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Solar Based Combined Heating, Cooling and Power production System Towards Zero Energy Buildings

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Abstract

The extensive use of fossil fuels contributes to the emission of toxic pollutants, including sulfur oxides, nitrogen oxides, and greenhouse gases. Notably, a significant quantity of carbon dioxide is emitted, along with other energy forms. Consequently, transitioning to renewable or clean energy sources is crucial for long-term sustainability of energy development. Climate change has emerged as a major concern for human life in the 21st century, potentially leading to various problems, such as more frequent and intense heatwaves, increased occurrences of floods and droughts, alterations in seasonal patterns, impacts on disaster likelihood, and malnutrition. Achieving carbon neutralityby 2050 through adoption of clean and green energy sources is imperative. To attain net-zero emissions, the implementation of an energy-efficient technology known as a poly-generation energy system is recommended. This system offers high energy efficiency by simultaneously producing multiple energy carriers and services from one or more primary energy sources. Poly-generation systems are versatile, as they can operate using both fossil fuels and renewable energy resources. In this study, a sustainable solar-powered polygeneration energy system was proposed for a residential building located in Bengaluru (12.885138°N, 77.572538°E), Karnataka, India. The energy system integrates three main components: a Photovoltaic-Thermal (PVT) hybrid collector, Reverse Osmosis (RO) water purification unit, and Vapour Absorption chiller to assess the system's suitability for residential applications. The daily energy demands were estimated on a typical housing cluster comprising seven 1 BHK and five 2 BHK houses totaling approximately 60 dwellings. The system is proposed to meet a comprehensive range of daily energy requirements of electrical demand, amounting to 1185 kWh/day for electricity (general use), freshwater, and space cooling, as well a thermal demand for hot water. Performave evalution revealed that the CHCP (Cooling, Heating and Power) system achieved an electrical efficiency, thermal efficiency and overall efficiency of the proposed CHCP system were found as 18.1%, 50% and 68.1% respectively. These results highlight the system's potential as a viable and sustainable energy solution for integrated residential needs, contributing to both energy efficiency and environmental conservation.

Major Findings: *Excessive use of fossil fuels contribute significant amount of green house gas emission leads to environmental degradation, thereby underscoring the inevitable shift toward clean and sustainable energy systems. In this context, a solar-driven poly-generation configuration, integrating photovoltaic–thermal (PVT) technology with reverse osmosis (RO) and a vapor absorption chiller, was proposed to simultaneously satisfy the electricity, cooling, and freshwater requirements of a*

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residential building. The system achieved an overall efficiency of 68.1%, highlighting its potential as a sustainable pathway for advancing carbon-neutral and energy-efficient residential applications.

Keywords: *CHCP, Clean Energy, Photovoltaic-Thermal (PVT) Hybrid Collector, Reverse Osmosis*

1.0 Introduction

In the context of India's evolving energy sector, Combined Heating, Cooling, and Power (CHCP) systems are increasingly recognized for their potential to enhance energy efficiency and promote sustainability. These systems generate electricity, heat, and cooling simultaneously from a single energy source, offering significantly higher efficiency compared to traditional separate systems. CHCP systems can meet various energy needs in residential, commercial, and industrial sectors while reducing overall energy consumption and greenhouse gas emissions. With India's energy demand rising due to rapid urbanization, industrialization, and population growth, there is an urgent need to shift towards cleaner and more efficient energy systems to address climate change and air pollution concerns. CHCP systems provide a practical solution by improving energy efficiency, typically achieving overall efficiency levels of 70-90 %, compared to 30-40 % for conventional power-only systems.

The efficiency of a solar cell is primarily determined by its energy band gap, which sets the minimum photon energy required to produce electricity. Only photons with energy equal to or exceeding this band gap can excite electrons

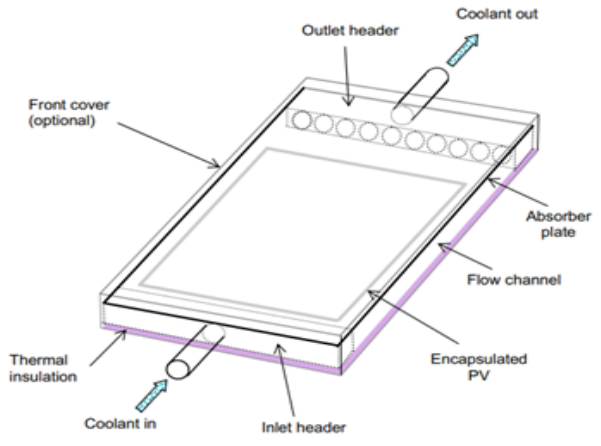


Figure 1. Schematic representation of a flat-plate PVT collector[3].

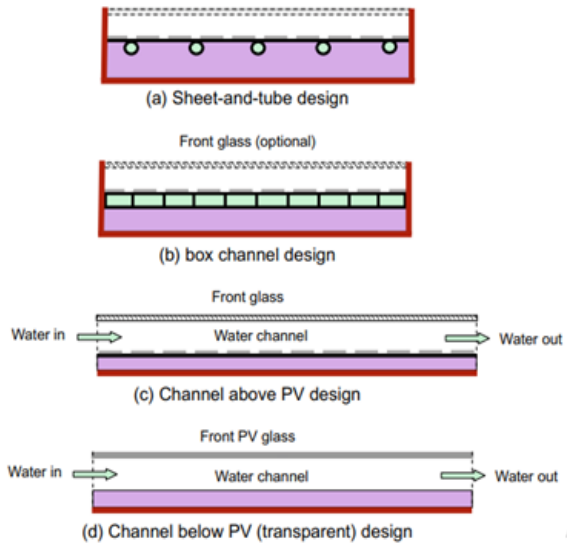


Figure 2. Cross sections of some common PVT collectors[4].

to create electron–hole pairs, thereby initiating current flow. Photons with lower energy (longer wavelengths) lack the necessary energy and instead contribute to the cell's thermal heating by releasing their energy as heat within the module. In real-world applications, a typical Photovoltaic (PV) module—depending on the material used (such as monocrystalline silicon, polycrystalline silicon, or thin-film cells) and its operating conditions—usually converts only about 4% to 17% of the incoming solar radiation into usable electrical energy. The rest, after accounting for reflection losses, is mainly transformed into heat. This inefficient conversion results in significant thermal buildup, raising the solar panel's operating temperature, often by as much as 50°C above the ambient temperature. Such high operating temperatures have two main negative impacts on solar cells. Firstly, the efficiency of crystalline silicon (c-Si) solar cells generally decreases with rising temperature—typically at a rate of about 0.4% for every 1°C increase above standard test conditions (usually 25°C).

A solar-powered Combined Heat, Cooling, and Power (CHCP) system presents significant advantages over

traditional energy supply methods, especially in terms of reducing carbon emissions. Unlike conventional methods such as fossil fuel-based power plants, which emit harmful pollutants and greenhouse gases, solar CHCP systems can greatly decrease these emissions by using a renewable energy source.

Advantages of Solar-Powered CHCP Systems:

- Decreased Carbon Emissions: Solar energy is a clean and renewable resource with minimal environmental impact, in contrast to fossil fuels that contribute to air pollution and greenhouse gas emissions. By utilizing solar power, CHCP systems can significantly lower their carbon footprint compared to conventional energy sources.
- Enhanced Energy Efficiency: Solar CHCP systems can boost overall energy efficiency by producing electricity, heat, and cooling from a single energy source. This integrated method reduces energy waste and lessens dependence on multiple energy sources, resulting in cost savings and a reduced environmental impact.
- Reduced Operating Costs: The cost of solar power generation is decreasing and is not affected by the price fluctuations of fossil fuels. This can result in lower operating costs for the CHCP system throughout its lifespan.
- Increased Energy Security: Expanding energy sources with renewable options like solar power enhances energy security by reducing reliance on a single fuel source.

A Photovoltaic-Thermal (PVT) system integrates a solar thermal absorber with a Photovoltaic (PV) unit. The PV cells are responsible for generating electricity, while the thermal component captures excess heat from the cells, lowering their temperature and improving their efficiency[1-3]. PVT technology provides two main benefits: firstly, actively cooling the PV laminate can enhance the efficiency of PV cells, and the captured heat can be used later. Secondly, by merging a PV and thermal system into a single unit, the total area needed for solar energy devices can be reduced. Among the most economical working fluids, water and air are prominent, with water being more efficient[4]. Hybrid PVT collectors can achieve combined efficiencies (both electrical and thermal) of 70% or more, with electrical efficiencies ranging from 15-20 % and thermal efficiencies surpassing 50%, depending on the conditions[5]. Girishkumar G S, *et al.*,[6] conducted an analysis of a single slope solar still model. Their simulation results indicated that the solar still produces distillate at a rate of 2 liters per square meter for 10 liters of saline water over a 12-hour period each day (from 7:00 am to 6:00 pm). The ability of PVTs to produce both electricity and heat simultaneously makes them beneficial for residential use. Nevertheless, despite their significant potential, commercial PVT systems have not gained the same popularity as separate, individually installed PV and thermal systems[7,8]. PVT technologies offer the potential to minimize material consumption, shorten installation durations, and save space. The thermal and electrical outputs are influenced by several factors, including irradiance, ambient temperature, wind speed, and the temperature and flow rate of the circulating fluid[9,10]. Unlike controlled indoor testing environments, changing weather conditions can significantly affect the overall performance and durability of these designs. Javier Uche, *et al.*,[11] examined various polygeneration setups for an 80-dwelling building, aiming to fulfill energy needs sustainably. The study highlights significant energy and CO_2 savings compared to traditional methods, with electric options, notably HP and RO, emerging as favorable solutions due to their reliability and lower investment requirements. Girishkumar G S, *et al.*,[12] introduced an energy system that incorporates waste heat recovery alongside hydrogen production using solar energy. They also demonstrated that reversible fuel cells are more efficient than basic fuel cells for hydrogen production. Amaya Martínez-Gracia, *et al.*,[13] investigated four novel polygeneration schemes for a multi-family building in Valencia, Spain, aiming to meet water, electricity, heating, and cooling demands from RESs. Results highlight significant energy and CO_2 reductions compared to conventional methods, with the electric option, incorporating heat pump and reverse osmosis, emerging as the most favorable solution due to its reliability, affordability, and environmental benefits. Adewale Giwa, *et al.*,[14] explored advancements in PV-T and CPV-T polygeneration systems for water desalination, power generation, cooling, and heating. It delves into various desalination methods like Reverse Osmosis (RO), Multi-Effect Distillation (MED), and Humidification-Dehumidification (HDH), solar stills, MD (Membrane Distillation), MVC (Mechanical Vapor Compression) compatible with these systems. Despite

higher installation costs, PV-T systems promise long-term cost reductions and environmental benefits compared to PV systems. Ayman *et al.*,[15] explored the integration of a biomass-based polygeneration system with a concentrated solar power facility to maintain a steady electricity supply year-round. The research includes a superstructure that features two types of gasification technologies (direct and indirect), two reforming methods (partial oxidation or steam reforming), and three options for syngas utilization (a water gas shift reactor for hydrogen production, a furnace for thermal energy, and an open Brayton cycle). This system is integrated with a concentrated solar plant that employs tower technology, molten salts, and a regenerative Rankine cycle. Rami. S *et al.*,[16] investigated a renewable-based integrated energy system powered by concentrated solar thermal and biomass energies, with biomass serving as a backup energy source when solar energy is unavailable. Through optimization, the system achieves energy and exergy efficiencies of 39.99% and 27.47%, respectively. Luis Gabriel Gesteira, *et al.*,[17] This study contributes to the evolving literature on polygeneration systems by conducting a thermo-economic analysis of a solar-assisted desiccant cooling plant for residential buildings. The sensitivity analysis explores the impact of varying costs on economic feasibility, revealing potential for up to an 85% reduction in the simple payback period. Acknowledging uncertainties in climate conditions and energy prices over a 20-year span, the study underscores the system's potential as a renewable energy solution, particularly with capital investment subsidies. M R Kamesh, *et al.,*[18] proposed a sustainable multigeneration system designed to fulfill the basic energy needs of rural communities in three different villages in southern India. Luis Gabriel Gesteira *et al.*,[19] focused on incorporating electrical storage into a polygeneration system for off-grid residential use in Almería, Spain. Findings highlight considerations for PVT collectors and batteries in off-grid setups, emphasizing theimportance of an energy and environmental approach. Alibakhsh Kasaeian *et al.,*[20] This review explores different solar technologies such as flat plate collectors and parabolic trough collectors within polygeneration systems. The research indicates that solar-powered polygeneration systems, especially those employing parabolic trough collectors and thermal photovoltaics, hold significant potential for future energy uses. Dereje S. Ayou *et al.,*[19] examined the energy and exergy performance in Almería, Spain, where the system delivers 130 kW of cooling, 6.4 kW of electricity, and 41.4 m3/day of desalinated water. Utilizing Conductive Gap Membrane Distillation (CGMD) reduces membrane surface area by 53%, enhancing overall efficiency and cost-effectiveness, especially in regions with high cooling demand and freshwater scarcity. Mohammadjavad Khodadadi *et al.,*[20]. This paper underscores the importance of thermal management for photovoltaic cells, highlighting the efficiency challenges posed by increased working temperatures. The review categorizes PVT systems based on types and coolants employed, emphasizing the use of PCMs and nanofluids for maximizing energy harvest. Maksymilian Homa *et al.*,[21]. It underlines the importance of energy storage solutions, ranging from batteries to hydrogen systems. The review identifies potential pathways for future investigations, including exploring unconventional renewable source pairings, advanced energy storage integration, and expanding the scope of applications beyond traditional case studies. André Rodrigues *et al,*[22] This paper presents experimental results of a polygeneration solar system focusing on its thermal sub-system. Performance testing of a new thermal storage with 400 L capacity, capable of storing both sensible and latent heat, was conducted. Results indicate successful heating for 8 hours with temperatures maintained between 22°C and 26°C, demonstrating the system's potential to meet heating and cooling needs in real-world applications. Kuntal Jana *et al.*,[23] Results highlight biomass heat value's impact on power output, while other utilities benefit from waste heat recovery, showing no distinct biomass dependency. Significant fuel savings are observed through process integration, underscoring the efficiency of biomass-based polygeneration systems. Edwin S. Pinto *et al.*,[24] emphasizes the role of polygeneration in reducing energy consumption and greenhouse gas emissions. The findings suggest a shift towards utilizing thermal energy storage over batteries for cost-effective solutions, challenging the prevailing reliance on battery systems for future energy systems. Pei Liu *et., al.*,[25] addressed that polygeneration system runs with biomass energy is the reliable pathway to meet energy demands. This paper introduced a model and case study focusing on methanol and electricity production in

China from 2010 to 2035, encompassing diverse feed stocks and technologies. M R Kamesh *et al.*,[26] presented an energy solution for community housing, showing that reliance on grid sources decreased by up to 10% daily and as much as 12% annually, solely through the use of solar and wind turbines in a hybrid system. This significantly contributes to long-term sustainability, offering a viable sustainable housing solution for community living.

2.0 Materials and Methodology

Figure 3 shows the pictorial representation of the residential building where the CHCP system is proposed.

Table 1. Community building details

Particulars	Quantity
Community type	Apartment
Floors	4 (Ground+3)
Number of 1 BHK (80 units/ month)	7
Number of 2 BHK (125 units/ month)	5
Miscellaneous (electricity consumed by the motor, pump and lights used in staircases)	250 units/month

2.1 Integration of Subsystems in a Solar PVT-Based Polygeneration System

The proposed polygeneration system utilizes Photovoltaic-Thermal (PVT) panels as the primary solar energy conversion unit to simultaneously generate electrical and thermal energy. These outputs are then routed into dedicated subsystems to meet the diverse demands of a residential building, including electricity, fresh water, hot water, and chilled water. The system architecture facilitates energy cascading and resource sharing across the subsystems, maximizing solar utilization and overall system efficiency.

3.0 Energy Demand

Modern daily life depends heavily on four key resources: fresh water, electricity, hot water, and cooling. Typical values (approximated) for consumption of electricity, hot water, fresh water and cooling demand per person/1 BHK or 2 BHK have been considered and listed in Table 2. Total energy requirement by considering the number of residents in the community housing has been determined as shown in Table 3.

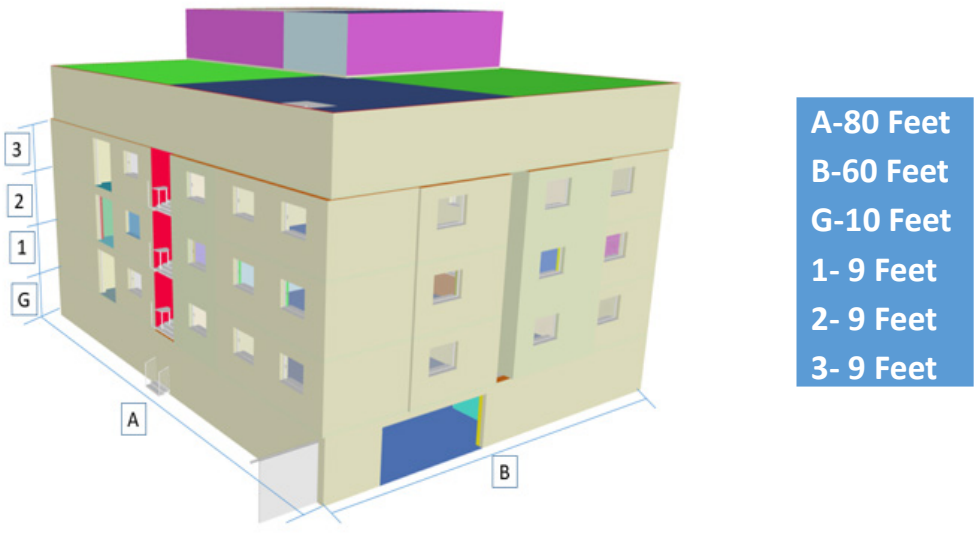


Figure 3. 3D model of the residential building.

Table 2. Specific input values

Input Parameters	Value
Electricity demand	5 kWh/day (These values include lighting, appliances, fans, cooking (if electric), and cooling.)
Hot Water demand	50 Liters/day/person
Fresh Water demand	20 Liters/day/person
Cooling load	20 Liters/day
ΔT for Hot Water	30°C
Specific Heat of Water	4.18 kJ/kg°C
Solar Irradiance	5.5 kWh/m²/day
Electrical Efficiency	15%
Thermal Efficiency	50%
Panel Area	2 m²
Loss Factor	1.2

Table 3. Energy demand (approx. for 60 residents)

Parameter		Value
Electricity demand (General use)	Typical use	1BHK-80 and 2BHK-125 kWh/month
	Energy needed	1185 kWh/ month **(i)**
Thermal Energy for Hot Water (Temperature rise 30°C)- Thermal demand 0.8-1 kWh/ day	Typical use	3000 Litres/day
Fresh Water via RO (Specific Energy consumption is 5kWh/m³)	Typical use	720 Litres/day
	Energy needed	1.04 kWh/day **(ii)**
Cooling load/Chiller water demand	Energy needed	145 kWh/day **(iii)**
Total Energy demand per day **(i + iii + iii)**		1331 kWh/day

3.1 System Sizing- PVT Panel

Based on the energy demand required, sizing of PVT panel is essential in the modelling i.e., the number panel requirement according to the specification/rating is listed in Table 4.

Table 4. PVT panel sizing

Component	Specification/Rating
PVT Panels	330 Wp × 978 panels (~312 kW total)
Total Area	978 × 1.6 m² ≈ **1565 m²**
Inverters	~312 kW capacity (string inverters or centralized)
BOS (Balance of System)	DC combiner boxes, surge protection, cabling, junctions
Mounting Structure	Roof/ground mount, south-facing, 15–20° tilt (India)
Monitoring	Solar charge controller + data logger
Number of PVT panel (330Wp, daily output=1.36 kWh/ daily)	978

4.0 Data Analysis

4.1 PVT Performance Indices—Heat Gained, Thermal Energy Yield and Efficiency

The overall efficiency of a PVT system is derived from both its photovoltaic (electricity) and thermal (heat energy) components. The thermal gain is calculated as follows:

$$E_{th}=M_w c_p \Delta T \quad (1)$$

where Mw represents the water mass flow rate (kg/s), cp is the specific heat capacity of water (kJ/kg ∘ C), and ΔT(∘ C) is the temperature difference, expressed as:

The mass flow rate M_w can also be described in volumetric terms as:

$$Mw=V_w \rho(T) \quad (2)$$

Where, V_w is the volumetric flow rate in m^3/s and ρ (T) is the density of water (kg/m^3) at temperature T. Both c_p and ρ (T) were assumed to be constant (c_p= 4.18 J/kg ∘ C, ρ(T) = 1000 kg/m^3) throughout the analysis presented in the study.

The thermal efficiency of the PVT is given as:

$$\eta th = \frac{100\ X\ Eth}{Am\ X\ Gp}\ \% \tag{3}$$

The electrical efficiency of the PVT is given as:

$$\eta ele = \frac{100\ X\ Edc}{Am\ X\ Gp}\ \% \tag{4}$$

Where, A_m is the module total surface area (m^2) and G_p is the in-plane solar irradiance (kW/m^2). E_{th} and E_{dc} are thermal gain of the system and DC power from the module in kW respectively.

4.2 Module Temperature

The maximum or rated power of a Photovoltaic (PV) module is evaluated under Standard Test Conditions (STC), which include a solar irradiance of 5 kW/m^2, a module temperature of 25℃, and an Air-Mass Ratio (AM) of 1.5 (AM = 1.5). However, in real outdoor settings, these conditions vary from STC, leading to differences in the PV module's power output compared to its rated power. The cell temperature Tcell (℃) at any given ambient temperature Tamb (℃) is determined as follows:

$$\frac{T_{cell} - T_{amb}}{NOCT - T_{amb,NOCT}} = \frac{G_p}{G_{p,NOCT}} \times \frac{U_L \cdot NOCT}{U_L}\left[1 - \frac{\eta_{cell}}{(\tau\alpha)}\right] \tag{5}$$

here, NOCT represents the nominal operating cell temperature (℃), Gp denotes the in-plane global irradiance (W/m^2), ηcell is the cell efficiency (%), (τα) stands for the effective transmittance-absorptance, UL is the loss coefficient (W/m^2℃), and ZNOCT indicates parameter Z at NOCT.

5.0 Results and Discussion

According to the Global Solar Atlas, the average annual Global Horizontal Irradiation (GHI) and clearness index are approximately 5.5 kWh/m^2/day and 0.55 respectively in bengaluru as shown in Figure 4.

Figure 5 illustrates a schematic representation of the proposed Combined Heating, Cooling, and Power (CHCP) system. In this configuration, crucial environmental factors specifically wind speed, ambient temperature, and the tilt angle of the Photovoltaic-Thermal (PVT) collector act as significant input variables affecting the system's efficiency. The PVT unit produces electrical energy, which is then strategically allocated within the system. A portion of this electricity is used to power two vital subsystems: the Reverse Osmosis (RO)

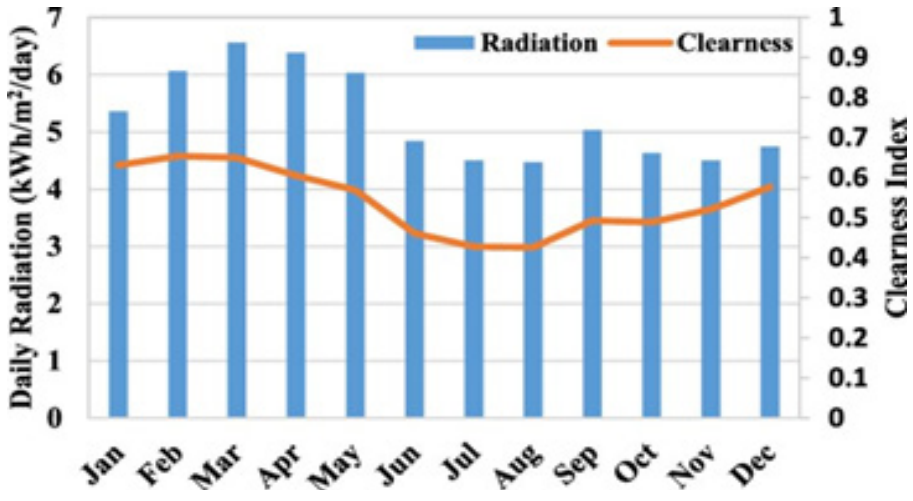


Figure 4. Monthly-average-solar-GHI-Bengaluru.

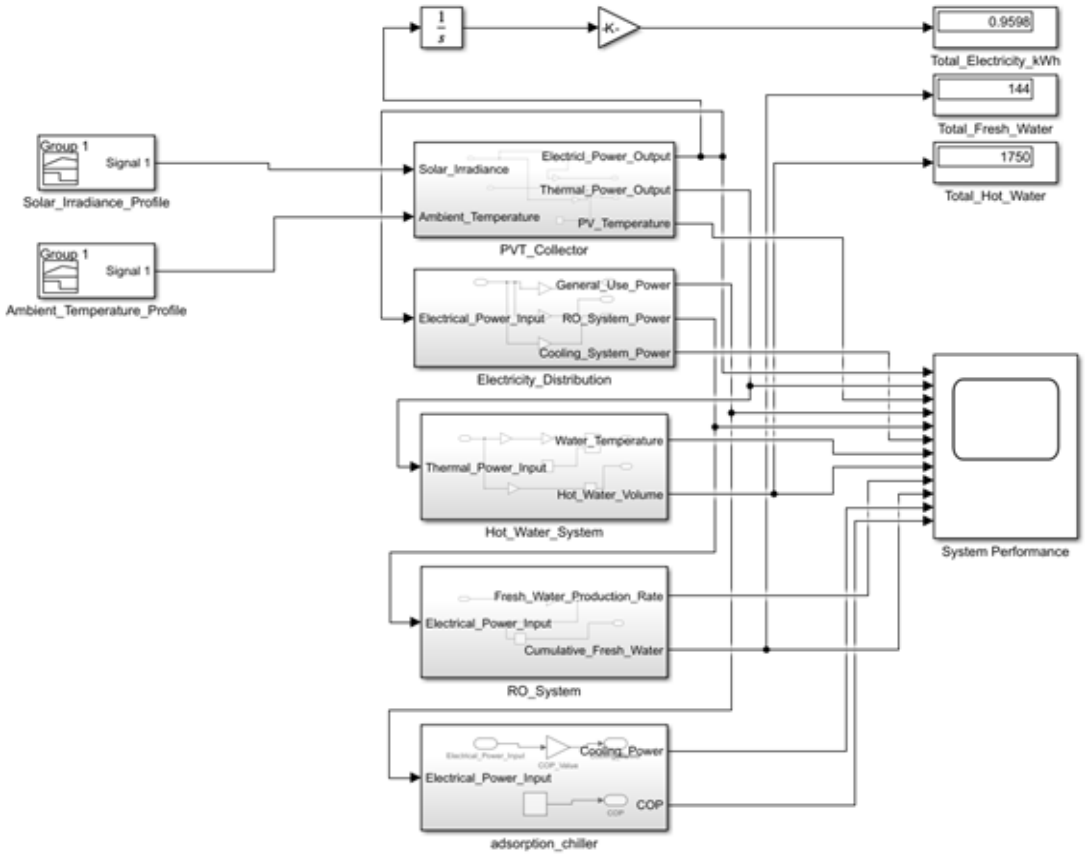


Figure 5. Modelling of proposed PVT based CHCP energy system.

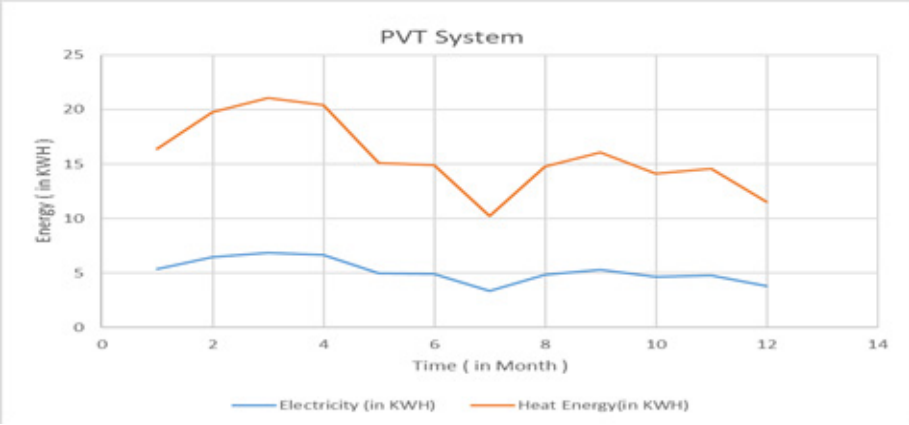


Figure 6. Electricity and thermal energy outputs from PVT panel.

unit for generating freshwater and the absorption chiller for cooling spaces. The remaining electrical energy is utilized to power general household electrical devices, thereby promoting efficient and sustainable energy use across various applications.

Figure 6 illustrates the electrical energy output from the PVT system, which remains fairly consistent throughout the year. There is a slight increase around March-April, reaching approximately 6.5 kWh, and a decrease in July to about 4 kWh. Post-July, the output

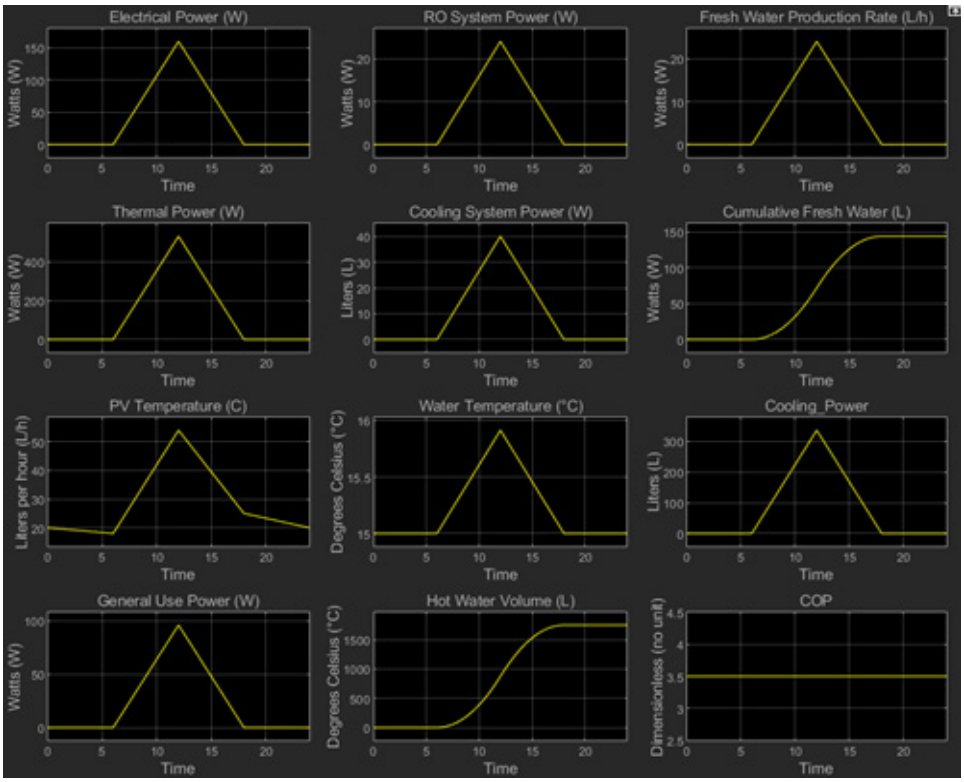


Figure 7. CHCP energy system overall metrics.

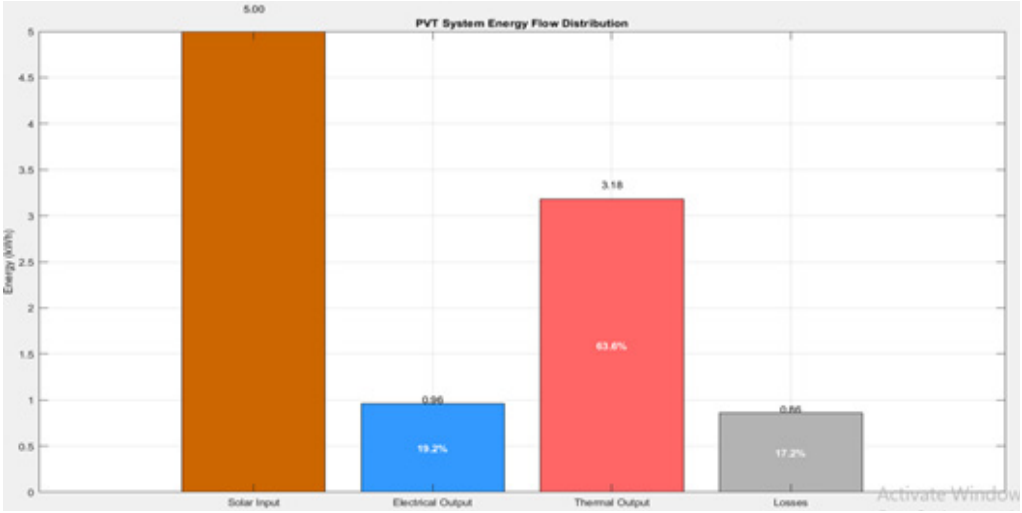


Figure 8. PVT energy flow pattern.

shows minor fluctuations but generally trends downward towards December. The orange line represents the heat energy output in kWh, which is considerably higher than the electrical output, a common characteristic of PVT systems. The thermal output reaches its peak in March at around 21 kWh, then gradually decreases until July, where it hits the lowest point of about 10 kWh. From August to November, there is a partial recovery, followed by another decline in December. The heat energy output is more affected by seasonal variations compared to electricity. The thermal component is the dominant factor in the energy output, underscoring the dual-generation benefit

of the PVT system, particularly for applications requiring both electricity and heat.

Figure 7 presents a series of graphs depicting the hourly efficiency of a PVT-based CHCP system throughout a 24-hour cycle. The system operates at its peak during daylight, especially around noon, with simultaneous surges in power, cooling, and water output. Its performance significantly declines to nearly zero during night time.

Figure 8 represents the system demonstrates a combined energy conversion efficiency of 82.8% (Electrical + Thermal). This hybrid nature allows better utilization of solar energy compared to standalone PV or thermal systems. The relatively low electrical efficiency is compensated by the high thermal output, making the system well-suited for combined power and heat applications such as CHCP (Cooling, Heating, and Power) setups.

6.0 Conclusion

This research entails the modeling and simulation of a poly-generation system engineered to fulfill the routine energy requirements for electricity, hot water, fresh water, and space cooling. The system integrates Photovoltaic-Thermal (PVT) panels, a Reverse Osmosis (RO) unit, and a Vapour Absorption Chiller unit to concurrently address the electrical, thermal, and freshwater needs of a residential building. The study further underscores the potential of poly-generation systems to enhance environmental sustainability, energy independence, and efficient resource management across diverse applications. Electricity generation from the PVT panels was sufficient to satisfy both general household demand and the operational energy requirements of the RO and Vapour Absorption Chiller.

The findings indicated that the proposed Combined Heat, Cooling, and Power (CHCP) system achieved an electrical efficiency of 18.1%, a thermal efficiency of 50%, and an overall efficiency of 68.1%.

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