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Development of an Integrated Solar-Biomass Energy System for Near-Zero Energy Buildings: A Technical and Environmental Study

Ehsan Karkon[1,*]*, Mohammad Liravi* [1]*, Laurent Georges*[1]*, Jinping Li*[2]*, Vojislav Novakovic*[1]
[1]Norwegian University of Science and Technology, Department of Energy and Process Engineering, NO-7491 Trondheim, Norway
[2]College of Energy and power Engineering, Lanzhou University of Technology, Lanzhou, 730050, China
*Ehsan.g.karkon@ntnu.no

Abstract. The present study aims to satisfy the energy demands of a set of Norwegian residential structures with the least carbon dioxide and most renewable energy. Real-time data on building domestic hot water (DHW), heating, and electricity usage is used to plan and expand the renewable energy supply side. PVT panels provide DHW and electricity in the hybrid solar and biomass energy system. Heat is produced by the digester and heat pump. Also used is a twofold effect absorption refrigeration system for cooling. Rule-based regulation manages heat streams and redirects flows on the supply side. We provide the plant's size and execute the dynamic energy simulation. Electricity and biomass expenses determine building heating. The system is then tuned for operational conditions and compared to the design point. PVT may generate over 80% of annual DHW. Summertime radiation is more intense and can be turned into cooling energy, therefore 64.8% of cooling output comes from it. Digester/CC heats 66.55% of the structure, suggesting designers use biomass in winter due to increased energy costs. A parametric analysis shows that increasing PVT duration and tank size affects efficiency and emissions differently. Cost, efficiency, and emission index at TOPSIS are 9.73 $/hr, 36.8%, and 7.75 kg/MWh, according to optimization findings.

1 Introduction

The need of using renewable energy to mitigate climate change is amplified by the fact that the global population is only predicted to increase. Coal, oil, and natural gas are examples of fossil fuels that have been heavily relied upon in the past to provide the energy needs of a growing global population [1]. The vast amounts of greenhouse gases released by these fossil fuels are a major factor in the greenhouse effect and global warming. Switching to renewable energy sources like solar, wind, hydropower, and geothermal is crucial if we want to prevent this crisis from becoming worse. These eco-friendly choices lower the carbon footprint of energy production and usage because they supply power without generating greenhouse gases. Using renewable energy solutions on a global scale may help us greatly in our efforts to mitigate climate change, preserve our planet for future generations, and create a brighter, safer, and more secure future for all of humanity. In this sense the employment of renewable energy are increasingly crucial to the GHG emission and greater dependability of the systems [2].

Building energy modelling is crucial in the fight against excessive energy use and greenhouse gas emissions. Energy modelling is becoming more relevant in the face of climate change and diminishing energy resources. Architects, engineers, and legislators may utilize advanced software tools to study and simulate the energy efficiency of buildings in a variety of contexts and with a variety of design possibilities [3]. By adhering to these guidelines, environmentally friendly, low-energy buildings may be constructed. Using energy simulation, it is simpler to implement energy-saving measures such as better insulation, efficient lighting, and state-of-the-art HVAC systems. Greenhouse gas emissions from buildings are considerable and may be reduced significantly using these measures [4]. A key instrument in the quest for a greener and more sustainable future is building energy modelling, which is used in the development and renovation of structures to optimize energy efficiency and conform to wider environmental goals. Numerous researchers have put in long hours studying how to power buildings with just renewable energy [5].

Spiru [6] investigated a renewable based energy system based on wind, hydro, solar, and biomass sources to decarbonize the energy sector and achieve a justified energy evolution. The goal of this study is to determine how much energy demand can be met by wind and solar power given the intermittent and unpredictable nature of these renewable resources. From a purely technical perspective, Mehrpooya et al. [7] looked at a CCHP based on a fuel cell plant for use in a building. The efficiency and payback time data for the 900-square-meter building was estimated to be 8.3 years.

This study suggests a PVT/HP/digester and chiller hybrid with the primary purpose of producing electricity and domestic hot water, respectively. In a system with rule-based smart regulating, the cost of biomass and energy at each hour of the year determines whether or not the HP is used for heating, and vice versa for the digester. Here is a quick rundown of what this system is trying to accomplish and what makes it unique:

Maintain simultaneous satisfaction of heating, cooling, and electrical needs.

- The DHW need is met by a solar system scaled for the warmest day of the year, and the solar system may then be utilized to meet the heating and cooling requirements.
- The system's auxiliary heater, high-performance components, etc. are all powered by energy generated by solar panels.
- The Digester and burner are utilized to heat up the areas according to cost of the biomass and energy.
- The system is examined from several angles, including efficiency, cost, and environmental impact.

2 Methodology

Figure 1 is a schematic representation of the proposed system, displaying the movement of streams, heat, electricity, and cooling throughout the system. There are three primary cycles in the system, as shown in Figure 1. These are the solar loop, the heating loop, and the cooling loop. Each component of the solar loop—PVT panels, pumps, heat storage tanks (HSTs), and controllers—works together to produce energy. This model uses a combination of on/off and proportional/integral/derivative (PID) controls to maximize the use of thermal and electrical energy flows. The primary function of the solar loop is to supply the DWH.

The draw off profile may be found in the cited sources, and the DWH is adjusted to 45ºC, the norm in Norway.

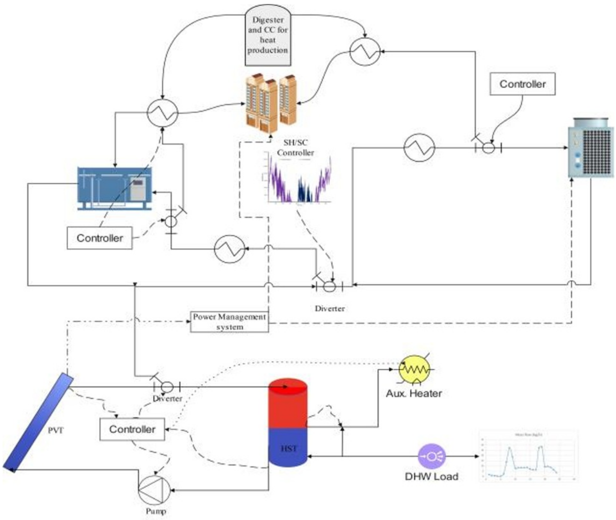

Fig. 1. The schematics of the proposed energy system

The model of the controllers is presented in Figure 2.

The modelling of the system is based on Energy, economic, and environmental analysis of each component. Finally, the operational index of the overall system can be written as [8,9]:

$$\eta = \frac{\dot{W}_{PVT} + \dot{Q}_{chilled\ water} + \dot{Q}_{DHW} + \dot{Q}_{space\ heating} - (\dot{W}_{auxiliary} + \dot{W}_{heat\ pump} + \dot{W}_{chiller})}{\dot{Q}_{heater} + \dot{Q}_{sun}} \quad (1)$$

$$\xi = \frac{\dot{m}_{CO2}}{\dot{W}_{PVT} + \dot{Q}_{chilled\ water} + \dot{Q}_{DHW} + \dot{Q}_{space\ heating}} \quad (2)$$

$$LCOE = \frac{C_{total}}{\dot{W}_{PVT} + \dot{Q}_{chilled\ water} + \dot{Q}_{DHW} + \dot{Q}_{space\ heating}} \quad (3)$$

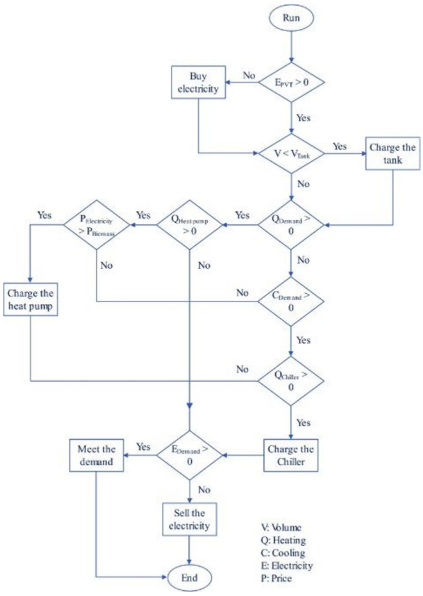

Fig. 2. Operational logic of the controllers

Moreover the flowchart of solving the problem is summarized in figure 3.

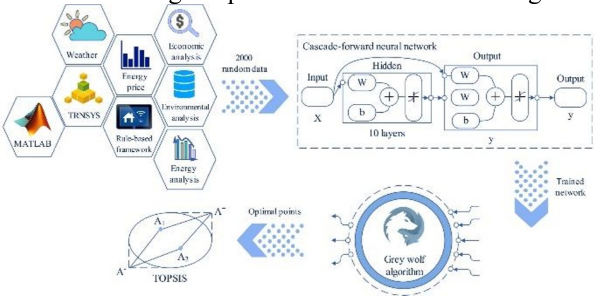

Fig. 3. The flowchart of solving the proposed energy system.

3 Results and Discussions

Figure 4 represents the heating demand over the course of a year in Trondheim, with the x-axis indicating time in hours from 0 to 8,760—the total number of hours in a non-leap year. The y-axis quantifies the heating demand, which fluctuates significantly throughout the year. Seasonal Variations: The cyclical pattern likely reflects the seasonal demand for heating, with peaks presumably during the colder winter months and troughs likely in the warmer summer months. The sharp spikes suggest sudden increases in heating demand, which could be due to particularly cold snaps or possibly the operational cycles of the heating system.

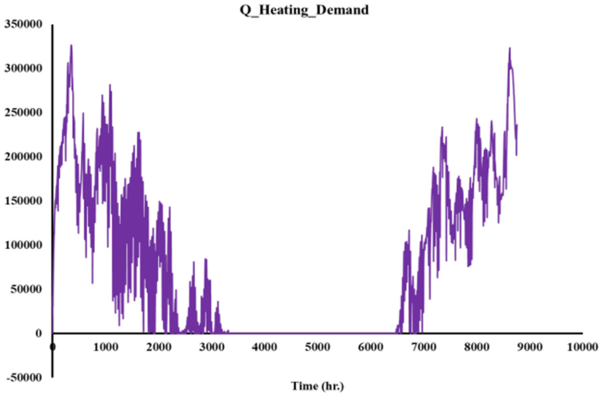

Fig. 4. The heating demand of the typical building in Trondheim, Norway

Figure 5 displays the shown prices of biomass and electricity. It is the cost of energy and biomass that determines how often the heat pump and heater are used. The water from Heat Exchanger 1's output flows into the heat pump, which absorbs heat from the air outside using a liquid refrigerant if electricity is less expensive than biomass. When the cost of electricity is high, the heater starts burning biomass and air to create syngas, which is then used to heat water. Last but not least, the space heating heat exchanger receives the hot water supply during the colder hours from the biomass heater, heat pump, or solar system.

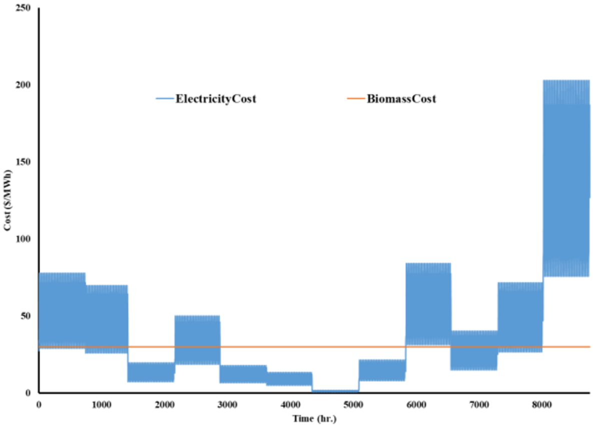

Fig. 5. The cost of electricity and biomass in one year

Finally Figure 6 shows the amount of heating generated by solar panels, heat pump and biomass. According to the data, approximately 275 MWh of heating is needed to bring the building to the desired temperature during the coldest hours of the year. The photovoltaic thermal panels provide just under 7% of this demand, around 18.28 MWh, due to limited sun availability and intensity. The biomass heater meets more than 65% of the annual heating requirement, supplying about 184.03 MWh, which suggests that the cost of electricity during the colder hours is higher, leading to a lower reliance on the heat pump for heating needs.

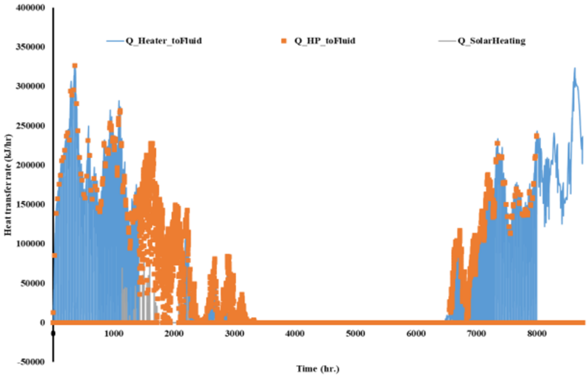

Fig. 6. The amount of heating generated by solar panels, heat pump and biomass

Figure 7 and 8 present an analysis of various performance parameters for a solar photovoltaic thermal (PVT) and tank volume and their impact on efficiency, cost, and emissions. based on these figures it can be seen that as the area of the PVT panels increases, the total power output and heat generated by the panels increase (this is reflected in the numerator of the efficiency equation). However, because the denominator of the efficiency equation also increases (the input energy to the system, which is the product of the panel area and solar radiation), the overall efficiency fraction decreases. This is depicted in the top left graph, where the efficiency (η) decreases as the PVT area increases. Also, when the PVT area increases, both the power and heat output increase (denominator of the LCOE equation) as well as the system's cost (numerator of the LCOE equation). The overall effect is that the increase in cost outweighs the increase in energy output, leading to an increase in the LCOE. This relationship is shown in the top middle graph, where the LCOE increases with the increasing PVT area. Moreover, with an increase in PVT area, the emission factor (ζ), defined as the mass of CO2 emitted per unit of net energy output, decreases. This happens because the denominator (net energy output from the panels) increases with the area, while the numerator (CO2 emitted) remains constant. The top right graph illustrates this downward trend in emissions with a larger PVT area. Besides, a larger tank volume can lead to faster cooling of hot water, necessitating more energy from the electrical coil to maintain the water at the setpoint temperature. This results in decreased efficiency. The bottom left graph likely shows efficiency decreasing as tank volume increases. The cost associated with a larger tank (greater volume) is higher, which drives up the LCOE. This is because, although a larger tank might provide more thermal storage, the increased cost does not proportionally translate to increased energy output, leading to a higher LCOE. The bottom middle graph is expected to show an upward trend in LCOE with increasing tank volume.

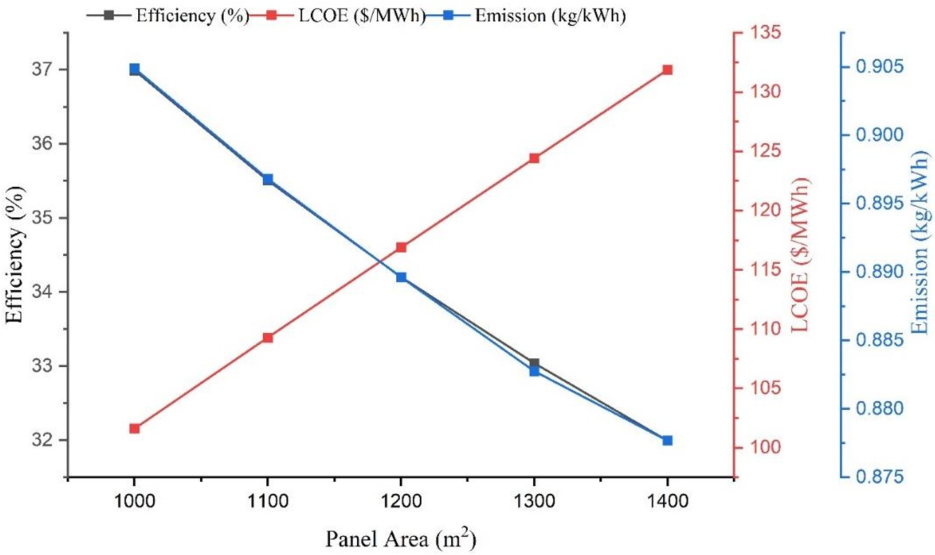

Fig. 7. The effect of panel area on performance indices of the system

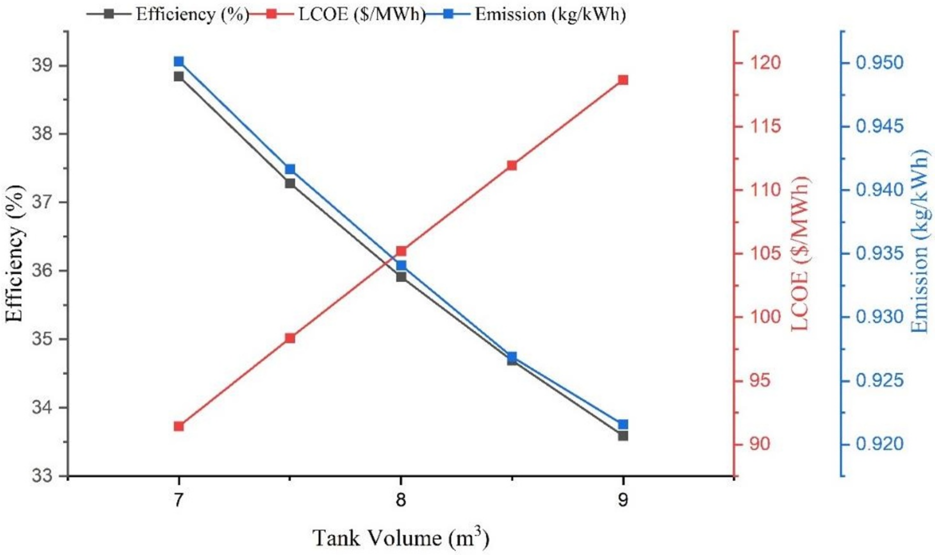

Fig. 8. The effect of tank volume on performance indices of the system

Table 1 compares performance indices between a system's initial design parameters and those obtained after applying TOPSIS, which is a multi-criteria decision-making method. The table includes four different indicators of system performance. At the TOPSIS optimized point, the efficiency is 33.8%, which is higher than the design point's efficiency of 30.1%. This indicates a 3.7 percentage point improvement in the system's ability to convert fuel into useful energy. The total cost at the TOPSIS point is lower at €9.6 per hour compared to €11.7

per hour at the design point. This suggests that the TOPSIS optimization led to a more cost-effective operation, saving €2.1 per hour. The LCOE at the TOPSIS point is €104.6 per MWh, which is notably less than the design point's LCOE of €121.5 per MWh. This represents a more economically efficient energy production after optimization, reducing the LCOE by €16.9 per MWh. The emission index at the TOPSIS point is 7.7 kg/MWh, while at the design point, it is 11.9 kg/MWh. The optimized system thus emits 4.2 kg less CO2 per MWh, which indicates a significant reduction in emissions and a move towards a more environmentally friendly performance. It can be seen that, the TOPSIS optimized points show improvements across all performance indices, demonstrating increased efficiency and environmental benefits while also reducing costs.

Table 1. Comparison of the performance indices in design and optimized points.

Indicator	TOPSIS	Design
Efficiency (%)	33.8	30.1
Total cost (€/h)	9.6	11.7
LCOE (€/MWh)	104.6	121.5
Emission index (kg/MWh)	7.7	11.9

4 Conclusion

This study's overarching goal is to provide for the energy demands of a sample of Norwegian residences in a way that minimizes carbon dioxide emissions and maximizes the usage of renewable energy sources. Using real-time data on the draw-off profile of hot water (DHW), heating, and power needs for the buildings as input data, a supply side based on the renewable based energy system is designed and scaled. The hybrid solar and biomass-based energy system relies on PVT panels for both the generation of DHW and electricity. The heat pump works in tandem with the digester to provide heating for the structure. Additionally, a double effect absorption refrigeration system provides the required cooling. Both the rerouting of flows on the supply side and the management of heat streams are under the jurisdiction of a rule-based control system. The full modelling results for the plant's size and dynamic energy consumption are provided. The price of biomass and energy are the primary considerations when determining how to heat the buildings. At last, the system as a whole is optimized in light of real-world conditions and compared to the original blueprint. The most important findings are:

- Parametric analyses reveal conflicting effects of increasing PVT duration and tank capacity on efficiency (negative) and emissions (positive).
- The optimized data shows that at the TOPSIS point, the overall cost, and are 9.73 USD/hr, 36.8%, and 7.75 kg/MWh respectively.
- Norway's renewable energy production drops dramatically throughout the winter months, from 82.7 MWh in the summer to 28.52 MWh in the fall.

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