A smart zero-energy building having bidirectional interaction with electricity/heating networks: an attempt to achieve a higher renewable penetration

Amirmohammad Behzadi1, Behrouz Nourozi1, Trond Thorgeir Harsem1,2, Sasan Sadrizadeh1,3

1Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm, Sweden
2Norconsult AS, 1338 Sandvika, Norway
3School of Business, Society and Engineering, Mälardalen University, Västerås, Sweden

Abstract. The present research introduces an innovative zero-energy building complex equipped with a rule-based control approach for higher integration of renewable resources in the local energy network while bringing down energy costs. The idea centers on establishing several smart controllers to achieve a bidirectional interaction with the heating/electricity network for peak demand shaving and mitigate energy costs. The proposed system comprises Alkaline fuel cells integrated with a hydrogen storage tank driven by either a vanadium chloride cycle or an electrolyzer unit. The system also has an absorption chiller and smart thermal energy storage to supply the heating and cooling demands. TRNSYS-MATLAB developed code is applied to assess the system’s indicators from techno-economic standpoints for a residential building complex in the Scandinavian climate. Also, the parametric investigation and time-dependent analysis are carried out to examine the impact of decision parameters and the ambient condition. According to the results, the solar system's physical appearance is very important since it significantly affects performance efficiency and total cost. The results further reveal that picking up the cells' current from 300 A to 500 A improves the performance efficiency by around 12% while lowering the total cost, illustrating the importance of optimization. The results highlight the importance of smart controllers by showing that over 70% of the year's net energy values are positive, indicating that the proposed system may meet demand and sell excess electricity–heating productions to regional networks. The results further demonstrate that since the net energy values are positive for the majority of days in the spring and summer, the system might operate more independently from the local energy networks on warmer days. Eventually, the higher share of solar in summer and wind energy in colder days for hydrogen production shows that the renewable resources combination results in a secure energy supply to obtain the highest independence from the local grid throughout the year.

1 Introduction

Residential and commercial buildings use more energy, resulting in higher power and heat demand and considerable increases in greenhouse gas emissions. Buildings play a significant role because they use less than 50% of primary energy and more than 35% of natural gas [1]. As a result, many nations, including the EU, have already started reviewing their energy and climate policy. Thus, progress in sustainable energy supply is essential for supplying dependable and clean energy sources and enhancing humankind’s standard of living [2]. Zero-energy or smart energy buildings are introduced to accomplish this goal. Maintaining internal thermal comfort and minimizing energy usage are the key goals of energy regulation in a building [3].

In the future, smart energy systems will rely heavily on component like smart energy buildings. Smart energy buildings have both a high level of energy efficiency and access to the local energy distribution grids through their own renewable energy systems. The energy distribution systems are expected to communicate bidirectionally with smart buildings [4]. In order to achieve bidirectional interaction, buildings can purchase energy from the grids when their energy systems are underproducing and sell energy to the grids when they are overproducing (for peak shaving, for example). Arabkoohsar et al. [5] introduced an innovative smart building energy system driven by solar energy with bidirectional interaction with the local heating and electricity grids. According to their outcomes, high costs and emissions are saved than the traditional system in Denmark by establishing smart controllers. Solar-powered systems, which may be installed in a number of different configurations, are among the most common renewable energy sources for buildings. Solar energy systems are beneficial to the environment because they produce cleaner, renewable power and heat from the sun [6]. Additionally, solar energy systems have net-zero emissions of carbon dioxide. Since parabolic trough collectors operate at higher temperatures than other solar-powered devices, which lowers the cost of hot storage systems, its significance cannot be overstated. The collector’s trough design helps it to capture more solar radiation than a flat panel, which results in a higher heating generating rate per m² [7].
biggest issue with solar-powered devices, though, is the erratic nature of the energy source, which results in discontinuous production. Combining solar energy with wind is a viable approach to solving this problem because it is popular for residential usage and produces energy at a reasonable cost. Yang et al. [8] introduced an innovative wind and solar hybridization system, resulting in more than 9% energy cost reduction. Cao et al. [9] proposed a smart building energy system based on wind and solar resources. They revealed that a considerable greenhouse gas emission is removed, showing the importance of renewable hybridization. In another research, Shboul et al. [10] studied an integrated building energy system comprising parabolic trough collectors and wind turbines. According to their observation, the suggested smart combination leads to acceptable energy costs. Wang et al. [11] investigated a solar/wind/driven smart system to run Alkaline fuel cells. They concluded that the suggested model generates 10 kWh of electricity with a promising efficiency of 58%.

In the present research work, a grid-connected building is introduced and comprehensively evaluated to achieve the real meaning of the net-zero-energy building and reduce the peak demand. The system comprises Alkaline fuel cells, the primary electricity and heating production unit, driven by hydrogen. The green hydrogen is generated by wind and solar energies through the wind turbines and high-temperature parabolic trough collectors running the electrolyzers and vanadium chloride cycle. This renewable integration results in higher penetration of sustainable resources in the energy network and aids the worldwide environmental-friendly transition process. The hot storage tank and absorption chiller are added to enjoy the additional waste heat for cogeneration of heating and cooling. Through this strategy, not only the building's heating and electricity demands are satisfied, but energy costs are also reduced thanks to the waste heat recovery procedure. The suggested model is combined with an intelligent monitoring unit to determine the best operating strategy for optimal energy management between the production, usage, and storage units while buying/selling from/to the local networks. The system's viability is examined for a case residential building in Sweden by implementing TRNSYS-MATLAB engines.

2 Methodology

2.1 System description

Fig. 1 demonstrates the pictorial representation of the suggested smart hydrogen-powered building system for electricity, heating, and cooling generations. As depicted, the wind and solar energies drive the vanadium chloride cycle and electrolyzer unit for hydrogen generation stored in the H2 storage tank. Alkaline fuel cells are added as the hydrogen usage component to generate electricity with maximum efficiency and minimum pollution compared to conventional engines. The fuel cells' waste heat is exploited via the absorption chiller and stored in the hot storage tank for cooling and heating generations. The most significant aspect of the proposed zero-energy building is the rule-based control strategy designed to cleverly manage energy production, usage, and storage in different scenarios to achieve the minimum cost while maximizing efficiency. The wind turbine and electrolyzer unit have a bidirectional interaction with the local electricity network to either sell the additional production or purchase the electricity when there is no wind availability and the tank is vacant. Moreover, the hot storage tank and fuel cells are also connected to the district heating network and the electricity grid in a two-way monitored by the smart control unit.

Fig. 1. The suggested intelligent renewable-driven building energy system

2.2 TRNSYS-MATLAB model

The feasibility of the proposed intelligent zero-energy system is evaluated for a case-building model in Sweden. TRNSYS software is applied to perform a comprehensive transient assessment to find the most significant techno-economic metrics throughout the year. Since the thermodynamic equations of some components, including the vanadium chloride cycle, cannot be found in the TRNSYS library, MATLAB-developed code is implemented and linked to TRNSYS to accomplish the evaluation of the entire system [12]. The modularly designed transient modeling tool TRNSYS actively simulates the system and evaluates the performance metrics. Using the local weather information, TRNSYS calculates the thermodynamics formulas, such as the mass and energy balances. The building is simulated using TRNBuild (part of TRNSYS), and the requisite amounts of heating and cooling are calculated. TRNSYS is made up of numerous parts that collectively function as one unit. The various parts of the software are each identified by a distinct "Type" designation. The components used to model the recommended building energy system are broken down in more detail below.

In TRNSYS, Type 1257 simulates the parabolic trough collectors to absorb solar radiation to generate high-temperature heating products. The parabolic trough collector is separated into various nodes investigated over a user-specified simulation time. Since the working fluid is incompressible, a temperature variation is the only factor that affects its characteristics. A quadratic formula represents this effect. The transient equation is numerically solved at each node using the second-order Runge-Kutta method. The electrolyzer is another part of an electrically powered hydrogen generator.
The TYPE 160a simulator in TRNSYS is used to model the alkaline electrolyzer by utilizing the first principles of thermodynamics, heat transfer formulas, and chemistry correlations learned through experience. A current-voltage pattern is presented as a function of temperature for a specific pressure and Faraday efficiency while figuring out the dynamic model for this element. Another essential part of hydrogen production and storage systems is the Type 164a, which simulates a compressed gas storage tank utilizing the ideal gas's thermodynamics. Power in the suggested smart system might come from wind-driven turbines and hydrogen-fueled Alkaline fuel cells. The power production of wind turbines is assessed using the Type 90, which relies on its results on the power vs. wind speed characteristic curve that the manufacturers offer. Also taken into account are variations in air density and the fact that wind speeds increase with altitude. The basic equation for an alkaline fuel cell in TRNSYS is Type 173. The electrochemical model's current-voltage curve at normal operating temperature is derived from an experimental correlation. Type 158 represents a vertically oriented, fluid-filled tank with a set volume. In every time interval, there are two streams of flow, one entering and the other leaving the tank. Isothermal temperature nodes form the basis for the tank's stratification, managed by adjusting the number of nodes. Each node in a network with a fixed volume has two thermal interfaces with its neighbors: fluid conduction and motion. A single-effect, hot water-driven absorption chiller is simulated by Type 718 using the user-provided measured database. The machine provides the user-specified desired set temperature for the cooling water flow based on the current cooling capacity. The cooling water set point and intake chilled water temperature affect capacity. After conducting a complete techno-economic evaluation, the main key indicators, including performance efficiency and the total cost, are evaluated to assess the effectiveness and cost viability of the suggested smart model.

3 Results and discussion

The transient simulation of the suggested solar/wind-driven smart building is conducted via the TRNSYS-MATLAB developed code. The most significant techno-economic metrics, including the bought energy from the electricity/heating grids, total cost, and energy efficiency, are calculated to examine the performance and cost-effectiveness of the proposed intelligent system. Then, the impact of key decision variables on the efficiency and cost of the system is assessed via sensitivity evaluation. Afterward, the time-dependent diagrams, including hourly, daily, and monthly variations of bought/sold energy from/to the local energy grids and hydrogen generated by the VCl cycle and electrolyzer, are presented to examine the effect of ambient condition variation on the proposed intelligent system. Fig. 2 demonstrates the effect of collector length, as a key decision variable in the solar system, to evaluate the changes in the techno-economic indicators, including performance efficiency and total cost. According to the figure, picking up a higher collector length increases performance efficiency. This is rational because the denominator of the equation increases by raising the input solar energy. On the opposite, Fig. 2 shows that the increment of the collector length is not economically beneficial because the total cost increases by around 4 $/h by raising the collector length from 30 m to 45 m. The trend is reasonable since the parabolic trough collectors’ area directly affects the purchased cost.

![Fig. 2. The impact of collector length on the cost and performance efficiency of the suggested intelligent building system](image-url)

The variation of total cost and performance efficiency of the proposed intelligent renewable-driven building system with the changes in fuel cells' current is investigated in Fig 2. The fuel cell's hydrogen consumption increases as the current density rise from 300 A to 500 A. As a result, more power is produced, and the performance efficiency increases considerably by around 12%, as presented. Fig. 2 further reveals that by increasing the current from 300 A to 500 A, the total cost increases from 16.16 $/h up to 16.77 $/h and then falls to 16.7 $/h. This claim is credible because the fuel cell's purchase price is proportional to the amount of power it produces. So, the total cost first increases and then reduces due to the investment cost reduction of other components.

![Fig. 3. The impact of fuel cell current on the cost and performance efficiency of the suggested intelligent building system](image-url)

As mentioned above, one of the most significant novelties of the present system is the establishment of a clever rule-based control strategy to achieve an intelligent bidirectional interaction with the local electricity/heating networks. Fig. 4 represents the daily changes and duration curve of the electricity+heating bought from (negative) or sold to (positive) the local energy grids. According to the duration curve, more than 70% of the year's energy values are positive, meaning that the suggested system could supply the demand and sell the
additional electricity-heating productions to the regional networks. Besides, it can be observed that on warmer days, the system could operate more independently from the local energy networks since the energy values are positive on most of the spring and summer days. Fig. 4 shows that while the maximum daily energy sold to the grid of 340 kWh is achieved on the 183rd day of the year, the minimum value of -204 kWh (bought from the grids) corresponds to day 15.

Another significant aspect of the present intelligent model is the combination of two different renewable resources for a secure energy supply all around the year. Fig. 5 compares the share of solar and wind energy for hydrogen production through the vanadium chloride cycle and electrolyzer unit. According to the figure, the share of the vanadium chloride cycle from total hydrogen production is increased by raising the ambient temperature and solar radiation from winter to summer. As depicted, from June to September, the proposed system fully depends on solar energy to satisfy the demand's heating, electricity, and cooling needs. Conversely, in cold months when the solar availability is less and the wind intensity is higher, the role of the electrolyzer in generating hydrogen will increase. The figure shows that in January and February, the highest dependence of 74% and 47% on wind energy is achieved, revealing the significance of wind and solar hybridization for secure autonomous operation.

![Fig. 4. The daily variation and time duration curve of energy transferred from/to the local heating and electricity grids (positive: sold and negative: bought).](image)

![Fig. 5. The share of hydrogen produced by the vanadium chloride cycle and electrolyzer unit from the total generation.](image)

### 4 Conclusions

In the present study, energy-efficient smart heating, electricity, and cooling system with bidirectional interaction with energy networks is proposed and thoroughly investigated. The system is integrated with several intelligent monitoring units to cleverly manage energy production, usage, and storage to achieve the true meaning of net zero energy building. This idea diminishes the majority of energy costs, and high renewable energy is exported to the local energy network. Parabolic trough collectors and wind turbines drive the system to run a vanadium chloride cycle and electrolyzer unit for hydrogen production. The Alkaline fuel cells, as the hydrogen usage component, are added to supply the building heating and electricity needs and run the absorption chiller for a cooling generation. The effectiveness and cost viability of the suggested system is examined via TRNSYS-MATLAB developed code contemplating a residential building complex in Sweden. In a nutshell, the main outcomes of the present research work are listed as follows:

- The findings indicate that the physical characteristics of the solar system are crucial, as they have a major impact on both performance efficiency and total cost. By picking up the collector length from 30 m to 45 m, while the performance efficiency reduces by around 12%, the total cost increases 4 $/h, which is unfavorable.

- In addition, the results show that increasing the current across the cells from 300 A to 500 A boosts performance efficiency by roughly 12% while reducing the total cost, demonstrating the significance of optimization.

- According to the transient results, over 70% of the annual net energy values are positive, demonstrating that the suggested system may fulfill demand and sell excess electricity+heating productions to regional networks, highlighting the necessity of the designed intelligent control strategy.

- From the daily variation of energy transferred to/from the local network, it could be observed that the system works more autonomously in warmer hours due to the high solar intensity and ambient temperature.

- The higher proportion of solar energy during the summer and wind energy during the colder days for hydrogen generation demonstrates that combining renewable resources produces a reliable energy supply to achieve the greatest level of autonomy from the local grid throughout the year.

The authors are grateful to the Swedish Energy Agency (Energimyndigheten) for financing this research study. This article is drafted in line with Annex 37 (Smart Design and Control of Energy Storage Systems).

### References


