

## AUTONOMOUS AND HYBRID RENEWABLE ENERGY SYSTEMS FOR ELECTRICITY AND HEAT SUPPLY IN RESIDENTIAL BUILDINGS: TECHNICAL, ECONOMIC, AND ENVIRONMENTAL ASSESSMENT

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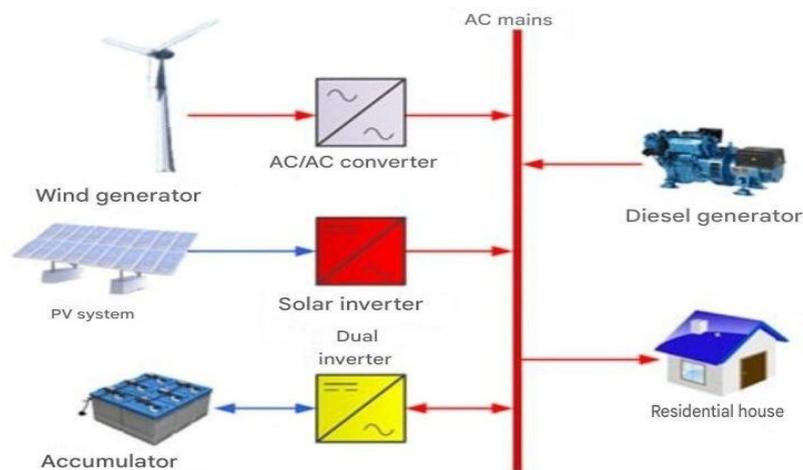
**Abstract:** The rising energy costs, climate change, and increasing loads on centralized energy networks emphasize the importance of autonomous and hybrid renewable energy systems in residential buildings. This study reviews global and local research on photovoltaic, wind, biomass, and battery-based hybrid systems for electricity supply, as well as solar air collector-based heating solutions. Results indicate that hybrid systems can significantly reduce electricity costs (LCOE \$0.149–0.664/kWh) and CO<sub>2</sub> emissions while ensuring reliable energy supply. Solar air-based heating systems provide 300–900 kWh of thermal energy per square meter annually, maintaining indoor temperatures within 18–22°C. Although electricity supply using hybrid systems has been widely studied, autonomous heat supply requires further investigation. This review highlights the potential of combining electric underfloor heating with solar air heating to optimize energy efficiency, technical reliability, and environmental sustainability in residential buildings.

### Introduction

The steadily rising energy prices, ecological restrictions associated with climate change, and increasing loads on centralized energy networks make the implementation of autonomous electric and heat supply systems in residential buildings a critical scientific and practical problem. Autonomous systems based on renewable energy sources enhance the continuity of energy supply, reduce losses, and significantly decrease carbon emissions. At the same time, the real-world performance of such systems under varying climatic conditions and load regimes, as well as the integration of electric and heat supply, has not been systematically studied. Therefore, analyzing the technical, energetic, and economic characteristics of autonomous electricity supply systems in residential buildings remains a relevant scientific and practical task. In this context, it is necessary to analyze both foreign and local studies, identify the advantages and disadvantages of existing approaches, and establish a scientific basis for future research. For example, Forrousso et al. [1] investigated the optimal configuration of an autonomous microgrid with building-integrated photovoltaics (BIPV) for a net-zero energy (NZE) residential building across six climate zones in Morocco. Using a particle swarm optimization algorithm, the levelized cost of electricity (LCOE) ranged from \$0.366 to \$0.664/kWh depending on the region. Integration of the BIPV system reduced battery capacity by 17.7–37.8% and decreased energy costs by 8.7–20.72%. The study found higher system costs in cold climates and greater economic efficiency in hot-arid zones. Similarly, Kumar and Channilar [2] evaluated the techno-economic and environmental feasibility of a solar-photovoltaic and biomass-based hybrid renewable energy



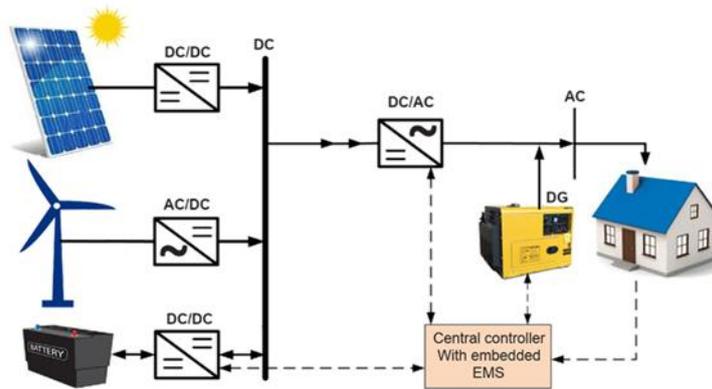
(HRES) system for the Sidhvanbet village in Punjab, India. Using HOMER Pro 3.14, the optimal configuration for 770 households was modeled and assessed via the TOPSIS method. The system, consisting of a 10 kW biomass generator, 1.1 kW PV, five lithium-ion batteries, and a 3.96 kW inverter, operated over 25 years with a total cost of \$21,087. Approximately 35.6% of the electricity was supplied by solar energy and 64.4% by biomass, with a PV payback period of 1.58 years. Kolhe et al. [3] investigated an optimal HRES configuration for a rural settlement in Siyambalanduva, Sri Lanka, with 150 households.[Fig.1] The region had an average solar radiation of 5.0 kWh/m<sup>2</sup>·day and wind speeds of 6.3 m/s at 25 m elevation. The optimal system consisted of 40 kW wind turbines, a 30 kW PV system, 222 kWh battery storage, and a 25 kW diesel generator, ensuring the lowest energy cost over a 20-year lifespan.



**Figure 1. Hybrid system with autonomous electricity supply**

This system ensured electricity at an LCOE of approximately \$0.30/kWh, with fluctuations in wind speed (4.5–6.3 m/s) and solar radiation (4.0–5.5 kWh/m<sup>2</sup>) increasing LCOE by no more than \$0.1/kWh. Moreover, the system remained economically viable when operated off-grid for the first 10 years and grid-connected for the following 10 years[Fig.2]. Bukara et al. [4] determined the optimal configuration of an autonomous microgrid for five residential buildings based on PV/wind/battery/diesel, using the Grasshopper Optimization Algorithm to minimize energy cost and eliminate energy deficits. The optimal system included twenty-six 275 W PV panels, a 4 kW wind turbine, 40 kWh battery, and a 4 kW diesel generator. The LCOE was \$0.365/kWh, with capital expenditures reduced by 19.3% and 14% compared to PSO and Cuckoo Search methods, respectively. Sensitivity analysis revealed that diesel fuel price had the strongest influence on energy costs.





**Figure 2. Autonomous microgrid system diagram**

El-houari et al. [5] conducted a comprehensive assessment of the energy, economic, and environmental performance of autonomous hybrid wind-solar-battery energy systems across 24 cities in Morocco. Using the HOMER Pro software environment, the optimal configurations for each region were determined under a daily load of 319.35 kWh and a peak capacity of 30.89 kW, with the levelized cost of energy (LCOE) ranging from \$0.171 to \$0.32/kWh. The lowest energy costs were recorded in the cities of Eddaxla and Laayun, with LCOE values of \$0.171 and \$0.172/kWh, respectively. The results indicated that in most regions, photovoltaic (PV) generation dominates electricity production, while in cities where wind energy is economically less viable, PV-battery-only configurations are preferable. The study also estimated that implementing hybrid systems could reduce total CO<sub>2</sub> emissions by more than 3,711 tons across the 24 cities. Furthermore, a 30% reduction in capital expenditure could lower the energy cost in Eddaxla from \$0.171 to \$0.125/kWh, suggesting that decreasing technology costs could significantly enhance the future competitiveness of hybrid systems. Arabzadeh et al. [6] evaluated the technical and economic performance of an autonomous solar-wind-diesel-battery system for household use in Winnipeg, Canada, using HOMER software. The optimal configuration consisted of a 1 kW PV array, one wind turbine, a 2 kW diesel generator, five batteries (34.7 kWh), and a 2 kW inverter, supporting an average daily load of 16 kWh and a peak load of 1.9 kW. The net present cost (NPC) of the system was \$33,110, with an energy cost of \$0.444/kWh. In this configuration, 74% of electricity was supplied by wind, 16% by solar, and only 10% by the diesel generator, resulting in a renewable energy share of 81.5%. Shaahid and Elhadidy [7] assessed the technical and economic feasibility of a PV/diesel/battery hybrid system designed to meet the energy demand of a building in Dhahran. Their analysis determined that the cost of electricity (COE) was \$0.149/kWh. Fazelpour et al. [8] examined the economic feasibility of using a hybrid system to meet the energy demand of a hotel, excluding environmental impacts. Their study found that a diesel/battery system offered the lowest comparative energy cost at \$0.315/kWh. Shaahid and Elhadidy [9] analyzed the potential of hybrid PV/diesel systems to supply electricity to a typical residential building in a hot climate. Their calculations indicated that even with 225 m<sup>2</sup> of PV panels and a 12-hour battery capacity, a diesel backup system was required to cover approximately 9% of the load. Baseer et al. [10] evaluated the technical and economic feasibility of PV/wind/diesel/battery hybrid systems for three residential complexes in Jubail Industrial City, Saudi Arabia, using HOMER Pro. For daily loads of 11,160 kWh, 4,865 kWh, and 3,288 kWh, the PV/Wind/Diesel/Battery configuration provided the lowest energy costs, with LCOE values of \$0.183, \$0.224, and \$0.244/kWh, respectively. Although fully renewable PV/Wind/Battery systems increased energy costs by up to 30%, they could reduce CO<sub>2</sub> emissions by up to 2,800 tons annually.



Fazelpour et al. [11] analyzed the feasibility of a hybrid diesel/PV/wind system with battery backup for a residential building in Zabol, Iran. The building's average daily load was 28.8 kWh. The optimal system configuration was a wind/diesel/battery combination, yielding an LCOE of \$0.360/kWh and an NPC of \$888,500, with initial capital costs of \$370,000. Duman and Güler [12] proposed an off-grid PV/wind/fuel cell hybrid system for disconnected holiday homes in İzmir, Turkey. Two scenarios were modeled—seasonal and continuous usage—with two energy storage options: hydrogen and batteries. The lowest LCOE of \$0.282/kWh was achieved in the continuous usage scenario with a PV/wind/fuel cell/diesel system. Rashid et al. [13] proposed an optimal PV/wind/diesel hybrid system for St. Martin and Kuakata islands near the Bangladesh coast. With an average annual solar radiation of 4.65 kWh/m<sup>2</sup>/day and a wind speed of 4.81 m/s at 25 m height, the LCOE for the two islands was \$0.393 and \$0.392/kWh, respectively. Fulzele and Dutt [14] suggested a similar PV/wind/diesel hybrid system with battery backup for Yavatmal district, Maharashtra, India. The PV system with battery, inverter, and generator achieved the lowest NPC of \$386,000 and an LCOE of \$1.096/kWh. Adding a wind turbine produced a slightly higher LCOE of \$1.106/kWh. Micangeli et al. [15] studied a hybrid system in Habaswein, Kenya, consisting of an 808 kW PV array, a 202 kW inverter, a 2.6 MWh energy storage system, and three diesel generators (50 kW, 100 kW, and 410 kW). The system achieved a comparative energy cost of \$0.253/kWh, reducing diesel consumption by 362,566 liters, CO<sub>2</sub> emissions by 951,658 kg, and other pollutants by 7,310 kg annually.

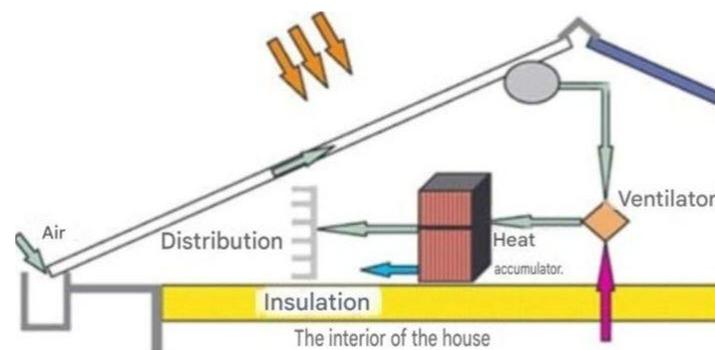
Mandal et al. [16] analyzed various hybrid system designs for rural electrification. In a village with a daily load of 243 kWh and a peak load of 51.5 kW, the optimal system comprised a 73 kW PV array, a 57 kW diesel generator, a 387 kWh battery bank, and a 28 kW inverter, yielding a comparative energy cost of \$0.37/kWh. Shaahid et al. [17] evaluated an off-grid wind/PV/diesel hybrid system with battery storage for the “KLIA Sepang Station” in Malaysia. The average daily load was 33 kWh, and the calculated energy cost was \$1.877/kWh, lower than conventional local electricity costs. The system was estimated to reduce greenhouse gas emissions by approximately 16 tons per year. Elhassan et al. [18] proposed hybrid system designs for residential energy supply in Khartoum, Sudan, with conditions similar to Jubail Industrial City. Simulations covering 1 to 50 households indicated that LCOE decreased as the number of houses increased—from \$1.1/kWh for a single household to \$0.44/kWh for 50 households. The optimal system for 50 houses included 3.5 kW PV modules, two 3 kW wind turbines, and eight 6 V, 225 Ah batteries. These studies clearly demonstrate the technical and economic feasibility of hybrid systems for residential electricity supply. At the same time, their application for direct heat supply, particularly in autonomous heating systems, requires separate scientific investigation and performance evaluation. Üрге-Vorsatz et al. [19] analyzed global and regional energy consumption trends in building heating and cooling, noting that this sector accounts for 32% of final global energy demand and 30% of energy-related CO<sub>2</sub> emissions. Residential heating and cooling energy shares vary regionally from 18% to 73%, with the highest values in hot, developing regions. Between 2010 and 2050, under a “frozen efficiency” scenario, global residential heating and cooling energy demand is projected to increase by 79–80%, and commercial buildings by 84%. Key drivers include a 115% increase in households, 38–50% growth in per-capita floor area, and sharp increases in economic activity. Specific energy consumption in many regions remains nearly constant or decreases slightly, highlighting the importance of energy efficiency policies for regulating thermal loads in buildings. Wang et al. [20] evaluated the performance of a complex winter heating system consisting of a solar air collector, a phase-change thermal storage channel, and a floor air distribution system using numerical modeling. Under a solar radiation intensity of 860 W/m<sup>2</sup>, the air temperature at the



collector outlet increased from 283 K to 328 K. After passing through the phase-change thermal storage channel, the air temperature stabilized at 307 K, enabling storage of excess daytime heat. Air delivered to the room at 0.7 m/s maintained an indoor temperature of approximately 292 K (~19°C), fully meeting heating requirements. However, during night-time conditions with outdoor temperatures dropping to 267 K, solar input alone was insufficient, and an auxiliary electric heating source was necessary to maintain an indoor temperature of 291 K.

Boynazarov and Uzbekov [21] investigated the energetic and economic efficiency of heating greenhouses using solar air collectors under the climatic conditions of Uzbekistan. For a greenhouse with a total area of 400 m<sup>2</sup> and a volume of 1120 m<sup>3</sup>, twenty rhombic solar air collectors with a working area of 1 m<sup>2</sup> each were utilized. During winter design conditions (indoor temperature  $T_i=19^{\circ}\text{C}$ , outdoor temperature  $T_t=-1^{\circ}\text{C}$ ), total heat losses amounted to 21.35 kW. Heat losses through concrete walls were 18.34 kW, while insulated exterior cladding accounted for only 2.85 kW, confirming the high thermal resistance of the air layer. When solar radiation was at maximum, the collectors produced up to 3.5 kW of heat, allowing a total daily energy saving of 18.85 kWh. Qayumov et al. [22] explored constructive improvements in hybrid solar-air collectors to enhance solar utilization and air heating efficiency. Installing the collectors at an optimal seasonal tilt increased the temperature of the working air relative to ambient conditions by 25–40°C. Using 12 W mini photovoltaic-powered fans under forced circulation ensured fully autonomous operation, independent of the electric grid. The results confirmed that hybrid solar-air collectors can provide simultaneous heating, ventilation, and humidity control, representing an energy-efficient and technically feasible solution.

Belusko et al. [23] modeled the energy performance of a roof-integrated solar air heating system with transparent glazing. [Fig.3] Simulations indicated that transparent coverings increased collector efficiency by 30–50%, significantly reducing heat losses via convection and incident radiation.



**Figure 3. Roof-mounted solar air heating system**

Matching collector area with the heat storage volume allowed annual energy savings of 9–22%. Overall, roof-integrated transparent solar air collectors were evaluated as a promising, cost-effective technical solution to improve heating efficiency in buildings. Budea [24] conducted experimental and numerical analyses of solar air collectors for space heating and ventilation in Romanian climatic conditions. For a 200 m<sup>3</sup> residential building under 500 W/m<sup>2</sup> solar radiation, 4–6 m<sup>2</sup> of collector area was sufficient to achieve a 10–15°C temperature difference, enabling effective natural ventilation. Choudhury and Baruah [25] highlighted the high energy-saving



potential of solar air heaters in residential space heating. According to their research, conventional flat-plate collectors achieve a typical efficiency of 50–60%, while modern vacuum tube collectors can reach 70–90%. One square meter of collector surface can provide 300–900 kWh of heat annually under average climatic conditions, covering a significant portion of a household's seasonal heating demand. Economic analyses indicated that the delivered heat cost in solar heating systems ranges from 20–220 \$/MWh, which is competitive with natural gas (40–100 \$/MWh) and electricity (75–260 \$/MWh). Furthermore, such systems can reduce residential CO<sub>2</sub> emissions globally by approximately 6–10%, confirming their technical and environmental efficiency. Analyzed scientific studies indicate that the effective use of autonomous and hybrid electricity supply systems in residential buildings can significantly reduce energy costs. The optimal system configuration strongly depends on climatic conditions, load profiles, and technology costs. It has been demonstrated that combinations of PV, wind, biomass, and battery systems are economically feasible in many regions. Moreover, air-based heating systems utilizing solar air collectors in residential buildings are technically efficient and environmentally friendly solutions for heat supply. Both international and local studies have scientifically confirmed that such air-based systems can provide 300–900 kWh of thermal energy per 1 m<sup>2</sup> of collector area annually, while maintaining indoor air temperatures within the range of 18–22°C. However, the majority of existing research has focused primarily on electricity generation, and the application of autonomous systems for heat supply has not yet been studied in sufficient depth. The presented results demonstrate the high potential of renewable energy-based autonomous systems for electricity supply in residential buildings. However, the issue of heat supply in residential buildings—primarily through air-based solar heating systems, which constitute the main portion of energy consumption—requires a separate scientific approach. Therefore, comprehensive research on the use of autonomous electric underfloor heating systems is necessary. Additionally, studying the combined application of these systems with air-based solar heating is essential to optimize energy efficiency, ensure technical reliability, and reduce environmental impact in residential buildings. The integration of autonomous or hybrid renewable energy systems (such as combinations of photovoltaic panels, wind turbines, biomass generators, and batteries) has been shown to significantly reduce energy costs and CO<sub>2</sub> emissions. Moreover, the proper design and optimization of solar air collectors can provide 300–900 kWh of heat per square meter annually, maintaining indoor air temperatures within 18–22°C. Such systems are technically feasible, environmentally friendly, and economically competitive compared to conventional energy sources, including natural gas and grid electricity. Overall, the reviewed studies highlight the urgent need for further development and implementation of autonomous and hybrid renewable energy systems for both electricity and heat supply in residential buildings. These solutions contribute to sustainable energy consumption, lower greenhouse gas emissions, and increased energy independence, aligning with global and regional environmental objectives.

## Conclusion

Autonomous and hybrid renewable energy systems in residential buildings reduce electricity costs by 8–30%, with LCOE ranging from \$0.149 to \$0.664/kWh, depending on the configuration and location. Solar air-based heating systems provide 300–900 kWh/m<sup>2</sup> of thermal energy annually, maintaining indoor temperatures between 18–22°C, and can lower CO<sub>2</sub> emissions by 3–10% per household. Combining electric underfloor heating with solar air collectors can cover 40–70% of heating demand from renewable sources, optimize energy consumption, and ensure reliable indoor thermal comfort.



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