Journal of Sustainable Development of Natural Resources Management

http://www.sdewes.org/jsdnarema

Year 2025, Volume 1, Issue 3, 1010616

Original Research Article

LCA-Based Evaluation of the Environmental and Economic Sustainability of the RESHeat Demonstration Sites in Italy

Ting Pan[1], Sheng Zhang[2, 3], Marzena Nowak-Ocłoń*[3]

[1]Department of Process Engineering, Institution, Faculty of Mechanical Engineering, Brno University of Technology - VUT, Technická 2896/2, 616 00 Brno, Czech Republic
email: Ting.Pan@vutbr.cz

[2]Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic
email: sheng.zhang@vutbr.cz

[3]Department of Energy, Faculty of Environmental Engineering and Energy, Cracow University of Technology, 31-864 Cracow, Poland
e-mail: marzena.nowak-oclon@pk.edu.pl

Cite as: Pan, T., Zhang, S., Nowak-Ocłoń, M., LCA-Based Evaluation of the Environmental and Economic Sustainability of the RESHeat Demonstration Sites in Italy, Journal of Sustainable Development of Natural Resources Management, 1010616, 2025, https://doi.org/10.13044/j.sdnarema.d1.0616

ABSTRACT

This study presents a detailed Life Cycle Assessment of the RESHeat system installed in a residential building in Italy. The system integrates photovoltaic/thermal modules, a high-performance heat pump, thermal storage, and intelligent control systems to supply heating, cooling, and domestic hot water. The ReCiPe 2016 Midpoint (H) methodology was applied to assess the environmental impacts across the entire life cycle: construction, operation, and end-of-life stages. The results indicate that total greenhouse gas emissions from the construction phase can be reduced by 80.6 % through the implementation of reuse strategies. Fossil resource consumption decreases by 86 %, and water use is reduced by 65 %. The analysis identified construction activities and Photovoltaic/Thermal modules as the components with the highest environmental burdens, together contributing to over 80 % of the impacts in several key categories.

KEYWORDS

Renewable energy, Combined Cooling Heating and Power, Life Cycle Assessment, Environmental Impacts, RESHeat, Sustainable Development.

INTRODUCTION

According to Eurostat data cited by the European Commission, approximately 50 % of all energy consumed in the European Union (EU) is used for heating and cooling [1]. Alarmingly, over 70 % of this energy is still sourced from fossil fuels, with only about one-quarter derived from renewable sources [2]. These figures underscore the urgent necessity to decarbonise this sector, which remains one of the most carbon-intensive components of the EU's energy landscape. Aligned with the European Green Deal and the Fit for 55 packages [3], the EU has committed to reducing Greenhouse Gas (GHG) emissions by at least 55 % by 2030 compared to 1990 levels. Additionally, the revised Renewable Energy Directive (RED III) sets a binding target of at least 42 % share of renewable energy in final energy consumption, with the potential to rise to 45 %, while energy efficiency improvements must reach about 10 % relative to projected primary and final energy consumption levels.

In this policy context, modernising heating and cooling systems is crucial. The transition to energy-efficient, low-carbon, renewable-based heating technologies, such as heat pumps, district heating powered by Renewable Energy Sources (RES) and solar thermal systems, can contribute significantly to the achievement of climate and energy targets. This shift aids emissions reduction, enhances energy security, reduces dependency on fossil fuel imports and supports the creation of green jobs across EU member states.

Current state of CCHP systems

Combined Cooling, Heating, and Power (CCHP) systems have emerged as highly efficient solutions for simultaneous electricity, heating, and cooling generation, significantly improving energy utilization efficiency and reducing environmental impacts compared to traditional energy systems [4]. CCHP systems typically reach energy efficiencies of around 80 %, greatly surpassing separate generation systems, which typically operate at efficiencies between 30 % and 40 % due to significant losses during energy transmission and distribution [5]. The integration of renewable energy sources including solar, geothermal, and biomass into CCHP systems is a prospective field of research and development, although deployment remains somewhat limited in practical settings [6]. Solar-driven CCHP systems (S-CCHP), for instance, employing Stirling engines have demonstrated robust potential, achieving Coefficients of Performance (COP) up to approximately 2.27, reflecting a notable performance improvement of nearly 74.9 % compared to conventional systems [7]. Another significant advancement includes a hybrid Photovoltaic/Thermal (PV/T) based CCHP system equipped with dual-tank latent heat storage, reporting solar energy utilization fractions between approximately 10 % and 40 % [8]. Geothermal-based CCHP systems offer considerable promise, utilizing medium and low-temperature geothermal resources [9]. A dynamic analysis of a geothermal-driven CCHP system highlighted sensitivity to geothermal water temperature variations, showing a decrease of 28.87 % in heating capacity and 14.72 % in cooling capacity when geothermal water temperatures decreased from 120 °C to 108 °C [10]. Furthermore, direct geothermal utilization has expanded significantly worldwide, reaching a global installed thermal capacity of approximately 107,727 MWt by 2019, reflecting substantial potential for broader application in integrated energy solutions [9].

Despite the promising integration with renewables, CCHP systems face technical and operational challenges requiring complex optimization and control methods [11]. Advanced computational techniques have become crucial to addressing these challenges. The genetic algorithm combined with Back Propagation (BP) neural network optimization achieved comprehensive energy performance improvements between 5.78 % and 27.68 % across various scenarios, emphasizing the effectiveness of machine learning-based strategies in enhancing CCHP performance [12]. Besides, innovative methods like the Improved Chameleon Swarm Algorithm (ICSA) have optimized energy management within micro-grid CCHP systems, resulting in 6.89 % operational cost reductions compared to traditional control strategies [13].

Innovations in energy storage integration have significantly improved CCHP performance. The introduction of an isobaric compressed CO_2 energy storage cycle within a CCHP system notably improved the system's roundtrip efficiencies from 49.36 % to 56.47 %, simultaneously improving the system's COP from 0.56 to about 2.17 [14]. Likewise, a thermoacoustic-based CCHP system demonstrated impressive capability in harnessing waste heat and liquefied natural gas cold energy, achieving an overall exergy efficiency of 24.1 % and saving approximately 78.4 MWh of primary fuel annually [15]. CCHP systems utilizing hybrid fuels, including hydrogen-methane blends, have recently gained attention due to their potential to further decarbonize energy systems. A study on hydrogen-methane fuelled CCHP systems optimized for commercial buildings revealed substantial cost savings of around 5 % and greenhouse gas emissions reductions exceeding 14 % over a 20-year period compared to traditional energy setups [16]. Passive radiative cooling techniques integrated with CCHP frameworks have attracted research interest due to their potential in improving overall energy efficiency. A structured polymer film exhibiting passive radiative cooling capabilities demonstrated sub ambient cooling of around 8.2 °C during nighttime and approximately 6.0 °C - 8.9 °C during daytime, significantly enhancing the cooling efficiency of integrated systems [17]. Economic analysis remains a vital component of CCHP system optimization. Recent optimization approaches, considering operational strategies and multi-objective evaluation criteria including economic feasibility [18], environmental impact [19], and energy independence [20], indicate that appropriately optimized CCHP configurations can significantly outperform traditional energy solutions. One notable analysis emphasized that optimal configuration planning of a CCHP system coupled with heat pumps can notably improve economic returns by increasing the utilization rates of high-investment equipment and minimizing operational expenditures [21]. Despite substantial progress and potential demonstrated by renewable-combined and optimized CCHP systems, widespread implementation remains constrained by economic, technical, and operational limitations [22]. Continued advances in integration techniques, optimization methodologies, and control strategies are essential to realizing the full potential of CCHP systems, ultimately contributing significantly to sustainable and efficient energy management practices [23].

Introduction to the RESHeat System

The RESHeat (Renewable Energy System for Residential Building Heating and Electricity Production) is a pioneering renewable-integrated solution precisely designed to meet residential heating, cooling, and domestic hot water (DHW) requirements [24]. Developed under the EU Horizon 2020 initiative, RESHeat strategically combines PV/T modules, solar energy collectors, advanced heat pump technology, underground thermal energy storage, and intelligent control systems [25]. Its design aims to achieve maximum renewable energy utilization, reduce environmental impacts, and optimize economic viability for residential settings.

The RESHeat system realizes its holistic integration of renewable energy sources with advanced thermal energy management and storage technologies. Aligning to its operation are sun-tracked and stationary PV/T modules, which simultaneously generate electricity and thermal energy [19]. Due to the reuse of waste heat from PV/T combined with underground energy storage, the high COP of the heat pump with a yearly average of over five is achieved [26]. A highly efficient ground regeneration technique is developed due to the thermal energy recovery underground. Another notable innovation is the employment of a glycol-water heat pump integrated with thermal energy storage solutions. The underground thermal storage exploits stable ground temperatures to support consistent heat pump performance throughout seasonal changes, thus ensuring high system efficiency [27]. The system employs these modules to improve overall efficiency, significantly outperforming conventional photovoltaic or thermal collectors operated separately [28].

The RESHeat project has established demonstration sites in both Poland and Italy, enabling comparative analysis of system performance under distinct European conditions. The Polish demonstration represents a cold temperate continental climate with long heating seasons and relatively stable ground temperatures, whereas the Italian demonstration is situated in a Mediterranean climate characterised by hot summers, mild winters, and higher solar availability. In addition to these climatic contrasts, the two sites differ in terms of system configuration, component sizing, and operational strategies, which significantly affect energy demand patterns and environmental outcomes. While a Life Cycle Assessment (LCA) of the Polish demonstration has been reported in our previous work [19], the present study provides the first in-depth environmental assessment of the Italian demonstration. This offers novel insights into the regional dependence of RESHeat's sustainability performance and complements the earlier findings from Poland, thereby contributing to a more comprehensive understanding of the system's applicability across diverse contexts.

Italian demonstration sites at the ATER building, located in Palombara Sabina near Rome, exemplify the practical application of RESHeat technology. The building, constructed in 1980 - 1985, comprises 13 apartments and was initially equipped with a conventional natural gas boiler [27]. The original system had a maximum heat input of 69 kW, delivering a heating output ranging from 51.8 kW to 65 kW, with an efficiency of 96 %. The annual heating demand for the building is approximately 54.92 MWh, while its annual cooling demand reaches 37.70 MWh [29].

The RESHeat installation at the ATER demo site comprises (shown in **Figure 1**):

- 75 stationary PV/T modules, each module rated at 300 W, collectively delivering a peak electrical output of 22.5 kW.
- Water-to-water RE56 heat pump, providing a maximum heating capacity of 85 kW and cooling capacity of 74 kW.
- 4 1000-liter buffer tanks without heat exchangers and 2 800-liter buffer tanks with integrated heat exchangers.
- 1 dry cooler with a maximum capacity of 146.7 kW for thermal regulation.
- 26 fan coil units distributed throughout the apartments for precise heating and cooling delivery.

The RESHeat system operation is specifically tailored to seasonal variations, effectively managing energy production and utilization throughout the year.

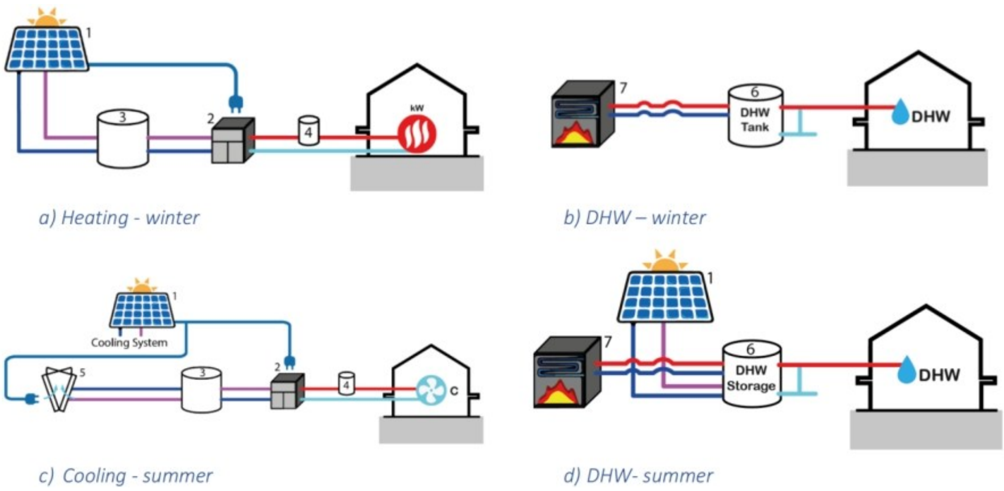

Figure 1. The schematic of RESHeat in Italy [29]

Winter Mode: During the heating season, the PV/T modules primarily provide electricity to power the heat pump. Simultaneously, thermal energy captured by the PV/T modules is utilized directly at the heat pump's source side, enhancing the COP of the heat pump. Excess thermal energy is stored in buffer tanks, maintaining optimal temperature levels for efficient heat pump operation. The heat pump supplies heat to the apartments through fan coils, achieving precise and comfortable indoor temperatures.

Summer Mode: In the non-heating season, the system continues to utilize PV/T modules for electrical and thermal energy production. The heat pump operates in cooling mode, providing cooling to the apartments via fan coils. Excess thermal energy generated by the PV/T modules and the operational heat from the heat pump are dissipated using the dry cooler, ensuring efficient thermal management and maintaining optimal system performance.

The RESHeat system is still in the demonstration phase, making early-stage environmental evaluation essential for guiding future development and deployment. Conducting a comprehensive LCA is necessary to accurately capture the system's environmental footprint across all life cycle stages, including production, operation, and end-of-life. Such an evaluation enables the identification of environmental hotspots, quantifies potential trade-offs, and provides a scientific basis for decision-making in system optimization. Moreover, early environmental assessment ensures that the RESHeat system aligns with sustainability goals and regulatory frameworks, particularly those related to climate neutrality, resource efficiency, and the circular economy.

This paper evaluates the environmental impacts of the RESHeat system implemented at the Italian demonstration site, focusing on its overall sustainability within the context of residential heating, cooling, and domestic hot water supply. The ReCiPe 2016 Midpoint (H) method was applied to ensure a robust and multidimensional environmental evaluation. This method enables detailed quantification of environmental impacts across several key categories, such as global warming potential, fossil resource scarcity, water consumption, human toxicity, ecotoxicity, terrestrial acidification, and particulate matter formation. The assessment includes not only the direct emissions from system operation but also the embedded environmental impacts of the materials and processes involved in the system's construction and decommissioning. Particular attention was paid to the impact of material reuse and recycling strategies. These strategies can significantly reduce environmental impacts, particularly greenhouse gas emissions and the consumption of non-renewable natural resources. A comprehensive environmental analysis of the RESHeat system installed in Italy was conducted by integrating real operational data with a detailed breakdown of the system's components into their constituent parts and applying the advanced life cycle assessment (LCA) methodology.

The novelty of this study lies in its comprehensive scope and in the fact that it is the first in-depth environmental assessment of a fully operational RESHeat system implemented in Italy. The analysis covers all stages of the system's life cycle: from raw material extraction and component manufacturing, through the operational phase, to end-of-life scenarios. The potential environmental benefits of material reuse and recycling were also assessed.

The findings offer valuable insights into the environmental impact of individual components, such as PV/T modules, heat pumps, and storage tanks, on the overall footprint of the system. These results serve as a foundation for future system optimization and support the advancement of sustainable heating and cooling technologies in the residential sector, aligning with the principles of the circular economy.

METHODS

Life Cycle Assessment was employed to assess the environmental impacts of the RESHeat system across its lifecycle stages: construction, operational and end-of-life stages. The ReCiPe 2016 (Midpoint H) method was used to evaluate environmental categories, including global warming potential, resource scarcity, water consumption, and human health impacts. The functional unit is the environmental impact associated with electricity and heat generation by the RESHeat system over one year. No allocation procedure was applied to the PV/T system since both energy outputs are included within the same functional unit, allocation between thermal and electrical outputs was avoided. The system boundaries of the study are defined on a cradle-to-grave basis (**Figure 2**), covering from material acquisition and system construction, operation and end-of-life stages. The methods follow the International Organization for Standardization (ISO) 14040 guidelines. Solar irradiation used for electricity and heat generation was considered carbon-free. Given the relatively minor contribution of transportation processes, their impact is considered negligible and thus excluded from the analysis. The impact assessment includes ecological damage, resource depletion and health damage. For waste management in the end-of-life stage, it is assumed that 61.7% of steel, 90% of aluminium, and 41% of copper are recycled and reused. The remaining parts are treated by landfilling **[30]**. Their reported figures are based on Ecoinvent data and European waste management statistics available at that time. These values are adopted to ensure methodological consistency and comparability with previous LCA studies. Furthermore, the recycled materials are assumed to be directly reused in the system without additional processing [19].

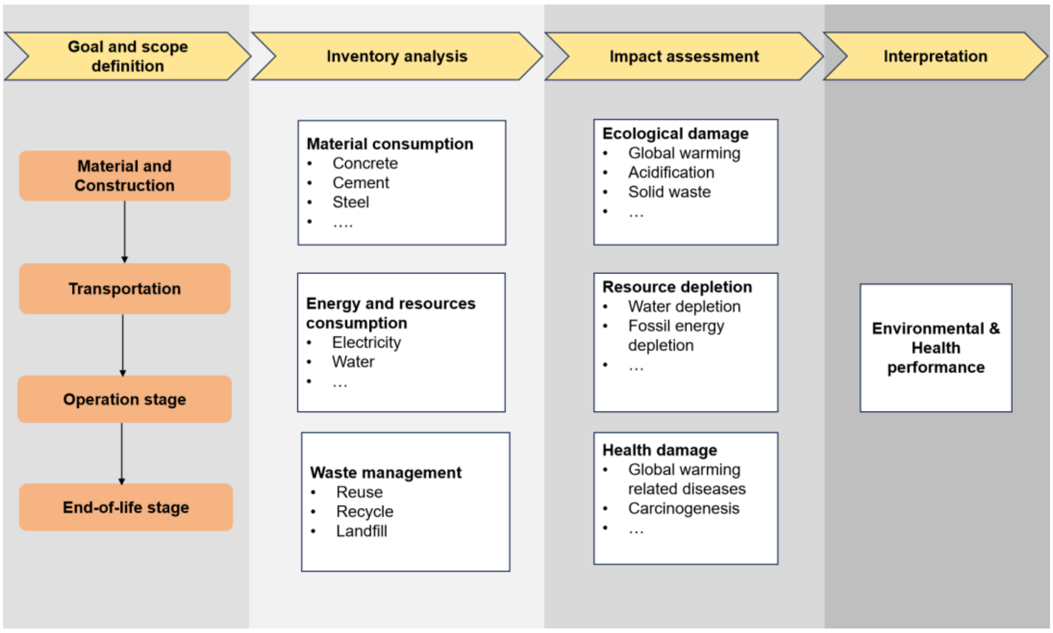

Figure 2. The system boundary defined and the four steps of LCA methodology

The energy flows of Italy's demonstration are shown in Table 1. In the RESHeat system demonstration in Italy, the total heating demand reaches 103.42 MWh/y, which is primarily met through central heating and domestic hot water needs, at 54.92 MWh/y and 48.5 MWh/y respectively. Additionally, the system encounters a cooling demand of 37.7 MWh/y. The energy supply side features a significant contribution from PV/T systems, which generate 54.65 MWh/y of thermal energy. Heat pumps supplement this by providing another 16 MWh/y of thermal energy. On the electricity front, the PV/T systems produce 30 MWh/y, comfortably exceeding the total electricity demand of the system, which is 28 MWh/y.

Table 1. Summary of the energy analysis in Italy demonstration

Generation and demand	Energy flow	Unit
Central heating demand	54.92	[MWh/y]
Domestic hot water demand	48.50	[MWh/y]
Cooling demand	37.70	[MWh/y]
PV/T thermal energy generation	54.65	[MWh/y]
Heat pump thermal energy generation	16.00	[MWh/y]
PV/T electricity generation	30.00	[MWh/y]
Total Electricity Demand	28.00	[MWh/y]
Total Heating Demand	103.42	[MWh/y]

The inventory may encompass materials such as steel, copper, and plastics, among others, and the production and disposal of these materials entail varying degrees of environmental impacts. The inventory list of the heat pump and gas boiler systems draws on data from Greening and Azapagic [30]. Additionally, data for the PV/T panels are sourced from Fthenakis and Kim [31], while sun-tracking solar system data are obtained from Chow and Ji [32] and Menzies and Roderick [33]. The underground storage tank inventory is sourced from Suer et al. [34]. The inventory of system infrastructure is from the site survey. The inventories of the facilities installed in the Italy demonstration are provided in Tables 2 to 7. This comprehensive coverage includes components such as heat pumps, PV/T panels, heat exchangers, hybrid systems, storage tanks, and fan coils.

Table 2. The inventory of the heat pump in Italy demonstration

Components	Material per year	Mass	Unit//y
Evaporator and condenser	Low-alloyed steel	6.57	[kg]
Housing and compressor	Reinforcing steel	24.64	[kg]
Wiring, piping and expansion valve	Copper	7.23	[kg]
Pipework insulation	Elastomere	3.29	[kg]
Wiring insulation	Polyvinylchloride	0.33	[kg]
Lubricating oil	Polyolester oil	0.14	[kg]
Refrigerant	R-410A	0.25	[kg]
Assembly of pump units	Medium-voltage electricity (European mix)	26.96	[MJ]
	Natural gas	70.00	[MJ]
Heat collector pipework	High density polyethylene (vertical heat collector)	15.59	[kg]
Heat collector pipework insulation	Low density polyethylene	0.38	[kg]
Heat carrier liquid	Ethylene glycol (vertical heat collector)	8.55	[kg]
weighs	Cast iron	0.68	[kg]
Manifold	Brass	0.53	[kg]
Back-fill	Cement	0.24	[kg]
	Bentonite	0.05	[kg]
Scaffolding, rods, supports	Reinforcing steel	0.41	[kg]
Installation	Diesel (vertical heat collector)	43.20	[MJ]
Maintenance	Refrigerant	0.37	[kg]

The combination of OpenLCA software and the Ecoinvent database, along with the ReCipe 2016 midpoint (H) impact assessment method, forms a robust framework for conducting a comprehensive and reliable environmental evaluation of the heating systems as shown in **Figure 3**. This approach ensures the study's credibility and enables informed decision-making for promoting sustainable heating solutions with reduced environmental impacts. The core part of LCA is the life cycle impact assessment, where the life cycle inventory data is weighted to derive the system's potential impacts on the environment. During this process, the significance of different environmental impact impacts is considered, such as global warming potential, acidification potential, resource depletion, etc. Ultimately, through the interpretation of results, we gain a comprehensive understanding of the system's environmental performance and guide system improvement and optimization to minimize its environmental impacts.

Figure 3 illustrates the methodological framework adopted to quantify environmental impacts at both the component and system levels. The procedure begins with defining product and energy flows, establishing corresponding processes, and constructing product systems, followed by calculation of properties using the ReCiPe 2016 Midpoint (H) method. This stepwise approach ensures consistency in assessing material inputs, energy categories, and allocation strategies, thereby enabling a comprehensive life cycle evaluation of the RESHeat system.

Table 3. The inventory of the PV/T panels in Italy demonstration

Components	**Material**	**Mass**	**Unit/y**
Modules	Cell materials	9.37	[kg]
	Glass	56.87	[kg]
	Ethylene vinyl acetate	6.25	[kg]
Energy	Electricity	1,762.39	[kWh]
	Oil	0.31	[L]
	Natural gas	2,256.11	[L]
Mounting system	Stainless steel	3.06	[kg]
	Aluminium	3.37	[kg]
	Frame	19.00	[kg]
Cabling	Copper	0.52	[kg]
	Thermoplastic elastomer	0.40	[kg]
Inverters	Steel	0.20	[kg]
	Aluminium	1.73	[kg]
	Copper	0.01	[kg]
	Polycarbonate	0.17	[kg]
	ABS	0.38	[kg]
	Other plastics	0.01	[kg]
	Printed circuit board	0.25	[kg]
	Connector	0.13	[kg]
	Transformers, wire-wound	0.79	[kg]
	Coils	0.19	[kg]
	Transistor diode	0.03	[kg]
	Capacitor, film	0.18	[kg]
	Capacitor, electrolytic	0.14	[kg]
Heat recovery unit	Thermal insulation (polyurethan)	6.25	[kg]
Mechanical balance of system (support structure and air circuit)	Collector frame (aluminium profiles)	25.00	[kg]
	Collector back cover (aluminium sheet)	6.25	[kg]
	Only for PVT/TFMS systems (aluminium sheet)	1.87	[kg]
	Galvanized iron rods (support structure for tilted roof)	18.75	[kg]
	Aluminium (support structure for tilted roof	6.25	[kg]
	Pipes for air circulation (galvanized iron)	12.50	[kg]
Fan for air circulation	Copper	1.87	[kg]
	Steel	2.50	[kg]
	Plastic (polyvinyl chloride)	0.62	[kg]
	Heat exchanger (copper)	12.50	[kg]

Table 4. The inventory of the heat exchanger in Italy demonstration

Components	**Material**	**Mass**	**Unit/y**
Piping	High density polyethylene	7.31	[kg]

Table 5. The inventory of the hybrid system in Italy demonstration

Components	Material per year	Mass	Unit/y
Hydraulic system	Steel	25.61	[kg]
	Cast iron	3.96	[kg]
	Stainless steel	4.19	[kg]
	Plastic, polypropylene, polyethylene materials	1.31	[kg]
	Polypropylene	13,815.87	[kg]
	Brass	5.36	[kg]
	Galvanised steel	7.66	[kg]
	Nickel	0.34	[kg]
	Copper	2.53	[kg]
	40% glycol solution	20.00	[L]
	Synthetic rubber	14.03	[kg]
Electrical installation, installation materials	Aluminium	0.05	[kg]
	Steel	0.07	[kg]
	Plastic, polypropylene, polyethylene materials	4.86	[kg]
	Brass	0.02	[kg]
	galvanised steel	2.57	[kg]
	Copper	4.23	[kg]
Electronics (mixing valves, controllers, control and measurement system)	Stainless steel	0.06	[kg]
	Plastic, polypropylene, polyethylene materials	0.13	[kg]
	Brass	0.77	[kg]
	Copper	0.09	[kg]

Table 6. The inventory of the tanks in Italy demonstration

Components	Material per year	Mass	Unit/y
Buffer tanks	Plastic, polypropylene, polyethylene materials	2	[kg]
	Steel	26.8	[kg]

Table 7. The inventory of the fan coil in Italy demonstration

Components	Material per year	Mass	Unit/y
Fan for air circulation	Copper	0.62	[kg]
	Steel	0.83	[kg]
	Plastic (polyvinyl chloride)	0.21	[kg]
	Heat exchanger (copper)	4.17	[kg]

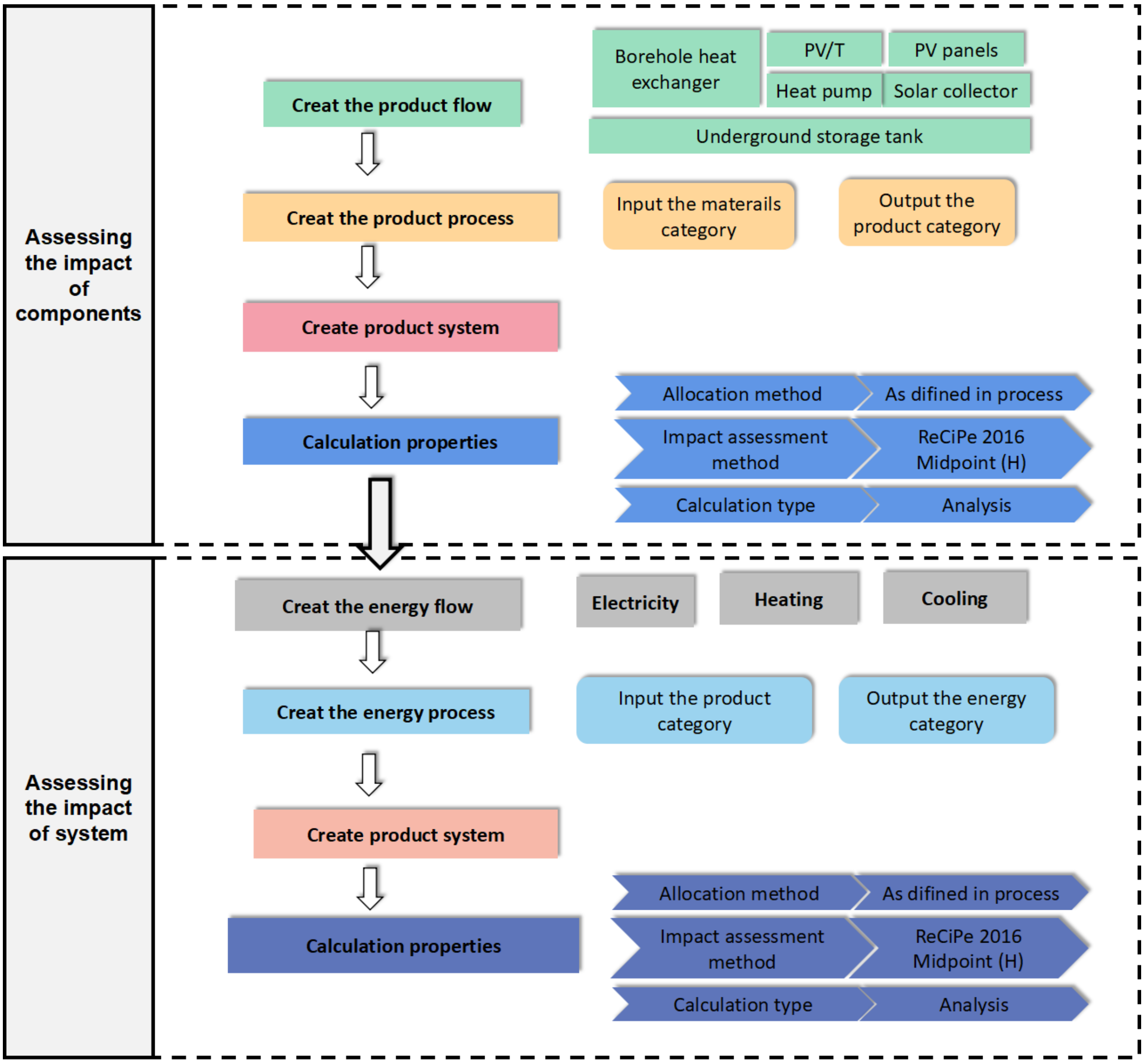

Figure 3. A block diagram of the calculation process

RESULTS AND DISCUSSIONS

The environmental impact results for the RESHeat system demonstration are shown in Table 8. The total greenhouse gas emissions associated with the construction of the RESHeat system amount to 7,227.62 kg CO_2 eq after accounting for material recycling and reuse. Without reuse, the material-related emissions would reach 36,982.26 kg CO_2 eq. However, the application of reuse strategies is expected to reduce this by up to 29,796.25 kg CO_2 eq, representing 80.57 % of the total material-related impact. Fossil resource scarcity shows a considerable initial demand of 24,284.70 kg oil eq due to material use. However, through reuse, this figure is dramatically reduced by over 20,902.10 kg oil eq, leading to a much lower net impact of 3,394.73 kg oil eq. This significant decrease highlights the potential of reuse strategies in conserving non-renewable fossil resources, which is crucial for sustainable development. Water consumption initially stands at 456.25 m^3, but is effectively reduced to 158.43 m^3 through the reuse of materials, showcasing efficient water management and conservation within the system. The impact on terrestrial and marine ecotoxicity also sees substantial reductions through reuse, with terrestrial ecotoxicity decreasing from 104,089.66 kg 1,4-DCB to 38,434.03 kg 1,4-DCB, and marine ecotoxicity from 1,676.66 kg 1,4-DCB to 742.69 kg 1,4-DCB.

Table 8. The environmental impacts of the RESHeat system in Italy

Impact result	Unit	Material (Construction)	Recycle	Landfill	Reuse	Total
Fossil resources circuity	kg oil eq.	24,284.70	0.72	11.41	-20,902.10	3,394.73
Global warming	kg CO_2 eq.	36,982.26	5.83	35.77	-29,796.25	7,227.62
Water consumption	m^3	456.25	0.02	0.03	-297.87	158.43
Terrestrial acidification	kg SO_2 eq.	109.57	0.01	0.19	-81.03	28.75
Terrestrial ecotoxicity	kg 1,4-DCB	104,089.66	43.72	42.82	-65,742.17	38,434.03
Stratospheric ozone depletion	kg CFC11 eq.	0.01	0.00	0.00	-0.01	0.00
Marine ecotoxicity	kg 1,4-DCB	1,676.66	2.62	0.25	-936.85	742.69
Freshwater eutrophication	kg P eq.	9.32	0.00	0.00	-5.14	4.18
Human carcinogenic toxicity	kg 1,4-DCB	2,049.70	0.51	1.31	-1,318.12	733.39
Mineral resource scarcity	kg Cu eq.	89.12	0.03	0.06	-54.18	35.03
Freshwater ecotoxicity	kg 1,4-DCB	1,270.47	1.99	0.16	-703.62	569.01
Human non-carcinogenic toxicity	kg 1,4-DCB	26,031.16	39.92	3.66	-15,331.16	10,743.59
Ionizing radiation	kq Co-60 eq.	1,166.64	0.31	0.45	-720.62	446.78
Fine particulate matter formation	kg PM2.5 eq.	44.16	0.01	0.10	-32.30	11.96
Marine eutrophication	kg N eq.	0.77	0.00	0.00	-0.46	0.32
Ozone formation, Terrestrial ecosystems	kg NOx eq.	84.89	0.01	0.43	-68.53	16.81
Land use	m^2a crop eq.	236.81	0.46	-2.82	-167.65	66.80
Ozone formation, Human health	kg NOx eq.	79.68	0.01	0.43	-64.00	16.13

The end-of-life stage analysis highlights the vital role of recycling and reuse in mitigating these impacts. Recycling plays a modest yet important role in reducing reliance on virgin materials, contributing marginally to fossil resource and ecotoxicity reductions. In contrast, reuse has a much more pronounced effect, significantly lowering total environmental burdens. Reuse proves significantly more effective, cutting fossil resource scarcity by 86 % and global warming potential by 80 %. Reuse also leads to major reductions in water use, terrestrial and marine ecotoxicity, and particulate matter formation. These findings demonstrate that integrating reuse strategies in system design is crucial for improving sustainability performance. Overall, the RESHeat system can significantly reduce its environmental footprint through effective material reuse and recycling, aligning better with circular economy principles and long-term climate and resource conservation goals.

From a component-level perspective, the environmental impacts of the RESHeat system in Italy are primarily driven by the construction phase and the PV/T panels. Construction dominates in categories such as fossil resource scarcity (88 %), terrestrial ecotoxicity (65 %), and fine particulate matter formation (91 %), indicating a heavy reliance on non-renewable, mineral-intensive materials and emission-intensive processes. PV/T panels also contribute substantially across multiple impact categories, including water consumption (75 %), global warming (50 %), freshwater eutrophication (77 %), and ionising radiation (79 %), due to their material composition and manufacturing complexity (**Figure 4**).

Heat pumps and other auxiliary components show relatively minor environmental burdens across most categories. However, their cumulative impact still warrants consideration, especially as system deployment scales up. Overall, construction and PV/T panels are the most environmentally intensive parts of the RESHeat system. Prioritising reuse, material innovation, and cleaner manufacturing processes for these components is key to reducing the system's life cycle footprint and supporting long-term sustainability goals.

From the sensitivity analysis in previous study **[19]**, results showed that shorter lifetimes increase environmental impacts, for example CO_2 emissions were 19.8 % higher at 20 years compared to the 25-year baseline. While longer lifetimes reduce them, with a 13.2 % decrease at 30 years. Resource use and ecotoxicity categories were identified as the most sensitive.

While comparing with other heating systems, the RESHeat systems exhibit significant environmental advantages over the conventional gas boiler, with reductions of 62 % - 95 % in global warming potential **[19]**. Compared with other CCHP systems, RESHeat shows intermediate performance: while CCHP-2 **[35]** has the highest impacts (125 kg CO_2 eq/m^2y) due to high energy demand and grid dependency, the compact CCHP-1 system **[35]** demonstrates the lowest burdens (1.3 kg CO_2 eq/m^2y). Overall, RESHeat provides a balanced solution with substantial environmental benefits over fossil-based heating, while being more scalable than the highly compact CCHP-1 design.

CONCLUSIONS

This article presents a comprehensive LCA of the RESHeat system implemented at the Italian demonstration site, using the ReCiPe 2016 (Midpoint H) methodology. The primary objective is to evaluate the system's environmental performance over one year of electricity and heat production, covering all life cycle stages - from raw material extraction, through operation, to end-of-life.

The analysis provides a detailed breakdown of individual components including the construction phase, fan coils, buffer tanks, heat exchangers, PV/T modules, and the heat pump, and quantifies their contributions across a wide range of environmental impact categories. These include global warming potential, fossil resource scarcity, water consumption, ionizing radiation, eutrophication, ecotoxicity, human toxicity, particulate matter formation, ozone formation, land use, and mineral resource depletion.

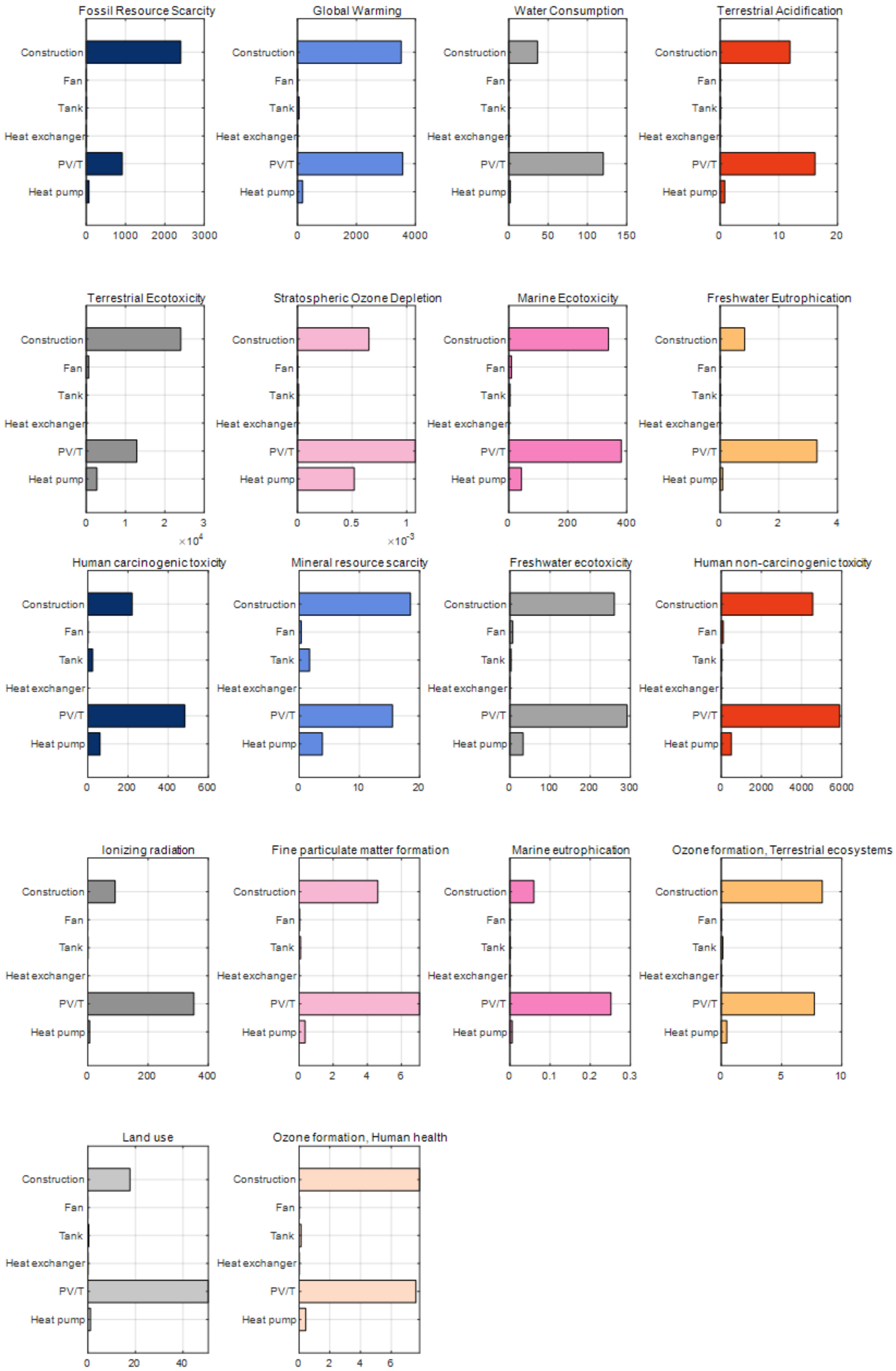

Figure 4. The environmental impacts of the RESHeat system in Italy

A particular focus is placed on the role of reuse and recycling strategies, which demonstrate substantial potential for environmental impact mitigation - achieving up to 80.6 % reduction in CO_2 emissions, 86 % in fossil resource use, and 65 % in water consumption. The results identify the construction phase and PV/T modules as the most environmentally burdensome components, suggesting that improved material selection and cleaner manufacturing processes are key to further reducing the system's environmental footprint.

The main assumptions and innovations presented in the article are as follows:

- A comprehensive LCA of the RESHeat system demonstration in Italy, covering the entire life cycle - from raw material extraction, through operation, to end-of-life-which is rarely addressed in full in existing literature. The calculations are based on empirical data from a fully operational RESHeat installation, ensuring high practical relevance and bridging the gap between theoretical modelling and real-world performance.
- The use of a robust, multi-indicator ReCiPe 2016 Midpoint (H) methodology to evaluate a broad spectrum of environmental impact categories, including global warming potential, fossil resource depletion, water consumption, and toxicity.
- A component-level assessment, in which each major element of the system (e.g., PV/T panels, heat pump, heat exchangers) is individually analysed to determine its specific environmental contribution. The construction phase and PV/T modules are identified as the most environmentally impactful, providing a clear direction for targeted optimization in future system iterations.
- The evaluation of multiple end-of-life strategies, demonstrating that reuse and recycling of materials can reduce the environmental impact of the system by up to 80 % in key impact categories, significantly supporting circular economy objectives.

The research presented in this article also identifies promising directions for future work. These include the further optimization of material selection and component design, as well as the integration of economic and social impact assessments to enable a complete Life Cycle Sustainability Assessment (LCSA). The results not only deliver site-specific environmental insights but also underline the potential relevance of RESHeat for policy frameworks promoting low-carbon building energy solutions and its replicability in other climatic and operational contexts. Nevertheless, this study primarily addressed environmental dimensions, and future research will incorporate a more detailed techno-economic assessment to complement the present findings. In addition, the application of dynamic LCA modelling under variable operating conditions is recommended to more accurately reflect the system's real-world performance over time. These measures will contribute to the development of a heating system that is not only environmentally sustainable but also economically viable and socially responsible. Ultimately, they will enhance the overall sustainability of the RESHeat system and support its broader implementation in residential energy applications. The proposed research directions are fully aligned with current EU strategies on resource efficiency and the principles of the circular economy.

ACKNOWLEDGMENT(S)

The authors are pleased to acknowledge that the work presented in this paper was performed with financial support from the European Union HORIZON 2020 research and innovation programme under Grant Agreement No. 956255, RESHeat project.

NOMENCLATURE

Abbreviations

CCHP	Combined Cooling, Heating, and Power
COP	Coefficients of Performance
EU	European Union
GHG	Greenhouse Gas
ICSA	Improved Chameleon Swarm Algorithm

ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
PV/T	Photovoltaic/Thermal
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RESHeat	Renewable Energy System for Residential Building Heating and Electricity Production
S-CCHP	Solar-driven CCHP

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Paper submitted: 25.06.2025
Paper revised: 26.08.2025
Paper accepted: 02.09.2025