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Optimizing the energy consumption of a residential building in four climates of Australia and Iran by providing it using a multiple generation solar system

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Extended Abstract

Introduction

The increasing energy demand of residential buildings, together with the environmental consequences associated with fossil-fuel consumption, has made the development of renewable and highly efficient energy systems an important research priority. Buildings account for a substantial share of energy consumption, particularly because they simultaneously require electrical power, heating, and cooling. Consequently, the development of integrated energy systems capable of supplying these demands from renewable resources can contribute significantly to reducing fossil-fuel dependence and carbon dioxide emissions. In this context, zero-energy buildings represent an important approach toward sustainable energy utilization. Such buildings aim to balance their annual energy demand through renewable energy production and substantially reduce or eliminate their dependence on fossil fuels. Multi-generation energy systems are particularly attractive for residential applications because a single energy-conversion system can simultaneously produce several useful energy forms. In the present study, solar energy is employed as the primary renewable energy source, while a modified steam Rankine cycle is integrated with a heliostat solar-concentration system and molten-salt thermal energy storage. The proposed configuration is designed to provide three major energy services required by residential buildings, namely electricity, heating, and cooling. The system is therefore intended not only to reduce the environmental impact of residential energy consumption but also to improve the utilization of available solar energy through integrated energy conversion and storage. Previous investigations have examined biomass-based, hydrogen-based, wind-energy, solar-driven, and multi-generation systems from thermodynamic, exergetic, economic, and environmental perspectives. However, the present work focuses specifically on integrating a solar-driven multi-generation system with the actual annual energy requirements of a residential building under different climatic conditions. Accordingly, the effects of climate on heating, cooling, and electricity demand are considered together with the performance of the proposed energy system. Four cities—Sydney and Melbourne in Australia, and Ahvaz and Isfahan in Iran—are selected as representative climates. The residential building considered consists of 16 units distributed over four floors, with an area of 90 m² per unit. Building energy requirements are first determined using BEopt, after which the ability of the proposed solar multi-generation system to satisfy these requirements is evaluated. The main objective is therefore to optimize the proposed solar multi-generation system from both technical and economic perspectives and to investigate whether it can provide the annual heating, cooling, and electricity demands of the residential building in the four selected climates.

2. Materials and Methods

The proposed renewable multi-generation system consists principally of a heliostat solar-concentration subsystem, a solar receiver, a modified steam Rankine cycle, and molten-salt thermal energy storage. The system is designed to generate electricity and simultaneously recover thermal energy for heating and cooling applications. Solar radiation is concentrated by the heliostat field and transferred to the receiver, where thermal energy is supplied to the working fluid. The resulting high-temperature working fluid is used in the modified Rankine cycle to produce electrical power. After expansion through the turbine, the working fluid enters downstream components, where its remaining thermal energy is recovered and utilized for building heating and cooling before returning to the cycle. The thermodynamic analysis is based on mass and energy balances applied to the control volumes of the system components. The principal simplifying assumptions include steady-state operation, isentropic behavior of the turbines and pumps, saturated-liquid conditions at the condenser and evaporator outlets, and negligible changes in kinetic and potential energy. These assumptions are employed to establish the thermodynamic performance of the proposed configuration while keeping the system model computationally manageable. The analysis considers the major components of the cycle, including the steam turbine, pump, evaporator, condenser, superheater, economizer, absorber, receiver, heliostat field, hot and cold storage tanks, and recuperator. The net power output and the round-trip exergy efficiency (ERTE) are calculated to evaluate the energetic and exergetic performance of the system. An economic analysis is also performed by considering the cost contributions of the different system components. To optimize the system, the Response Surface Method (RSM) is employed. Six decision variables are selected: the number of heliostats, turbine inlet pressure, cold-storage tank temperature, hot-storage tank temperature, pump efficiency, and turbine efficiency. The ranges considered for these parameters are 200–400 heliostats, 20–40 kPa turbine inlet pressure, 500–650 K cold-storage temperature, 750–900 K hot-storage temperature, and efficiencies of 0.70–0.95 for both the pump and turbine. Two objective functions are considered simultaneously: improving the system performance and reducing the system cost rate. Minitab is used to perform the optimization and identify the most desirable operating point. Before applying the optimization procedure, the thermodynamic model is validated against previously published results for a Rankine-cycle system. For a heat-source temperature of 300 °C and a turbine inlet pressure of 3.988 bar, the present model predicts a mass flow rate of 0.86 kg/s, turbine power of 541.2 kW, net power of 519.3 kW, and total energy efficiency of 14.09%. The corresponding reference values are 0.836 kg/s, 541.3 kW, 516.6 kW, and 14.03%, respectively, indicating errors of 2.8%, 0.01%, 0.52%, and 0.42%. This close agreement demonstrates the acceptable accuracy of the developed thermodynamic model. Following system optimization, the performance of the integrated energy system is investigated under the climatic conditions of Sydney, Melbourne, Ahvaz, and Isfahan. The annual heating, cooling, and electrical loads of the residential building are calculated using BEopt. The resulting building demands are then compared with the corresponding energy production of the proposed multi-generation system.

3. Results and Discussion

The optimization results indicate that the best solution is associated with a desirability of 0.92. At this operating point, the number of heliostats is 210, the turbine inlet pressure is 40 kPa, the cold-storage temperature is 660 K, the hot-storage temperature is 980 K, the pump efficiency is 0.94, and the turbine efficiency is 0.86. Under these optimized conditions, the proposed system achieves a round-trip exergy efficiency of 19.4% and a system cost rate of approximately 169.9 USD/h. The climatic analysis demonstrates that the performance of both the building and the energy-generation system is strongly affected by local weather conditions. The investigated annual ambient temperatures vary approximately from −15 to 55 °C, while wind speed ranges from 0 to 20 m/s. Solar radiation varies from approximately zero to 1000 W/h according to the reported study data. The solar resource is particularly favorable in Isfahan and Sydney, where higher solar irradiation is available during the year. This climatic variability directly influences the thermal and electrical requirements of the residential building and consequently affects the amount of energy that must be supplied by the proposed system. The annual energy production of the multi-generation system varies considerably among the four cities. The annual cooling production is approximately 1,037,909 kWh in Sydney, 1,180,346 kWh in Ahvaz, 1,446,790 kWh in Isfahan, and 864,107.3 kWh in Melbourne. The corresponding annual heating production is 7,553,880 kWh, 8,589,600 kWh, 10,527,768 kWh, and 6,493,034 kWh, respectively. In addition, annual electrical production reaches approximately 1,169,050 kWh in Sydney, 1,329,422 kWh in Ahvaz, 1,629,562 kWh in Isfahan, and 1,110,223 kWh in Melbourne**.** These results demonstrate that the proposed configuration has the capacity to provide substantial amounts of all three required energy products under different climatic conditions. The building-load analysis further illustrates the importance of climatic conditions. The annual heating demand varies approximately between 0 and 100,000 kWh on the reported monthly/annual graphical scale, with Ahvaz requiring the lowest heating energy because of its relatively warm climate. Conversely, Ahvaz exhibits the highest cooling demand, reaching values within the reported range of up to approximately 140,000 kWh. Therefore, the dominant energy requirement changes with climate: colder conditions increase the importance of heating, whereas warmer conditions substantially increase cooling demand. The annual electricity consumption of the residential building varies within the reported range of approximately 0–30,000 kWh on the monthly scale. The comparison between building demand and system production indicates that the proposed system is capable of generating energy beyond the instantaneous requirements of the building during some periods. The excess energy can therefore be considered as stored or potentially utilized for other applications. The study separately evaluates surplus cooling, heating, and electrical energy. The analysis of surplus electricity is particularly important from an economic perspective. The excess electrical power is calculated from the difference between the electricity generated by the turbine and the electrical demand of the residential building. Such surplus electricity could potentially be supplied to the electricity grid and thereby generate additional revenue. Similarly, excess heating and cooling production can be used for other applications rather than being wasted, improving the overall utilization of the solar energy resource. Overall, the results indicate that integrating solar concentration, thermal storage, and a modified Rankine cycle allows the system to respond simultaneously to the electrical, heating, and cooling requirements of a residential building. The use of thermal storage is particularly important because solar energy availability changes during the day and throughout the year, whereas building energy demand does not necessarily follow the same temporal pattern. Consequently, the proposed configuration provides a mechanism for better matching renewable energy production with variable residential loads.

4. Conclusions

In this study, a solar-driven multi-generation energy system was proposed and thermodynamically, economically, and operationally evaluated for supplying the energy requirements of a 16-unit residential building under four different climatic conditions in Iran and Australia. The proposed system combines a heliostat solar-concentration field, a solar receiver, a modified steam Rankine cycle, and thermal energy storage to simultaneously produce electricity, heating, and cooling. The annual energy requirements of the building were determined using BEopt, while the thermodynamic model of the energy system was developed and optimized using the Response Surface Method. The model validation showed very good agreement with previously reported Rankine-cycle results, with the maximum reported deviation being approximately 2.8% for the mass flow rate and less than 1% for turbine power, net power, and total energy efficiency. The multi-objective optimization resulted in a desirability of 0.92, with an optimized configuration characterized by 210 heliostats, 40 kPa turbine inlet pressure, a pump efficiency of 0.94, and a turbine efficiency of 0.86. The optimized system achieved a round-trip exergy efficiency of 19.4% and a cost rate of 169.9 USD/h**.** The case-study results demonstrated that climatic conditions have a major influence on the heating and cooling requirements of the building as well as on the renewable energy potential of each location. Nevertheless, the proposed solar multi-generation system was found to be capable of supplying the required energy services throughout the year in the four investigated cities. The availability of surplus heating, cooling, and electricity during some periods also indicates the potential for energy storage, alternative utilization, or electricity-grid interaction. Therefore, the study demonstrates that coupling an optimized solar multi-generation system with a residential building can provide an effective pathway toward zero-energy residential buildings, while simultaneously improving renewable-energy utilization and reducing dependence on fossil fuels. The results suggest that the proposed configuration can serve as a promising approach for sustainable energy supply in residential buildings exposed to substantially different climatic conditions.

Keywords: Solar Energy, Multi Generation System, Multi-Objective Optimization, Response Surface Method, Residential Building.

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