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

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### Summary

This study assesses the environmental and economic performance of a second-generation polymer-based photovoltaic-thermal retrofit collector (V2 PVT-SP) with optimised absorber design for building applications. A cradle-to-grave and cradle-to-cradle life cycle assessment combined with an economic analysis is used to quantify global warming potential, energy payback time (EPBT), levelized cost of equivalent heat ($LCOH_{eq}$), and payback time (PBT). Results show that the V2 PVT-SP achieves GWP emissions of 22-27 kg $CO_2$-eq/m$^2$ and a relatively short EPBT (below 1 year) under cradle-to-cradle boundary. For the analysed multi-family building case, it achieves $LCOH_{eq}$ of 0.01-0.02 €/kWh and a PBT of 1.2-3.4 years. When both thermal and electrical outputs are valorised, 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.*

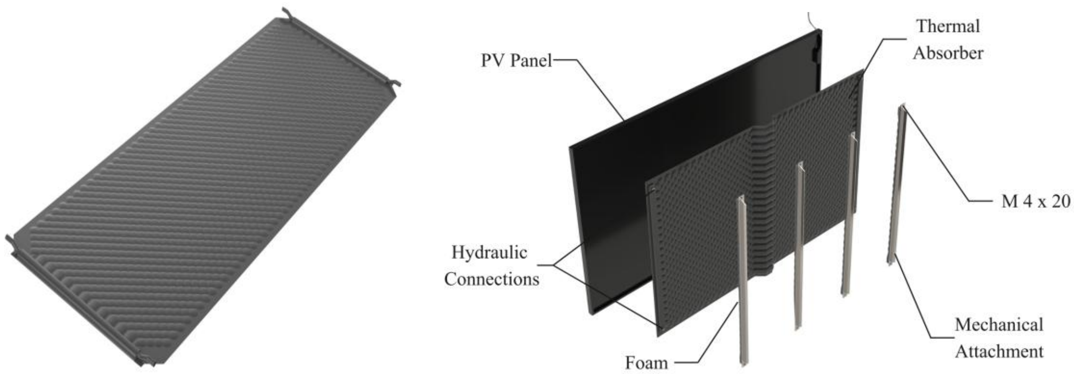
## 1. Introduction

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).

Polymer materials for PVT retrofits offer critical advantages over metallic absorbers by reducing system weight and eliminating corrosion risks, while offering a low-density, customizable alternative for low-to-moderate temperature applications. While metal collectors provide higher conductivity, polymers are preferred for ease of integration, provided that their lower thermal conductivity is acceptable (Sharma et al., 2026).

In the PVT4EU project, the design of the second-generation polymer-based photovoltaic-thermal retrofit collector (V2 PVT-SP) is modified from the first version of the same retrofit (V1 PVT-SP). The V2 PVT-SP with modified absorber design thermal absorber has the absorber area of 1465 mm x 920 mm, which corresponds to 67.4 % of the area occupied on a 2 $m^2$ PV panel, resulting in more heat transfer area compared to the V1 PVT-SP (1665 mm x 552 mm). Fig. 1 shows the computer-aided designs (CAD) for (a) V1 PVT-SP and (b) V2 PVT-SP retrofit designs. The V2 PVT-SP includes mechanical attachments, which were neglected when studying the environmental impact of V1 PVT-SP. V1 PVT-SP was developed and assessed using cradle-to-grave (C-G) life cycle assessment (LCA) and energy payback indicators, demonstrating low embodied GWP and short energy payback time (EPBT) when applied to standard PV modules (Acosta-Pazmiño et al., 2025). Building on these results, 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.

The LCA is conducted to assess the environmental performance of PVT technology emphasizing global warming potential (GWP) and EPBT as key indicators. A C-G 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).




**(a) V1 PVT-SP** **(b) V2 PVT-SP**

***Fig. 1: Thermal absorber developed by SolarPeak (PVT-SP).***

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). 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 levelized cost of heat (LCOH) 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 (Başaran and Koç, 2024).

Evaluating the economic feasibility of upgrading operational photovoltaic assets into hybrid systems requires a firm understanding of allowable capital cost thresholds. Recent techno-economic modelling by Arto Delgado et al. demonstrates that a baseline PV-to-PVT retrofit can accommodate an additional capital expenditure of up to 51% compared to the initial PV investment while maintaining a target payback period of 15 years. However, their model relies on conventional, high-density metallic collector specifications. To reduce these capital barriers and avoid structural load constraints, this study evaluates the economic and environmental trade-offs of a low-density polymer-based heat absorber retrofit (Asefi et al., 2023).

While the physical implementation of renewable energy upgrades can be direct, evaluating the concurrent technical, economic, and environmental trade-offs presents significant analytical complexity. Navigating this complexity requires structured assessment frameworks that isolate meaningful performance indicators, such as local generation cost reductions and lifecycle emission savings, to prove real-world viability to stakeholders (Ahmed et al., 2023). Accordingly, this study 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 (C-C) GWP and EPBT, complemented by an economic assessment that estimates CAPEX, equivalent levelized cost of energy ($LCOH_{eq}$), and 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

The aim of this work is to evaluate the environmental and economic performance of V2 PVT-SP retrofit absorber design. The assessment aims to quantify the life cycle impacts associated with material use, manufacturing, transportation, installation, end-of-life management and recycling of the possible components of the PVT collector. In addition, parametric analysis is conducted to assess the effect of geographical location on environmental and economic parameters. The economic assessment is also conducted to evaluate Life cycle costing (LCC), CAPEX, $LCOH_{eq}$ and PBT.

### *2.1 Life cycle assessment*

A system boundary of cradle-to-cradle approach is considered for all the scenarios considered in V2 PVT-SP. A system boundary of PVT-SP includes only the retrofitted components (absorber and mechanical attaching media). The boundary of the life cycle stages is shown in Fig. 2. It includes raw material extraction and processing, material production and manufacturing, transportation and distribution, installation and construction, operation and use stage, end of life (EoL) stage, and recycling, reuse and recovery stage. The system boundary of V2 follows the same stages as V1 except for the additional stages of mechanical attachment and the recycling/recovery/reuse stage.

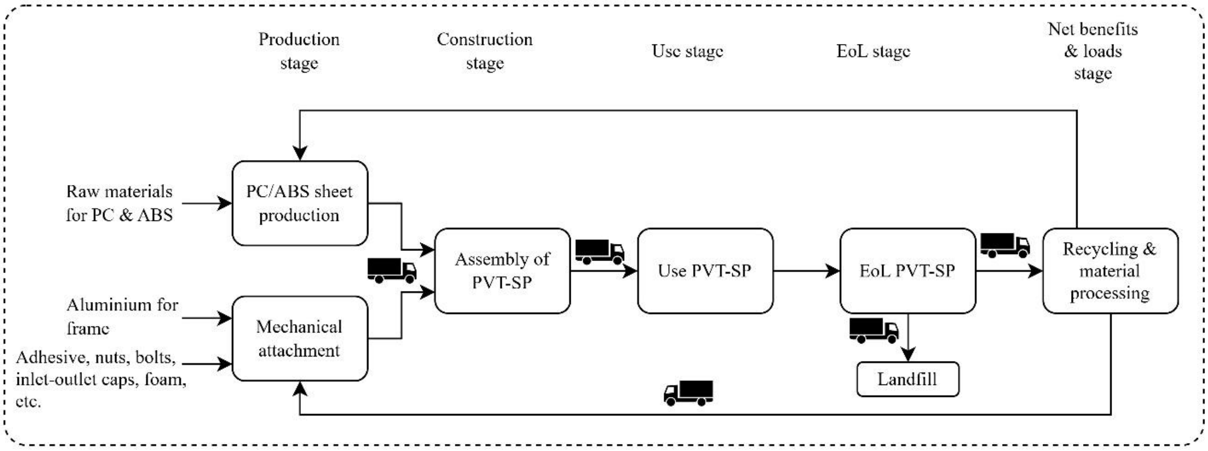



**Fig. 2: Life cycle stages and boundary of V2 PVT-SP.**

#### *2.1.1. Functional Units*

One retrofit unit of V2 PVT-SP comprises an absorber area of 1.35 $m^2$, a PV panel area of 2 $m^2$, an empty retrofit mass of 8.16 kg and heat transfer fluid (HTF) volume of 4.2 L. Tab. 1 show the description of V1 and V2 PVT-SP. The functional unit of this work is set to 1 $m^2$ absorber area.

**Tab. 1: Description of V1 and V2 PVT-SP retrofits.**

| Collector | Total weight (kg) | Absorber area ($m^2$) | HTF volume (L) |
|---|---|---|---|
| V1 PVT-SP | 2.0 | 0.93 | 2.14 |
| V2 PVT-SP | 8.16 | 1.35 | 4.2 |

#### *2.1.2. Life cycle inventory*

The LCI for PVT-SP retrofit collector is an updated dataset that reflects key design changes compared to V1, with the functional unit and system boundary defined in the previous section. The purpose of V2 is to replace the presumed LCI in V1 with the actual ones taken from the CFD and experimental work of the PVT4EU project. This improves the material choices, assembly strategies, electrical design, durability assumptions, end-of-life handling, and recycling of possible components. The transportation of all the raw materials to the manufacturing location and assembly location (Gävle) is the same as V1. The LCI for the unchanged flows and processes in V2 are kept the same as V1 and considered from the Ecoinvent database, wherever applicable. The LCI data for all PVT-SP scenarios is given in Tab. 2. This data focuses primarily on the updated retrofit components (thermal absorber and associated mechanical attachment components) developed in the project. The total V1 PVT-SP retrofit weight is 2 kg, consisting solely of the thermal absorber made from PC/ABS. No additional mechanical attachment or end-of-life recycling flows were considered in that earlier scenario. Therefore, V1 results in a minimal-material retrofit approach with limited system complexity.

The absorber of V1 was small; it was an off-the-shelf design for HVAC applications, whereas the absorber in V2 covers most of the PV panel area with improved heat transfer performance. Moreover, the V2 PVT-SP features a specialised retrofit design utilizing a modified absorber. The addition of auxiliary components as a mechanical attaching medium significantly increases the total material demand. The absorber weight increased to 6.28 kg for the V2 PVT-SP. This increase is mainly driven by the design changes in the absorber, the addition of aluminium material in the frame (1.79 kg) with a small contribution from foam-based support material (polystyrene), steel fasteners, polypropylene caps, and epoxy adhesive. These elements are essential for securely retrofitting the polymer absorber onto the existing PV system and ensuring structural stability during operation.

**Tab. 2: Key LCI parameters for V1 PVT-SP and V2 PVT-SP retrofit designs.**

| Description | V1 PVT-SP | V2 PVT-SP | Unit | Remark |
|---|---|---|---|---|
| Total retrofit weight | 2.0 | 8.16 | kg | Total weight of retrofit; empty load |
| Thermal Absorber | 2.0 | 6.28 | kg | PC/ABS |
| Heat transfer fluid volume | 2.14 | 4.20 | L | Tap water and/or ethylene glycol |
| Inlet and outlet Caps | - | 5.86 | g | Polypropylene |
| Mechanical Attaching media (Aluminium Frame) | - | 1.79 | kg | Aluminium alloy |
| Mechanical Attaching media (Foam) | - | 45.51 | g | Polystyrene foam slab |
| Nuts & bolts | - | 41.28 | g | Steel |
| Adhesive | - | 2.50 | g | Epoxy resin, liquid |
| Transportation distance: PC/ABS | 1385 | 1385 | km | Austria to Sweden |
| Transportation distance: manufacturer to assembly point | 488 | 488 | km | Within Sweden |
| Transportation distance: assembly point to use | - | 170/520/825/3772 | km | Stockholm, Gothenburg, Copenhagen and Lisbon |
| Transportation distance: Landfill | - | 100 | km | ~100 km from individual use location |
| Transportation distance: aluminium scrap | - | 1225/886/ 582/2707 | km | Aluminium scrap metal |
| Transportation distance: polymer scrap | - | 1804/1463/ 1160/2545 | km | PC/ABS scrap |
| PC/ABS recycled mass | - | 1.884 | kg | 30% PC/ABS is recycled |
| Aluminium recycled mass | - | 1.67 | kg | 93.3% aluminium is recycled |
| Mechanical attaching media | - | 1.88 | kg | Total weight |

Transportation assumptions are consistent with V1 PVT-SP for upstream processes, including PC/ABS raw material transportation from Austria to Sweden and transportation within Sweden from the manufacturer facility to the assembly location. As V1 PVT-SP was based on C-G, the EoL recycling and relevant processes were not included. However, V2 expands the system boundary by including distribution to multiple use-phase locations (Stockholm, Gothenburg, Copenhagen, and Lisbon), as well as explicit EoL transport and recycling scenarios (C-

C). These additions provide a parametric analysis with a comprehensive and geographically representative assessment compared to V1. Notably, avoided $CO_2$ emissions from heat and electricity production from PVT are excluded from this assessment. This consideration is typically reserved for analysing a complete heat generation system, whereas this work strictly targets the PVT collector and the HTF.

Recycling is mainly considered for Aluminium, and PC/ABS materials. Aluminium recycling accounts for 93.3% (Stig Tjøtta, 2024), and the PC/ABS recycling accounts for the 30% (Chiu et al., 2018). The transportation distance for aluminium and PC/ABS scrap is given in Tab. 2. Remaining components of the module were assumed to be waste and assumed to be transported to inert landfills located 100 km away from each use location. These distances are included to reflect realistic waste management logistics and their contribution to environmental impacts. The LCI of the V2 PVT-SP retrofit scenario presents a more detailed and realistic representation of the system, incorporating necessary structural components, expanded transport stages, and EoL scenarios. While this results in higher material use and system weight, it also enables a more robust and comprehensive LCA, better reflecting real-world implementation of PVT retrofit technologies.

The energy efficiency of a PVT system is determined by estimating energy payback time. The EPBT indicates the period required for a system to generate the amount of energy equivalent to that used in its production. It is calculated using the *eq. 1*. (Leda et al., 2023).

$$EPBT\ (years) = \frac{Total\ Non{-}Renewable\ CED\ (MJ)}{Annual\ Energy\ Savings\ (MJ/year)} \qquad (eq.\ 1)$$

The renewable cumulative energy demand (CED) of different scenarios is taken from the openLCA simulations and annual energy savings data is used from the ones reported in the economic section (Tab. 3). The equivalent energy is calculated using *eq. 2*.

## 2.2 Economic analysis

The economic assessment in this study is performed for the application scenarios given in Tab. 3. These scenarios cover multi-family concepts coupled with heat pumps (HPs) and boreholes, swimming pool heating, and district heating (LDH) field operation across multiple European locations. For each scenario, the annual electricity production and annual useful heat production are taken as primary energy-output inputs for the $LCOH_{eq}$ and PBT calculations.

**Tab. 3: The annual electricity and useful heat production for studied scenarios**

| PVT type | Application | Location | Annual electricity (MWh/y) | Annual useful heat (MWh/y) | Notes |
|---|---|---|---|---|---|
| PVT-SP | Multi-family + HP + borehole | Stockholm<br>Copenhagen<br>Gothenburg | 51.9<br>49.5<br>46.9 | 70.1<br>48.7<br>60.4 | 225 m² collectors; 30 apartments; SPF 2.92 |
| PVT-SP | Swimming pool heating | Lisbon, PT | 359 | 952 | 1000 m² collectors; Olympic pool; +2.1 K temperature rise |
| PVT-SP | Low District heating field | Stockholm<br>Gothenburg<br>Copenhagen<br>Lisbon | 14.264<br>14.519<br>14.98<br>24.455 | 11.431<br>11.694<br>14.006<br>39.73 | 30 panels; 62.4 m² PV & 27.3 m² absorber; T = 15°C |

### 2.2.1. Levelised Cost of Equivalent Heat

The Levelised cost of energy was considered equivalent to the $LCOH_{eq}$ by applying a conversion factor that translated the electrical energy output into an equivalent thermal energy value. This approach enabled a consistent economic comparison between the thermal and electrical outputs of the PVT systems and allowed the indicator to reflect the combined value of both energy streams within a unified heat-based metric. Since the financial feasibility of PVT systems is commonly assessed using heat-related indicators, this method was adopted to evaluate their long-term economic competitiveness relative to alternative technologies.

Two electricity-to-heat conversion approaches are used in the economic assessment, depending on the auxiliary heating strategy for each system configuration. This distinction is necessary because the economic contribution of electricity generated by the PVT system depends on how it is used to support the heat supply. In configurations where the electricity produced by the PVT system is assumed to operate an air-to-water heat pump, the electrical output is converted into equivalent thermal energy using the heat pump's coefficient of performance (COP). Based on the assumptions adopted in the analysis, a value of COP=3.0 is used. The total equivalent energy is therefore calculated as given in *eq. 2*.

$$E_{equivalent,t} = E_{thermal,t} + 3.0 \cdot E_{electrical,t} \qquad \textit{(eq. 2)}$$

In configurations where the generated electricity is assumed to directly offset electric resistance heating, the electrical output is converted on a one-to-one basis into thermal equivalent energy, assuming an efficiency of 100% for the electric heater. In this case, the total equivalent energy is expressed in *eq. 3*.

$$E_{equivalent,t} = E_{thermal,t} + E_{electrical,t} \qquad \textit{(eq. 3)}$$

These conversion approaches enable expressing the combined thermal and electrical benefits of the PVT system on a common thermal-equivalent basis. Once the equivalent annual energy output has been determined, $LCOH_{eq}$ is calculated as given in *eq. 4*.

$$LCOH_{eq} = \frac{CAPEX + \sum \frac{OPEX_t}{(1+r)^t}}{\sum \frac{E_{equivalent,t}}{(1+r)^t}} \qquad \textit{(eq. 4)}$$

Where, CAPEX is capital expenditure, corresponding to the initial investment cost, $OPEX_t$ is annual operation and maintenance cost, r is discount rate, t is year of analysis over the system lifetime, and $E_{equivalent,t}$ is annual equivalent energy output in year t, expressed in kWh.

### *2.2.2. Payback Time*

PBT represents the number of years required for the cumulative present value of the system's annual net cash flows to recover the initial capital expenditure. Annual cash flows include both the economic benefits associated with thermal and electrical energy savings and the annual operating costs. The PBT is reached when the cumulative discounted cash flow in the year k becomes equal to or greater than zero (*eq. 5*). The annual net cash flow is defined as given in *eq. 6*.

$$-CAPEX + \sum_{t=1}^{k} \frac{Net\ cash\ flow_t}{(1+r)^t} \geq 0 \qquad \textit{(eq. 5)}$$

$$Net\ cash\ flow_t = Thermal\ savings_t + Electrical\ savings_t - OPEX_t \qquad \textit{(eq. 6)}$$

When the cumulative discounted cash flow changes from negative in year k-1 to positive in year k, linear interpolation is applied between the two years to determine the PBT more precisely. This approach provides a more robust measure of economic viability than a simple payback calculation, since it explicitly accounts for the time value of money over the project lifetime.

## 3. Results and Discussion

### *3.1. Global warming potential*

The environmental impacts for V2 PVT-SP are assessed based on the methodology presented in V1 PVT-SP (Acosta-Pazmiño et al., 2025). For all the scenarios studied (given in Tab. 3), water is considered as a reference HTF for Lisbon and a mixture of 40% (volume basis) ethylene glycol with 60% (volume basis) water is considered for the Nordic locations (Stockholm, Gothenburg, and Copenhagen).

The environmental performance of V2 PVT-SP across four European deployment locations (Stockholm, Gothenburg, Copenhagen, and Lisbon) is given in Tab. 4. The LCA follows the same modular system boundary defined in the V1 (Acosta-Pazmiño et al., 2025) assessment, including production (A1-A3), construction (A4-A5), use stage (B1-B5), end-of-life stage (C1-C4), and benefits beyond the system boundary (Module D). All the results are expressed in terms of a functional unit of 1 $m^2$ absorber area.

The production stage (A1-A3) represents the dominant contributor to total lifecycle impacts across all geographic locations. The production-stage impacts accounts for 43.12 kg $CO_2$-eq GWP emissions. The higher emissions during the production stage are due to the absorber mass and manufacturing complications at the prototype stage.

Differences between deployment locations arise mainly from the transport stage (Module A4). The transport impacts increase progressively from Stockholm to Lisbon, reflecting longer transportation distance from the manufacturing location to the use location. The transport-stage impact ranges from 0.62 to 4.73 kg $CO_2$-eq GWP emissions. These results suggest that the weight of the absorber and use location from the assembly point increases the GWP emissions. Although transport impacts increase noticeably for southern European locations, they remain significantly smaller than production-stage impacts (A1). The use stage (B1) also contributes a small GWP impact (2.88 kg $CO_2$-eq) compared with the production stage. It should be noted that a 40% ethylene glycol-water mixture is considered the HTF for Nordic locations, and tap water alone is considered the HTF for the Portugal location. Therefore, negligible GWP emissions are noticed from the use stage for Lisbon.

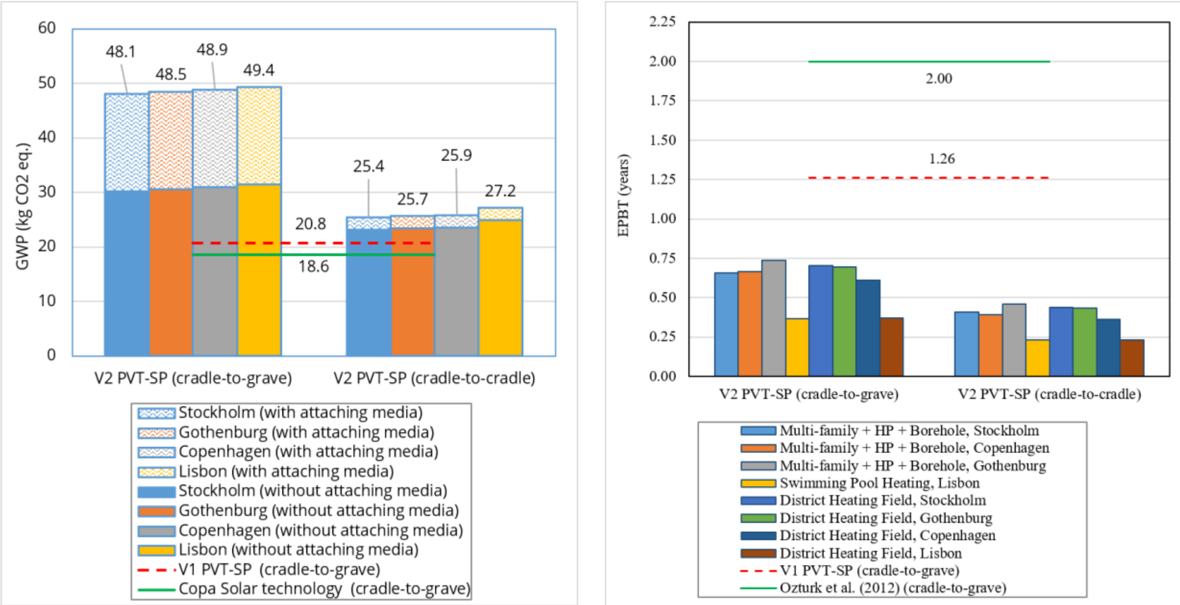
GWP associated with the EoL stage (C1-C4) also remains low for the retrofit design across all locations. Contributions from the transportation and waste-processing stages are below 0.2 kg $CO_2$-eq in all scenarios. This low impact at EoL is due to the recycling of potentially recoverable components within the system, resulting in limited emissions from the remaining materials during the landfill stage. However, the inclusion of Module D benefits beyond the system boundary significantly reduces the overall GWP of V2 PVT-SP due to its material recovery and recycling potential. Recycling credits range from –22.18 to –23 kg $CO_2$-eq for the V2 PVT-SP retrofit design. The recycled mass of possible components is given in the LCI section (see Tab. 2).

**Tab. 4: GWP (kg $CO_2$-eq) for different stages of the boundary of V2 PVT-SP retrofit absorber at different locations (FU: 1 $m^2$ absorber area).**

| Location | Stage | Stockholm | Gothenburg | Copenhagen | Lisbon |
|---|---|---|---|---|---|
| Production | A1 | 43.12 | 43.12 | 43.12 | 43.12 |
| | A2 | 1.22 | 1.22 | 1.22 | 1.22 |
| | A3 | 0.11 | 0.11 | 0.11 | 0.11 |
| Construction | A4 | 0.62 | 1.02 | 1.37 | 4.73 |
| | A5 | - | - | - | - |
| Use | B1 | 2.88 | 2.88 | 2.88 | - |
| | B2 | - | - | - | - |
| | B3 | - | - | - | - |
| | B4 | - | - | - | - |
| | B5 | - | - | - | - |
| End of life | C1 | - | - | - | - |
| | C2 | 0.1 | 0.1 | 0.1 | 0.1 |
| | C3 | 0.06 | 0.06 | 0.06 | 0.06 |
| | C4 | - | - | - | - |
| Net benefits and loads | D | -22.7 | -22.8 | -23.01 | -22.18 |

Fig. 3(a) presents the GWP comparison between the C-G and C-C performance of the V2 PVT-SP retrofit across four geographic deployment locations. These results are also compared with the results from V1 PVT-SP retrofit and other similar retrofit technologies (Copa Solar retrofit design) (E. Hub and C. Solar, 2025). The patterned bars in Fig. 3(a) also represent the GWP emissions for V2 PVT-SP with mechanical attachments across all geographic locations.

When compared with the reference Copa Solar retrofit technology (E. Hub and C. Solar, 2025), V2 PVT-SP retrofit exhibits higher GWP emissions by 55-56% under both C-G and C-C boundaries. This increase in GWP emissions is mainly due to the additional mechanical attachment required in the V2 retrofit concept, which contributes approximately 17.91 kg $CO_2$-eq per absorber area. This attachment improves compatibility with existing PV installations and enhances modular installation flexibility, but it also introduces additional material demand within the production-stage lifecycle boundary. The mechanical attachment was not considered for V1 PVT-SP, and the absorber attaching solution to the PV panel for the Copa Solar technology, is a double-sided tape (E. Hub and C. Solar, 2025) which might not be the best solution for this purpose that will allow a 25-year operation of the solution. The GWP results for V2 PVT-SP without mechanical attachments are shown as shaded bars in Fig. 3(a) for comparison with the V1 PVT-SP and Copa Solar technologies. It should be noted that a mechanical attachment is required for the absorber rather than adhesive bonding to the PV panel, due to legal considerations. Most PV module manufacturers will decline warranty liabilities after a module has been permanently altered by applying glue (Sanz et al., 2020). Moreover, this work does not consider avoided emissions from the heat and electricity produced from PVT and if they are considered, there would be a significant reduction of GWP emissions from V2 PVT-SP.




(a) Global warming potential (b) Energy payback time

**Fig. 3: Comparison of GWP and EPBT with C-G and C-C life cycle boundary with V1 PVT-SP and other technologies.**

### *3.2. Energy Payback Time*

The Energy Payback Time of the V2 PVT-SP retrofit collector is evaluated using the same methodology applied previously in V1 PVT-SP (Acosta-Pazmiño et al., 2025). The EPBT is calculated as the ratio between the cumulative energy demand (CED) from openLCA across lifecycle stages and the annual useful energy delivered by the collector system under representative application scenarios (*see eq. 1*). For each scenario considered in this work, the annual electricity production and annual useful heat production are taken as primary energy-output inputs for the EPBT calculations as reported in Tab. 3. The EPBT values are estimated for both C-G and C-C life cycle boundaries, allowing evaluation of the influence of recycling benefits beyond the system boundary on lifecycle energy performance.

Fig. 3(b) shows the EPBT results obtained for V2 PVT-SP for all considered applications and locations. As mentioned in the LCI section, tap water is considered the HTF for Portugal, and a mixture of tap water and 40% ethylene glycol is considered the HTF for Sweden and Denmark. Therefore, the EPBT results are evaluated using the respective HTF for different scenarios given in Fig. 3(b). For the multi-family building application coupled with a heat pump and borehole storage system, C-C EPBT values range from 0.39 to 0.46 years for V2 PVT-SP retrofit design across Stockholm, Copenhagen, and Gothenburg.

The V2 PVT-SP demonstrates lower EPBT values thank the V1 PVT-SP for all applications across both C-G and C-C boundaries, reflecting the improved design and performance associated with the retrofitted components of V2 PVT-SP. Despite the increase in embodied energy associated with the additional attachment system compared to V1 PVT-SP, EPBT results confirm the strong lifecycle energy performance of V2 PVT-SP. The V2 PVT-SP achieves EPBT lower by 41.45% to 70.81% compared to the V1 PVT-SP and 63.1% to 81.6% for different locations compared to a flat plate PVT collector (Ozturk et al., 2012).

### *3.3. Economic analysis*

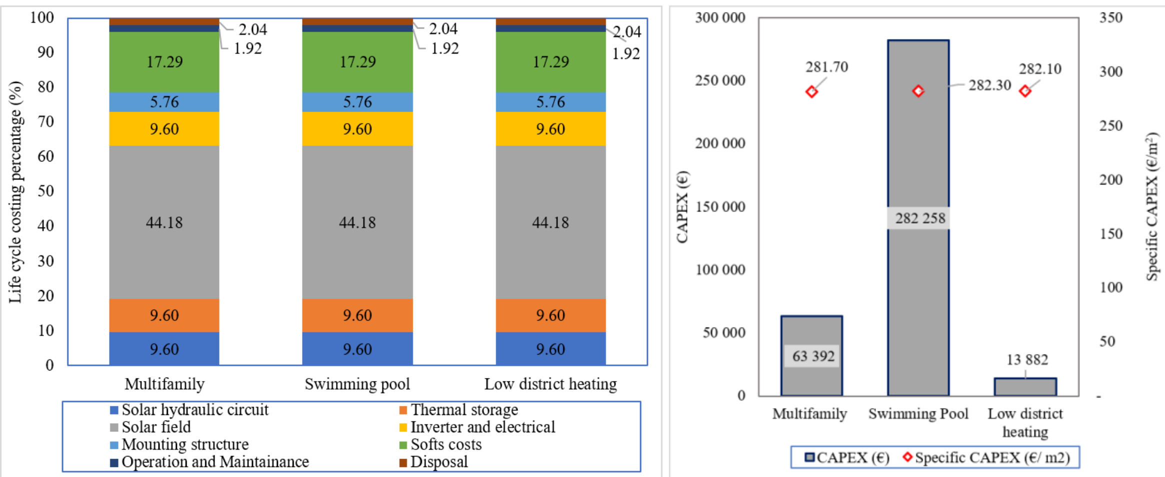
The economic results for the V2 PVT-SP scenarios are presented in terms of LCC, CAPEX, $LCOH_{eq}$ and discounted PBT for the different application scenarios given in Tab. 3. For comparison, the results can be related to those obtained for the V1 PVT-SP, for which a target PBT of 5 years and an average LCOE of 0.06 €/kWh were achieved. However, the V1 assessment was limited to single-house and apartment-building scenarios and considered only Stockholm as the location, whereas the present V2 analysis includes a wider range of application scenarios and multiple locations. To facilitate comparison, the results are discussed according to the main economic KPIs and interpreted by application group.

*3.3.1. Life cycle costing and CAPEX*

LCC is calculated as the percentage contribution of each cost component to the total system lifecycle cost. Fig. 4(a) shows the LCC percentage for different scenarios of V2 PVT-SP. This was calculated by summing the costs for all the stages (pre-project and soft costs (non-hardware expenses such as permitting, installation labour, customer acquisition, and financing), solar field costs, electrical subsystem costs, civil and mounting structure costs, peripheral works and commissioning costs, operation and maintenance costs, and disposal costs) over the entire lifetime (Ranganath and Sarkar, 2021). For all the scenarios, the CAPEX estimation was based on a component-level allocation in which the solar field was defined first and used as the reference element for deriving the total system cost. To establish this breakdown, percentage distributions reported in the ENDEF study for PVT systems for domestic hot water and space heating in buildings were used as reference values (Spörk-Dür, 2025). Based on the solar field share, the total CAPEX of the system was reconstructed, and the remaining component costs were subsequently derived according to the corresponding reference percentages.

The CAPEX and specific CAPEX values considered for the analysed scenarios are summarised in Fig. 4(b). The CAPEX values for three application cases are 63 392 € for multifamily, 282 258 € for swimming pool, and 13 882 € for low-temperature district heating when expressed as specific CAPEX, which is constant at 282 €/m$^2$ in all scenarios. This uniformity is not a physical characteristic of the systems but a direct consequence of the CAPEX estimation methodology. In the adopted approach, total CAPEX is reconstructed by applying fixed cost shares from the ENDEF reference study to the solar field area, which is the dominant cost driver. Because each scenario uses the same specific cost per square metre of PVT collector, the total CAPEX scales linearly with collector area (225 m², 1000 m², and 49.2 m², respectively), resulting in nearly identical specific CAPEX values. Consequently, scenario-specific differences in climate, operating temperature, or energy yield do not influence CAPEX, which instead reflects the underlying assumption of a fixed, component-based cost structure.

The LCC percentage is observed to be almost the same for different scenarios. The LCC structure is strongly dominated by the solar field, while the remaining components contribute moderate to minor shares. The solar field represents 44.2% of the total LCC, which confirms that PVT collector-related components remain the main economic driver of PVT systems. The solar hydraulic circuit (also known as balance of plant) and thermal storage contribute about 9.6% and the inverter and electrical subsystem account for 9.6%, followed by the soft costs, which represent 17.3% of LCC. The percentage-based LCC comparison confirms that lifecycle expenditures for all the scenarios are strongly dominated by solar field investment, followed by soft costs and thermal subsystem components. These findings indicate that the improvements in installation workflow efficiency and electrical integration could further enhance the lifecycle cost competitiveness of the PVT-SP configuration.




**(a) LCC percentage** **(b) Summary for CAPEX values**

**Fig. 4. Economic indicators for different scenarios (Number of PVTs for multifamily, swimming pool, and LDH are 137, 610 and 30, respectively).**

*3.3.2. Levelised cost of equivalent heat*

Fig. 5 presents the calculated $LCOH_{eq}$ values for all V2 PVT-SP scenarios, enabling direct comparison across different application scenarios and locations. For the multifamily configurations coupled with heat pumps, the $LCOH_{eq}$ is 0.02 €/kWh in Stockholm, Gothenburg, and Copenhagen, indicating very similar economic performance across the three scenarios. For the swimming pool applications, the heat pump-based configuration shows an $LCOH_{eq}$ of 0.01 €/kWh, while the electric resistance configuration reaches 0.02 €/kWh. This difference is mainly explained by the electricity-to-heat conversion approach adopted in the $LCOH_{eq}$ calculation, since the electricity generated by the PVT system is converted using a factor of 3 in the heat pump configuration and a factor of 1 in the electric resistance configuration. As a result, the equivalent energy output in the denominator is higher for the heat pump scenario, leading to a lower $LCOH_{eq}$ value.

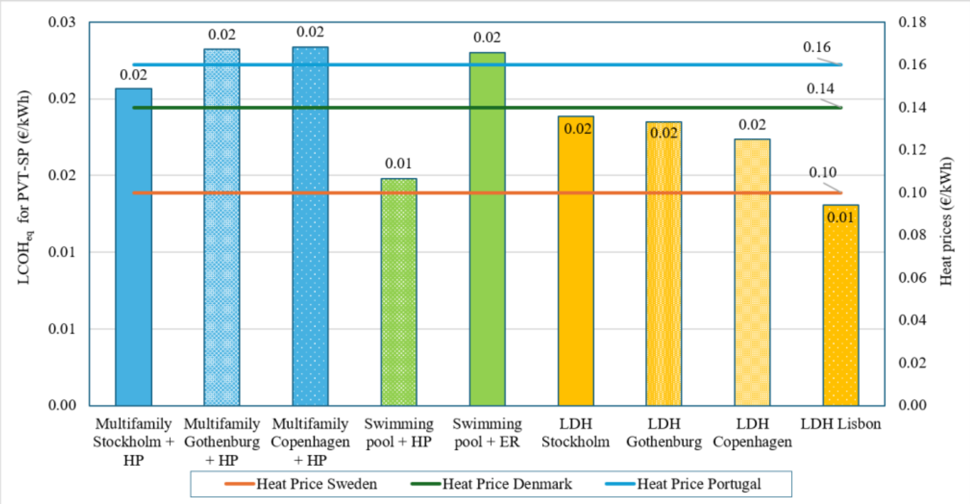



**Fig. 5: Calculated $LCOH_{eq}$ values for the V2 PVT-SP scenarios.**

For the LDH applications, the $LCOH_{eq}$ is 0.01 €/kWh in Lisbon and 0.02 €/kWh in Stockholm, Gothenburg, and Copenhagen. These results indicate that the LDH concept varies across locations, attributable not only to climate-related differences affecting energy production but also to economic factors such as inflation, the discount rate, and local energy prices. In addition, in all analysed scenarios, the calculated $LCOH_{eq}$ remains below the corresponding heat price of each location, indicating favourable economic performance under the assumptions adopted in the analysis. This outcome is further supported by the comparatively competitive cost structure of PVT technology, as the thermal absorber can be integrated at relatively low additional cost and therefore does not lead to the higher investment levels often associated with other PVT concepts.

*3.3.3. Payback time*

Fig. 6 shows the PBT obtained for the V2 PVT-SP scenarios given in Tab. 3. This indicator complements the $LCOH_{eq}$ results by showing the time required to recover the initial investment through the cumulative discounted net cash flows. For multifamily configurations coupled with heat pumps, the PBT ranges from 2.4 years in Copenhagen to 3.4 years in Gothenburg, with Stockholm at 3 years. These results indicate that all multifamily scenarios achieve investment recovery within a relatively short period compared with the V1 PVT-SP scenario, for which a 5-year PBT target was defined. Copenhagen shows the most favourable performance among the three locations. This can be attributed to the combined influence of system performance, local energy prices, and country-specific economic assumptions, which together determine the payback period in each case.

For the swimming pool applications, the PBT is 1.5 years for the heat pump configuration and 1.6 years for the electric resistance configuration. Both scenarios, therefore, exhibit very short PBT compared with the other applications analysed in the present report, as well as with the previously assessed V1 PVT-SP scenarios, confirming the strong economic attractiveness of this application. The slightly better result for the heat pump case is consistent with the previously observed lower $LCOH_{eq}$.

The V1 PVT-SP analysis corresponds to the single-family house and an apartment building, which exhibit lower specific CAPEX value. In the V1 assessment, the specific CAPEX reached 372 €/$m^2$ for the single-family house and 396.2 €/$m^2$ for the apartment building, whereas the applications analysed in the present work show values around 282 €/m$^2$. Furthermore, it should be noted that the V1 analysis was performed assuming a fixed PBT of 5 years, while the present results show considerably shorter payback periods, confirming the improved economic attractiveness of the new scenarios.

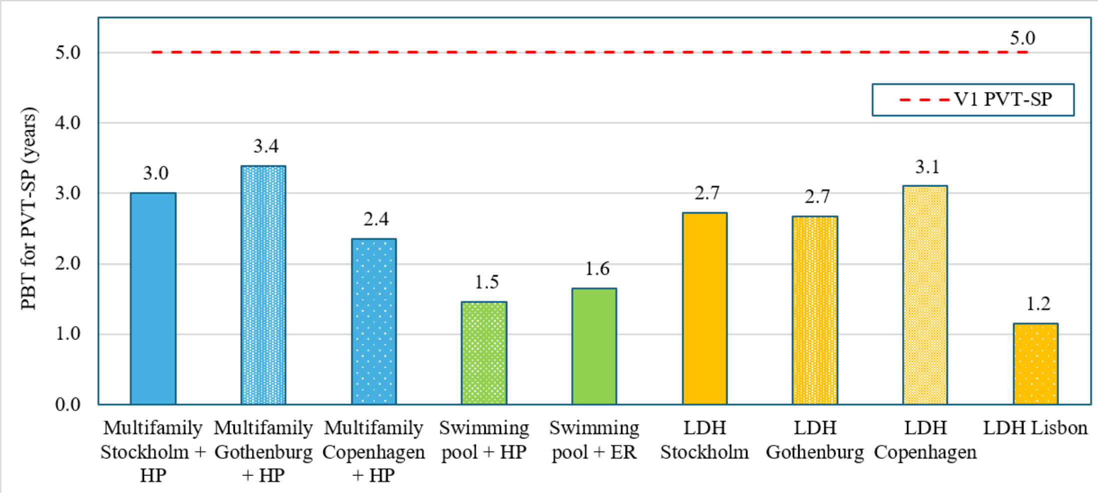



**Fig. 6: Calculated PBT values for the V2 PVT-SP scenarios.**

For the LDH applications, PBT varies more significantly across locations. The shortest PBT is obtained for Lisbon, at 1.2 years, followed by Gothenburg and Stockholm at 2.7 and 3.1 years, respectively. These results confirm that the economic performance of the LDH concept is highly dependent on local conditions and on the balance between investment cost and equivalent energy output. Overall, all analysed V2 PVT-SP scenarios achieve PBT within four years, indicating a very favourable economic outlook under the assumptions adopted in the present assessment. It is worth noting that even though district heating networks are not a common heating infrastructure in Portugal, where distributed heating systems are more prevalent, it was still considered an interesting analysis to perform within the project.

## 4. Conclusions

The environmental performance of the V2 PVT-SP retrofit collector have been evaluated using key indicators including GWP, and EPBT under both cradle-to-grave and cradle-to-cradle lifecycle boundaries, while the economic assessment was conducted to analyse the Life cycle costing, CAPEX, $LCOH_{eq}$ and PBT. Moreover, the results of V2 PVT-SP are compared with those of V1 PVT-SP, based on the C-G boundary, and with other similar retrofit technologies.

The V2 PVT-SP retrofit design achieves approximately 48-49 kg $CO_2$-eq GWP emissions under C-G life cycle boundary. The C-G GWP for V1 PVT-SP was around 21 kg $CO_2$-eq, without any mechanical attachments. When recycling benefits are included under C-C system boundary, GWP emissions decrease substantially to 25–27 kg $CO_2$-eq for V2 PVT-SP. These reductions confirm that aluminium alloy recovery from the mechanical attachment and PC/ABS absorber material recycling assumptions significantly improve environmental performance. In addition, EPBT values remained below one year across all investigated applications and locations under the C-C life cycle boundary, confirming a strong lifecycle energy performance of PVT-SP retrofit collector. However, the avoided emissions from heat and electricity production from PVT were not considered in this work, neglecting these avoided emissions underestimates their total environmental benefit. Future studies should include these avoided emissions to show a complete carbon footprint picture.

The economic assessment demonstrates that the V2 PVT-SP retrofit collector is an economically attractive solution across all investigated scenarios. The LCC structure is primarily driven by the solar field, which accounts for approximately 44% of total lifecycle costs, while soft costs and thermal subsystem components represent secondary cost contributors. The $LCOH_{eq}$ values range between 0.01 and 0.02 €/kWh across all analysed scenarios, remaining below local reference heat prices and significantly improving upon the 0.06 €/kWh for the V1 PVT-SP design. The most favourable results were obtained for swimming pool heating and low-temperature district heating applications in Lisbon, where higher solar yields contribute to lower equivalent energy costs. Payback time analysis confirms the economic viability of the V2 PVT-SP retrofit. All scenarios achieve discounted payback periods below four years, ranging from 1.2 to 3.4 years. Combined with low $LCOH_{eq}$ values, these results demonstrate the strong cost-effectiveness of the V2 PVT-SP retrofit collector.

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