Energy and Environmental Assessment of a Solar-Assisted Heat Pump for Water Heating

Evaluación Energética y Ambiental de una Bomba de Calor Asistida por Energía Solar para el Calentamiento de Agua

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Abstract

The study analyzes the performance of a solar-assisted heat pump for residential water heating, aiming to demonstrate its feasibility as a sustainable and energy-efficient alternative while contributing to CO_2 emission reduction in step to the Sustainable Development Goals. The research combined hands-on experimentation with energy analysis, monitoring operational parameters, heating time, and calculating the coefficient of performance for 10 liters of water under varying solar radiation conditions. Additionally, the environmental impact of photovoltaic panels and battery storage was evaluated, alongside operating costs and estimated CO_2 emissions. The results revealed a maximum coefficient of performance of 6.2 and a minimum of 3.3, with heating times ranging from 30 to 35 minutes, indicating stable and efficient performance. The system consumes just 2.33 kW·h per year for active components, producing only 9.6 kg of CO_2, far below conventional electric or LPG heaters, whereas solar integration further lowers its carbon footprint. Overall, the findings highlight that this solar-assisted heat pump is technically effective, economically competitive, and environmentally responsible.

Index terms— Solar-assisted heat pump, Energy efficiency, Renewable energy, Sustainable development goals, Carbon emissions.

Resumen

La investigación evaluó la eficiencia energética y el rendimiento de una bomba de calor asistida por energía solar para el calentamiento de agua, validando su viabilidad como alternativa sostenible, que se alinea con los Objetivos de Desarrollo Sostenible. El estudio combinó experimentación práctica y análisis energético, midiendo parámetros operacionales, tiempo de calentamiento y calculando el coeficiente de rendimiento en un volumen de 10 litros de agua en diferentes condiciones de radiación solar, además de la estimación de emisiones de CO_2 y costos de operación, incluyendo la contribución ambiental de paneles fotovoltaicos y baterías de almacenamiento. El coeficiente de rendimiento máximo fue 6.2 y un mínimo de 3.3, con tiempos de calentamiento de 30 a 35 minutos, con un rendimiento eficiente y estable. El sistema consume 2.33 kW·h anuales para sus componentes, generando 9.6 kg de CO_2, inferiores a alternativas eléctricas o a GLP, y reduce la huella de carbono mediante la integración de energía solar. Por lo que este sistema es una solución técnica, competitiva económicamente y ambientalmente responsable para la calefacción de agua residencial.

Palabras clave— Bomba de calor asistida por energía solar, Eficiencia energética, Objetivos de desarrollo sostenible, Energía renovable, Emisiones de carbono.

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1. INTRODUCTION

Ecuador still depends heavily on conventional energy sources, reflected in a per capita electricity consumption of approximately 1629 kW·h for 2024, with fossil fuels accounting for around 63 % of the country's primary energy supply [1]. For the housing sector, electricity demand has increased over the past decade at annual rates of 4 to 6 %, reaching 6428 GW·h. This trend is influenced by regulated energy prices and substantial subsidies for fuels such as liquefied petroleum gas (LPG), which promote intensive fossil fuel use for domestic water heating and other household needs. Globally, the transition to renewable energy sources, such as solar, has proven critical for decarbonizing electricity systems [2], emphasizing the need for Ecuador to accelerate the adoption of cleaner and more efficient energy solutions in the residential sector.

Despite a seemingly renewable energy matrix, with hydroelectric power providing 90% of electricity generation due to strategic investments in water resources [3], other renewables, such as solar, wind, and biomass, contribute only marginally, at 0.6, 0.7, and 1 to 2 %, respectively [4]. Although solar potential is high across several regions, its exploitation remains limited by installation and storage costs. This highlights the necessity of integrating complementary renewable technologies to strengthen energy security and reduce CO_2 emissions. Residential energy consumption, particularly through LPG and electricity from fossil fuels, directly affects the national carbon footprint, with the energy sector responsible for up to 69% of total greenhouse gas emissions [5].

According to Yildiz et al. [6], globally, water heating accounts for roughly 26 % of building energy use. In Ecuador, conventional electric and LPG water heaters significantly contribute to emissions without optimizing efficiency. This situation exacerbates environmental impacts, such as climate change, and increases household energy costs and dependence on imported fuels. Consequently, there is a pressing need for alternative solutions that reduce carbon intensity while enhancing the efficiency and sustainability of domestic hot water services, particularly in urban and residential contexts where equitable energy access is important.

Lu et al. [7] examined the energy performance of various solar-assisted heat pump (SAHP) configurations for water heating across 39 cities in China. The study compared parallel and series arrangements, incorporating auxiliary heat sources, such as air, water, or electric resistance, while accounting for solar irradiance, ambient temperature, and auxiliary system efficiency. The results showed that the parallel configuration, in which the solar collector and heat pump operate simultaneously, generally achieves better energy performance, especially with air-to-water heat pumps under irradiance above 500 W/m². Conversely, the series configuration, where the solar collector preheats the water before the heat pump, performs more efficiently only in colder climates or when the auxiliary system reaches a coefficient of performance (*COP*) above 6.9 with supply temperatures exceeding 45 °C. These findings highlight the importance of adapting SAHP design to local climatic conditions, providing practical guidelines for integrating hybrid solar systems into residential buildings.

SAHP systems combine solar thermal energy with the vapor compression cycle, using solar radiation as the primary heat for the evaporator. Over the past decade, research has highlighted their potential to replace electric and LPG water heaters in households. Hai et al. [8] demonstrated that an optimized SAHP system can significantly reduce electricity consumption, operational costs, and CO_2 emissions, making it a promising solution for urban areas with high hot water demand. Similarly, Abbasi et al. [9] reported that a dual-source solar/air SAHP system can achieve *COP* values between 2.4 and 3.94, cut electricity use by 25%, and lower annual CO_2 emissions by 1,450 kg, offering a stable and efficient operation despite solar variability, though with a payback period of about 19 years.

Meena et al. [10] directed an experimental study on the energy performance of SAHP systems aimed at water heating and improving building energy efficiency. Their setup featured a heat pump coupled with a single flat-plate solar collector with a transparent cover and copper absorber, capable of heating 60 liters of water from 15 to 45 °C in approximately 70 minutes under an average solar irradiance of 700 W/m², achieving a maximum *COP* of 6. The study showed that system efficiency scales with solar irradiance, reaching *COP* values above 5.6 under optimal conditions and dropping to around 2 when irradiance falls below 450 W/m². Energy consumption was only 0.3 to 0.4 kW·h, resulting in savings of up to 2.5 kW·h compared to conventional electric water heaters and estimated payback period of six years, four months.

The Sustainable Development Goals (SDGs), recognized in 2015 by the United Nations 2030 Agenda, present a framework for global efforts to eradicate scarcity, protecting the environment, and indorse prosperity for all [11]. Yumnam et al. [12] highlighted that research on SDGs has grown exponentially, particularly in areas, as renewable energy, weather action, impartial access to resources, and sustainable urban development. While developed nations remain the primary contributors, emerging economies are increasingly producing impactful scientific research, reflecting the global and interdisciplinary nature of sustainability challenges.

Olabi et al. [13] review recent progress in solar thermal systems and their potential as sustainable alternatives for water heating, emphasizing goals beyond simple energy efficiency. The study examines different solar collector types, including flat-plate, evacuated tube, and photovoltaic-thermal (PV/T) hybrid systems, and evaluates their performance under changing climatic conditions. It also identifies practical applications for residential, industrial, and agricultural contexts, such as zero-energy buildings, greenhouses, water pumping, and solar cooling. By effectively harnessing solar radiation and integrating thermal storage, these systems can provide a continuous hot water supply, enhance energy self-sufficiency, support environmental sustainability, and generate social and financial benefits, including job conception and reduced dependance on fossil fuels.

Prolonged dependence on unrenewable energy sources, as fossil-fuel electricity and LPG, leads to significant environmental and economic impacts, including higher CO_2 emissions, fuel import dependence, and vulnerability to market fluctuations [14]. As highlighted by Singh et al. [15], this situation relates directly to SDG 7, ensuring admittance to reasonably priced, unfailing, sustainable, and modern energy, and SDG 13, which emphasizes urgent climate action. Furthermore, adopting clean and efficient technologies boosts responsible consumption and sustainable production in line with SDG 12, optimizing energy use while reducing environmental impact. In this context, hybrid solar-based systems emerge as key strategies to improve energy efficiency, mitigate climate change, and foster sustainability in residential and urban settings, supporting global sustainability commitments.

Mercedes-Garcia et al. [16] investigate the enhancement of energy efficiency and the incorporation of renewable technologies in water heating systems to promote sustainability and advance the SDGs. The study evaluates 61 optimized water pumping and distribution systems that incorporate clean energy and energy recovery strategies, assessed through energy, economic, and environmental indicators. Findings show that more than 70 % of the systems achieved significant efficiency gains, with solar energy integration notably reducing fossil fuel consumption and greenhouse gas emissions. These improvements contribute to SDG 7, reasonable and clean energy, and support other SDGs, considering scarcity reduction, hunger, economic growth, and responsible consumption.

The present study aims to assess the performance of the SAHP system for water heating, validating its feasibility as a sustainable and energy-efficient solution. By optimizing energy use and integrating renewable sources, the work addresses SDGs related to clean energy, water sustainability, and emission reduction. The paper is organized as follows: the Methodology section details the SAHP system and the mathematical models used for analytical evaluation. The Results section presents comparative figures representing experimental and analytical outcomes. The Discussion section contrasts these results with existing literature to validate the findings and highlight potential innovations. Finally, the Conclusions summarize the key contributions and insights obtained from the study.

2. METHODOLOGY

2.1 SAHP System

A heat pump works on a thermodynamic refrigeration cycle, which transfers heat from a low-temperature source to a higher-temperature sink [17]. In this process, the evaporator absorbs heat either from the surrounding environment or from a solar collector, causing the refrigerant to vaporize. The vapor is subsequently compressed by the compressor, raising its pressure and temperature, then the stored energy is released to water in the condenser as the refrigerant condenses. The expansion valve drops the pressure of the liquid refrigerant, completing the cycle and allowing continuous operation. The SAHP system integrates these four main components: compressor, condenser, expansion valve, evaporator, into a coordinated system designed for efficient water heating. To monitor performance, pressure gauges (P) and thermocouples (T) are installed at the inlet of each component. Fig. 1 presents a schematic of the SAHP system and its instrumentation setup.

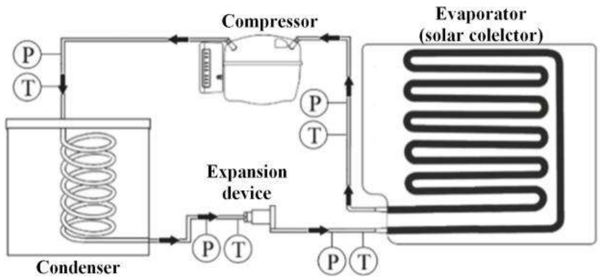

Figure 1: Schematic Representation of the SAHP System [18]

2.2 Thermodynamic Analysis

The thermodynamic cycle of the SAHP system was quantitatively analyzed using the heat transfer equation, which allows estimation of the thermal energy delivered to the water (Q_{water}) during the heating process. This analysis accounts for variations in the operating conditions of the working fluid, particularly the temperature difference between its initial and final states (ΔT) [19]. Following the first law of thermodynamics, which asserts energy conservation in a system according to equation (1), the energy absorbed or released by the refrigerant at each stage of the cycle can be expressed as:

$$Q_{water} = m_{water} \cdot c_p \cdot \Delta°T, \quad (1)$$

where m_{water} represents the water mass, assumed constant during operation, and c_p is the water specific heat water. The rate of heat transfer from a system component to the surrounding medium ($\dot{Q}_{ref}$) can be considered as the product of the working fluid's mass flow rate ($\dot{m}_{ref}$) and the enthalpy difference between inlet and outlet (Δh) [20]. This formulation is useful for processes where energy changes cannot be described solely by temperature differences, incorporating both internal energy variations and flow work. Equation (2), therefore, provides a practical representation of the system's real energy behavior and allows for the precise calculation of heat transfer at each stage of the cycle:

$$\dot{Q}_{ref} = \dot{m}_{ref} \cdot \Delta h \quad (2)$$

The electrical power supplied to the compressor ($\dot{W}_{comp}$) represents the effective energy input to the system, which is converted into mechanical work to compress the working fluid. This can be calculated using equation (3), accounting for the applied voltage (V), current (I), and motor efficiency (η) [21]:

$$\dot{W}_{comp} = V \cdot I \cdot \eta \quad (3)$$

The coefficient of performance (*COP*) is an important parameter for evaluating the energy efficiency of a heat pump, as it relates the useful thermal energy delivered to the fluid ($\dot{Q}_{out}$) to the electrical power consumed [22]. A higher *COP* indicates a more efficient system, transferring more thermal energy per unit of electricity. In solar-assisted heat pumps, *COP* can be notably enhanced because solar input preheats the refrigerant in the evaporator, reducing the compression work required. Equation (4) provides the calculation of this parameter:

$$COP = \frac{\dot{Q}_{out}}{\dot{W}_{comp}} \quad (4)$$

2.3 Energy Analysis

The thermal energy released by LPG combustion (E_{LPG}) is calculated using equation (5), by considering the lower heating value (LHV_{LPG}), which represents the energy available from complete combustion without including the latent heat of water vapor in exhaust gases, with a *LHV* of 11860 kcal/kg for LPG [23]:

$$E_{LPG} = m_{LPG} \cdot LHV_{LPG}, \quad (5)$$

where m_{GLP} is the mass of fuel consumed. The associated CO_2 emissions ($E_{emission}$) are estimated with equation (6), using the emission factor (EF_{LPG}), which reflects both the fuel composition and combustion efficiency, and for LPG, has a value of 2.96 kg CO_2 per kg fuel [24]:

$$E_{emission} = m_{LPG} \cdot EF_{LPG} \quad (6)$$

2.4 Cost Analysis

Data from the National Institute of Statistics and Censuses (INEC) [25] indicate that the average electricity consumption in urban areas of Ecuador is approximately 155 kW·h per month, with an average monthly cost of USD 18.52 in Quito, one of the cities with the highest electricity tariffs in the country. From these values, the unit electricity cost can be estimated at USD 0.0904 per kW·h. For a typical 5 kW electric shower used 20 minutes per day, the monthly energy consumption reaches roughly 55 kW·h, corresponding to an energy cost of about USD 17. When additional charges, such as distribution, public lighting, fire services, and waste collection, are included, the total monthly cost rises to USD 30, resulting in an effective cost ($c_{kW\cdot h}$) of USD 0.33 per kW·h consumed. The operational price of the SAHP system (*Cost*) is calculated applying equation (7), which evaluates the economic feasibility of the prototype in comparison with conventional water heating systems relative to the energy consumed ($E_{consume}$) [26]:

$$Cost = E_{consume} \cdot c_{kW\cdot h} \quad (7)$$

LPG represents another common energy source for Ecuadorian households, with prices heavily subsidized by the government. The market cost of a 15 kg cylinder is USD 12. However, due to a 650 % subsidy, the consumer price is reduced to just USD 1.60 [27]. Considering the lower heating value of 11860 kcal/kg, the actual cost per unit of energy is approximately USD 1.05×10^{-4} per kcal, equivalent to USD 0.0906 per kW·h. Without subsidies, LPG is comparable in cost to electricity, but the subsidized rate makes it a far more economical option for domestic water heating.

3. RESULTS

The analyzed SAHP system incorporates a solar collector that functions directly as the evaporator. In addition, a photovoltaic power source supplies 12 V of direct current to operate the digital display meters and the variable-speed compressor. The compressor's estimated monthly energy consumption is approximately 2.33 kW·h, which is fully provided by solar energy. Fig. 2 illustrates the experimental SAHP prototype, where a flat-plate aluminum collector serves as the evaporator, and a copper coil submerged in the storage tank performances as the condenser.

Figure 2: SAHP System Prototype

The experimental data, shown in Fig. 3, present the variation in the system's *COP* as a function of water temperature during the heating process. As the water temperature increases from its initial range of 16 to 17 °C, a gradual decline in *COP* is observed. This behavior results from the higher workload imposed on the compressor and the reduced thermal gradient between the evaporator and the condenser. To meet domestic hot water requirements of approximately 30 °C, the thermostat was adjusted to automatically switch off the system once the water temperature reached 45 °C, taking into account thermal losses along the distribution pipes before reaching the point of use.

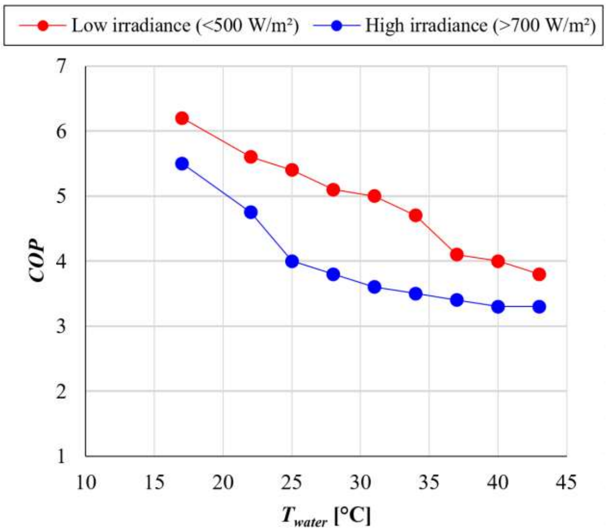

Figure 3: *COP* Analysis of the SAHP System

Under favorable solar conditions, with irradiance levels exceeding 700 W/m², the system achieved peak *COP* values of around 5.5, reflecting a strong energy performance due to the additional thermal input from the solar collector. This efficiency notably surpasses that of conventional heat pump systems, which typically operate with average *COP* values near 3. Conversely, when solar radiation dropped below 500 W/m², the *COP* ranged between 3.6 and 6.2, highlighting the direct influence of solar availability on system performance. Overall, these findings confirm that integrating solar energy with heat pump technology is a real-world and effective solution for domestic water heating, enabling significant reductions in electrical energy consumption.

Domestic water heating accounts for approximately 60 to 70 % of total household energy use in urban areas, equivalent to about 17.40 m³ of water per month from an average total consumption of 26 m³. Considering that heating 1 m³ of water requires 41.84 kW·h, the monthly cost of heating this volume is roughly USD 3.80 using LPG and USD 3.20 using electricity, excluding subsidies. With government subsidies applied to LPG, however, the monthly cost drops dramatically to USD 5.50, compared to USD 66.03 without subsidies. While the intrinsic energy costs of LPG and electricity are comparable, subsidies distort their real competitiveness, underscoring the need to explore sustainable alternatives, such as solar-assisted or hybrid systems, which can reduce both costs and emissions while minimizing reliance on government support.

Fig. 4 illustrates the cost of heating one cubic meter of water using different technologies. The analysis highlights the economic advantage of the SAHP system compared to conventional methods. Electric showers incur an average cost of USD 0.90 per m³, while LPG heaters cost USD 3.80 per m³ without subsidy, and USD 0.24 per m³ with subsidy. By contrast, the proposed SAHP system significantly lowers operational expenses by leveraging both photovoltaic and thermal solar energy, demonstrating its potential as a cost-effective solution.

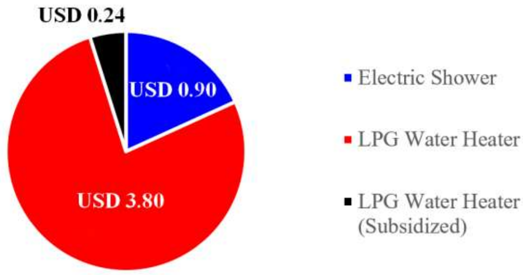

Figure 4: Comparative Cost of Heating per m³ of Water

Fig. 5 presents a comparative evaluation of energy consumption, monthly costs, and annual CO_2 emissions across different water-heating systems, emphasizing their environmental and economic impacts. Conventional systems, such as electric showers and LPG heaters, exhibit the highest energy consumption and emissions, 55 kW·h/month and 226.55 kg CO_2/year for electric showers, and up to 1,065.6 kg CO_2/year for LPG systems. Although LPG subsidies reduce monthly costs, from USD 66.03 to USD 5.50, emissions remain significant.

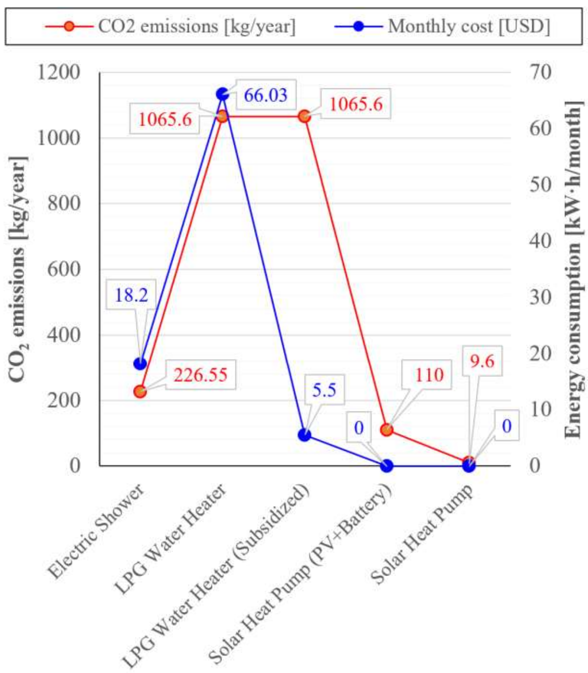

Figure 5: CO_2 Emissions and Energy Consumption for Different Water-Heating Systems

Conversely, the SAHP system, both in its standalone configuration and when assisted by photovoltaic panels and batteries, eliminates direct electricity use and reduces CO_2 emissions dramatically to only 9.6 and 110 kg/year, respectively, confirming the system's efficiency, sustainability, and economic viability for residential water heating.

While the solar heat pump generates no direct operational emissions, the manufacturing of photovoltaic panels and energy storage components contributes indirectly to its carbon footprint. Solar panel production typically releases 30 g CO_2 per kW·h generated over a 25-year lifespan, whereas gel batteries emit approximately 170 kg CO_2 per unit, with a 6-year lifespan. Distributed across their operational life, this results in an annual contribution of around 43.8 kg CO_2 from the panels and 56.7 kg CO_2 from the batteries, substantially lower than the emissions from conventional water-heating technologies.

4. DISCUSSION

Quitiaquez et al. [28] provided an important experimental foundation for understanding the thermal behavior of SAHP systems, emphasizing how the tilt angle influences the heat transfer coefficient (HTC) of an aluminum flat-plate collector/evaporator using R600a as the working fluid. Building on this principle, the present study also harnesses solar radiation as the primary thermal energy source for refrigerant evaporation, enhancing overall energy efficiency through improved *COP*. Unlike the earlier work, which focused on statistical analysis and two-phase flow transitions based on collector inclination, this research evaluates the practical performance of a photovoltaic-assisted SAHP system for sustainable water heating. Moreover, it incorporates a more integrated perspective by connecting thermal performance with environmental and economic outcomes, quantifying reductions in energy consumption and CO_2 emissions.

Similarly, Yi et al. [29] reviewed technological developments in SAHP systems, highlighting gains in energy efficiency and limitations at low temperatures. In line with these findings, this study implements a photovoltaic-assisted SAHP that enhances *COP* and reduces electrical dependence through the combined use of solar thermal and photovoltaic energy. Distinct from primarily theoretical studies, this work integrates experimental and multidisciplinary analysis in the Ecuadorian context, evaluating system performance, operational costs, and emissions under real conditions. The results confirm the technical, environmental, and economic feasibility of the system as a sustainable alternative for residential hot water, supporting SDGs 7 and 13 while aligning with global trends in energy transition and decarbonization.

Obura et al. [30] emphasize the importance of renewable energy technologies to improve water resource management and decrease reliance on conventional energy sources. This research addresses similar challenges, aligning with multiple SDGs. Specifically, it supports SDG 7 – Affordable and Clean Energy by demonstrating a solar-assisted heat pump that reduces conventional electricity and LPG consumption while promoting efficient renewable sources. It contributes to SDG 13 – Climate Action by showing that hybrid renewable systems can significantly lower CO_2 emissions from domestic energy use. Additionally, it addresses SDG 6 – Clean Water and Sanitation by improving heating processes and reducing energy waste associated with water usage, and SDG 12 – Responsible Consumption and Production by encouraging the adoption of sustainable, low-impact technologies that integrate efficiency, economic viability, and environmental responsibility. Fig. 6 illustrates the sequential relevance and overall feasibility of implementing clean energy-based solutions, positioning the proposed system as a practical contribution toward the SDGs of the 2030 Agenda.

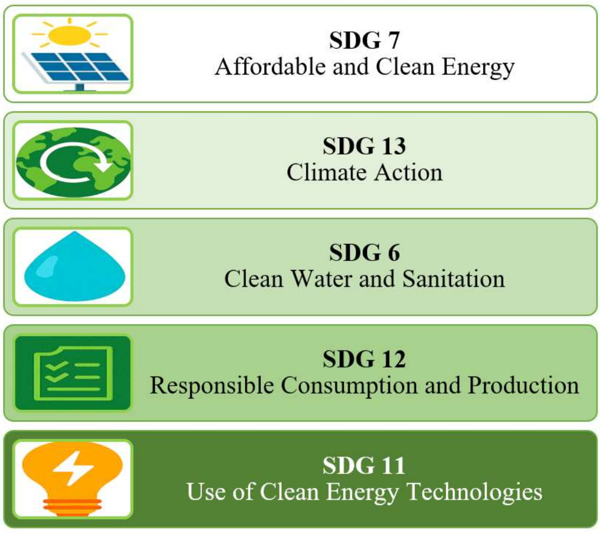

Figure 6: Relationship and Significance of the SDGs with the Proposed SAHP System

Manesh and Liu [31] highlight the importance of a multidisciplinary approach for advancing innovative energy technologies that consider technical, economic, and environmental dimensions. This research demonstrates that SAHP systems improve thermal performance through higher *COP* and solar efficiency, improving electricity consumption and reducing CO_2 emissions. Fig. 7 depicts the integrated approach, combining Mechanical Engineering, Renewable Energy, Environmental Engineering, and Economics to empower a comprehensive evaluation of the SAHP system. Thermodynamic analysis guided the design and assessment of thermal performance, while environmental evaluation addressed life-cycle impacts and emission reductions. Economic and energy assessments determined financial feasibility and operational efficiency. Collectively, these findings show that the proposed solution is technically sound, environmentally responsible, and economically viable, reinforcing its scientific relevance and alignment with the SDGs.

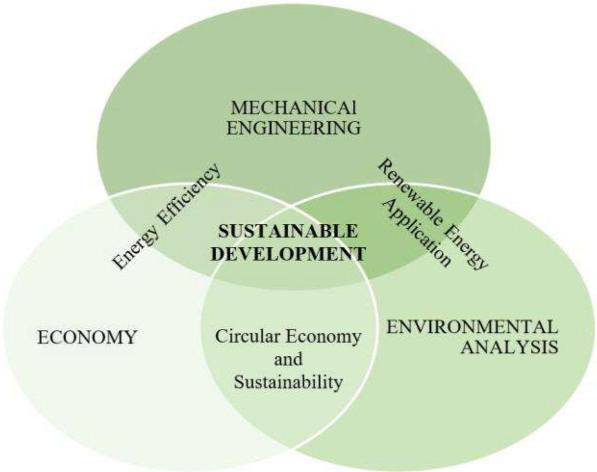

Figure 7: Multidisciplinary Framework for Evaluating the SAHP System

5. CONCLUSIONS

The solar-assisted heat pump revealed adequate thermal performance, achieving a maximum coefficient of performance (*COP*) of 6.2 and a minimum of 3.3 for heating 10 liters of water from 17 °C to 45 °C under varying solar radiation conditions. The integration of an aluminum flat-plate solar collector as the evaporator helped raise the refrigerant's evaporation temperature, improving heat transfer and ensuring stable operation across a solar irradiance range of 500 to 700 W/m². These findings confirm the technical feasibility of the system and highlight its economic advantage, as it reduces operating time and enhances energy efficiency compared to conventional water heating methods.

Energy consumption analysis exposed that the solar heat pump system requires only about 2.33 kW·h per year to power the compressor and digital components, resulting in 9.6 kg of CO_2 emissions annually. In comparison, a conventional electric shower emits 226.55 kg/year, and an LPG water heater emits 1,065.6 kg/year. Considering the lifecycle emissions of photovoltaic panels and batteries, indirect CO_2 emissions range from 43.8 to 56.7 kg/year, demonstrating a substantial reduction in household carbon footprint. These results establish the SAHP system as an environmentally sustainable option capable of significantly lowering greenhouse gas emissions while reducing residential electricity consumption.

The adoption of the SAHP system aligns with the SDGs, supporting reasonable and clean energy (SDG 7), climate action (SDG 13), sustainable water management (SDG 6), and responsible consumption and production (SDG 12). The verified reductions in energy use and CO_2 emissions illustrate that such hybrid renewable systems can be effectively integrated into local sustainability strategies, promoting cleaner energy transitions and contributing to climate change mitigation in line with the 2030 Agenda.

REFERENCES

[1] J. Hernández-Ambato, R. Fernández, A. Mora, and J. Alvarado, "Evaluación de la Huella de Carbono de Vehículos con Motor Eléctrico y de Combustión Interna según la Matriz Energética de Ecuador: Caso de Estudio KIA Soul vs KIA Soul EV," Novasinergia, vol. 5, no. 2, pp. 58–75, 2022. doi: https://doi.org/10.37135/ns.01.10.04

[2] S. Meraj, S. Yu, M. Rahman, K. Hasan, M. Hossain Lipu, and H. Trinh, "Energy Management Schemes, Challenges and Impacts of Emerging Inverter Technology for Renewable Energy Integration Towards Grid Decarbonization," Journal of Cleaner Production, vol. 405, p. 137002, Jun. 2023, doi: https://doi.org/10.1016/j.jclepro.2023.137002

[3] J. Chamorro and E. Mera, "Estudio de la Crisis Energética en el Ecuador por la Dependencia en la Generación de Energía Hidráulica," Revista Científica INGENIAR: Ingeniería, Tecnología E Investigación, vol. 8, no. 15, pp. 168–186, 2025, doi: https://doi.org/10.46296/ig.v8i15.0240

[4] M. Lozano-Rojas and E. Sandoval-Sandoval, "The Biomass as a Source of Electrical Energy Generation in Ecuador," Revista Científica Multidisciplinar G-nerando, vol. 5, no. 1, pp. 194–223, 2024. doi: https://doi.org/10.60100/rcmg.v5i1.189

[5] J. Borja-Patiño, A. Robalino-López, and A. Mena-Nieto, "Breaking the Unsustainable Paradigm: Exploring the Relationship Between Energy Consumption, Economic Development and Carbon Dioxide Emissions in Ecuador," Sustainability Science, vol. 19, no. 2, pp. 403–421, 2024. doi: https://doi.org/10.1007/s11625-023-01425-x

[6] B. Yildiz, J. Bilbao, M. Roberts, S. Heslop, J. Dore, A. Bruce, I. Macgill, R. Ega, and A. Sproul, "Analysis of Electricity Consumption and Thermal Storage of Domestic Electric Water Heating Systems to Utilize Excess PV Generation," Energy, vol. 235, p. 121325, 2021. doi: https://doi.org/10.1016/j.energy.2021.121325

[7] J. Lu, Y. Tang, Z. Li, and G. He, "Solar Heat Pump Configurations for Water Heating System in China," Applied Thermal Engineering, vol. 187, p. 116570, 2021. doi: https://doi.org/10.1016/j.applthermaleng.2021.116570

[8] T. Hai, N. Delgarm, D. Wang, and M. H. Karimi, "Energy, Economic, and Environmental (3 E) Examinations of the Indirect-expansion Solar Heat Pump Water Heater System: A Simulation-oriented Performance Optimization and Multi-objective Decision-making," Journal of Building Engineering, vol. 60, p. 105068, 2022. doi: https://doi.org/10.1016/j.jobe.2022.105068

[9] B. Abbasi, S. Li, and A. Mwesigye, “Energy, Exergy, Economic, and Environmental (4E) Analysis of SAHP Water Heaters in Very Cold Climatic Conditions,” Renewable Energy, vol. 226, p. 120391, 2024. doi: https://doi.org/10.1016/j.renene.2024.120391

[10] C. Meena, A. Prajapati, A. Kumar, and M. Kumar, “Utilization of Solar Energy for Water Heating Application to Improve Building Energy Efficiency: An Experimental Study,” Buildings, vol. 12, no. 12, p. 2166, 2022. doi: https://doi.org/10.3390/buildings12122166

[11] C. Anderson, M. Denich, A. Warchold, J. Kropp, and P. Pradhan, “A Systems Model of SDG Target Influence on the 2030 Agenda for Sustainable Development,” Sustainability Science, vol. 17, no. 4, pp. 1459–1472, 2022, doi: https://doi.org/10.1007/s11625-021-01040-8

[12] G. Yumnam, Y. Gyanendra, and C. Singh, “A Systematic Bibliometric Review of the Global Research Dynamics of United Nations Sustainable Development Goals 2030,” Sustainable Futures, vol. 7, p. 100192, 2024, doi: https://doi.org/10.1016/j.sftr.2024.100192

[13] A. Olabi, N. Shehata, H. Maghrabie, L. Heikal, M. Abdelkareem, S. Rahman, S. Shah, and E. Sayed, “Progress in Solar Thermal Systems and Their Role in Achieving the Sustainable Development Goals,” Energies, vol. 15, no. 24, p. 9501, 2022. doi: https://doi.org/10.3390/en15249501

[14] Y. Zhu, D. Taylor, and Z. Wang, “The Role of Renewable Energy in Reducing Residential Fossil Energy-related CO2 Emissions: Evidence from Rural China,” Journal of Cleaner Production, vol. 366, p. 132891, 2022. doi: https://doi.org/10.1016/j.jclepro.2022.132891

[15] D. Singh, D. Singh, V. Mishra, J. Kushwaha, R. Dev, S. Patel, R. Shankar, and B. Giri, “Sustainability Issues of Solar Desalination Hybrid Systems Integrated with Heat Exchangers for the Production of Drinking Water: A Review,” Desalination, vol. 566, p. 116930, 2023. doi: https://doi.org/10.1016/j.desal.2023.116930

[16] A. Mercedes-Garcia, P. López-Jiménez, F. Sánchez-Romero, and M. Pérez-Sánchez, “Objectives, Keys and Results in the Water Networks to Reach the Sustainable Development Goals,” Water, vol. 13, no. 9, p. 1268, 2021. doi: https://doi.org/10.3390/w13091268

[17] W. Quitiaquez, I. Simbaña, R. Caizatoa, C. Isaza, C. Nieto, P. Quitiaquez, and F. Toapanta, “Análisis del Rendimiento Termodinámico de una Bomba de Calor Asistida por Energía Solar Utilizando un Condensador con Recirculación,” Revista Técnica “Energía,” vol. 16, no. 2, pp. 111–125, 2020, doi: https://doi.org/10.37116/revistaenergia.v16.n2.2020.358

[18] I. Simbaña, W. Quitiaquez, J. Estupiñán, F. Toapanta-Ramos, and L. Ramírez, “Evaluación del Rendimiento de una Bomba de Calor de Expansión Directa Asistida por Energía Solar Mediante Simulación Numérica del Proceso de Estrangulamiento en el Dispositivo de Expansión,” Revista Técnica “Energía,” vol. 19, no. 1, pp. 110–119, 2022, doi: https://doi.org/10.37116/revistaenergia.v19.n1.2022.524

[19] A. Kijo-Kleczkowska, P. Bruś, and G. Więciorkowski, “Economic Analysis of Heat Pump Exploitation – A Case Study,” Energy, vol. 280, p. 128184, 2023. doi: https://doi.org/10.1016/j.energy.2023.128184

[20] X. Liu, X. Peng, Y. Yang, X. Qin, D. Wang, G. Wang, and D. Wang, “Energetic Analysis and Performance Improvement Algorithm of Transcritical CO2 Heat Pump Water Heater System,” Applied Thermal Engineering, vol. 236, p. 121823, 2024. doi: https://doi.org/10.1016/j.applthermaleng.2023.121823

[21] K. Tomczuk and P. Obstawski, “Analysis of the Cooperation of a Compressor Heat Pump with a PV System,” Sustainability, vol. 16, no. 9, p. 3797, 2024. doi: https://doi.org/10.3390/su16093797

[22] S. Zhang, S. Liu, J. Wang, Y. Li, and Z. Yu, “Analysis of a Solar-assisted Heat Pump System with Hybrid Energy Storage for Space Heating,” Applied Thermal Engineering, vol. 231, p. 120884, 2023. doi: https://doi.org/10.1016/j.applthermaleng.2023.120884

[23] R. Song, V. Terzija, T. Hamacher, and V. S. Perić, “Integrating Air-Source Heat Pumps into the Demand-Side Fast Frequency Response Service: A Study Based on Thermal Dynamic Uncertainty,” IEEE Transactions on Sustainable Energy, vol. 16, no. 1, pp. 323-335, 2025, doi: http://doi.org/10.1109/TSTE.2024.3456068

[24] P. Valdiserri, V. Ballerini, and E. di Schio, “Interpolating Functions for CO2 Emission Factors in Dynamic Simulations: The Special Case of a Heat Pump,” Sustainable Energy Technologies and Assessments, vol. 53, p. 102725, 2022. doi: https://doi.org/10.1016/j.seta.2022.102725

[25] S. Naranjo-Silva, D. Guerrero, and J. del Castillo, “Costo Comparativo por Kilovatio de los Últimos Proyectos Hidroeléctricos en Ecuador,” Revista InGenio, vol. 5, no. 1, pp. 22–34, 2022. doi: https://doi.org/10.18779/ingenio.v5i1.473

[26] M. Farghali, A. Osman, Z. Chen, A. Abelhaleem, I. Ihara, I. Mohamed, P. Yap, and D. Rooney, "Social, Environmental, and Economic Consequences of Integrating Renewable Energies in the Electricity Sector: A Review," Environmental Chemistry Letters, vol. 21, no. 3, pp. 1381–1418, 2023. doi: https://doi.org/10.1007/s10311-023-01587-1

[27] S. Peña-Murillo, J. Ochoa-Celi, F. Torres-Córdova, and E. Zambrano-Nevárez, "Subsidios de Combustibles en Ecuador: Análisis Bibliográfico de su Costo y Sostenibilidad," Revista Iberoamericana de Educación, vol. 9, no. 1, pp. 55–72, 2025. doi: https://doi.org/10.31876/rie.v9i1.288

[28] W. Quitiaquez, I. Simbaña, A. Herrera, P. Quitiaquez, C. Nieto-Londoño, E. Pilataxi, A. Andrade., and. Y. Retirado-Mediaceja, "Statistical Analysis of Heat Transfer Effects on Flow Patterns Maps in a Flat-Plate Collector/Evaporator with R600a Under Variable Tilt Angles," Processes, vol. 13, no. 11, p. 3419, 2025, doi: https://doi.org/10.3390/pr13113419

[29] Y. Fan, X. Zhao, Z. Han, J. Li, A. Badiei, Y. Akhlaghi, and Z. Liu, "Scientific and Technological Progress and Future Perspectives of the Solar Assisted Heat Pump (SAHP) System," Energy, vol. 229, p. 120719, 2021. doi: https://doi.org/10.1016/j.energy.2021.120719

[30] D. Obura, D. Kimera, and D. Dadebo, "Application of GIS and Hydraulic Modeling for Sustainable Management of Water Supply Networks: A Pathway for Achieving Sustainable Development Goal (SDG) 6," Process Integration and Optimization for Sustainability, vol. 8, no. 4, pp. 1017–1034, 2024. doi: https://doi.org/10.1007/s41660-024-00410-w

[31] A. M. Manesh and H. Liu, "Thermo-environ-economic Analysis of a Novel Solar-assisted Heat Pump System; Comparison with Conventional Single Stage and Cascaded Air Source Heat Pumps," Energy, vol. 322, p. 135647, 2025. doi: https://doi.org/10.1016/j.energy.2025.135647

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