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Footprint Evaluation of Household Operation Accounting for the Use of Different Utilities and Materials

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The increasing demands for heating and air conditioning of households are the main energy users, making them the greatest greenhouse gas emitters. Switching to clean and renewable energy sources is a critical step to reduce environmental impacts. The Renewable Energy System for Residential Building Heating and Electricity Production (RESHeat) system is proposed to use solar energy to supply electricity, heating, and cooling to residential and public buildings. However, since this is a new system in the process of prototype demonstration. Its environmental impact has to be evaluated fairly to enable assessment of the potential emission reductions on a life-cycle basis. The current work proposes a footprint evaluation matrix for buildings which accounts for the competition between the use of various utilities (upstream impacts) and the potentially different routes for waste disposal (building and downstream impacts). The results indicate that the RESHeat system exhibits 80 % lower GHG emissions and 70 % less water consumption than the gas boiler heating system due to the use of solar energy in the operation phase. It offers a sustainable solution to address energy crises and mitigate global warming. The future work will extend to the comparative analysis among such solar energy systems for the provision of heating, cooling and electricity in buildings.

1. Introduction

Household heating demand significantly contributes to carbon emissions, accounting for 80 % of direct CO_2 emissions in the buildings sector in 2021 (IEA., 2022). As the severity of the climate problem continues to increase, it is essential to prioritise the transition to cleaner energy sources. Various heating systems are commonly used in households for space and water heating, including boilers, furnaces, wood stoves, electric resistance heaters, heat pumps, and solar heating systems. The popular heating systems currently in operation rely heavily on non-renewable energy sources, such as natural gas and oil (Caracci et al., 2022). Heat pumps have emerged as an energy-efficient solution that extracts heat from the air (Naumann et al., 2022), water (Jung et al., 2022), or ground (Smith et al., 2021) outside the home for space heating and hot water. In particular, water-to-water heat pumps have been found to possess the least exergy destruction (Çakır et al., 2013), making them a viable and sustainable alternative to conventional heating systems. The Renewable Energy System for Residential Building Heating and Electricity Production (RESHeat) system is proposed (Yildirim et al., 2023) to make full use of renewable energy on combined cooling, heating, and power, as shown in Figure 1. Solar energy is the main source of electricity and thermal energy. Photovoltaic (PV) and Photovoltaic–thermal (PV/T) panels are installed to generate electricity for the heat pump and other facilities, with the grid serving as backup power storage. The low-temperature thermal energy produced by PV/T is stored in the borehole heat exchanger (BE) and will be used during the winter to improve the coefficient of performance (COP) of the heat pump (HP). The average annual COP for heat pumps is higher than 4.8. The thermal energy generated by solar collectors (SC)

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is stored in the buffer, and the excess heat will be stored in an underground heat storage tank (US) and used during the heating season. The cooling demand is satisfied by the heat pump in summer. As a new system, RESHeat is currently in the prototype demonstration stage. It is imperative to evaluate its environmental impact thoroughly to enable a fair assessment of its potential for emission reduction on a life-cycle basis.

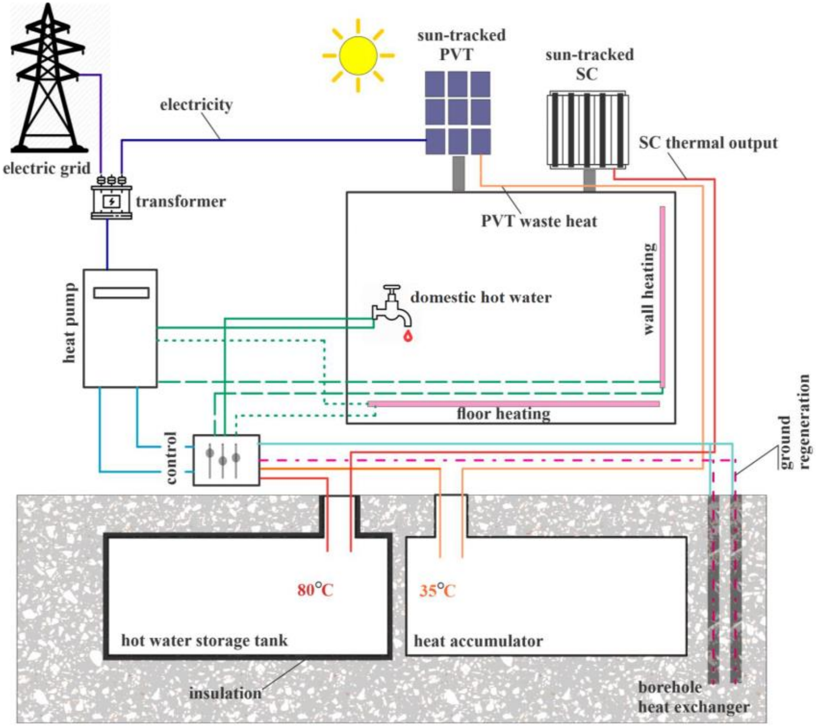

Figure 1: Composition of the RESHeat system

Environmental impact assessment commonly employs two primary approaches: input-output analysis, a top-down approach frequently used at the regional level (Pan et al., 2022), and process analysis, a bottom-up approach that can be applied to a process, product, or service (Shao and Chen, 2013). In this study, we adopt the life cycle analysis, a type of process analysis, to evaluate the environmental impact of the RESheat system throughout its entire life cycle (Finkbeiner et al., 2006), which focuses on greenhouse gas (GHG) emissions and water consumption and compare it with conventional heating systems.

Previous studies on heating systems have often overlooked the end-of-life stage (Yang et al., 2008) or focused primarily on waste disposal options such as landfill and recycling (Saoud et al., 2021), considering waste disposal as an environmental burden. However, it is important to recognise that recycled materials from heating systems can be reused, resulting in huge avoided GHG emissions (Fan et al., 2018), because the recycling process has a much lower environmental impact than producing the same amount of material such as steel (Suer et al., 2022). This study aims to fill this gap by providing a more comprehensive evaluation of the RESHeat system's environmental impact by delving into the end-of-life phase and considering the issue of material reuse, adopting a case study of a building in Limanowa, a large city in Poland.

2. Method and data

The present study employs a life-cycle analysis method to assess the environmental impact of the RESHeat and gas boiler heating systems. The LCA method employed adheres to the International Organization for Standardization (ISO) 14040 guidelines (Finkbeiner et al., 2006). In this study, the OpenLCA software is utilised for environmental evaluation. OpenLCA is a widely adopted software platform that enables users to perform Life Cycle Assessment (LCA) and analyse the environmental impacts of various products and processes. To support the LCA analysis in this study, the Ecoinvent database is the primary source of data, which offers comprehensive and detailed information on the environmental impacts of various products, including their production and use, as well as end-of-life disposal and recycling. The ReCipe 2016 midpoint (H) impact assessment method is selected for analysing GHG and water footprint of the two heating systems in this study. The LCA process entails four essential steps, as shown in Figure 2, which are goal and scope definition, inventory analysis, impact assessment, and improvement analysis, which will be elaborated on in the subsequent section.

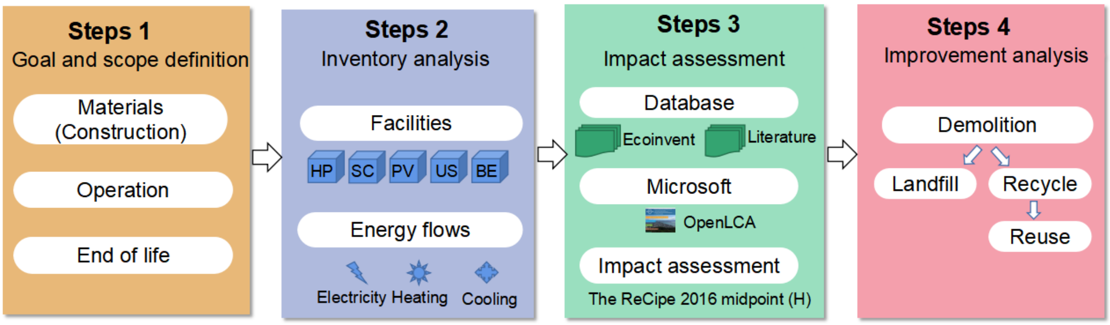

Figure 2: Four steps LCA methodology (based on ISO Citation14040, 2006)

2.1 Goal and scope definition

This paper aims to determine the GHG and water footprints of two heating systems, representing distinct heating ways. The RESHeat system employs renewable energy sources to supply thermal and electricity energy, whereas the gas boiler relies heavily on external energy sources. Households can select a more efficient and eco-friendly heating system by comparing the two systems. The study presents a heating system designed to cover the thermal energy and electricity demands of a 433 m^2 building. The building (restaurant) is located in Limanowa (Poland). The city is located in climate zone III - according to the division of Poland into climate zones (according to PN-EN 12831), where the average annual outdoor temperature is 7.6 °C and the designed outdoor temperature is -20 °C. The number of sunny days is 1,489 h on average. The scope of the study encompasses the material (construction), operation, and end-of-life stages.

2.2 Inventory analysis

Material and equipment data include the infrastructure for the heating system, heat pump, PV and PV/T panels, solar collector, underground storage tank, and gas boiler. The inventory list draws on data from Greening and Azapagic (2012) for both the ground heat pump and gas boiler systems. Additionally, data for the PV/T panels are sourced from Fthenakis and Kim (2011), while sun-tracking solar system data are obtained from Chow and Ji (2012) and Menzies and Roderick (2010). The underground storage tank is sourced from Suer et al. (2022). The two sun-tracking solar collectors provide a net power of 7 kW. The power of the heat pump is 20 kW. The volume of the underground storage tank is 50 m^3.

2.3 Impact assessment

The system comprises three distinct stages in Figure 3. The material phase encompasses each heating system's facilities and installation materials. The primary environmental impact stems from the GHG footprint (GHG FP) and water footprint (WF). The operational phase of household heating systems is critical, as daily heating and hot water demands require regular inputs of energy. The RESHeat system utilises solar radiation as inputs, producing electricity, thermal energy for space heating, and hot water as outputs. The heating demand for space and domestic hot water for this system is 37.96 MWh/y and 10.62 MWh/y, which can be satisfied by a combination of ground source heat pump technology (42.19 MWh/y), and solar collectors (22.65 MWh/y). The electricity required to operate the heat pump is 10.58 MWh/y, which could be satisfied by the electricity produced by PV and PV/T panels. In contrast, the gas boiler system requires natural gas as inputs, burning natural gas to generate thermal energy for space and hot water. To satisfy the heating demand, the gas boiler system would require burning 54.41 MWh/y of natural gas. The design heat loss of the analysed building is 4.22 MWh/y. In the final stage of the life cycle analysis, certain metals may be recycled and repurposed for future use, and some materials are landfilled.

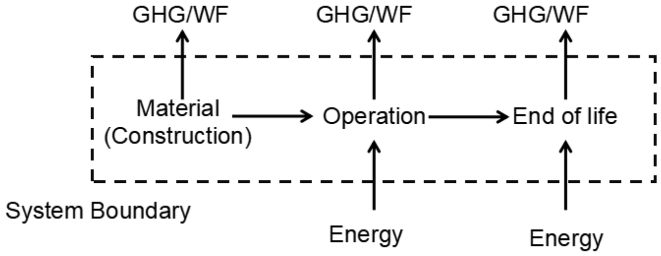

Figure 3: Three stages considered and their relationship with the atmosphere

2.4 Improvement analysis

To assess the environmental implications at the end of life, this section will explore material reuse to improve the final phase, yielding a more comprehensive evaluation. The recycling process requires energy consumption, which is known as an environmental burden shown in Figure 4. Conversely, reusing recycled materials in subsequent production processes reduces the amount of energy needed, referred to as unburden impacts on the environment. The net environmental impacts in the end-of-life phase are calculated as the difference between the burden and unburden impacts.

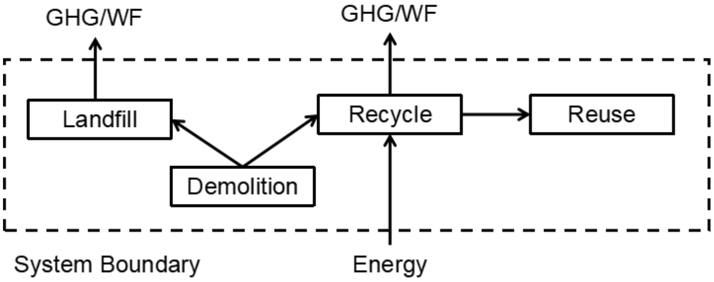

Figure 4: End-of-life system including landfill, recycle and reuse scenario

Then, the total environmental footprint is expressed as

$$EF = EL + ER - AE \tag{1}$$

where EL, ER and AE represent the emission released from landfill, the emission released from recycling and the avoided emission from the recovered product. The emissions can be estimated by calculating the product of the volume of waste processed and the respective emission factors per unit quantity treated, as shown in Eqs(2-4).

$$EL = AWL \times EF_{landfill} \tag{2}$$

$$ER = AWR \times EF_{\mathrm{recycle}} \tag{3}$$

$$AE = AMR \times EF_{\mathrm{production}} \tag{4}$$

where AWL, AWR and AMR represent the amount of waste to the landfill, the amount of waste to recycling and the amount of materials recycled. EF_{landfill}, EF_{recycle} and $EF_{\mathrm{production}}$ denote the emission factors of the landfill process, recycling process, and production process for the same materials.

3. Case study

It is revealed that the total annual GHG emissions of the RESHeat system are 7,508.22 kg CO_2 eq, with the material stage being the primary contributor, accounting for 13,108.21 kg CO_2 eq in Table 1. It is attributed to the use of steel in installing the underground storage tank, which is responsible for about 90 % of the total GHG emissions by material. Therefore, the infrastructure installation is critical in determining the RESHeat system's overall environmental impact. To mitigate the carbon footprint of heat pumps, adopting mild steel as an alternative to steel is identified as a feasible solution. The materials of the RESHeat system, especially silicon and aluminium, are also found to be significant contributors, with GHG emissions of 407.51 kg CO_2 eq and 375.87 kg CO_2 eq in Figure 5. The focus is primarily on steel due to its extensive use in the installation process and the potential for recycling.

In the end-of-life stage, the reuse of materials results in negative GHG emissions, indicating that recycling helps significantly reduce the environmental impact. The emissions from recycling, landfilling, and reuse are 25.25 kg CO_2 eq, 1784.61 kg CO_2 eq, and -7409.84 kg CO_2 eq, respectively. Reusing recycled materials leads to a 56.53 % reduction in GHG emissions. Regarding the operation stage, the RESHeat system realises zero GHG emissions, while the gas boiler emits 33,734.92 kg CO_2 eq due to its heavy reliance on the power grid and natural gas. The GHG emissions from gas boiler heating systems using natural gas and electricity are 3347.02 kg CO_2 eq and 30387.9 kg CO_2 eq, respectively. This highlights the substantial advantages of the RESHeat system. It's worth noting that in Poland, electricity generation is still predominantly based on thermal power, which puts significant pressure on resources and the environment.

Table 1: GHG FP and WF of RESHeat and gas boiler (negative values indicate reductions)

Heating system	**Life cycle stage**	**Component**	**GHG FP (kg CO_2 eq/y)**	**WFP (m^3/y)**
RESHeat	Material(Construction)	Installation and facilities	13,108.21	385.22
	End of life	Recycle	25.25	0.20
		Landfill	1,784.61	3.63
		Reuse	-7,409.84	-111.97
	Total	-	7,508.22	277.09
Gas boiler	Material(Construction)	Installation and facilities	1,950.18	24.80
	Operation	Natural gas	3,347.02	2.61
		Electricity	30,387.90	917.11
	End of life	Recycle	12.06	0.03
		Landfill	1,631.04	3.32
		Reuse	-588.48	-9.42
	Total	-	36,739.71	938.45

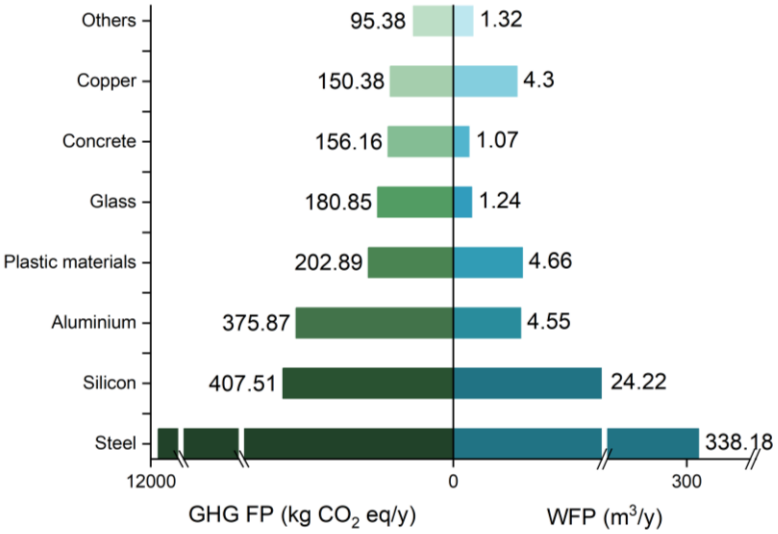

Figure 5: GHG FP and WF of materials of RESheat system

With regards to water consumption, the study found that the total consumption of the RESHeat system is 277.09 m^3, with material and end-of-life stages consuming approximately 385.22 m^3 and -111.97 m^3. Conventional gas boiler heating systems exhibit GHG emissions of approximately 36,739.71 kg CO_2 eq and water consumption of 938.45 m^3 in total. The environmental impact corresponding to each stage is shown in Table 1. The RESHeat system exhibited 80 % lower GHG emissions and 70 % less water consumption in total due to its renewable energy utilization. Although the GHG emissions and water consumption caused by the RESheat system in the material phase are higher compared with the gas boiler because more facilities are installed, recycled materials can reduce the environmental impacts.

4. Conclusions

This study compared the GHG footprint and water footprint of the RESHeat system and gas boiler heating system, revealing that the RESHeat system exhibited 80 % lower GHG emissions and 70 % less water consumption in total due to its renewable energy utilisation, which fulfilled 100 % of a household's electricity and heating demand. The embodied GHG emissions from the construction are higher for the RESHeat system, mainly because of steel usage in the installation process. However, the operational phase compensates significantly for this minor overhead. Furthermore, recycling and reusing materials could considerably reduce the system's environmental impacts. Adopting mild steel as an alternative to conventional steel emerged as a promising solution to minimise the carbon footprint. In general, although the RESHeat system initially requires the installation of multiple facilities, resulting in higher GHG emissions and water consumption in the material phase, it can fully utilize solar energy during the operational phase to provide users with electrical and thermal energy. This system reduces dependence on the power grid and significantly decreases the environmental impact of household heating systems. It offers a sustainable solution to address energy crises and mitigate global warming.

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References

Çakır U., Çomaklı K., Çomaklı Ö., Karslı S., 2013, An experimental exergetic comparison of four different heat pump systems working at same conditions: As air to air, air to water, water to water and water to air, Energy 58, 210–219.

Caracci E., Canale L., Buonanno G., Stabile L., 2022, Sub-micron particle number emission from residential heating systems: A comparison between conventional and condensing boilers fueled by natural gas and liquid petroleum gas, and pellet stoves, Science of The Total Environment, 827, 154288.

Chow T.-T., Ji J., 2012, Environmental Life-Cycle Analysis of Hybrid Solar Photovoltaic/Thermal Systems for Use in Hong Kong, International Journal of Photoenergy, 2012, 101968.

Comite Europeen de Normalisation, 2017, PN-EN 12831-1:2017-08-Energy performance of buildings--Method of calculation of design heat load--Part 1: Heat load, module M3-3.

Fan Y.V., Klemeš J., Perry S., 2018, GHG Emissions of Incineration and Anaerobic Digestion: Electricity Mix, Chemical Engineering Transactions, 72, 145–150.

Finkbeiner M., Inaba A., Tan R., Christiansen K., Klüppel H.-J., 2006, The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044, The International Journal of Life Cycle Assessment 11, 80–85.

Fthenakis V.M., Kim H.C., 2011, Photovoltaics: Life-cycle analyses. Solar Energy 85, 1609–1628Greening B., Azapagic A., 2012, Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK, Energy 39, 205–217.

Jung Y., Oh J., Han U., Lee H., 2022, A comprehensive review of thermal potential and heat utilization for water source heat pump systems, Energy and Buildings 266, 112124.

Menzies G.F., Roderick Y., 2010, Energy and carbon impact analysis of a solar thermal collector system, International Journal of Sustainable Engineering 3, 9–16.

Naumann G., Schropp E., Gaderer M., 2022, Life Cycle Assessment of an Air-Source Heat Pump and a Condensing Gas Boiler Using an Attributional and a Consequential Approach, Procedia CIRP 105, 351–356.

Pan T., Fan Y., Shao L., Chen B., Chu Y., He G., Pan Y., Wang W., Wu Z., 2022, Multiple accounting and driving factors of water resources use: A case study of Shanghai, Journal of Environmental Management 313, 114929.

Saoud A., Harajli H., Manneh R., 2021, Cradle-to-grave life cycle assessment of an air to water heat pump: Case study for the Lebanese context and comparison with solar and conventional electric water heaters for residential application, Journal of Building Engineering 44, 103253.

Shao L., Chen G.Q., 2013, Water Footprint Assessment for Wastewater Treatment: Method, Indicator, and Application, Environmental science & technology, 47, 7787–7794.

Smith M., Bevacqua A., Tembe S., Lal P., 2021, Life cycle analysis (LCA) of residential ground source heat pump systems: A comparative analysis of energy efficiency in New Jersey, Sustainable Energy Technologies and Assessments 47, 101364.

Suer J., Ahrenhold F., Traverso M., 2022, Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit, Journal of Sustainable Metallurgy 8, 1532–1545.

Yang L., Zmeureanu R., Rivard H., 2008, Comparison of environmental impacts of two residential heating systems, Building and Environment 43, 1072–1081.

Yildirim M.A., Bartyzel F., Vallati A., Woźniak M.K., Ocłoń P., 2023, Efficient energy storage in residential buildings integrated with RESHeat system, Applied Energy 335, 120752.