A Green and Energy-Efficient Smart Building Driven by Photovoltaic Thermal Panels Connected to the Grid

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Abstract: The present paper introduces a new smart building system driven by photovoltaic thermal panels. The concept is to improve the contribution of renewable energy in the local matrix for peak load shaving by having a two-way connection with the local electricity network via a rule-based energy monitoring control design. Besides, the feasibility of removing the electrical storage unit with high investment cost is studied by establishing a dynamic interaction between the energy production and usage components to reduce the energy costs over the year. The system has intelligent thermal energy storage integrated with an electrically-driven coil, heat exchanger, pumps, and several smart valves and control units. The transient system simulation (TRNSYS) package is implemented to assess the practicality of the suggested intelligent model for a building complex in Malmo, Sweden. According to the parametric outcomes, by raising the panel area, while the generated electricity increases, the solar utilization factor falls, indicating conflictive changes among performance metrics. The results also show that the renewable resource covers the building's heating and electricity demands for the majority of the year and that a significant amount of energy is sold to the neighbourhood electricity grid, demonstrating the viability of the introduced intelligent model.

1 INTRODUCTION

Greenhouse gas emissions from buildings are widely recognized as a major contributor to the environmental problem because of the rising demand for power and heating in homes. More than thirty percent of all of the natural gas used in the globe is used in buildings, and buildings account for forty percent of all domestic primary energy use. As a result, many nations have started implementing energy conservation measures in their building infrastructure, such as the 20-20-20 strategy that aims to increase building energy efficiency by 20% (Nourozi, Wang and Ploskić, 2019). Moving practically toward the genuine concept of a smart building is a viable and promising solution to the issues associated with the high levels of environmental pollution and energy use in the building sector. Two key features of smart buildings are having an individual renewable-driven energy supply and intelligent interaction with the local electricity/heating networks.

As part of its functionality, smart buildings are expected to communicate both ways with the energy distribution grids that supply them. The building's energy system can buy energy from the networks when it is not producing enough, and it can sell energy to the networks when it produces more than it needs. Al-Saqlawi et al. (Al-Saqlawi, Madani and Mac Dowell, 2018) proposed and comprehensively assessed the performance of a building driven by PV with two-way interaction with the electricity network. Their results showed that the suggested system is more cost effective than an off-grid one, revealing the importance of making the exisiting buildings smarter via the clever connection with the local energy distribution network. Baneshi and Hadinfard (Baneshi and Hadianfard, 2016) analyzed the techno-economic facets of a building consisting of PV panels with and without a battery to determine which was

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more efficient. Using a battery increases energy costs by 33%, proving that the grid-connected system is preferable to the off-grid one. Syed et al. (Syed, Hansen and Morrison, 2020) conducted a performance evaluation of a smart building equipped with PV panels that interacted with the regional electrical grid. According to their results, the suggested solar-based system can meet 75% of the electricity needs, and that two-way communication with the grid performs better than an independent off-grid system. In order to reduce the building's energy expenses, Sharma et al. (Sharma, Kolhe and Sharma, 2020) introduced an innovative smart energy system driven by PV panels having two-way connections with the local grid. They showed that the smart interaction with the local energy network mitigates the energy bills and aids in shaving the peak load.

While there are many different types of renewable energy systems for buildings, solar-powered systems are by far the most common and widely used option. Systems that harness solar energy generate carbon-free power or heat from the sun's rays, which is good for the environment (from the CO_2 emission point of view) (Behzadi *et al.*, 2022). Photovoltaic (PV) panels are one type of solar technology that produces clean, green energy. Solar PV is environmentally beneficial because it produces no damaging greenhouse gases while producing electricity. Photovoltaic thermal (PVT) panels have improved performance, integration potential, and overall efficiency than PV panels due to their ability to capture useable thermal energy from the same area. PVT panels provide the added benefits of reliability and lifetime due to their ability to run with minimal degradation for over twenty years (Gholamian *et al.*, 2020). Lately, Zarei et al. (Zarei *et al.*, 2020) assessed and compared the techno-economic indicators of a solar-driven building system comprising PVT panels with the same system integrated with PV. According to their observations, the PVTs were 11% more efficient due to their ability to generate heat and electricity simultaneously. Tse et al. (Tse, Chow and Su, 2016) conducted a techno-economic evaluation of PVT panels and a hybrid PV system combined with a solar thermal collector. They proved that PVT panels are superior due to the reduced payback time and increased performance efficiency to meet the electricity/heating of an office building. In another research, Kamel et al. (Kamel, Elbanhawy and Abo El-Nasr, 2019) found that PVT panels outperform hybrid PVs and solar collectors for residential use due to their less product unit costs and superior efficiency. Buonomano et al. (Buonomano *et al.*, 2017) used TRNSYS software to analyze the interaction between a hybrid building system equipped with PVT panels and a thermal energy storage tank. After calculating, they determined a 68.8% decrease in energy use and a 90.2% decrease in carbon dioxide emissions, showing the excellence of PVT-driven energy systems to achieve an efficient and green building. Behzadi and Arabkoohsar (Behzadi and Arabkoohsar, 2020) proposed an intelligent building equipped with PVT and concluded that significant savings can be made on the building's energy bills by producing both heat and electricity.

The present study proposes a novel solar-based smart building combined with photovoltaic thermal panels to shave the peak load and improve the renewable contribution in the neighboring energy grid. The system is equipped with thermal energy storage with an electrically-driven coil to smooth out the solar energy's rapid changes, making the energy accessible whenever and wherever it is needed and providing a dynamic operation for best use. By developing a dynamic interaction between energy production/usage/local grid via a rule-based energy monitoring unit, this research looks at the potential savings in annual energy expenses that could be realized by eliminating the costly electrical storage unit. A Swedish city Malmo, which benefits from abundant solar radiation, undergoes a full performance evaluation using TRNSYS software to investigate the viability of the proposed model to satisfy a residential building's complex heating and electricity demands. The transient assessment and parametric examination are accomplished to analyze the impact of local ambient conditions and main decision variables.

2 SYSTEM DESCRIPTION

Figure 1 demonstrates the simple schematic is the proposed intelligent building energy system. As shown, the system is driven by photovoltaic thermal panels generating electricity and heating with a promising performance efficiency. The most significant aspect of this model is the smart rule-based controllers designed to effectively monitor the energy generation, usage, and transfer to the local electricity and heating networks. According to the figure, the rule-based controllers determine that the heating produced by the solar panels could either charge the thermal energy storage tank to supply the building's demand or be sent to the heat exchanger to be sold to the local district heating network. Besides, the smart control unit regulates the electricity flow between the solar panels, electricity grid, thermal energy storage, and the building's load. In this regard, the priority is charging the tank and changing the generated electricity to the hot water via the electrical coil for domestic uses.

If the tank is full, the produced electricity provides the building's demand based on the rule-based strategy. Otherwise, the additional generation is sold to the local electricity grid to mitigate the energy cost and provoke the householders to adopt their own energy plant. Because the suggested smart model has a two-way connection with the electricity network, the system can purchase electricity when there is no solar radiation, or the solar intensity is not high enough to run the tank and supply the load. The proposed system is equipped with several controllers and intelligent valves for clever switching between different modes and effectively manages the energy flow between the components and grids.

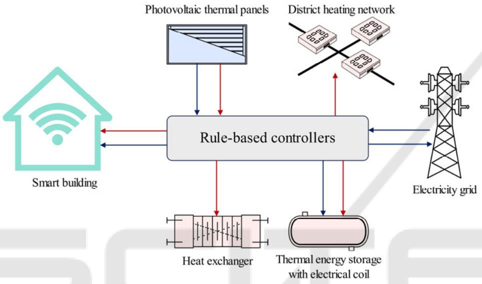

Figure 1: A simple schematic of the suggested new smart building model.

3 METHODOLOGY

In order to conduct the performance analysis of the proposed intelligent building system, a transient software simulator (TRNSYS), as a prominent tool for simulating renewable energy systems in transient mode, is applied. The thermodynamic formulation of thermal energy storage, photovoltaic thermal panels, heat exchangers, pumps, and smart valves are calculated and validated with the experimental data. Moreover, TRNBuild software is used to calculate the building's load needed to perform the transient simulation. The mass/energy balance computations contemplating each component as a control volume are assessed to conduct the thermodynamic analysis transiently as expressed as follows (Arabkoohsar, Behzadi and Nord, 2021):

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out}\, h_{out} - \sum \dot{m}_{in}\, h_{in} \quad (2)$$

These equations have three independent variables: $\dot{m}$, which stands for the mass flow into and out of each component; $\dot{W}$, which stands for the power produced/ used by each component; and $\dot{Q}$, which denotes the heating transferred from/to each piece of equipment.

Transient system modeling and control are the main uses of the simulation program TRNSYS. TRNSYS is separated into two parts. The first is a system calculation engine that loads and analyzes the input file, continuously calculates the system, validates for convergence, and displays system variables. The second component of TRNSYS is a wide library of components, each of which models a distinct subsystem's performance (Behzadi, Arabkoohsar and Perić, 2021). The standard library contains about one hundred fifteen models, including pumps, buildings solar technologies, weather data processors, and typical heating, ventilation, and air conditioning equipment. Users can modify existing components in models or add new ones, expanding the possibilities of the environment. The following is a detailed discussion of the components utilized to model the suggested building energy system (KLEIN and A., 1988).

By including a PV module in the conventional flat-plate collector (type 1), Type 50 simulates a photovoltaic thermal panel. It replicates a combined collector and considers both Florschuetz's research and work for flat plate collectors running at maximum power and a study provided in a report by Arizona State University for concentrating combination collectors. In the latter approach, peak power or current output at a specified voltage is solved using the I-V curves of the cells (or array). Type 158 describes a vertical, constant-volume storage tank. The working fluid's heat may be lost to the atmosphere through the top, bottom, and sides. In order to simulate stratification, the tank is divided into a user-specified number of isothermal nodes. Type 91 is a sensible heat exchanger with no capacitance, regardless of the installation. The input temperatures of the fluid on both the cold and hot sides can be used to determine the maximum practical heat transfer in this section. Type 2 represents the one-shot controller with a binary input of either 1 or 0. The current temperature is compared to two threshold values to establish the control signal's strength. Estimates of the current signal value are derived from the value of the input control function at a prior time step. Hysteresis can be triggered by linking a controller's input and output control signals. Moreover, the proposed smart model also includes numerous intelligent valves for diverse uses, such as mixer, diverter, and tempering valves. Depending on the location of a control valve, the Type 11f simulated flow diverter divides a single liquid input into two liquid outputs. The tempering valve is expressed by type 11b and determines the outlet split ratio which is necessary to achieve a specific temperature.

4 RESULTS AND DISCUSSION

In order to evaluate the viability of the suggested solar-driven smart system for a building complex in Malmo, Sweden, transient simulation and parametric study are performed. First, the variation of the most critical performance indicators with the key decision variables is examined and compared via the parametric investigation. Then, the hourly, monthly, seasonal, and yearly changes in system performance are evaluated to assess the impact of the ambient condition in detail.

The impact of the panels' area as a key design variable affecting the PVT and the entire system's performance is shown in Figure 2. According to the figure, by picking up a higher area (from 100 m2 to 200 m2), the annual electricity generated via the solar system increases drastically by about 9500 kWh. This is reasonable because the output products are directly affected by the panels' surface. The figure further shows that a lower solar utilization factor is obtained by raising the panels' area, which is unfavorable. The trend shows that the output production rise is lower than the input energy increment; therefore, a lower utilization factor is attained, as depicted in Figure 2.

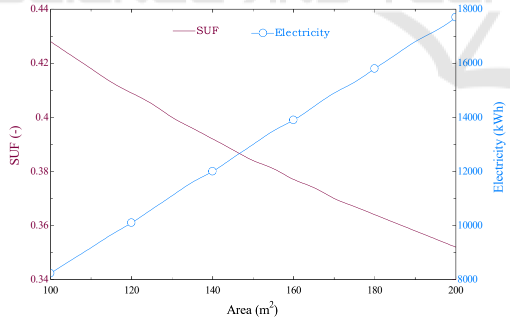

Figure 2: The variation of solar utilization factor and the produced electricity with the panels' area.

Figure 3 demonstrates the effect of heat exchanger effectiveness on the solar utilization factor and the heat transferred to the district heating network. By definition, effectiveness is a ratio of the actual heat transfer through the heat exchanger to the maximum heat transfer that may happen there. Ergo, more heat exchanger effectiveness results in higher heating transferred (by around 600 kWh) from the proposes smart system to the district heating network. Besides, the figure indicates that raising the effectiveness from 0.85 to 0.95 increases the utilization factor by about 0.007, which is negligible. This is justifiable since the increment in transferred heating is not considerable compared to the other terms in the utilization factor equation.

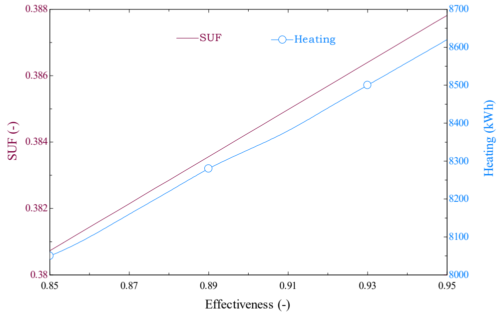

Figure 3: The variation of solar utilization factor and the transferred heating with the heat exchanger effectiveness.

Carefully constructed thermal storage systems usually result in cheaper capital costs as well as decreased energy usage. Thermal stratification improves storage tank effectiveness by allowing warmer layers to be heated by energy at moderate temperatures. The basis for the operation of a stratified TES tank is the thermal stratification process. Due to the inverse relationship between water density and temperature, stratification is a natural occurrence. As a result, heated water always floats above cold water. In order to simulate stratification and forecast how a unit would behave in terms of losses, charges, and discharges over time, nodes are added to the storage model. Figure 4 presents the temperature changes over the nodes of thermal energy storage over December. As shown in the figure, the stratification causes a constant temperature difference between neighbouring nodes. According to the figure, the temperature difference between the highest and lowest nodes at some hours increases by about 18°C.

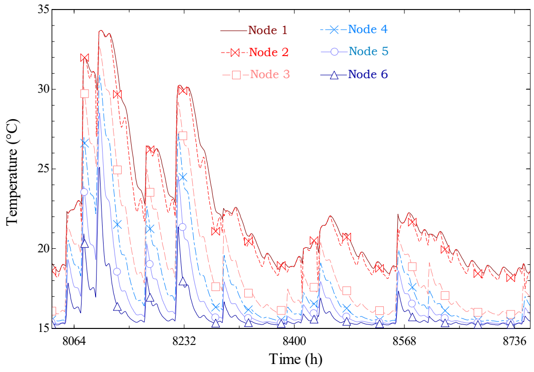

Figure 4: The temperature variation over the nodes of thermal energy storage in December.

In Figure 5, the temperature changes over the nodes of thermal energy storage in July are depicted and compared. While above-55°C water is being charged into the thermal energy storage at the first node, cold water is discharged from the tank with a temperature of around 22°C (at the sixth node). Figure 5 shows a constant temperature difference between the nodes because of the stratification over the year.

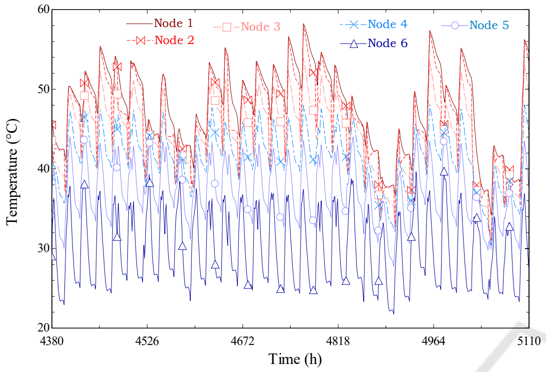

Figure 5: The temperature variation over the nodes of thermal energy storage in July.

Figure 6 illustrates the hourly variation and the time duration curve of the electricity generated via photovoltaic thermal panels to present the impact of the ambient condition on the panels' performance over the year. As presented, the produced electricity increases from winter to summer by raising the solar intensity. So, the share of the proposed smart renewable-based energy system on the local electricity grid increases, and the building's energy cost could be paid off on warm days. The figure further shows that the highest produced electricity equals 14,400 Wh, and about 43% of the year, the solar system could generate the electricity to either charge the tank, satisfy the demand, or sell to the local grid.

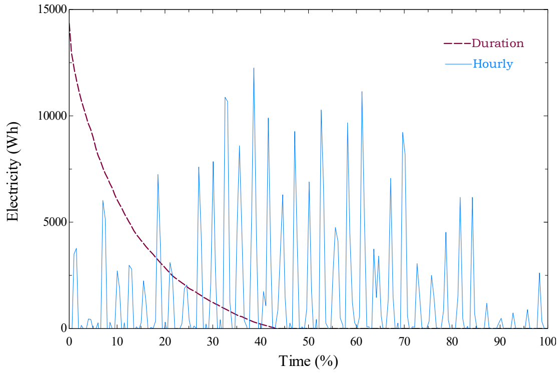

Figure 6: The hourly changes and time duration curve of the generated electricity.

In Figure 7, the hourly variation/duration curve of the heating generated via the panels is indicated to show the ambient condition impact on the other vital performance metric, heating production. Like the electricity trend, heating production rises from cold months to warm months due to the ambient temperature/solar intensity increment. According to this trend, the suggested smart model can sell significant hot water to the local district heating network in summer. The figure demonstrates that the suggested system can charge the tank or sell the additional production to the local district heating network for about 21% of the year. Also, the maximum hourly heating generation of 45,550 Wh is achieved at an hour in summer.

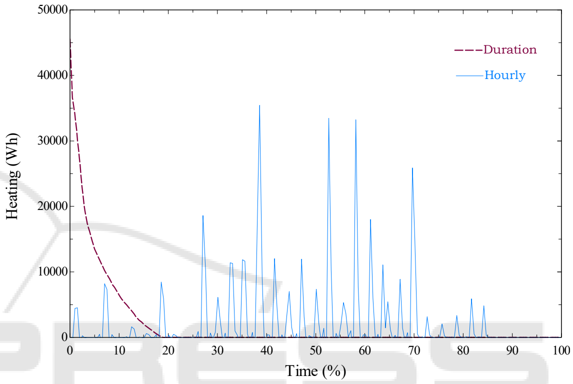

Figure 7: The hourly changes and time duration curve of the generated heating.

Figure 8 represents the monthly changes in the solar utilization factor and the heating transferred to the district heating network through the heat exchanger. According to the figure, the photovoltaic thermal panels will generate higher heating when the solar intensity rises from winter to summer. Hence, the thermal energy storage tank is filled, the building's demand is provided, and the maximum extra heat of 2,310 kWh is transferred to the local district heating network in July. The figure further depicts that in cold months, from October to February, the heating transferred to the network is almost zero, revealing the role of a rule-based model for smartly monitoring energy production/usage over the year. On the other hand, the figure illustrates that the solar utilization factor trend is not easily forecasted because of the simultaneous increase/reduction in/off useful production and input energy. It decreases from 0.43 in November to 0.28 in February and then increases to 0.46 in August.

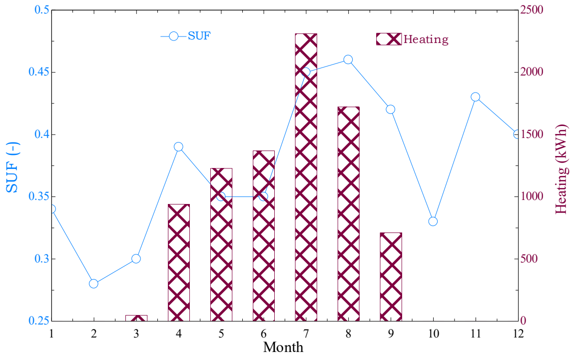

Figure 8: The monthly variation of solar utilization factor and the heating transferred through the heat exchanger.

4 CONCLUSIONS

An innovative smart building system powered by photovoltaic thermal panels is presented and wholly analyzed in this research. The idea is to have a two-way interaction with the local electricity network and a one-way connection with the disctrict heating gird via a rule-based energy monitoring control design to increase the proportion of renewable energy for peak demand reduction. Additionally, by establishing a dynamic interaction between energy production and usage parts to lower energy prices annually, the viability of eliminating the electrical storage unit with a high investment cost is investigated. The suggested system has an electrically driven coil integrated with thermal energy storage, a heat exchanger, pumps, several smart valves, and control units. The recommended intelligent model for a building complex in Malmo, Sweden, is tested using the transient system simulation (TRNSYS) program. For this, a parametric analysis is used to assess how important choice variables affect the model's performance. Additionally, the effect of local weather change is investigated by extracting results on hourly/monthly/seasonal/annual basis. According to the results, the panel's physical appearance must be selected carefully. In this regard, while the electricity generation is increased, the solar utilization factor decreases by picking up a higher panel area. The parametric results further show that the heat exchanger's effectiveness has a neutral effect on the solar utilization factor, and the heat transferred to the district heating network increases by raising the effectiveness from 0.85 to 0.95. On warmer days, the proposed system can sell considerable additional electricity/heating production to the local energy networks, signifying a rule-based model's role in effectively monitoring the energy production, usage, and storage components.

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