Modeling and Integration of Photovoltaic Thermal (PVT) Hybrid Solar Collectors in A Fifth-Generation District Heating and Cooling (5GDHC) Network

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Abstract

This paper investigates the modeling and integration of photovoltaic thermal (PVT) hybrid solar collectors into a fifth-generation district heating and cooling (5GDHC) network. The PVT-5GDHC system is modeled in Modelica using Dymola. The proposed system integrates PVT hybrid solar collectors with distributed water-source heat pumps to meet the energy demands of a diverse community in Denver, Colorado, USA, comprising a hospital, a commercial building, and ten residential apartment buildings. EnergyPlus is used to generate annual building thermal loads based on the U.S. Department of Energy (DOE) prototype building models. Compared to a baseline 5GDHC system without PVT, the PVT-5GDHC configuration achieves significant benefits, including a 61.7% annual energy savings, a reduction of annual electricity cost from $739,297 to $283,110, a reduction of 767 tons of carbon emissions, a primary energy reduction of 5008 MWh, a 32.8% peak electricity demand reduction from 3729 kW to 2506kW, and an increase in annual system coefficient of performance from 3.56 to 3.78. Compared to a PV-only configuration, the PVT system maintains the same peak electricity demand while exhibiting lower total electricity generation and coverage ratio but achieving higher carbon emission reductions and greater primary energy savings. Additionally, this study finds that appropriate control settings for the upper temperature limit of the PVT storage tank are critical to maximizing overall system efficiency. An optimal upper temperature limit of 40°C results in the lowest electricity cost of $283,110, compared to 75°C resulting in the highest cost of $293,630. These findings underscore the significant advantages of integrating PVT technology into 5GDHC networks for sustainable and efficient district energy systems.

Key Innovations

- Implementation of a PVT model in Modelica
- Design of a PVT-5GDHC incorporating renewable PVT solar collectors and distributed heat pumps
- Demonstration of PVT's benefits in 5GDHC systems
- Eight evaluation metrics for the PVT-5GDHC

Practical Implications

The developed PVT-5GDHC system model highlights the substantial benefits of PVT technology, including higher solar energy conversion efficiency and improved overall district energy system efficiency.

Introduction

Photovoltaic thermal (PVT) hybrid solar collectors represent an innovative advancement in solar energy technology by integrating solar thermal (ST) and photovoltaic (PV) modules into a single system (Beijneveld, Alpízar-Castillo, & Ramírez-Elizondo, 2024). This integration allows for dual energy extraction: electricity generation through the photovoltaic process and thermal energy capture for heating purposes. The synergy between PV and ST components in PVT systems results in a higher overall conversion efficiency of solar radiation compared to PV or ST modules operating independently (Barbu, Siroux, & Darie, 2021). By extracting surplus heat from the module, PVT systems mitigate the efficiency losses that PV modules typically experience due to overheating. In standard PV modules, excessive heat leads to thermalization losses (i.e., where energy from solar radiation is converted into heat instead of electricity) and non-absorption losses (i.e., where part of the solar spectrum is not absorbed and thus not converted into useful energy). The thermal management feature of PVT systems alleviates these losses by maintaining PV cells at a more optimal operating temperature and utilizing the surplus heat as useful thermal energy. This integration improves the overall energy efficiency of PVT systems, which achieve thermal efficiencies ranging from 27% to 79% and photovoltaic efficiencies between 6.4% and 58% (Tiwari, Chatterjee, Agrawal, & Singh, 2023). Additionally, from an economic perspective, PVT systems offer a faster return on investment by combining the generation of thermal and electrical energy, reducing the need for separate PV and ST installations (Ramos et al., 2017).

District heating and cooling (DHC) networks with electric heat pumps are a key enabling technology for decarbonizing the building energy sector, particularly when integrated with renewable energy sources such as solar energy. PVT hybrid solar collectors combine PV modules with heat-recovery configurations, enabling the simultaneous generation of electrical and thermal energy from a single array. This dual functionality makes PVT systems highly suitable for DHC networks, as they efficiently meet both electrical and thermal demands from buildings. Fifth-generation DHC (5GDHC) networks are characterized by their low-temperature operation, enabling simultaneous heating and cooling through distributed heat pumps. These systems offer enhanced

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energy efficiency by minimizing thermal losses through underground piping and facilitating the integration of low-grade renewable thermal energy sources (Zhang, Liu, O'Neill, & Wen, 2024a). Consequently, integrating PVT collectors into a 5GDHC network presents a promising approach to enhancing overall energy efficiency and sustainability in district energy systems.

This paper contributes by implementing a PVT model in Modelica, incorporating it into a 5GDHC virtual testbed, and demonstrating the energy efficiency and cost benefits of the PVT-5GDHC district energy system.

PVT Model

Figure 1 presents the schematic diagram of the PVT system, which includes PV panels, circulation pumps, and a stratified storage tank for thermal energy storage with built-in heat exchanger. The system consists of water flowing from the tank through the PV panels, a dedicated pump for the water tank, and another pump for extracting fluid from the district loop. Heat exchange occurs via a heat exchanger inside the water tank, where thermal energy is transferred between the district-loop fluid and the stored water.

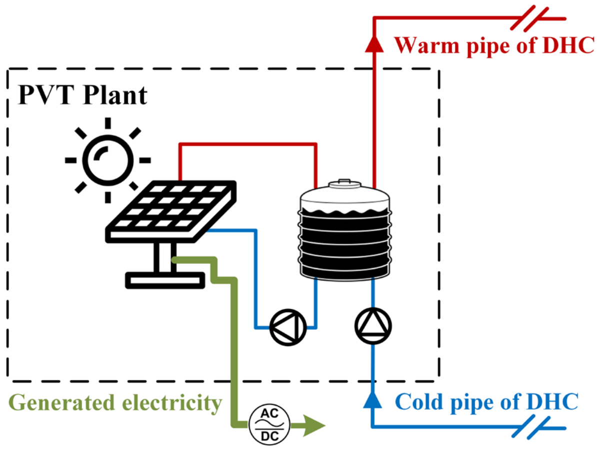

Figure 1: Schematic diagram of the PVT system.

A study by (Guarracino, et al., 2019) investigated the thermal efficiency of PVT under two operating conditions (open circuit mode and maximum power point mode). Additionally, the study examined the electricity efficiency of PVT when operating solely in PV mode. To comprehensively represent all operational scenarios, this study categorizes PVT operations into four modes:

- PVT Heating-Only Mode: This mode, also referred to as open-circuit mode, occurs when no electrical load is connected, and the PVT system is used exclusively for heating the water tank.
- PVT Electricity-Only Mode: This mode is activated when no thermal load is connected, allowing the PVT system to operate solely for electricity generation. For example, if the water tank temperature exceeds the upper limit, the heating function is deactivated, and the system functions as a PV-only generator.
- PVT Hybrid Mode: This mode corresponds to the maximum power point mode, where both electrical and thermal energy are generated simultaneously.
- PVT OFF Mode: The PVT system is inactive, generating neither electricity nor thermal energy, and all pumps remain off.

The steady-state thermal efficiency is calculated from the experimental data using Eq. (1), followed by a non-linear regression applied to the data, in accordance with the procedure described in the European Standard EN 12975-2 (Standard & EN, 2006) as shown in Eqs. (2) and (3).

$$\eta_{TH} = \frac{\dot{m}c(T_{f-o} - T_{f-i})}{GA} \tag{1}$$

$$\eta_{TH} = \eta_{TH,0} - a_1 T^* - a_2 G T^{*2} \tag{2}$$

$$T^* = \frac{T_c - T_a}{G} \tag{3}$$

where $\dot{m}$ represents the mass flow rate of the working fluid in the PVT system, c is the specific heat capacity, T_{f-o} and T_{f-i} denote the outlet and inlet fluid temperatures, G is the solar irradiance, A is the panel area, $\eta_{TH,0}$, a_1 and a_2 are model parameters determined by the regression algorithm. The reduced mean temperature is represented by T^*, while T_c is the mean fluid temperature, taken as the linear average of T_{f-0} and T_{f-i}. T_a denotes the ambient temperature.

The electrical efficiency is evaluated by measuring the electrical power at the maximum power point across the module's operating temperature range, as described in Eq. (4) (Skoplaki & Palyvos, 2009).

$$\eta_E = \eta_{E,0}[1 - \beta(T_{PV} - T_0)] \tag{4}$$

where $\eta_{E,0}$ is the electrical efficiency at the reference temperature $T_0 = 25$°C , and β is the temperature coefficient obtained from the PV module manufacturer's datasheet. When a direct measurement of the PV cell temperature (T_{PV}) is not available, the mean fluid temperature (T_c) is used as an approximation.

To streamline the modeling process, the partial solar collector module (`Buildings.Fluid.SolarCollectors.BaseClasses.PartialSolarCollector`) from the Modelica Buildings Library (version 10.0.0) (Wetter, Zuo, Nouidui, & Pang, 2014) and the cell temperature module (`AixLib.Electrical.PVSystem.PVSystem.CellTemperature`) from the AixLib (version 2.1.0) (Maier, et al., 2024) are extended and modified to develop the PVT model in this study. The partial solar collector module is expanded to create the solar collector model based on EN12975 rating data. The cell temperature module calculates the PV cell temperature used for the electrical efficiency calculation. The PV cell temperature is used to calculate the electricity efficiency when PVT is in the electricity-only mode, and the mean fluid temperature is used to calculate the electricity efficiency and thermal efficiency when PVT is in the hybrid mode or heating-only mode. It's noted that the PVT model, as specified in Eqs. (2)-(4), is a general model developed by (Guarracino et al., 2019). Table 1 shows the coefficients used in a specific PVT as a case study.

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Table 1: Coefficients of the PVT efficiency equations (Guarracino et al., 2019).

Coefficients / Variables	PVT Heating-Only	PVT Electricity-Only	PVT Hybrid
$\eta_{TH,0}$	0.42	×	0.37
a_1	4.96	×	4.64
a_2	0.003	×	0.03
$\eta_{E,0}$	×	0.126	0.126
β	×	0.0038	0.0038
T_c	✓	×	✓
T_{PV}	×	✓	✓

Solar water heating systems can generally be categorized as active or passive. Active systems incorporate circulating pumps and control mechanisms, while passive systems do not. The developed PVT system with a water tank is classified as an active solar water heating system with an additional power generation capability. According to a sizing guideline from U.S. Department of Energy (DOE, 2025), a storage-to-collector area ratio of 1.5 to 2 gallons is recommeneded for active solar water heating systems, which helps prevent the system from overheating when the demand for hot water is low. Based on this guideline, 2 gallons of water storage per square foor of collector area (0.08 m^3 water per unit square meter of the PVT collector area) is selected for the PVT system with a water storage tank.

The control logic governing the four operational modes of the PVT system is illustrated in Figure 2. The system determines its operational mode primarily based on two key measured variables—solar irradiation and water tank temperature.

- The PVT Electricity-Only mode is activated when the incident solar radiation (G) surpasses the minimum solar radiation level (G_{min}) and the tank temperature (T_{tank}) exceeds the lower threshold (T_{low}). The lower threshold of water tank temperature should be set based on the temperature of the cold pipes in the district loop to ensure that the water tank can effectively transfer heat to the district loop fluid.
- The PVT Heating-Only mode is activated when the incident solar radiation exceeds the critical solar radiation level ($G_{critical}$) and the tank temperature is below the upper threshold (T_{high}). The critical solar radiation level represents the minimum incident solar radiation required for the system to operate efficiently, ensuring that the energy gained from solar radiation exceeds the thermal losses from the collector. $G_{critical}$ is a threshold to determine whether the circulation pump and heating function of the PVT should be activated or deactivated, which is calculated using the module (`Buildings.Fluid.SolarCollectors.Controls.CollectorPump`) from Modelica Buildings Library (version 10.0.0) (Wetter et al., 2014). The selection of the water temperature upper limit should be tuned for overall system efficiency and will be tested through simulation results under different parameter settings.
- If both heating and electricity generation conditions are met, the system operates in PVT Hybrid mode. Conversely, if neither condition is met, the PVT system remains in OFF mode.

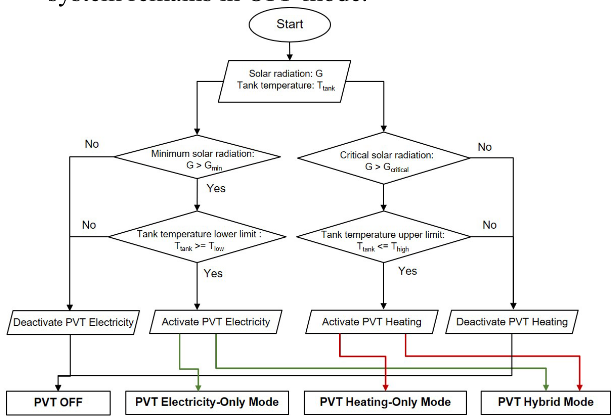

Figure 2. The control logic of PVT operational modes.

PVT-5GDHC Testbed

Figure 3 illustrates the schematic diagram of the proposed PVT-5GDHC system including two energy hubs (one central energy plant with air-source heat pumps and one PVT plant), a network of bidirectional pipelines, and three substations with distributed water-source heat pumps (large office building, hospital building, and high-rise apartment buildings). Figure 4 presents the developed PVT-5GDHC system model, which extends the fifth-generation DHC system model from a published work (Zhang et al., 2024a). The selected location for this study is Denver, Colorado, USA, classified as ASHRAE climate zone 5B. The PVT-5GDHC network comprises three primary components: energy hubs, pipelines, and substations.

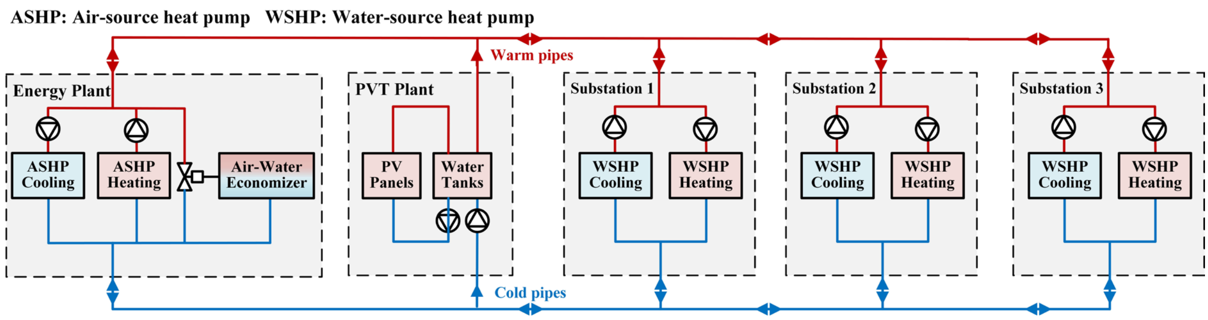

Figure 3. Schematic diagram of the proposed PVT-5GDHC system.

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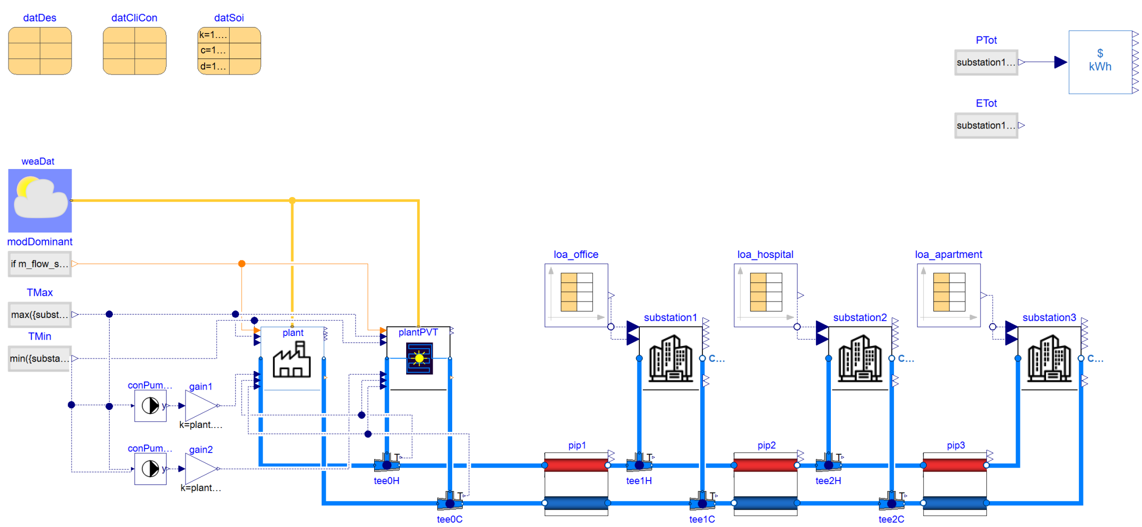

Figure 4. PVT-5GDHC Modelica virtual testbed.

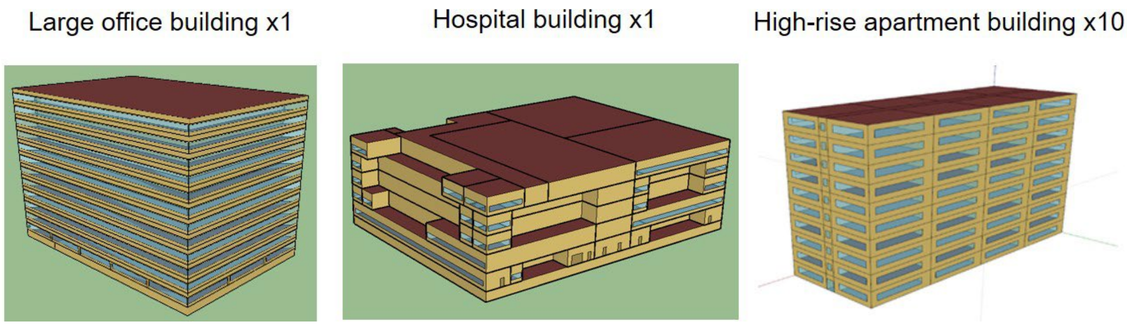

Figure 5. DOE prototype building EnergyPlus models used in this study (DOE, 2014).

- **Energy Hubs**: The energy hub, also referred to as the balancing unit, plays a crucial role in managing and balancing heat within the network. It maintains the network temperature by addressing excessive heat imbalances. The selection of thermal energy sources within the energy hub depends on local availability and the specific temperature requirements of the network. Two energy hubs are implemented: a PVT farm, which generates electricity and provides auxiliary heating, and an energy plant comprising an air-to-water heating heat pump, an air-to-water cooling heat pump, and an air-to-water heat-exchanger-based economizer. The economizer harnesses ambient air as a “free” thermal energy source for supplementary heating and cooling. These two energy hubs are designed to maintain the network temperature within a predefined range of $[6, 40]$°C.
- **Pipelines**: A network of pipes serves as the physical infrastructure that connects the substations and energy hubs. These pipelines distribute both warm and cold water to all end users within the 5GDHC network. Based on the number of pipelines at different temperature levels, medium flow direction, and substation connection configurations, 5GDHC systems can be classified into multiple categories (Zhang, Liu, O'Neill, & Wen, 2024b). This study focuses on one of the most common system configurations known as *two-pipe bidirectional parallel* network. In this setup, the pipeline flow direction varies according to the load conditions, deviating from the conventional supply and return pipe arrangement. Instead, distribution pipes are categorized as warm pipes and cold pipes based on operating temperature levels. A consistent temperature differential of 4°C is maintained between the warm and cold pipes in this study.
- **Substations**: The substations in this study represent three building types: one large office building, one hospital, and ten high-rise apartment buildings, each corresponding to a dedicated substation. The load profiles for these buildings are derived from simulations of the DOE prototype building models developed by the Pacific Northwest National Laboratory (Goel et al., 2014) using EnergyPlus, as shown in Figure 5. To ensure a balanced load representation across diverse building types, the load of the high-rise apartments is scaled up by a factor of 10 (Zhang et al., 2024b). These building load profiles serve as input data for the substations. In each substation, the domestic hot water load and space heating load are aggregated as the total heating load,

which is supplied by a water-to-water heating heat pump. The cooling load is covered by a water-to-water cooling heat pump. The cumulative annual heating demand ($E_{loa,hea}$) is 5030 MWh, while the cumulative annual cooling demand ($E_{loa,coo}$) totals 7100 MWh. Figure 6 illustrates the hourly heating and cooling load profile throughout the year.

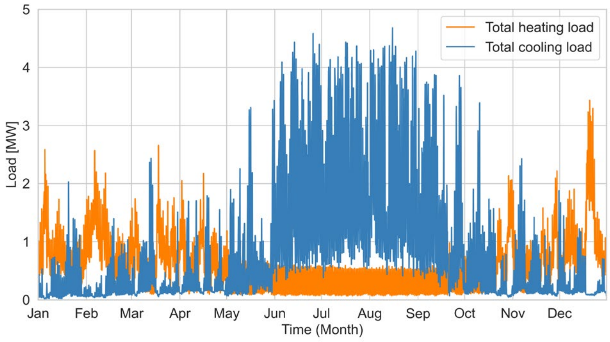

Figure 6. Annual hourly demand profile (Denver city, climate zone 5B)

Table 2 summarizes the key parameters used in the PVT-5GDHC system model. Through multiple annual simulations, it was determined that 17250 m^2 of PV panels would be required to design a zero-emission 5GDHC system. However, due to space limitations in an urban environment, the total available roof area serves as the upper limit for PV panel size. Based on the total available roof area of 12 buildings (12441 m^2) and an 80% utilization ratio, the PVT panel area is selected to be 9952 m^2.

Table 2: Key parameters in the PVT-5GDHC system

Parameter	**Value**
Building chilled water supply temperature setpoint	12 °C
Building hot water supply temperature setpoint	35 °C
Controlled temperature range of warm pipes	[8, 40] °C
Controlled temperature range of cold pipes	[4, 36] °C
Length of each pipe	300 m
Nominal pressure drops per length	100 Pa/m
PVT water tank temperature range	[8, 75] °C
PVT water tank volume	796 m^3
PVT panel area	9952 m^2

Key Performance Indicators

Eight key performance indicators (KPI) are selected to evaluate the energy system performance including total energy consumption, annual coefficient of performance, carbon emissions, peak electricity demand, coverage ratio, and primary energy reduction.

- **Total energy consumption** (E_{tot}) includes energy usage from substation heating and energy hub heating (E_{hea}), substation cooling and energy hub cooling (E_{coo}), and pumping (E_{pum}).

$$E_{tot} = E_{hea} + E_{coo} + E_{pum} \tag{5}$$

- **Net electricity demand** ($E_{ele,dem}$) is total energy consumption (E_{tot}) minus the electricity generation ($E_{ele,pvt}$).

$$E_{ele,dem} = E_{tot} - E_{ele,pvt} \tag{6}$$

- **Total electricity cost** (C_{tot}) is the total electricity demand multiplied by the utility rate. This study applied a Time-of-Use utility rate, r_{ele}, according to (Xcel Energy, 2025), where the on-peak rate is \$0.218/kWh, the mid-peak rate is \$0.158/kWh, and the off-peak rate is \$0.098/kWh.

$$C_{tot} = \int E_{tot}(t) \times r_{ele}(t)\, dt \tag{7}$$

- **Annual system coefficient of performance** (COP_{sys}) is the ratio of the total thermal load (heating and cooling) to the required system input energy.

$$COP_{sys} = \frac{E_{loa,hea} + E_{loa,coo}}{E_{tot}} \tag{8}$$

- **Carbon emissions** (CO_2) entail the release of carbon dioxide into the atmosphere. According to the statistics provided by the U.S. Energy Information Adminstration (EIA, 2024b), the CO_2 emission factor, c_{ele}, is 365 kg/MWh.

$$CO_2 = E_{tot} \times c_{ele} \tag{9}$$

- **Peak electricity demand** (P_{peak}) refers to the highest electricity consumed by the whole system within a specified period. Peak demand has significant implications for power systems and energy supply, as the system must be designed to meet the peak demand to ensure the stability and reliability of power supply.

$$P_{peak} = \max(P_{hea}(t) + P_{coo}(t) + P_{pum}(t)) \tag{10}$$

- **Coverage ratio** (CR) represents the percentage of electrical energy demand covered by the self-generated solar power from the PVT system.

$$\mathrm{CR} = \frac{E_{el,PVT}}{E_{tot}} \times 100\% \tag{11}$$

- **Primary energy reduction** (PER) represents the reduction of primary energy consumption determined by the PVT system calculated by Eq. (12), where the Primary Energy Factor (PEF) is defined as the amount of primary energy required to deliver one unit of usable energy to end-users. According to the statistics provided by U.S. Energy Information Adminstration (EIA, 2024a), this factor is 2.38 $kWh_{primary}/kWh_{delivered}$.

$$PER = E_{el,PVT} \times PEF \tag{12}$$

Results and Discussion

This section analyzes annual simulation results and evaluation metrics of the developed PVT-5GDHC system with different configurations.

- PVT-5GDHC vs. Baseline (5GDHC) without PVT

Integrating PVT into the 5GDHC system significantly improves energy efficiency compared to the baseline configuration without PVT. The total annual energy

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consumption (from HVAC equipment) decreases by 5.8%, from 3404 MWh to 3207 MWh. With the PVT system generating 1907 MWh of electricity, the total annual electricity demand is reduced by 61.8%, from 3404 MWh to 1300 MWh. Additionally, since the PVT system converts solar energy into thermal energy, which contributes to meeting the heating load, the annual system COP increases by 6.2%, from 3.56 (5GDHC) to 3.78 (PVT-5GDHC). Figure 7 shows the energy consumption breakdown of PVT-5GDHC compared to the baseline.

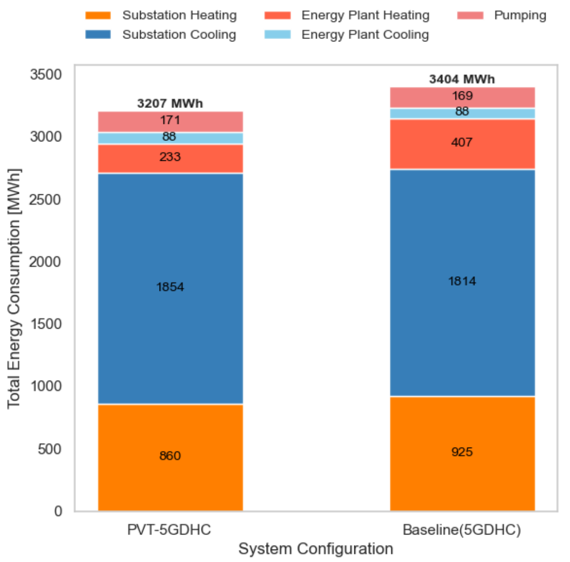

Figure 7. Energy performance comparison between PVT-5GDHC and baseline (5GDHC without PVT).

- PVT vs. PV-only

The PV-only configuration outperforms the PVT configuration in terms of annual total electricity generation and coverage ratio. PVT-5GDHC generates 1907 MWh of electricity annually, whereas PV-5GDHC generates 2056 MWh, leading to a higher coverage ratio of 60.4% for PV compared to 59.5% for PVT. In both configurations, more than half of the HVAC energy demand in the 5GDHC system is met by the generated electricity.

However, PVT outperforms PV-only in other key aspects, including annual system COP, carbon emission reductions, and primary energy savings. The PVT system provides both electricity and heat, with excess energy stored in thermal storage and utilized within the 5GDHC network for heating purposes. As a result, the PVT configuration achieves a higher system COP of 3.78 compared to 3.56 for both the PV-only and baseline configurations, leading to reduced carbon emissions and increased primary energy savings. Figure 8 shows the comparison results between the PV-only configuration and the PVT configuration in the same 5GDHC system.

In terms of peak electricity demand reduction, PVT-5GDHC performs similarly to PV-5GDHC, with both configurations achieving a 32.8% reduction—from 3729 kW in the baseline system to 2506 kW. This occurs because, under peak electricity demand scenarios, the PVT system primarily operates in electricity-generation mode rather than hybrid mode, behaving similarly to the PV system.

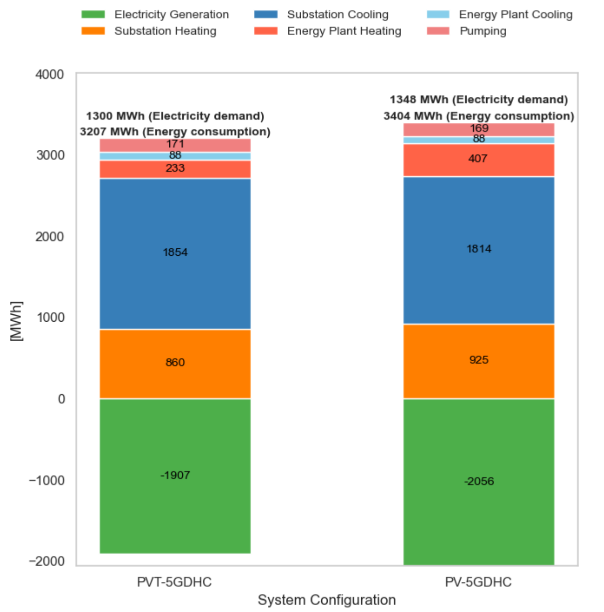

Figure 8. Energy performance comparison between PVT and PV-only in the same 5GDHC.

- Summary of KPI results for three configurations

Comparing all configurations, the annual utility cost of $739,297 in the baseline system is reduced to $291,923 (a 60.5% savings) by integrating 9952 m² of PV panels and to $283,110 (a 61.7% savings) when integrating the same area of PV panels with 796 m³ of water storage as PVT. Additionally, the annual system COP increases by 6.2%, from 3.56 (5GDHC or PV-5GDHC) to 3.78 (PVT-5GDHC).

In terms of decarbonization, the baseline system's annual carbon emissions of 1242 tons (from HVAC operations) are reduced to 492 tons (a 60.5% reduction) by integrating PV panels and further reduced to 475 tons (a 61.7% reduction) by integrating PVT into the 5GDHC network. Similarly, PV-5GDHC achieves a primary energy reduction of 4893 MWh, while PVT-5GDHC achieves a higher reduction of 5008 MWh.

Table 3 summarizes the detailed KPI results comparing the final PVT-5GDHC system with the baseline and PV-5GDHC configurations.

Table 3. KPI results of 5GDHC with different configurations (5GDHC without PVT, with PVT, and with PV-only).

KPI	**Baseline (w/o PVT)**	**PVT**	**PV-only**
Total electricity cost	$739,297	$283,110	$291,923
Net electricity demand	3404 MWh	1300 MWh	1348 MWh
PV electricity generation	0 MWh	1907 MWh	2056 MWh
Total energy consumption	3404 MWh	3207 MWh	3404 MWh
Substation heating	925 MWh	860 MWh	925 MWh

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Substation cooling	1664 MWh	1854 MWh	1664 MWh
Energy plant heating	401 MWh	233 MWh	401 MWh
Energy plant cooling	215 MWh	88 MWh	215 MWh
Pumping	164 MWh	171 MWh	164 MWh
Annual system COP	3.56	3.78	3.56
Annual carbon emissions	1242 tons	475 tons	492 tons
Peak electricity demand	3729 kW	2506 kW	2506 kW
Coverage ratio	0%	59.5%	60.4%
Primary energy reduction	N/A	5008 MWh	4893 MWh

- Impact of PVT tank upper temperature limits

Since experimental PVT data was collected for water flow temperatures up to 76℃ (Guarracino, et al., 2019), this study evaluates the effect of different upper temperature limits (25, 30, 35, 40, 45, 55, 65, and 75℃) on system performance. Figure 9 illustrates the annual electricity cost of PVT-5GDHC with different PVT water tank upper temperature limits. The results indicate that increasing the upper temperature limit from 25℃ to 40℃ reduces annual electricity costs, whereas further increases beyond 40℃ lead to rising costs.

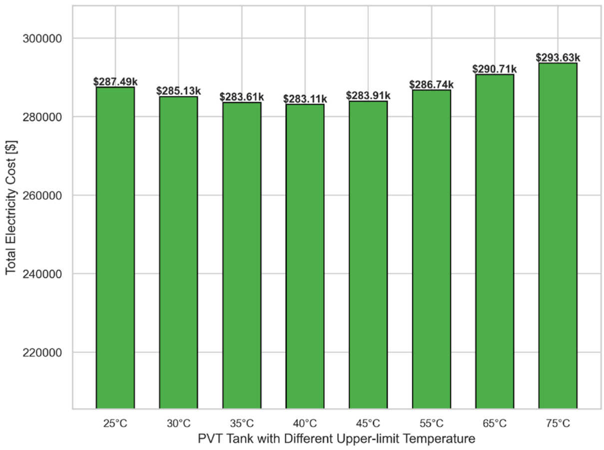

Figure 9. Total electric cost for PVT different temperature control.

This trend results from the trade-off between thermal efficiency and electricity efficiency of the PVT system. Lower water temperatures improve PV efficiency by keeping PV cell temperatures lower, enhancing electricity generation. Higher upper temperature limits allow for greater thermal energy storage in the water tank, but they also increase the inlet water temperature flowing through PV panels, which can negatively impact power generation efficiency. For example, previous studies (Kang, Korolija, & Rovas, 2022) have shown that PV cell temperatures above 25℃ results in a 0.37%/℃ reduction in electricity power output. Additionally, during winter, higher PVT supply water temperatures may result in lower collector thermal efficiency due to an increased temperature differential between the ambient and collector temperature. Thus, selecting an optimal control setting for the PVT tank's upper temperature limit is critical to maximizing overall system efficiency. In this case study, Figure 9 shows that setting the upper temperature limit at 40℃ achieves the highest overall efficiency and results in the lowest electricity cost of $283,110, compared to 75°C resulting in the highest cost of $293,630.

Conclusion

This paper developed a PVT Modelica model and extended a 5GDHC network to incorporate renewable PVT hybrid solar collectors. The proposed PVT-5GDHC system consists of two energy hubs (one central energy plant with heat pumps and one PVT plant), a network of bidirectional pipelines, and three substations (one large office building, one hospital building, and ten high-rise apartment buildings). EnergyPlus was employed to generate annual building thermal loads using U.S. Department of Energy (DOE) prototype building models, while Modelica was used to model and simulate the PVT-5GDHC system.

The findings highlight the significant benefits of PVT integration in 5GDHC networks. Compared to a baseline 5GDHC configuration without PVT, the PVT-5GDHC system achieves substantial improvements, including 61.7% annual energy savings, a reduction of 767 tons in carbon emissions, a 5008 MWh reduction in primary energy consumption, and a 32.8% decrease in peak electricity demand from 3729 kW to 2506kW. Furthermore, the annual system COP increases by 6.2%, from 3.56 (5GDHC or PV-5GDHC) to 3.78 (PVT-5GDHC).

This study also emphasizes the importance of optimizing the upper temperature limit of the PVT tank. Results indicate that setting the upper temperature limit at 40°C maximizes cost savings and enhances overall system efficiency. Future studies include optimizing the operational parameters of the proposed PVT-5GDHC system and performing a lifecycle cost analysis to evaluate the long-term decarbonization potential and payback period associated with upgrading 5GDHC systems to incorporate PV or PVT technology.

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Nomenclature

PVT	Photovoltaic Thermal
5GDHC	Fifth-Generation District Heating and Cooling
ST	Solar Thermal
A	Area, m^2
a_1, a_2	Collector heat loss coefficients, $W/(m^2K)$
β	PV temperature coefficient, K^{-1}
c	Specific heat capacity, J/(kgK)
G	Solar irradiance, W/m^2
G_{min}	Minimum solar radiation level, W/m^2
$G_{critical}$	Critical solar radiation level, W/m^2

$\dot{m}$	Mass flow-rate, kg/s
η_{TH}	PVT thermal efficiency
η_E	PVT electricity efficiency
$\eta_{TH,0}$	Reference thermal efficiency
$\eta_{E,0}$	Reference electricity efficiency
T_{f-i}	Inlet fluid temperatures, K
T_{f-o}	Outlet fluid temperatures, K
T^*	Reduced mean temperature, m^2K/W
T_a	Ambient temperature, K
T_c	Mean fluid temperature, K
T_{PV}	Photovoltaic cell temperature, K
T_0	PV reference temperature, K
T_{tank}	Water tank temperature, K
T_{low}	Water tank temperature lower limit, K
T_{high}	Water tank temperature upper limit, K
$E_{loa,hea}$	Building heating load, MWh
$E_{loa,coo}$	Building cooling load, MWh
E_{tot}	Total energy consumption, MWh
E_{hea}	Total heating energy consumpion, MWh
E_{coo}	Total cooling energy consumpion, MWh
E_{pum}	Total pumping energy consumption, MWh
$E_{ele,dem}$	Net electricity demand, MWh
C_{tot}	Total electricity cost, $
r_{ele}	Time-of-Use utility rate, $/kWh
COP_{sys}	System coefficient of performance, 1
c_{ele}	CO_2 emission factor, kg/MWh
$E_{el,PVT}$	Total electricity generation, MWh
PEF	Primary energy factor, $kWh_{primary}/kWh_{delivered}$

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