/T collectors (150 m^2) at a 45° slope

with an identical thermal storage V/A ratio configuration on the seasonal energy generation for preheating. The increase in PV/T collector enables enough electrical and thermal energy generation to meet the complete DHW load during April and achieve 88% for both July and October, while achieving 28% in January.

Discussion

The results show the impact of thermal storage on PV/T systems for preheating DHW. Thermal storage sizing for low-temperature preheating is complex since it is necessary to maximize the temperature quality to achieve 60°C of DHW while lowering tank temperatures to maximize the solar output. In this way, high solar radiation with low city water supply temperature – such as the studied April 2023 data – has the greatest potential to maximize the system's performance. On the opposite, January's limited solar production and low exterior temperature, severely affect the potential PV/T heat gains. Therefore, the studied system installation is ideal to maximize the total captured yearly solar energy to reduce DHW load, while a system designed to maximize winter heat production would require a heat pump to increase the heat quality and operate the PV/T and solar tanks in lower temperatures to maximize solar thermal gains.

Another aspect of the study is the impact difference of varying preheating versus solar tank configurations. Results showed that with a certain minimum of solar tanks, preheating tanks that are connected in series enable large preheating energy gains. Variation in energy gains can be as high as 28.3% for thermal preheating and 1.81% for electricity generation by lowering PV/T temperatures. These variations in performance a likely caused by additional stratifications between the two tank types, increasing solar efficiency and heat quality. Nonetheless, the final V/A ratio of 0.048m selected corresponds with other studies evaluating solar collector correct sizing for DHW heating with ratio varying from 0.05m up to 0.5m (Baneshi & Bahreini, 2018; Cirrincione et al., 2020; Çomaklı et al., 2012; Rodríguez-Hidalgo et al., 2012).

Furthermore, another configuration of the reference system was evaluated. The effect of increasing the slope from 20° to 45° can significantly increase winter total solar radiation and the total energy generated. However, the overall winter energy gains are similar to the summer energy losses, minimizing the potential yearly gains. Notably, depending on the location winter energy gains can be preferred since they can reduce the winter high demand peak. Additionally, the studied January week had significantly fewer sunny days (common in winter) affecting the potential solar energy gain. Winter snow blocking the collectors could also be reduced by a greater slope, potentially increasing winter gains and minimizing the near to clear the panels of snow.

When the PV/T surface area is high enough to meet the totality of the warmer month's energy loads, a greater slope is a good alternative to maximize the yearly energy gains during the 4 seasons as shown in the 80 PV/T analysis.

The study's main limitations are that it was applied on a specific PV/T-thermal storage system configuration with 2 types of tanks connected in series where different preheating configurations could have slightly different conclusions. Additionally, the analysis was performed on 4 different seasons utilizing the sunniest week of each month from historical data to minimize the computational time for the sensitivity analysis. In this way, weekly variations in solar radiation, exterior temperature, and wind influence the final results. Similarly, the effect of snow was not considered in the analysis but could have a significant impact on performance.

Conclusion

The study presented a sensitivity analysis of thermal storage design for PV/T system when applied for preheating DHW for a case study building in Mégantic, Canada. Seasonal analysis found that a PV/T preheating system can achieve significant energy consumption reduction for most of the year. Results showed a V/A ratio of 0.048 was optimal when consisting of 3 solar tanks and 3 preheating tanks to maximize energy generation without increasing costs. Appropriate sizing was found to enhance thermal energy generation by as much as 28.3% while increasing the electrical generation by 1.8%. The studied system was shown to reduce DHW heating by as much as 60% depending on the season and weather conditions and with additional PV/T, meet the entirety of the load. Increasing the collectors' slope angle was found to increase winter while reducing summer solar generation without any significant impact on the yearly total energy used for preheating. Finally, the study highlights the ideal design configuration and sizing for future PV/T-thermal storage systems used for preheating DHW in colder climates with a high degree of weather variations between seasons.

Acknowledgements

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Nomenclature

Parameter	Description
U	Heat transfer coefficient [W/m^2-K]
T	Temperature [°C]
T_{amb}	Ambient temperature [°C]
$T_{in_{coil},i}$ $T_{out_{coil},i}$	Coil temperature inlet and outlet at each node [°C]
C	Thermal capacitance [kJ/K]
S_{PV}	Solar gains [W/m^2]
P_{el}	Useful electrical energy [W/m^2]
q_{th}	Useful thermal energy [W/m^2]
A_c	Collector area [m^2]
A_i	Area between each tank node [m^2]
$\dot{m}$	Mass flow rate [kg/s]
c_p	Specific heat [kJ/kg-K]

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