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Environmental Life Cycle Assessment of a PEORC-Driven Hybrid Micro-CHP System for Residential Buildings in Greece

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Abstract:

Residential micro-Combined Heat and Power (CHP) systems can drastically improve the energy efficiency and sustainability of households. By generating heat and power locally, these systems efficiently meet household needs, resulting in reduced carbon emissions and primary energy savings (PES). This study evaluates the life cycle environmental impacts of a novel solar-biomass hybrid heat-driven micro-CHP system designed for residential applications in Greece. The cogeneration unit is driven by a hybrid solar-biomass renewable energy mix and employs a high-efficiency Partially Evaporating Organic Rankine Cycle (PEORC) as its prime mover. The proposed configuration comprises a biomass boiler, a PEORC engine, a field of Evacuated Tube Collectors (ETC) coupled with a Solar Thermal Tank (STS) tank, and a Heating Buffer Tank (HBT) that receives heat from the PEORC engine's condenser and supplies the building's space heating system. The proposed micro-CHP system covers the annual space heating demand and a substantial share of the electricity demand of multi-family buildings in Greece fully and cost-efficiently. The present study reports the results of an environmental life cycle impact assessment (LCIA) of the proposed micro-CHP system. The assessment is based on a life cycle inventory (LCI) developed using site-specific primary data, supplemented with secondary data from established databases and the scientific literature. A cradle-to-grave system boundary (SB) was defined, encompassing raw material extraction, manufacturing, transportation, installation, use (operation), and end-of-life (EoL) stages. The functional unit (FU) was defined as 1 kWh_{th} of useful heat delivered at the building level. The system achieves a Climate Change impact of 7.813E-03 kg CO_2-eq per kWh_{th}. While providing nearly carbon-neutral heat, a significant burden-shift is identified: Particulate Matter (PM) formation dominates the environmental profile, representing 71.69% of the total score due to decentralized biomass combustion. Additionally, manufacturing the solar field and PEORC engine drives mineral resource intensity, contributing 47.09% and 17.28% to abiotic depletion, respectively.

Keywords:

Micro-Combined Heat and Power; Partially Evaporating Organic Rankine Cycle; Solar Energy and Biomass Utilization; Residential Heating; Life Cycle Assessment.

1. Introduction

Reducing greenhouse gas (GHG) emissions in the residential sector is a priority for the European Union's strategy to reach carbon neutrality by 2050 [1]. Currently, buildings account for approximately 40% of the EU's energy consumption and 36% of its energy-related GHG emissions [2], with residential structures responsible for two-thirds of that impact [3]. In Greece, energy demand in the residential sector is primarily thermal (69.4%), followed by electricity (30.6%) [4].

CHP systems provide a highly efficient alternative to the separate generation of heat and electricity, leading to significant PES and lower emissions [5]. Systems with an electrical capacity below 50 kW_{el} are defined as micro-CHP [6] and, because of their smaller scale, and are particularly appropriate for residential applications. Among the various prime movers available for CHP applications, the Organic Rankine Cycle (ORC) has demonstrated significant potential for low-to-medium temperature heat recovery, with electric efficiencies of medium- and large-scale systems reaching 20% [7]. ORC operates on the same principle as the steam Rankine Cycle, but the utilization of alternative WFs increases significantly the power cycle efficiency at lower heat source temperatures [8,9]

Recent advancements have introduced the PEORC, as a more efficient alternative compared to standard subcritical ORCs by omitting the vaporization of the working fluid (WF) at the evaporator of the power cycle by vaporizing a fraction of the WF's mass in the evaporator, achieving higher heat transfer rates from the heat source to the WF than in the ORC [10]. Research indicates that PEORC significantly enhances power output, especially under low pump efficiency, and achieves superior thermal efficiency across various WFs [11]. These gains are maximized when expansion begins within the two-phase region [12]. Experimentally, PEORC has demonstrated an exergy efficiency increase of up to 80% compared to ORC when using R1233zd(E) [13].

Hybridizing CHP systems with solar energy and biomass has gained significant attention due to the complementary nature of these sources [14]. Solar energy offers a carbon-neutral, modular, and decentralized energy solution; however, its high investment costs and stochastic availability often necessitate a secondary power source to ensure system stability [15]. By integrating solid biomass, currently the European Union's primary renewable source with a 41.1% share [16], these systems gain a dispatchable energy component. This synergy allows biomass to compensate for low solar irradiance, ensuring the uninterrupted operation of the cogeneration unit and overcoming the limitations of solar-only systems.

To ensure that the transition to such innovative renewable energy sources technologies is genuinely sustainable, it is critical to evaluate their environmental impacts from a holistic, whole-system perspective [17]. The Life Cycle Assessment (LCA) methodology is an internationally standardized framework for the quantitative characterization of environmental impacts [18].

LCA studies of ORC systems across capacities ranging from a few kW_{el} to over 200 kW_{el} consistently identify the manufacturing or construction phase as a major contributor to overall environmental impacts [19–24]. In particular, Global Warming Potential (GWP) is largely driven by the production of structural and functional metals (primarily steel, stainless steel, copper, and aluminum) widely used in heat exchangers, expanders or turbines, piping, and structural frames. The energy-intensive extraction and processing of these metals result in high embodied emissions, making them key drivers of life cycle impacts. Several studies report that manufacturing alone accounts for the majority of climate change impacts, while other materials and electronic components contribute less significantly. The influence of the WF varies with fluid type, system scale, and assumptions regarding leakage or end-of-life release; although its manufacturing contribution is typically smaller than that of metals, high-GWP refrigerants can substantially affect overall life cycle impacts when emissions are considered. Overall, material composition and WP selection emerge as critical determinants of the environmental performance of ORC technologies. Despite the extensive research activity on ORC systems, LCA studies remain relatively scarce, representing only a small fraction of ORC-related publications in the literature [25].

LCA studies of biomass-based CHP and trigeneration systems consistently identify fuel procurement and thermochemical conversion, rather than system manufacturing, as the primary sources of environmental impacts [26–28] Across systems ranging from 100 kW_{el} micro-units to 50 MW_{el} plants, GWP is largely driven by energy-intensive biomass processing, particularly drying and pelletization of sawmill residues, which can lead to GHG emissions 4-7% higher than natural gas alternatives when biogenic carbon and regrowth delays are considered [26,28]. Technology selection also plays a decisive role: gasification–internal combustion engine systems often exhibit 30-47% higher GWP than ORC configurations due to the auxiliary energy required for syngas cleaning, while combustion and fuel distribution may account for up to 90-95% of Acidification and Eutrophication Potentials [28,29]. System architecture improvements, such as two-stage waste heat recovery or optimized ORC WF selection, can mitigate impacts by enhancing exergy efficiency and reducing GWP and human health burdens per unit of energy produced [30,31]. Overall, the environmental sustainability of biomass CHP systems depends strongly on biomass supply chain logistics, carbon accounting methodology, and the efficiency of the thermal recovery cycle. While current literature recognizes the potential of hybridized solar-biomass CHP systems and the use of the ORC as a prime mover, research into ORC-based systems has focused primarily on thermodynamic and economic performance. To the authors' knowledge, aside from the relevant contributions of Stoppato and Benato [24], there are currently no published studies assessing the environmental performance of residential micro-CHP systems driven by hybridized solar-biomass sources and high-efficiency PEORC power cycles.

The present study addresses this gap by conducting a rigorous environmental LCIA of a novel solar-biomass hybrid heat-driven micro-CHP system utilizing a PEORC prime mover, based on operational data obtained through dynamic simulation of the system's performance. By analyzing the system from a cradle-to-grave perspective, this study aims to quantify its environmental profile, identify the life cycle stages with the highest impacts, and assess its viability as a decarbonization solution for the Greek residential sector.

2. Methodology

2.1. System Description - Goal and Scope Definition

The hybrid micro-CHP system combines a biomass boiler, ETC, and thermal storage to continuously meet heating and electricity demands. The system is designed to primarily cover the annual space heating demand, and a significant portion of the electricity demand of a group of multi-family residential buildings. A representative group of typical Greek multi-family residential buildings in Athens (Central Greece) was selected as the simulation case study. The key characteristics of the building stock are summarized in Table 1 below.

Table 1. *Building characteristics considered in the sizing of the micro-CHP system.*

Category	Parameter	Value & Description
References Building	No. of buildings	5
	Apartments	20 apartments (4 per floor, 100 m^2)
	Dimensions	20m (L) × 20m (W) × 15m (H)
	Conditioned Space - Volume	2,000 m^2 - 6,000 m^3
	Thermal Envelope U-values ($W\ m^{-2}\ K^{-1}$)	Ex. walls: 0.50, Roof: 0.45, Floor: 0.6, Openings: 2.80
	Orientation	4 main facades (N, S, E, W)
	Glazing Ratio	20% of total surface area per facade
Thermal Comfort	Setpoint Temperature	21 °C (Day) / 18 °C (Night: 22:00–08:00)
Occupancy	Density	5 persons per 100 m^2
	Profile	Standard residential (daily occupancy, typical lighting/appliances)
	Heating Schedule	Continuous (24 h)
Internal Gains	People / Appliances / Lighting	3 / 7 / 5 Wm^{-2}
Ventilation	Fresh Air Requirements	15 m^3/h per person
	Air Infiltration	5.5 m^3/h per m^2 of opening
Shading	Vertical Openings / Elements	Factor: 0.20 / 0.15
	Horizontal Elements	Factor: 0
Heating System	System Efficiency	100% (Distribution losses neglected)
	Thermal Delivery	Via the HBT

The system's architecture comprises five primary sub-systems (Figure 1):

- An ETC solar field for thermal energy generation.
- An STS buffer tank that stores excess solar heat, mitigating the intermittency of solar energy availability.
- A biomass boiler of the Hybrid Thermal System (HTS) that serves as a dispatchable heat source, combusting biomass pellets to ensure continuous operation when solar thermal input is insufficient.
- The PEORC engine, which functions as the prime mover of the micro-CHP system, utilizing thermal energy supplied by both the STS and the biomass boiler for electricity generation.
- A HBT that captures the rejected heat from the PEORC engine’s condenser and delivers it at the required temperature to the building’s space heating distribution network.

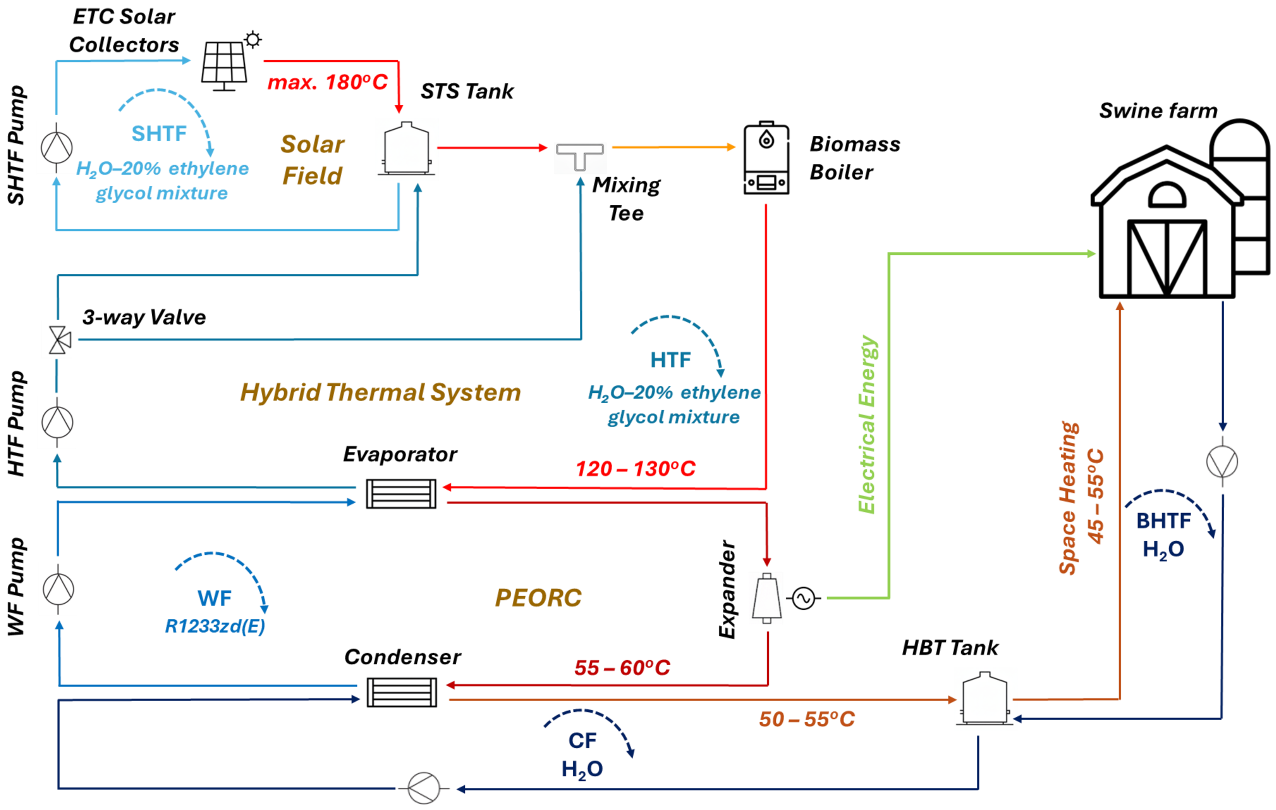

Figure. 1. *Overall micro-CHP system architecture.*

The goal of this LCA study is to quantify the life cycle environmental impacts associated with the production (manufacturing and installation), use (20-year operation), and end-of-life (recycling/disposal) stages of the micro-CHP system, and to evaluate its potential as a sustainable alternative to conventional fossil-based residential heating systems in Greece.

2.2. System Boundary (SB) and Functional Unit (FU)

A comprehensive cradle-to-grave SB was established for this environmental assessment. The boundaries encompass:

- Extraction of raw materials, manufacturing of all system components, and transportation to the installation site
- The operational phase inputs (biomass pellets, processing, and transportation; maintenance requirements).
- The EoL management of the system components (i.e., recycling and disposal)

The selected FU, which provides a quantified reference for all inputs and outputs within the analysis, is defined as 1 kWh of useful heat delivered at the building level.

Because the micro-CHP system yields more than one useful output (heat and electricity), it is a multifunctional process. Following the hierarchy of ISO 14040/14044 standards, multifunctionality was addressed via system expansion (substitution). The co-produced electricity is assumed to substitute an equivalent amount of electricity drawn from the Greek national grid. The environmental burdens of this avoided grid electricity production were subtracted from the total life cycle impacts of the micro-CHP system.

2.3. Life Cycle Inventory (LCI) Analysis

The LCI model was developed using a combination of primary and secondary data. System-specific data, including component sizing, material composition, and prototype specifications, were primarily provided by the technology developer and complemented by data from component manufacturers, resulting in a detailed bill of materials (BoM). For the ETC system, secondary data representing a typical installation of comparable size and capacity were adopted.

For the purposes of this study, the refrigerant R1233zd(E), which is not available in the ecoinvent 3.11 database, was modelled based on literature sources [32,33]. A summary of the LCI for the hybrid micro-CHP system is presented in Table 2. Most major components (e.g., expander, ETC, and biomass boiler) were assumed to last for the entire system lifetime (20 years). To more accurately represent the use phase, components with shorter lifetimes, such as pumps and electronic equipment, were assumed to be replaced once, based on average lifetimes of 11.5 and 12.5 years, respectively.

Where primary data were unavailable, background processes (e.g., raw material extraction, component manufacturing, and the Greek electricity mix) were sourced from the ecoinvent 3.11 database [34], implemented within the openLCA software [35].

Table 2. *LCI summary for the PEORC-driven hybrid micro-CHP system.*

Sub-system	Components	Key technical parameters for LCI modelling
PEORC Engine	Steel frame	100 kg
	Plate Evaporator	50.5 kg, ~ 210 kW
	Plate condenser	49.3 kg, ~ 190 kW
	Expander	380 kg, 230 m^3 hr^{-1}
	POE220 Lubricant Oil	14 kg, leakage rate: 3% annually
	Refrigerant Pump	125 kg, 5.5 kW
	R1233zdE refrigerant	35 kg, leakage rate: 3% annually
	Liquid (70 lit) and oil (10 lit) receivers	49 kg and 10 kg, respectively
	Copper pipping (insulated)	13 kg
	Miscellaneous - *Electronics (PLC, Inverter - Regenerative drive, Electric panel and cabling), valves and fittings*	
ETC Solar Field	ETCs	100 m^2
	Buffer Tank	2 m^3 (high thermal insulation)
	Heat Transfer Fluid Pump	35 kg, 5.5 kW
	Heat Transfer Fluid	2.05 m^3, 20% water-glycol mixture, leakage rate: 3%
	Miscellaneous - *Steel pipping (~12 m), valves and fittings*	
HTS	Biomass Boiler (incl. silo)	200 kW$_{th}$
	Buffer Tank	6 m^3 (moderate thermal insulation)
	Heat Transfer Fluid Pump	35 kg, 5.5 kW
	Heat Transfer Fluid	6.08 m^3, 20% water-glycol mixture, leakage rate: 3%
	Miscellaneous - *Steel pipping (~15 m), miscellaneous valves and fittings*	

Based on the annual operational profiles, the results indicate that the micro-CHP system can fully satisfy the heating demand of the building group, with energy input derived from ENplus A1 class wood pellets (moisture content <10%) and solar energy at an approximate ratio of 11:1. Detailed values of biomass consumption and the corresponding thermal and electrical energy outputs are provided in Table 3.

Table 3. *Annual fuel input and energy outputs of the micro-CHP system.*

Fuel consumption	Amount
Biomass pellets consumption (LHV: 5 kWh$_{th}$ kg^{-1})	84,360.00 kg
Thermal energy generation	151,205.00 kWh$_{th}$
Electrical energy generation	29,800.00 kWh$_{el}$

The EoL treatment assumptions consider both recycling and landfill pathways for the system materials. Steel, copper, and other metals are assumed to have a recycling rate of 92%, with the remaining 8% directed to landfill. Plastics are assumed to be equally split between recycling and landfill (50% each), while the refrigerant is assumed to be fully recovered, while account for 3% emissions during the process. For the water–glycol mixture, wastewater treatment is assumed, whereas for solar collectors, where material separation is not feasible, landfilling is considered

In this study, the EoL modelling accounts only for the environmental burdens associated with the collection, transportation, and treatment of materials at disposal. Potential benefits from material recovery, such as avoided emissions from the substitution of virgin materials (e.g., steel or aluminum), are not considered.

2.4. Life Cycle Impact Assessment (LCIA)

The environmental impacts were evaluated using the Environmental Footprint (EF) v3.1 method [36], as embedded in the openLCA software environment. Sixteen Environmental Impact Categories (EICs), including Climate Change, Resource Use (Fossils and Minerals/Metals), and Particulate Matter, were taken into account. To facilitate a hotspot analysis, normalization and weighting were applied based on [37], to identify and prioritize the most significant impact categories [38], despite recognized methodological limitations inherent in these steps [39]. Normalization assesses the magnitude of impacts within a broader environmental context by scaling them against global reference levels, whereas weighting integrates normative societal or stakeholder priorities to enable a more meaningful interpretation of the system's total environmental profile. A Single Environmental Score (SES) was calculated, providing an aggregated metric of the system's overall environmental performance.

3. Results and Discussion

3.1. Impact Analysis

Generally, the lack of methodological harmonization is a major source of inconsistency in reported environmental impacts, complicating cross-study comparisons [40]. SBs range from cradle-to-gate to cradle-to-grave, while most studies use energy-based units, but some report per unit of installed capacity or per year of operation [41]. Finally, concerning the impact categories investigated, Climate Change is nearly universal, while other categories are less consistently included [42]. Table 4 presents the midpoint-level environmental impacts of the hybrid micro-CHP system per FU.

Table 4. *Environmental impacts of the hybrid micro-CHP system per 1 kWh of useful heat at building level.*

Impact category	Reference unit	Result
Acidification	mol H+-Eq	9.114E-04
Climate change	kg CO_2-Eq	7.813E-03
Ecotoxicity: freshwater	CTUe	2.565E-01
Energy resources: non-renewable	MJ, net calorific value	2.237E-01
Eutrophication: freshwater	kg P-Eq	-6.813E-05
Eutrophication: marine	kg N-Eq	4.518E-04
Eutrophication: terrestrial	mol N-Eq	5.372E-03
Human toxicity: carcinogenic	CTUh	1.474E-10
Human toxicity: non-carcinogenic	CTUh	2.209E-09
Ionising radiation: human health	kBq U235-Eq	2.450E-02
Land use	dimensionless	2.394E+01
Material resources: metals/minerals	kg Sb-Eq	8.814E-07
Ozone depletion	kg CFC-11-Eq	-1.489E-09
Particulate matter formation	disease incidence	1.424E-07
Photochemical oxidant formation: human health	kg NMVOC-Eq	1.356E-03
Water use	m^3 world Eq deprived	6.691E-02

At EIC level (midpoint), results allow us to focus more confidently on climate change, which is the most established impact indicator and the main driver for reduction in studies of this type. A comparison is presented in Table 5, highlighting the difficulty of cross-study comparisons

The environmental performance of the hybrid micro-CHP system, expressed as kg CO_2-eq per kWh of thermal energy, is compared with values reported in the literature. In the present study, the system exhibits a value of 7.813E-03 kg CO_2-eq kWh_{th}^{-1}, with electricity considered as an avoided co-product. For comparison, Guest et al. (2011) [27], using the midpoint CML 2 Baseline 2000 impact assessment method, reported values ranging from 8.640E-03 to 1.008E-02 CO_2-eq kWh_{th}^{-1} for biomass-based district heating CHP plants using gasification technology, corresponding to differences of -9.6% to -22.5% relative to the present study. Stoppato and Benato (2020) [24], applying the ReCiPe 2016 method, reported a value of 8.528E-02 CO_2-eq kWh_{el}^{-1}. No system expansion was considered for the co-product (thermal energy). The environmental impact for heat generation was approximated using the indicated power-to-heat ratio (3:1), resulting to 0.232 CO_2-eq kWh_{th}^{-1}, a difference of -72.3% compared to the present work.

Table 5. *Comparison of Climate Change (kg CO2-Eq) per 1 kWh_{th} with relevant literature.*

Study	Result (kg CO_2-Eq kWh_{th}^{-1})	Difference (%)	Notes
Present study	7.813E-03	-	Electricity as avoided product, EF v3.1
Guest et al. (2011) [27]	8.640E-03 to 1.008E-02	-9.57% to -22.50%	Biomass-based district heating CHP, gasification, CML 2 Baseline 2000
Stoppato and Benato (2020) [24]	0.232[a]	-72.34%	No system expansion for co-product, ReCiPe 2016, FU 1 kWh electricity, heat approximated via 3:1 power-to-heat ratio

3.2. Single Environmental Score (SES)

At the endpoint level, the normalization and weighting of the midpoint categories yield the SES.

Table 6. *Normalized and weighted results per EIC.*

Impact category	Normalized	SES (mPt)	Contribution
Acidification	1.640E-05	1.017E-03	3.40%
Climate change	1.034E-06	2.178E-04	0.73%
Ecotoxicity: freshwater	4.522E-06	8.683E-05	0.29%
Energy resources: non-renewable	3.442E-06	2.864E-04	0.96%
Eutrophication: freshwater	-4.240E-05	-1.187E-03	-3.97%
Eutrophication: marine	2.311E-05	6.842E-04	2.29%
Eutrophication: terrestrial	3.039E-05	1.127E-03	3.77%
Human toxicity: carcinogenic	8.543E-06	1.820E-04	0.61%
Human toxicity: non-carcinogenic	1.716E-05	3.158E-04	1.06%
Ionising radiation: human health	5.805E-06	2.908E-04	0.97%
Land use	2.921E-05	2.320E-03	7.76%
Material resources: metals/minerals	1.385E-05	1.046E-03	3.50%
Ozone depletion	-2.845E-08	-1.795E-06	-0.01%
Particulate matter formation	2.393E-04	2.144E-02	71.69%
Photochemical oxidant formation: human health	3.318E-05	1.586E-03	5.30%
Water use	5.834E-06	4.965E-04	1.66%
TOTAL		2.991E-02	

The micro-CHP system achieves a nearly carbon-neutral thermal energy output, with Climate Change and Non-renewable Resource categories representing only 0.73% and 0.96% of the total weighted environmental score, respectively. This performance is primarily attributed to the system expansion credit from avoided grid electricity, which effectively offsets the cumulative impacts of infrastructure manufacturing and operation. Similarly, the displacement of carbon-intensive grid power yields a net environmental benefit for Freshwater Eutrophication by avoiding the upstream mining and treatment requirements associated with conventional energy. While the system's construction requires significant quantities of high-value minerals like copper, steel, and aluminum, the Material Resources impact remains relatively low at 3.5%.

Conversely, the analysis identifies PM formation as the dominant environmental trade-off, accounting for 71.69% of the total environmental score. This hotspot is driven by direct emissions from decentralized biomass combustion, highlighting the critical necessity for high-efficiency flue gas cleaning. Biomass combustion also serves as the primary driver for Photochemical Oxidant Formation (5.30%), though to a much lesser extent. Finally, the Land Use contribution (7.76%) is a direct consequence of the biomass supply chain, specifically the extensive forest area required for wood pellet production over the system's 20-year operational lifespan.

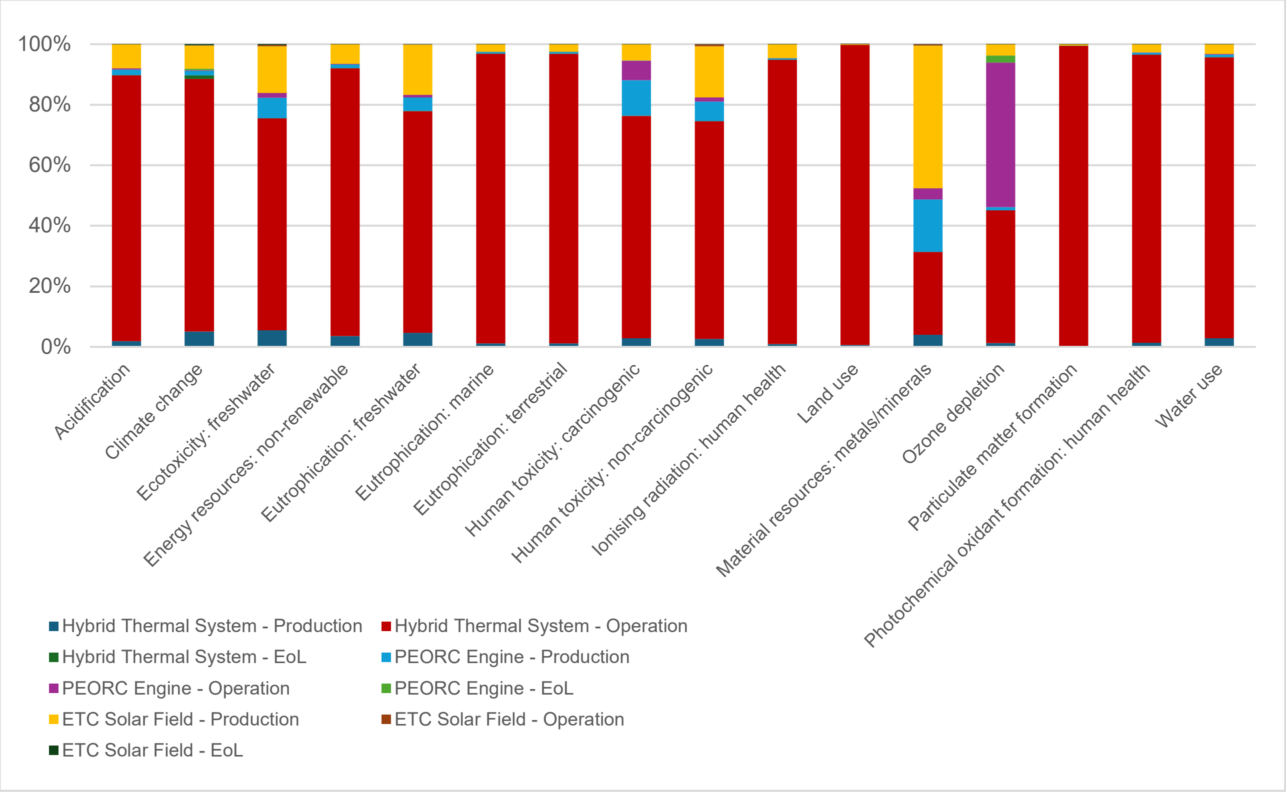

Figure. 2. *Life cycle phase contribution per EIC.*

Figure 2, showing the relative contributions of different life cycle phases to the EICs, indicates that the operation phase of the HTS dominates most categories, particularly Particulate Matter formation and Land Use, due to biomass combustion and the land required for fuel production. The production phase of the ETC and PEORC engine contributes notably to the Material Resources category, while PEORC engine operation influences Ozone Depletion. End-of-life impacts are minimal across all categories.

3.3. Contribution Analysis of System Components

The system's lifecycle reveals a distinct distribution of environmental burdens across its primary stages: manufacturing, operation, and EoL. The operational phase is the primary driver of atmospheric impacts, accounting for 83.51% of the gross GWP and 99.09% of PM formation (of which direct combustion contributes 15.59%). These results are dictated by the biomass loop (specifically fuel supply chain logistics and combustion emissions) and are heavily influenced by the system expansion approach. While displacing the carbon-intensive Greek electricity grid (ecoinvent 3.11) provides a substantial GWP credit of -93.22%, its impact on PM mitigation is negligible (-1.77%). This disparity highlights a significant burden-shift, as decentralized biomass emissions far outweigh the benefits of the displaced centralized grid. Furthermore, Land Use is predictably dominated by biomass supply chains (99.44%).

In contrast, the manufacturing phase determines the system's mineral resource intensity. The production of the ETC solar field is the primary hotspot for abiotic depletion (47.09%), followed by the HTS (27.38%) and the PEORC engine (17.28%), reflecting the high consumption of copper, steel, and aluminum. Scheduled maintenance, such as the replacement of PEORC refrigerant pumps and drives, contributes an additional 3.7% to this category. Although electricity credits offset 52.33% of these mineral burdens, the net result remains positive, emphasizing the "mineral debt" required for this renewable transition.

Finally, EoL phase is environmentally insignificant across all categories, with contributions rarely exceeding 1.2%, primarily arising from the waste treatment of mineral oils and electronic scrap. Ultimately, the system achieves successful decarbonization through system expansion, though this performance is balanced against increased mineral resource intensity and a localized burden-shift toward particulate matter formation.

Overall, as illustrated in Figure 3, the HTS is dominated by operational impacts (98.28%), whereas the PEORC engine shows a major contribution from production (79.51%) and a smaller operational share (17.88%). The ETC solar field is almost entirely production-driven (98.12%), with minimal operational and EoL impacts. Across all sub-systems, the EoL phase remains negligible, highlighting that manufacturing and operation are the critical phases for environmental burden allocation.

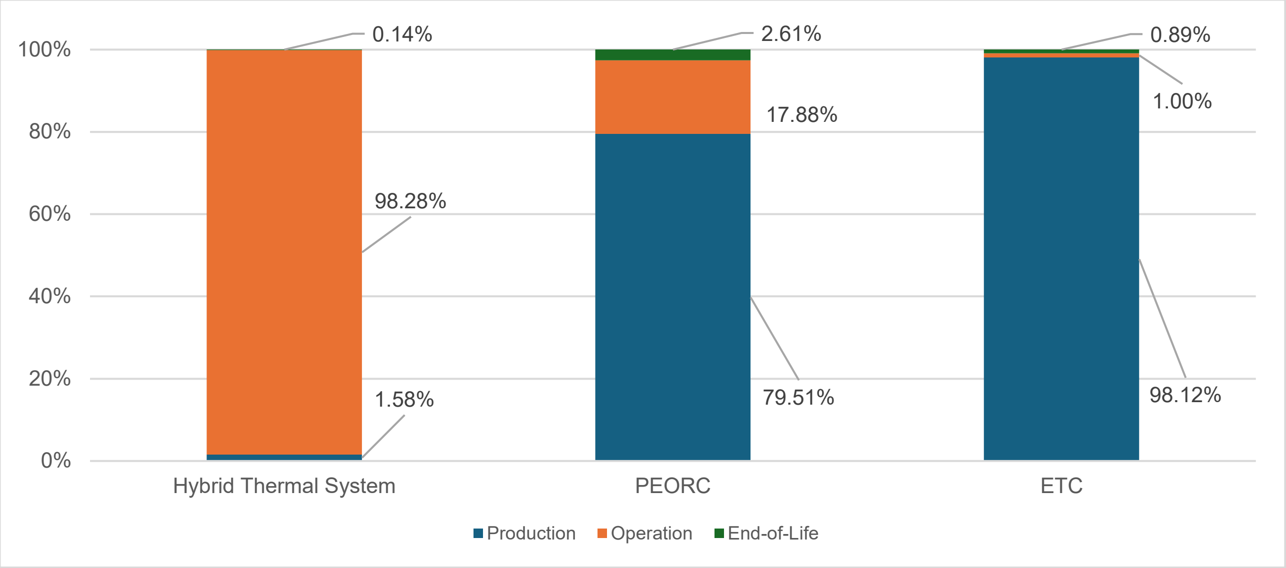

Figure. 3. *Life cycle phase contribution per sub-system.*

4. Conclusions and Future Work

The cradle-to-grave environmental performance of a novel solar-biomass hybrid micro-CHP system, employing a PEORC as the prime mover for residential applications in Greece, was evaluated using the EF v3.1 methodology. The system represents a sustainable decarbonization pathway for residential heating. By displacing grid electricity and utilizing renewable thermal sources, it achieves a highly favorable GWP profile per kWh of useful thermal energy. Process-level analysis identifies the manufacturing of ETCs and the biomass supply chain as the primary environmental hotspots. Consequently, optimizing solar field dimensions and prioritizing local, sustainably sourced biomass are essential for maximizing the system's environmental benefits. Furthermore, the multifunctionality of the PEORC (i.e., co-production of electricity) is fundamental to the system's overall environmental viability.

The analysis confirms the system's decarbonization potential, with Climate Change and Non-renewable Resource categories each representing less than 1% of the total weighted environmental score. However, this is balanced against a localized burden-shift toward Particulate Matter formation (71.69%), driven by direct biomass emissions. While the operational phase accounts for 83.51% of gross Global Warming Potential, the manufacturing phase dictates the system's abiotic resource footprint, particularly through the copper and steel requirements of the solar collectors and PEORC engine. Finally, the End-of-Life phase was found to be environmentally negligible, contributing less than 1.2% across all impact categories.

While this study provides a robust environmental baseline, future research should incorporate sensitivity analyses of various biomass supply chains to further explore the system's sustainability potential. The results highlight the importance of implementing effective particulate filtration technologies during pellet combustion. Furthermore, future iterations should replace standard background datasets with prospective or custom electricity mix models to reflect current trends, such as increased renewable penetration and the reduction of energy imports, to ensure that avoided burden credits are not overestimated. As European electricity grids become increasingly decarbonized, the environmental benefits of displacing grid energy will diminish, making the intrinsic thermodynamic efficiency of the PEORC engine an increasingly important sustainability factor. Future work should also account for detailed material inventories and temporal efficiency degradation during the operational phase. Finally, integrating an assessment of economic feasibility and payback periods will be necessary to evaluate the system's overall market readiness.

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Nomenclature

Subscripts

el electrical energy

th thermal energy

References

[1] European Commission, The European Green Deal. Brussels, Belgium: European Commission; 2019. COM/2019/640 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN [accessed 06.04.2026].

[2] European Commission, Energy efficiency in buildings. Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings_en [accessed 06.04.2026].

[3] Rousselot M., Da Rocha F.P., Energy efficiency trends in buildings in the EU. Paris, France: Enerdata; 2021. Available at: https://www.odyssee-mure.eu/publications/other/odex-indicators-database-definition.pdf [accessed 06.04.2026].

[4] Hellenic Statistical Authority, Survey on energy consumption in households, 2011-2012. Piraeus, Greece: ELSTAT; 2013.

[5] Amber K.P., Day T., Ratyal N.I., Kiani A.K., Ahmad R., Techno, economic and environmental assessment of a Combined Heat and Power (CHP) system-a case study for a university campus. Energies 2018;11(5):1133. doi:10.3390/en11051133.

[6] European Parliament, Council of the European Union, Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. Off J Eur Union 2012;L315:1-56.

[7] Dong L., Liu H., Riffat S., Development of small-scale and micro-scale biomass-fuelled CHP systems - A literature review. Appl Therm Eng 2009;29(11-12):2119-26. doi:10.1016/j.applthermaleng.2008.12.004.

[8] Papingiotis T., Koronaki I., Komninos N., Antonakos G., Thermodynamic analysis and optimization of Transcritical and Supercritical Organic Rankine and Brayton Cycles coupled to parabolic trough collectors. In: IOP Conference Series: Materials Science and Engineering; 2021. IOP Publishing:012044. doi:10.1088/1757-899X/1037/1/012044.

[9] Morais P.H.S., Lodi A., Aoki A.C., Modesto M., Energy, exergetic and economic analyses of a combined solar-biomass-ORC cooling cogeneration systems for a Brazilian small plant. Renew Energy 2020;157:1131-47. doi:10.1016/j.renene.2020.04.147.

[10] Lecompte S., van den Broek M., De Paepe M., Thermodynamic analysis of the partially evaporating trilateral cycle. In: 2nd International Seminar on ORC Power Systems; 2013 Oct 7-8; Rotterdam, Netherlands. ASME Organic Rankine Cycle 2013.

[11] Daniarta S., Kolasiński P., Imre A.R., Thermodynamic efficiency of trilateral flash cycle, organic Rankine cycle and partially evaporated organic Rankine cycle. Energy Convers Manage 2021;249:114731. doi:10.1016/j.enconman.2021.114731.

[12] Skiadopoulos A., Kosmadakis G., Lecompte S., De Paepe M., Manolakos D., Numerical modeling of flashing in TFC expanders for the efficient exploitation of low-grade heat. Therm Sci Eng Prog 2023;46:102171. doi:10.1016/j.tsep.2023.102171.

[13] Dawo F., Buhr J., Schifflechner C., Wieland C., Spliethoff H., Experimental assessment of an Organic Rankine Cycle with a partially evaporated working fluid. Appl Therm Eng 2023;221:119858. doi:10.1016/j.applthermaleng.2022.119858.

[14] Martinez S., Michaux G., Salagnac P., Bouvier J.L., Micro-combined heat and power systems (micro-CHP) based on renewable energy sources. Energy Convers Manage 2017;154:262-85. doi:10.1016/j.enconman.2017.10.035.

[15] Chen H., Xue K., Wu Y., Xu G., Jin X., Liu W., Thermodynamic and economic analyses of a solar-aided biomass-fired combined heat and power system. Energy 2021;214:119023. doi:10.1016/j.energy.2020.119023.

[16] European Commission, Report on the sustainability of bioenergy. Brussels, Belgium: European Commission; 2023. COM(2023) 77 final. Available at: https://energy.ec.europa.eu/publications/bioenergy-sustainability-report_en [accessed 06.04.2026].

[17] Shu D.Y., Deutz S., Winter B.A., Baumgärtner N., Leenders L., Bardow A., The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment. Renew Sustain Energy Rev 2023;178:113246. doi:10.1016/j.rser.2023.113246.

[18] International Organization for Standardization, ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework. Geneva, Switzerland: ISO; 2006.

[19] Cioccolanti L., Rajabi Hamedani S., Villarini M., Environmental and energy assessment of a small-scale solar Organic Rankine Cycle trigeneration system based on Compound Parabolic Collectors. Energy Convers Manage 2019;198:111829. doi:10.1016/j.enconman.2019.111829.

[20] Ding Y., Liu C., Zhang C., Xu X., Li Q., Mao L., Exergoenvironmental model of Organic Rankine Cycle system including the manufacture and leakage of working fluid. Energy 2018;145:52-64. doi:10.1016/j.energy.2017.12.123.

[21] Intaniwet A., Chaiyat N., Levelized electricity costing per carbon dioxide intensity of an organic Rankine cycle by using a water hyacinth-municipal solid waste fuel. Energy 2017;139:76-88. doi:10.1016/j.energy.2017.07.135.

[22] Kythavone L., Lerdjaturanon W., Chaiyat N., Life Cycle Assessment of Organic Rankine Cycle for Low-Environmental Working. In: 7th Asian Academic Society International Conference (AASIC); 2019 Mar 26-27; Bangkok, Thailand. p. 568-81.

[23] Uusitalo A., Uusitalo V., Grönman A., Luoranen M., Jaatinen-Värri A., Greenhouse gas reduction potential by producing electricity from biogas engine waste heat using organic Rankine cycle. J Clean Prod 2016;127:399-405. doi:10.1016/j.jclepro.2016.03.125.

[24] Stoppato A., Benato A., Life cycle assessment of a commercially available organic Rankine cycle unit coupled with a biomass boiler. Energies 2020;13(7):1835. doi:10.3390/en13071835.

[25] Oyekale J., Emagbetere E., A review of conventional and exergetic life cycle assessments of organic Rankine cycle plants exploiting various low-temperature energy resources. Heliyon 2022;8(6):e09833. doi:10.1016/j.heliyon.2022.e09833.

[26] Havukainen J., Nguyen M.T., Väisänen S., Horttanainen M., Life cycle assessment of small-scale combined heat and power plant: Environmental impacts of different forest biofuels and replacing district heat produced from natural gas. J Clean Prod 2018;172:837-46. doi:10.1016/j.jclepro.2017.10.241.

[27] Guest G., Bright R.M., Cherubini F., Michelsen O., Strømman A.H., Life cycle assessment of biomass-based combined heat and power plants: Centralized versus decentralized deployment strategies. J Ind Ecol 2011;15(6):908-21. doi:10.1111/j.1530-9290.2011.00375.x.

[28] Isler-Kaya A., Meydan Z., Karaosmanoglu F., Evaluating the environmental impact of electricity generation from combined heat and power plants utilizing woody biomass: A life cycle assessment approach. Biomass Bioenergy 2025;202:108260. doi:10.1016/j.biombioe.2025.108260.

[29] Rajabi Hamedani S., Villarini M., Marcantonio V., di Matteo U., Monarca D., Colantoni A., Comparative energy and environmental analysis of different small-scale biomass-fueled CCHP systems. Energy 2023;263:125846. doi:10.1016/j.energy.2022.125846.

[30] Anvari S., Medina A., Khalilarya S., Enhancing biomass CHP sustainability through two-stage waste heat recovery: An exergy, exergoeconomic, and life cycle assessment approach. Energy Convers Manage X 2026;29:101543. doi:10.1016/j.ecmx.2026.101543.

[31] Moharamian A., Soltani S., Rosen M.A., Mahmoudi S.M.S., Morosuk T., A comparative thermoeconomic evaluation of three biomass and biomass-natural gas fired combined cycles using organic Rankine cycles. J Clean Prod 2017;161:524-44. doi:10.1016/j.jclepro.2017.05.174.

[32] Shirmohammadi R., Vázquez D., Calvo-Serrano R., Llovell F., Gonzalez-Olmos R., Absolute Environmental Sustainability Assessment of Emerging Working Fluids in Organic Rankine Cycles. ACS Sustain Chem Eng 2025;13(18):6685-95. doi:10.1021/acssuschemeng.5c01290.

[33] Shirmohammadi R., Vázquez D., Calvo-Serrano R., Llovell F., Gonzalez-Olmos R., Supporting Information: Absolute Environmental Sustainability Assessment of Emerging Working Fluids in Organic Rankine Cycles. ACS Sustain Chem Eng 2025;13(18). doi:10.1021/acssuschemeng.5c01290.

[34] Wernet G., Bauer C., Steubing B., Reinhard J., Moreno-Ruiz E., Weidema B., The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21(9):1218-30. doi:10.1007/s11367-016-1087-8.

[35] GreenDelta GmbH, openLCA 2.1 [Software]. Berlin, Germany: GreenDelta GmbH; 2024. Available at: https://www.openlca.org/ [accessed 06.04.2026].

[36] Fazio S., Zampori L., De Schryver A., Kusche O., Diaconu E., Thellier L., Guide for EF compliant data sets. Luxembourg: Publications Office of the European Union; 2020. doi:10.2760/53398.

[37] Sala S., Cerutti A.K., Development of a weighting approach for the Environmental Footprint. Luxembourg: Publications Office of the European Union; 2018. doi:10.2760/446145.

[38] Castellani V., Sala S., Benini L., Hotspots analysis and critical interpretation of food life cycle assessment studies for selecting eco-innovation options and for policy support. J Clean Prod 2017;140:556-68. doi:10.1016/j.jclepro.2016.05.078.

[39] Pizzol M., Laurent A., Sala S., Weidema B., Verones F., Koffler C., Normalisation and weighting in life cycle assessment: quo vadis? Int J Life Cycle Assess 2017;22(6):853-66. doi:10.1007/s11367-016-1199-1.

[40] Wolf C., Klein D., Weber-Blaschke G., Richter K., Systematic Review and Meta-Analysis of Life Cycle Assessments for Wood Energy Services. J Ind Ecol 2016;20(4):743-63. doi:10.1111/jiec.12321.

[41] Stamford L., Greening B., Azapagic A., Life cycle environmental and economic sustainability of Stirling engine micro-CHP systems. Energy Technol 2018;6(6):1119-38. doi:10.1002/ente.201700854.

[42] Osman A., Ries R., Life cycle assessment of electrical and thermal energy systems for commercial buildings. Int J Life Cycle Assess 2007;12(5):308-16. doi:10.1065/lca2007.02.310.