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ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF POLYMER-BASED RETROFIT FOR PHOTOVOLTAIC PANELS

Summary

This study assesses the environmental and economic performance of a second-generation polymer-based photovoltaic-thermal retrofit collector (V2 PVT-SP) for building applications. A cradle-to-grave/cradle life cycle assessment (LCA) combined with a techno-economic analysis (TEA) is used to quantify global warming potential (GWP), cumulative energy demand, energy payback time, levelized cost of energy, and payback time. Results show that the V2 PVT-SP achieves low embodied emissions (16.8-19.6 kg CO_2 eq/m^2) and a short energy payback time (1.16-1.27 years) compared with similar technologies. For the analyzed multi-family building case of a collector area of 225 m2 in Stockholm, the system achieves $LCOH_{eq}$ of 0.021 €/kWh and a simple payback time of 2.8 years. When both thermal and electrical outputs are valorized, the system demonstrates competitive energy costs. The findings highlight the potential of modular retrofit solutions for PV panels to enhance the utilization of solar energy in existing building stocks while supporting low-carbon, cost-effective energy transitions.

Keywords: Photovoltaic-thermal, retrofit solar systems, life cycle assessment, techno-economic analysis, energy payback time, global warming potential.

Field of application for the findings: Building-integrated solar energy systems, retrofit solutions for existing buildings, low-carbon heating and electricity generation, sustainable building energy design.

Addressed audience: Researchers in solar thermal and PVT technologies, building energy system designers, life cycle and sustainability analysts, policymakers, and stakeholders involved in building decarbonization and renewable energy integration.

1. Introduction

The global shift toward low-carbon energy systems demands retrofit solutions that can upgrade existing photovoltaic (PV) installations to deliver both reliable electricity and useful heat with substantially lower life-cycle impacts than fossil-based alternatives (Abian et al., 2025). In conventional rooftop PV systems, module operating temperatures frequently exceed 60 °C, which reduces electrical conversion efficiency by roughly 0.4–0.5 %/°C above the 25 °C reference and accelerates material degradation, thereby shortening effective service life while leaving the incident thermal energy unutilized (Abian et al., 2025; Herrando et al., 2023). Converting such installed PV capacity into hybrid photovoltaic-thermal (PVT) collectors offers a pathway to actively cool the PV panel, stabilize performance over time, and simultaneously harvest low-temperature heat for building applications using the same aperture area and mounting infrastructure (Er-Raki et al., 2024; Herrando et al., 2023). Hence, modular polymer-based retrofit absorbers that can be mechanically attached to existing PV panels are particularly promising, because they enable stepwise upgrading of the current PV stock without full system replacement and can be tailored to typical building-scale operating conditions in European climates (Acosta-Pazmiño et al., 2025).
Life cycle assessment (LCA) research has quantified the environmental performance of both PV and PVT technologies, emphasizing global warming potential (GWP), cumulative energy demand (CED), and energy payback time (EPBT) as key indicators. A cradle-to-grave LCA study reports GWP values for a modern PV configuration with GWP emission of 20-70 kg CO_2 eq/kWh and EPBT of 1-10 years, depending on technology, irradiation level, and supply chain configuration (Abian et al., 2025). Hybrid PVT collectors enhance primary energy savings by up to 40-50% compared to standalone PV systems by leveraging combined thermal and electrical outputs, maximizing resource utilization in similar climates. This integration also reduces GWP emissions by 25-35% and shortens the EPBT to under 1.5 years versus 2-3 years for PV alone (Abian et al., 2025). Moreover, techno-economic studies have evaluated PVT systems using metrics such as levelized cost of energy (LCOE), net present value (NPV), internal rate of return (IRR), and payback time (PBT) (Hansen, 2019). LCOE accounts for CAPEX, OPEX, discount rates, and dual thermal/electrical outputs, often revealing higher initial costs for hybrids vs. standalone PV or solar thermal systems. PBT and equivalent levelized cost of heat ($LCOH_{eq}$) analyses show variability by climate, with shorter periods in high-irradiance areas and longer periods in Nordic conditions due to lower yields, mitigated by incentives such as feed-in tariffs. Sensitivity to material costs, heat transfer fluid, and heat pump integration further influences viability.
Within the PVT4EU initiative, a first-generation polymer (60% polycarbonate (PC) and 40% acrylonitrile butadiene syrene)-based retrofit collector (V1 PVT-SP) was developed and assessed using cradle-to-grave LCA and energy payback indicators, demonstrating low embodied GWP and short EPBT when applied to standard PV modules (Acosta-Pazmiño et al., 2025). Building on these results, the second-generation V2 PVT-SP aims to enhance thermal performance, robustness, and circularity through improved polymer design, while preserving the advantages of low weight and straightforward retrofitting to existing PV systems. This paper investigates the environmental and economic performance of the V2 PVT-SP collector under representative European building-scale operating conditions. A comprehensive LCA is conducted to quantify cradle-to-grave and cradle-to-cradle GWP, CED, and EPBT, complemented by an economic assessment that estimates CAPEX, $LCOH_{eq}$,

and payback time (PBT) relative to reference PV, solar thermal, and state-of-the-art PVT systems. This work aims to position novel PVT collectors within the broader context of sustainability by comparing their environmental and economic parameters against established PV, solar thermal, and hybrid technologies.

2. Methodology

This study combines life cycle assessment and techno-economic analysis to evaluate the environmental and economic performance of V2 PVT-SP. The methodology builds on the framework applied previously for V1 PVT-SP but extends it to include design changes in the second-generation prototype and an economic assessment. The LCA aims to quantify cradle-to-grave and cradle-to-cradle environmental impacts with a focus on GWP, CED, and EPBT. The functional unit is defined as 1 m^2 absorber area operating over its expected service life, delivering combined thermal and electrical energy to a reference building in Stockholm. The boundaries of this process are consistent with EN 15804 and EN 15978, covering raw material extraction, transportation, assembly, product use, and end-of-life stages. The background system uses the Ecoinvent 3.9 cut-off allocation model, ensuring consistency with earlier work on V1 PVT-SP and with comparable PVT or solar-thermal systems. The life cycle inventory (LCI) data are primarily derived from experimental work, computational fluid dynamics (CFD) work, and data collected from Ecoinvent v3.9. Global Warming Potential over a 100-year time horizon (GWP100) is quantified using the Ecoinvent ReCiPe 2016 Midpoint (H) method, whereas the CED is quantified using Ecoinvent cumulative energy demand method implemented in OpenLCA v 2.5.0 by coupling a detailed foreground model of the V2 PVT-SP retrofit unit to an Ecoinvent-based background database.

The techno-economic assessment was carried out for Stockholm and considers a PVT system (retrofitted PV panels) coupled with a ground-source heat pump and borehole thermal energy storage, designed to supply space heating, domestic hot water, and electricity to a multi-family building. Two economic indicators were evaluated: $LCOH_{eq}$ and PBT. $LCOH_{eq}$ was calculated over the project lifetime using the upfront investment (CAPEX), annual operation and maintenance costs (OPEX), performance degradation, and the discounted PBT was computed as the number of years required for the cumulative discounted net annual benefits (i.e., present values) to recover the initial CAPEX using annual cash flows and annual savings from energy generation. A project lifetime of 25 years was adopted, with a real discount rate of 1.75% and a general inflation rate for heat of 3.01%. Year-1 energy prices were set to 0.27 €/kWh for electricity and 0.10 €/kWh for heat. The system size was defined by a total PVT area of 225 m^2 (1.64 m^2 per collector, 137 collectors), and annual degradation rates of 0.50% (thermal) and 0.70% (electric) were applied. A key step in the economic model was a detailed CAPEX breakdown, including a PV panel, thermal absorber, mechanical attaching media, solar hydraulic circuit, thermal storage, inverter, and electrical components, and soft costs (installation and permits).

3. Results and discussion

This section presents the environmental and economic performance of the V2 PVT-SP retrofit collector under representative operating conditions for buildings. The results in Table 1 and Fig. 1 are discussed in terms of life-cycle impacts, energy performance, and economic indicators. The cradle-to-grave/cradle life cycle assessment shows that the environmental impact of the PVT-SP retrofit collector is primarily driven by material production and manufacturing, while the use phase yields significant avoided emissions from renewable heat and electricity generation. The GWP for cradle to cradle of the collector is estimated at 16.79 and 19.66 kg CO_2 eq/m^2 for the water-based HTF and 60% water + 40% ethylene-glycol (EG) HTF, respectively, and the breakdown is presented in Fig. 1a. The slightly higher value for the glycol configuration is primarily attributed to the upstream production of glycol and its associated energy demand. In both cases, polymer components and metallic fittings represent the largest contributors to manufacturing-stage emissions, followed by transportation and assembly processes.

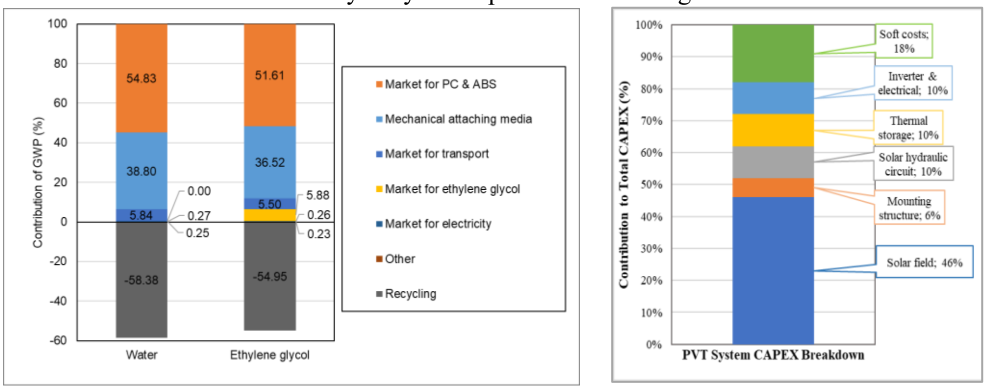
End-of-life impacts remain comparatively small due to the relatively low material mass and the assumed recycling potential of metals. The cumulative energy demand is around 0.8-0.9 GJ, resulting in an energy payback time of approximately 1.16-1.27 years. These results indicate that the system rapidly offsets its embodied energy over its lifetime when deployed in building applications such as the reference case in Stockholm. This confirms that the retrofit PVT concept provides a low-carbon solution, with further reductions possible through material optimization and improved recycling strategies.

Table 1. LCA and TEA for V2 PVT-SP using water and EG-water as HTF.

Impact categories	Water	EG+water	PVT-SP V1	Other retrofit PVT technologies	Unit
GWP (Cradle to grave)	43.67	46.55	18.62-20.80	21.62 (E. Hub & C. Solar, 2025)	kg CO_2 eq
GWP (Cradle to cradle)	16.79	19.66	-	11.22 (E. Hub & C. Solar, 2025)	kg CO_2 eq
CED	828.20	904.04	292.6-348.1	385.20 (E. Hub & C. Solar, 2025)	MJ eq
EPBT	1.16	1.27	1.04-1.44	2.0 (Ozturk et al., 2012)	Years
$LCOH_{eq}$	0.021		0.064	0.52-0.79 (IEA SHC, 2026)	€/kWh
PBT	3		5.0	7-9 (Berglund, 2019)	Years

From an investment perspective, the CAPEX of EUR 63,392.28 states that the value distribution highlights which subsystems dominate costs and therefore drive the economic performance. For the considered system configuration, the largest CAPEX share is typically associated with the solar field (collector area and installation), followed by balance-of-system components. This breakdown, as shown in Fig. 1b is useful because it directly points to the most effective cost-reduction levers: decreasing solar-field-specific costs (€/m² installed), simplifying hydraulics and integration, and reducing soft costs through standardisation and repeatable retrofit procedures. Preliminary results for the Stockholm case yield an $LCOH_{eq}$ of 0.021 €/kWh and a PBT of 3 years, suggesting that the proposed retrofit PVT solution can deliver low-cost useful heat under Nordic conditions. Notably, the calculated $LCOH_{eq}$ is well below a representative district heating price in Stockholm (0.10 €/kWh), indicating potential economic competitiveness relative to conventional heat supply options.

To compare this technology against other technologies and business-as-usual solutions, two comparisons are instructive. First, the $LCOH_{eq}$ level (0.021 €/kWh) is far below the district heating price benchmark (0.10 €/kWh), which is consistent with the short, simple PBT obtained here, since avoided heat purchases translate into high annual savings. Second, compared to typical rooftop PV economics in Sweden, payback times are commonly reported in the range of 7-9 years for businesses with good production-consumption matching, i.e., notably longer than the 2.83 years obtained for the PVT-SP heat-driven case. This suggests that, under the assumed boundary conditions and energy price context, displacing thermal energy costs in a multifamily setting can provide stronger short-term economic returns than electricity-only rooftop PV in similar regions.



(a) GWP **(b) CAPEX**

Figure 1. Contribution of (a) GWP and (b) CAPEX for the V2 PVT-SP.

4. Conclusions

This study assessed the environmental and economic performance of the V2 polymer-based PVT collector retrofit through combined life-cycle and techno-economic analyses. The results show GWP emissions of about 16.79-19.66 kg CO_2-eq per square meter and an EPBT below 2 years, confirming the low-carbon nature of the system. For the reference multi-family building case in Stockholm, the system achieves an $LCOH_{eq}$ of 0.021 €/kWh and a payback time of 3 years, indicating strong economic potential when thermal energy is effectively utilized. Overall, the findings demonstrate that retrofit PVT collectors can significantly increase solar utilization in existing buildings while delivering both environmental benefits and competitive energy costs. Future work should focus on durability assessment, manufacturing scale-up, and evaluation under different climatic and building conditions.

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