Photovoltaic and Thermal for Europe

D6.1 Report containing the final KPIs and the methodology to evaluate the PVT systems' impacts

Work Package: WP6 Business models, and impact assessment towards exploitation

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Executive Summary

This report defines the Key Performance Indicators (KPIs) to be utilized in evaluating the environmental, economic, and social impacts of photovoltaic thermal (PVT) technologies within the PVT4EU project. These KPIs serve as essential tools to guide the development of PVT systems that align with the goals of sustainability, cost-efficiency, and societal benefit. The report is structured into three sections, each dedicated to a specific scope of analysis—environmental, economic, or social. Within each section, the relevant KPIs are defined, along with the methodologies required for their assessment, ensuring a comprehensive framework for evaluating the performance and impact of PVT technologies.

The environmental impact is assessed using four KPIs: the Reparability Index (REPA), Recycled Content (RC), Energy Payback Time (EPBT), and Global Warming Potential (GWP). The last two indicators are derived from a Life Cycle Assessment (LCA), enabling a comprehensive evaluation of the technology's environmental impact, from raw material extraction to end-of-life management.

The economic impact is evaluated using the Levelized Cost of Energy (LCOE) and Payback Period (PBP), ensuring that these technologies are both financially viable and competitive in the market. Given that the PVT technologies are still under development, the report describes a reverse analysis methodology. This approach identifies a targeted installation cost by working backward from pre-defined LCOE and PBP benchmarks, providing valuable guidance for cost optimization in higher technology readiness levels (TRL).

The report finally presents a comprehensive social impact assessment, employing a holistic approach that adheres to international standards and methodologies tailored to meet the project's specific requirements. By gathering insights from scientific literature alongside the established guidelines, this assessment aims to provide a detailed understanding of the stakeholders' perspectives on multifaceted impacts such as environmental, social, energy-efficiency, and economic areas.

The defined KPIs will support informed decision-making processes, advance sustainable development goals, promote recyclability and renewable energy solutions, and foster greater acceptance and awareness among society and diverse stakeholders. This report closely relates to deliverables 6.2 and 6.3, "LCA-based environmental and economic positioning of PVT4EU technologies," serving as the basis for the environmental impact assessment of the project.

1. Environmental impact

The environmental KPIs proposed in this report align with the ecodesign recommendations developed in WP3, as outlined in Deliverable 3.1, "Report on PVT4EU Technologies Ecodesign Recommendations." These KPIs are designed to evaluate how well the final product adheres to these recommendations. However, for certain ecodesign considerations, it is not feasible to develop specific indicators at the current and targeted TRLs. For instance, the report emphasizes the importance of material selection, particularly the use of natural components. However, since natural components for photovoltaic systems are still under research, evaluating the natural composition of the product is not meaningful at this time, as its inclusion would be negligible. Additionally, while incorporating recyclability into a product's design is crucial, developing an indicator for this aspect poses challenges. Recyclability involves multiple factors, including material composition and the disassembly process. Furthermore, a European project is currently underway to establish a standardized Recyclability Index for photovoltaic products, which will address these aspects comprehensively [1]. Therefore, it has been decided that recyclability will not be assessed in this project. However, we strongly recommend monitoring the development of the Recyclability Index and incorporating it into future assessments when the TRL has reached 9.

This environmental impact assessment focuses exclusively on the two technologies developed within the PVT4EU project: PVT-SP, which is a thermal absorber, and PVT-MG, which represents a complete PVT panel. This targeted approach deliberately excludes other components, such as the PV panel for PVT-SP or the heat pump, as these are not integral to the products developed under this project. By narrowing the scope of the analysis to the products themselves, we ensure a more precise evaluation of the environmental performance directly attributable to the innovations introduced in PVT-SP and PVT-MG. This approach avoids conflating the impact of external components outside the project's development focus.

1.1. Environmental indicators

This section outlines and defines the key performance indicators for evaluating the environmental impact of PVT systems within the PVT4EU project. The environmental indicators that have been chosen are the **Reparability index** (REPA), the **Recycled content** (RC), the **Global Warming Potential** (GWP), and the **Energy Payback Time** (EPBT).

1.1.1. Reparability index

The reparability of solar technology plays a crucial role in extending its lifespan, thereby contributing to reduced waste and emissions throughout its lifecycle. A high reparability index indicates how easily and effectively the system can be repaired and maintained over time. This supports sustainability by minimizing the need for premature replacements and enhances resource efficiency by allowing components to be reused or refurbished. Moreover, a strong reparability index empowers consumers with the Right to Repair, enabling them to make informed choices and actively participate in prolonging the usability of their investments in renewable energy technology.

Since January 1st, 2021, France has been the first European country to implement a repairability index for electronic devices. This index is designed to inform consumers about the repairability of products, encouraging repairs and thereby reducing waste. Between 2021 and 2023, the introduction of the index has led to a significant shift in consumer behavior: more people are opting for products with higher repairability scores. On the production side, repairability index scores have consistently improved, demonstrating that products are becoming increasingly repairable [2].

The calculation of the repairability index includes five criteria: ease of access to documentation, ease of disassembly and access, availability of tools and fasteners, availability and pricing of spare parts, and specific category-related criteria [3]. The score is given on a scale of 1 to 10, and the detail is shown in **Table 1.1**.

Table 1.1 Calculation of the Reparability Index developed in France [3]

Criterion	Sub-criterion	Score of the sub-criterion	Sub-criterion coefficient	Score of the criterion	Total score of the criteria
1. Documentation	1.1. Duration of technical support availability and advice on usage and maintenance.	../10	2	../20	../100
2. Disassembly, accessibility, tools, fasteners	2.1. Ease of disassembly of parts from list 2*	../10	1	../20	
	2.2. Required tools (list 2)	../10	0,5		
	2.3. Characteristics of the fasteners between parts from list 1** and list 2	../10	0,5		
3. Availability of spare parts	3.1. Duration of availability of spare parts from list 2	../10	1	../20	
	3.2. Duration of availability of spare parts from list 1	../10	0,5		
	3.3. Delivery time of parts	../10	0,3		

	from list 2				
	3.4. Delivery time of parts from list 1	../10	0,2		
4. Price of spare parts	4.1. Ratio of prices of spare parts from list 2 to the price of new equipment.	../10	2	../20	
5. Specific criterion	5.1.	../10	1	../20	
	5.2.	../10	0,5		
	5.3.	../10	0,5		
Index score out of 10					../10

* List 2: List of 3 to 5 components most frequently subject to breakage or failure.
** List 1: List of 10 other spare parts essential for the proper functioning of the equipment.

While originally designed for electronic devices, this index can be adapted to evaluate the reparability of solar panels, explicitly focusing on PVT technologies. A calculation tool, an Excel file, will be developed to facilitate easy evaluation of the reparability grade. This tool will be based on the French Reparability Index and will be explained in the following section, which focuses on the methodology for evaluating the impacts of PVT collectors. It is important to note that given the fact that PVT4EU is developing two distinct technologies (a heat recovery device and a PVT panel), two separate calculation tools will be created. PVT-SP will only consider a thermal absorber and its accessories, while PVT-MG will consider all the subcomponents, including the PV modules. The reparability of PVT4EU technologies will be assessed using a Reparability Index that provides a final grade out of 10.

1.1.2. Recycled content

Integrating recycled materials into solar panels holds significant potential to reduce the environmental impact of solar energy and promote a circular economy within the industry. Moreover, the increasing availability of materials like aluminium and silicon encourages incorporating these recycled materials into production.

The Recycled Content (RC) can be evaluated by assessing the proportion of recycled material used in the product. However, solar panels are composed of critical materials such as silicon and silver, whose total weight in the module is low compared to materials like glass and aluminium [4]. For instance, in a PV panel with a mass of 11.6 kg/m^2, glass accounts for 67% of the total weight, and aluminium accounts for 12%. In contrast, silicon constitutes only 2.7%, and silver makes up approximately 0.05% [5]. To enhance the use of recycled content in these critical materials, a criticality index will be applied in the calculation and is defined in equation 1. The Recycled Content is defined as follows:

$$RC\ (\%) = RR(\%) * WC(\%) * \mathrm{I} \qquad (1)$$

$RR\ (\%)$: recycled rate per component
$WC\ (\%)$: weight of the component in the module
Ic : criticality index

Table 1.2 Criticality index of materials [4]

Material	Criticality index
Silicon	3
Silver	3
Copper	2
Indium	6
Cadmium	1
Other materials	1

The term "Other materials" refers to any additional materials used in the fabrication of the technologies. For PVT-SP, polymers are considered part of the "other materials," while for PVT-MG, the frame, encapsulant, and glass are also included under this category.

1.1.3. Global Warming Potential

A Life Cycle Assessment (LCA) will also evaluate the environmental impact. This LCA assesses the product's impact across various aspects, focusing on the Global Warming Potential (GWP), also known as the carbon footprint. The GWP quantifies the potential of a product or process to contribute to global warming by comparing its greenhouse gas emissions to the warming potential of carbon dioxide (CO2). These emissions are expressed as CO2 equivalents, allowing for comparing the warming potential of different greenhouse gases, such as methane (CH4) and nitrous oxide (N2O), relative to CO2 over a specified time horizon.

GWP is the most widely used KPI for environmental impact assessment because it provides a standardized way to evaluate and compare the climate effects of different technologies, aiding in policymaking and mitigation strategies.

The methodology and results of the LCA are detailed in deliverables 6.2 and 6.3, "Life Cycle-based environmental and economic positioning of PVT4EU technologies".

1.1.4. Energy Payback Time

Calculating the overall energy used during the lifetime of solar panels allows for a better understanding of their efficiency and environmental impact. By analysing the energy consumed during the manufacturing, transportation, installation, and maintenance of solar panels, stakeholders can assess the net energy savings and the carbon footprint of the technology. This information is crucial for evaluating the sustainability and economic viability of solar technologies, helping consumers make informed decisions, guiding policy development, and driving technological improvements aimed at reducing energy consumption and enhancing the efficiency of renewable energy systems.

The energy efficiency of a renewable energy system can be determined using the Energy Payback Time (EPBT). The EPBT is the period required for a renewable energy system to generate the same amount of energy used to produce the system itself [6]. This KPI is widely used to evaluate the sustainability and environmental performance of renewable energies.

The EPBT formulation can be expressed as:

$$EPBT = (E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL})/E_{gen} \tag{2}$$

Where E_{mat} is embodied energy of raw materials processing; E_{manuf} is embodied energy demand to manufacture the system; E_{trans} is embodied for transporting PVT module from factory to installation site; E_{ins} is embodied energy demand to install the system; E_{EOL} is embodied energy for end-of-life management; E_{gen} is the annual energy generation (thermal and electric energy). A conversion factor to transform thermal to electrical energy will be used to account for the difference between both energy types. The conversion factor could be the coefficient of performance of a heat pump or an electric boiler, depending on the temperature levels produced at the outlet of the collectors.

The embodied energy associated with operation and maintenance is neglected, as it is assumed that no additional energy would be required for these phases. All energy values are expressed in kWh and will be further detailed in the methodology section.

1.2. Methodology for the environmental impact

This subsection outlines the methodology for calculating the Reparability Index and Global Warming Potential (GWP) through an Excel file and Life Cycle Assessment (LCA). Methodologies for the other KPIs are not specified here because they are more straightforward and can be determined through simpler calculations.

1.2.1. Reparability Index calculation tool

The calculation tool for the Reparability Index has been developed in the form of an Excel file, modelled after the French government's initiative to combat obsolescence [3]. The Reparability Index consists of five criteria, each accounting for 20% of the final grade, divided into sub-criteria and standards.

- The first criterion analyses the duration of technical support availability and advice on usage and maintenance over the product's lifetime to extend its end-of-life. This criterion evaluates and grades the availability of technical instruction manuals, usage instructions, and maintenance guidelines based on the duration of their availability. For solar technologies, the expected lifetime is 25 years, so points are awarded if the duration of availability exceeds 25 years.

- The second criterion evaluates the disassembly and accessibility of each component, as well as the tools required. In this section, the product's components are divided into lists (List 1 and List 2) based on their breakdown frequency. List 2 comprises 3 to 5 elements that are most frequently subject to breakage or failure, while List 1 includes 10 other spare parts essential for the proper functioning of the equipment. This criterion is divided into sub-criteria, which assess the ease of disassembly of parts from List 2 according to the number of steps required to disassemble these spare parts, the tools needed for the dismantling, and the characteristics (removability and reusability) of the fasteners used for parts in List 1 and List 2.
- The third criterion rates the availability of spare parts based on the duration of availability for parts from List 1 and List 2. Similar to the first criterion, points are awarded only if the duration exceeds 25 years. Additionally, the delivery time of spare parts is evaluated.
- The fourth criterion is established by calculating the ratio between the pre-tax price of the most expensive part in List 2 plus the average of the pre-tax prices of the other parts in List 2, divided by 2, and the pre-tax cost of the model of the equipment concerned. A grade is given according to the score.
- The last criterion is specific and changes depending on the type of product evaluated. For the heat exchanger, it has been decided to assess the ability to repair particular breakdowns, such as a puncture in the plastic sheet or a pipe leak.

Two different Excel files have been developed for each product category in the PVT4EU project. For both technologies, the scope of product reparability does not include the sensors required for integration into a heating system, as these sensors are not provided with the product. Details of the components considered in each list are available in **Table 1.3**.

Table 1.3 Description of the component in List 1 and List 2

	SolarPeak collector	Solarus PVT
List 2	Plastic sheet Hydraulic connection	PVT Receiver Junction box Cover glass Hydraulic connectors
List 1	Clamps	Reflector Frame

1.2.2. Life Cycle Assessment calculation

As part of eco-design recommendations, a comprehensive Life Cycle Assessment (LCA) is essential to evaluate the environmental impact of PVT4EU technologies from raw material extraction to end-of-life disposal. This assessment aids in identifying areas for improvement and guides eco-design decisions. ISO 14040 defines the methodology for conducting LCAs.

Deliverables 6.2 and 6.3, *"Life Cycle-based environmental and economic positioning of PVT4EU technologies" define the entire methodology for the LCA*. In this report, only the choice of the software and the database will be elaborated.

Software

Conducting LCA for complex products can be challenging due to the extensive data required for accurate calculations. However, ensuring the credibility of life cycle assessment results is crucial and necessitates using robust and reliable LCA software. Numerous software options are available on the market. Since purchasing software can entail significant expenses, selecting one that aligns well with our needs is crucial. This review aims to assist in making the right software choice.

Each paid software provides a user-friendly interface that simplifies the process of conducting a life cycle analysis. The primary differences between these software tools are the databases they include and the types of impact assessments they perform. These distinctions are detailed in **Table 1.4**.

Table 1.4 Comparison between LCA software

	SimaPro	GaBi	Mobius	OneClick	openLCA
Price	€5900/year	From $1500	€3120/year	€3720/year	Free

	SimaPro	GaBi	Mobius	OneClick	openLCA
Free trial	No	30-days	14-days	Demo version	–
LCIA methods	All	CML, EDIP, EcoIndicator, ReCiPe…	EF method, ReCiPe, CML 2001	PEF methods	All
Databases included	ecoinvent v3, national database…	ecoinvent v3, GaBi	ecoinvent v3, PEF	EPD data	None
Used for solar energy	Yes	Yes	Uncertain	Uncertain	Yes

SimaPro software stands out as the most used tool for conducting LCAs, particularly for solar energy assessments. Nevertheless, it is also the most expensive option, allowing only a one-year subscription. Therefore, it may be more advantageous to consider more cost-effective alternatives with monthly payment options, such as Mobius, or the open-source and free software openLCA.

The determination to utilize openLCA for the life cycle assessment (LCA) analysis of the PVT4EU project underscores our dedication to sustainability principles, open science, and collaborative research endeavors. As a software solution characterized by its open-source nature, openLCA promotes accessibility and inclusivity by enabling all stakeholders to employ, modify, and critically evaluate the tool without the impediments posed by proprietary licensing fees. Although the interface of openLCA may present challenges in terms of user-friendliness when compared with specific commercial alternatives, this drawback is mitigated by its open characteristics, which enhance transparency, reproducibility, and the capacity to tailor the tool to fulfil specific project requirements. This choice not only improves the credibility and transparency of our findings but also reinforces our dedication to fostering trust and collaboration among partners while contributing to the broader advancement of sustainable technology development.

Life Cycle Inventory database

Life Cycle Inventory (LCI) databases provide a detailed inventory of all natural resources consumed and substances emitted into the environment throughout the entire life cycle of a product, process, or activity. These datasets are compiled from scientific literature or aggregated industry data, and the selection of these elements directly affects the results of your LCA model. Most of the time, databases are included when purchasing software. However, for openLCA, a separate database must be purchased.

The ecoinvent database is widely recognized as an essential resource in Life Cycle Assessment (LCA). Its comprehensive data collection includes a wide array of environmental inputs and outputs associated with various products, processes, and activities. This extensive coverage enhances the rigor and reliability of LCAs, making ecoinvent an indispensable tool for practitioners. The commercial database costs 1350€ per year.

1.2.3. Embodied energy

This subsection outlines the methodology for determining the energy inputs required for the EPBT calculation.

One of the Life Cycle Assessment (LCA) outputs is the metric 'Energy resources: non-renewable, fossil,' expressed in kilograms of oil equivalent (koe). This value accounts for energy consumption across the exact system boundaries defined in the LCA. A cradle-to-grave analysis includes the energy requirements for raw material extraction, manufacturing, transportation, and end-of-life processing. Installation energy is excluded from the study, as it is assumed to be negligible and is not modelled in the software. The energy demand in koe is thus converted to kWh using the standard conversion factor, where one koe is equivalent to 11.63 kWh.

The annual energy generation, comprising thermal and electrical outputs, is derived from simulations conducted as part of WP5 of the project, where the energy generation potential of selected residential and industrial applications will be determined. Additional details regarding energy generation are provided in the subsequent economic evaluation section.

1.3. Environmental criteria

The preparatory study for Ecodesign and Energy Labelling of photovoltaic modules, conducted by the Joint Mission Group of Solar Industry Experts and Researchers, developed recommendations for policymakers in the PV industry. It also began developing environmental criteria for PV modules and inverters to compile this environmental information into a rating scale [7]. As shown in **Figure 1.1**, the results can be presented in a radar chart, providing an easy-to-read visual representation similar to the Energy Labelling Index.

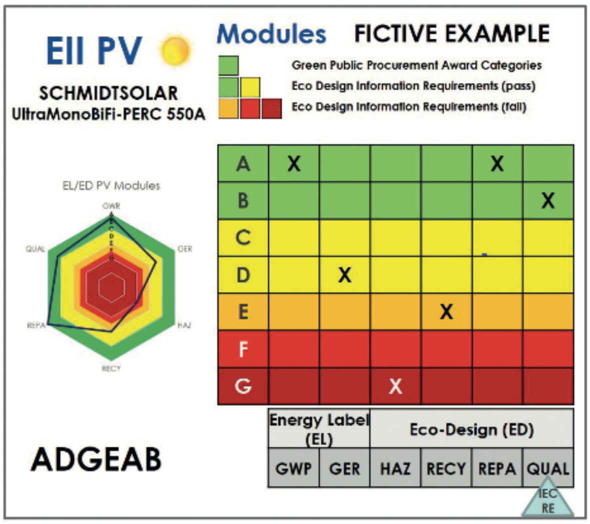

Figure 1.1 Example of an integrated Environmental Impact Index for PV Modules [5]

The rating scale facilitates easy understanding for consumers, enabling them to make informed decisions and effortlessly compare the environmental performance of different products. By providing a clear and standardized measure of environmental impact, the rating scale helps promote transparency and encourages manufacturers to adopt more sustainable practices. This initiative is crucial in guiding consumers towards more eco-friendly choices and driving the market towards higher sustainability standards.

Similarly, a grading chart has been developed for the PVT4EU technologies to assess their environmental impact. This chart, presented in **Table 1.5**, is based on the same principles, allowing for a straightforward comparison of the environmental performance of the technologies developed within the project. By adopting this system, stakeholders in the PVT4EU project can ensure that environmental considerations are consistently integrated into the decision-making process, from product development to implementation, driving the development of more sustainable technologies within the project.

Table 1.5 Recommended references for each criteria

KPI	**GWP** ***(kgCO2eq)***		**EPBT** ***(y)***		**REPA**		**RC** ***(%)***	
Rating	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
A	0	20	0	1	8	10	40	100
B	21	150	1	2	6	7,9	30	39
C	151	300	2	3	4	5,9	20	29
D	301	450	3	4	2	3,9	10	19
E	451		5		0	1,9	0	9

The grading scale for the Global Warming Potential (GWP) and the Energy Payback Time (EPBT) is based on a thorough literature review to ensure that the scale is accurate and reflective of the current market realities. However, it is important to note that the PVT technology market is still emerging, resulting in a limited number of available studies evaluating the environment impact. This is even more pronounced for the heat exchanger component, as it represents a newer technology.

For the energy labelling, the value for the GWP and the EPBT refers to the result for single equipment. The GWP of a heat exchanger could reach approximately 30 kgCO_2eq, while it ranges between 190 and 345 kgCO_2eq for a PVT collector. A GWP grade of A is assigned for values below 20 kgCO_2eq, with the rest of the scale divided so that a GWP above 450 kgCO_2eq receives a grade of E. A low EPBT is crucial for renewable energy systems to ensure the manufacturing process does not consume excessive energy. An A grade is given if the EPBT is below 1 year, with grades increasing for each additional year.

For the ecodesign grading, it has been assumed that the Reparability Index can easily reach 10. Therefore, an "A" grade of 8 out of 10 and above is assigned. The same consideration has been made for the Recyclability Index, where it is common for a product to be 100% recyclable. The rest of the scale is equally divided down to 0. For the Material Selection, a different grading system has been used because the integration of natural components in solar technology is still in its early stages. This scale reflects this by awarding an "A" grade when a product contains at least 25% natural components, with incremental grade increases for any inclusion of natural materials. The trend of integrating recycled content in PVT technology is more developed due to the recycling of aluminium, glass, and the initial stages of silicon recycling, although it remains relatively limited. Consequently, a grade of A is assigned to products with over 40% recycled content. The rest of the scale is evenly distributed down to 0%, reflecting varying levels of recycled content below this threshold.

2. Economic impact

The economic evaluation of a new technology is essential as it provides a roadmap for assessing financial viability, identifying market potential, comparing with market-ready technologies, and aligning the technology with strategic goals. By tracking and optimizing economic KPIs, manufacturers can enhance their chances of achieving successful product commercialization and long-term sustainable growth. This analysis is particularly important for ensuring that the product remains competitive in the market by meeting or exceeding industry benchmarks.

Since the PVT technologies developed in this project are still in the development phase, conventional KPIs cannot yet be fully calculated due to uncertainties around certain costs, such as capital expenses and installation costs. However, an economic analysis can still be performed through a reverse approach to guide development and ensure competitiveness. This involves setting target reference values for key KPIs based on benchmarks derived from the financial performance of existing photovoltaic and thermal technologies. By adopting this strategy, the project aims to create a product that is economically viable and competitive in the renewable energy market.

2.1. Economic indicators

The economic metrics chosen for the PVT4EU initiative encompass the **Levelized Cost of Energy (LCOE)** and the **Payback Period**, as these metrics proficiently encapsulate both the longitudinal and transient economic viability of the PVT systems. LCOE is extensively acknowledged as a robust criterion for evaluating the cost-efficiency of energy systems throughout their operational lifespan, incorporating all capital, operational, and maintenance expenditures in relation to the energy yield. This characteristic renders it an optimal selection for comparing the competitiveness of PVT technologies against other renewable and traditional energy systems. Conversely, the Payback Period confronts the issue of investment recuperation duration, which constitutes a pivotal consideration for investors and stakeholders evaluating the economic viability of embracing novel technologies. By synthesizing these two metrics, we guarantee a comprehensive assessment that contemplates both long-term sustainability and short-term financial feasibility, thereby aligning with the project's objectives of fostering economically sustainable and market-ready innovations.

2.1.1. Levelized Cost of Energy

The financial and economic viability of energy technology is regularly assessed via the Levelized Cost of Energy, LCOE [8]. This metric reflects the minimum cost per unit of energy at which it must be produced to cover all expenses over the entire duration of the project. This calculation considers all financial aspects, including initial investment, operating expenses, maintenance costs, taxes, and any subsidies or support received. The LCOE is measured in €/kWh.

The $LCOE$ $[€/kWh]$ formulation can be expressed as [9]:

$$LCOE = \frac{\sum_t (INV_t + O\&M_t) \times (1+r)^{-t}}{\sum_t E_t \times (1+r)^{-t}} \tag{3}$$

Where INV_t represents the Investment cost or Capital Expenses (CAPEX); $O\&M_t$ the Operation and Maintenance cost per year; or Operational Expenses (OPEX) t; E_t represents the Energy generation at year t, in kWh, and r the discount Rate.

The operation and maintenance (O&M) costs will be estimated to range between 0.5% and 5% of the installation cost, depending on the specific technology being assessed. For example, a heat exchanger requires less maintenance than a PVT panel, as it does not necessitate regular aperture area (receiver) cleaning.

The energy generation of a PVT system includes both electricity and heat. The LCOE for a PVT system evaluates the levelized cost of total energy produced, expressed as equivalent electricity. This consists of the actual electricity output plus the equivalent electricity derived from thermal energy output. A conversion factor of 1 is used for converting thermal energy to electricity, based on the assumption that the electricity generated could be used directly for heating in an electric resistance water heater, which operates at close to 100% efficiency hence a conversion factor of 1. Alternatively, if the heat is to be generated through a heat pump, the coefficient of performance (COP) could be considered.

For an energy source to be profitable, the LCOE must be lower than the energy price of its market or the costs associated with the competing technologies against which it is being evaluated. Compared to alternative energy sources such as wind, coal, and gas, utility-scale PV exhibits a competitive levelized cost of electricity (LCOE), pointing out the potential for sustained and robust growth in the PV industry.

2.1.2. Payback Time

The Payback Time (PBT) represents the time required to recover the initial investment in a project or product. It is a key indicator of financial viability, with shorter payback periods being more desirable as they reflect a quicker return on investment. Factors such as discount and inflation rates are typically considered [10] to ensure a more precise calculation. This is commonly referred to as the discounted payback time.

The PBT $[year]$ formulation can be expressed as [11]:

$$PBT = \frac{\ln\left(\frac{C_0 \cdot (i_F - d)}{C_S} + 1\right)}{\ln\left(\frac{1 + i_F}{1 + d}\right)} \tag{4}$$

Where C_0 [€] is the total installation cost or CAPEX; C_S $[€ \cdot year^{-1}]$ is the annual savings from thermal and electrical energy generation; i_F is the inflation rate; and d is the discount rate.

In the current state of district heating systems, heat prosumers cannot sell surplus heat back to the network, unlike electricity prosumers, who can sell excess electricity. Therefore, for this study, we assume the heat produced is utilized directly at the production site. The associated cost savings are calculated based on "avoided costs," meaning expenses saved by not purchasing electricity or heat due to self-production. The annual savings from thermal and electrical energy generation, C_S $[€ \cdot year^{-1}]$, are thus defined as:

$$C_S = E_{th} \cdot C_{th} + E_{elec} \cdot C_{elec} \tag{5}$$

Where E_{th} $[kWh \cdot year^{-1}]$ and E_{elec} $[kWh \cdot year^{-1}]$ are respectively the annual thermal and electricity energy production of the PVT installations; and C_{th} $[€ \cdot kWh^{-1}]$ and C_{elec} $[€ \cdot kWh^{-1}]$ are, respectively, the prices of purchased heat and electricity.

2.2. Methodology for the economic impact

This subsection presents the methodology used to perform the reverse analysis and outlines the approach for determining key values required for calculating economic indicators. These include parameters such as the discount rate and the annual energy generation.

2.2.1. Reverse analysis

The economic analysis in this study focuses on determining two optimal capital expenses (CAPEX) through a reverse analysis using the two previously defined KPIs: the LCOE and the PBP. The CAPEX will consider all the costs needed for the system to be capable of delivering energy (heat and electricity) to the final user. Therefore, it consists of the collectors, all the ancillary equipment, and the manpower needed to install such systems. These indicators are crucial for assessing the financial viability and market competitiveness of the proposed technology.

To guide the reverse analysis, targeted values for the LCOE and PBP will be defined based on a benchmarking process. This approach compares the economic performance of similar photovoltaic and thermal technologies to establish realistic and competitive reference points. These benchmarks ensure that the resulting product is economically viable and aligned with market expectations. By identifying these optimal CAPEX, the analysis provides a clear pathway for the cost-efficient deployment of the technology while maintaining competitiveness and financial sustainability in the renewable energy market.

2.2.2. Evaluation of economic values

The formula of the economic indicator used unknown values that are described here:

Annual energy generation

The annual energy generation of the PVT technology represents the total amount of thermal and electrical energy produced by the system over one year. For this study, the annual energy generation will be derived from simulations conducted as part of WP5. These simulations consider various operating conditions, system configurations, and applications to ensure accurate energy production estimations. By incorporating realistic energy generation data, the analysis aims to provide a reliable foundation for evaluating the economic performance of the developed PVT technologies.

Discounted and inflation rate

The discount rate and inflation rate are critical parameters for calculating economic indicators. They account for the time value of money and future economic trends. The discount rate reflects the opportunity cost of capital and is used to discount future cash flows to their present value. The inflation rate, however, adjusts for changes in purchasing power over time. Together, these rates ensure that economic calculations accurately reflect real-world financial conditions.

To maintain the realism and reliability of the analysis, the discount and inflation rates will be determined at the time of calculation through a thorough literature review. This approach allows the study to adopt the most current and contextually relevant values.

Electricity and heat price

The prices of electricity and heat are critical factors in determining the cost savings associated with PVT technology due to the displacement of conventional sources, fossil fuels, or electricity obtained through onsite energy generation.

Similar to the discount and inflation rates, electricity and heat prices will be determined later in the project to ensure the analysis reflects accurate and context-specific data.

Energy prices vary significantly by location; therefore, local databases may be used, or Eurostat could serve as a source for more globally applicable data. The study ensures that the economic evaluation remains realistic and practical by aligning these values with current market trends.

3. Social impact

A social impact assessment is a comprehensive process involving research, planning, and managing social change or consequences that may arise from policies, plans, developments, and projects. This includes evaluating both positive and negative outcomes, both intended and unintended. Local knowledge is vital to consider while making decisions, as residents are the most knowledgeable about their environment [12].

The term "social impacts" refers to the consequences of public or private actions on human societies, altering how people live, work, relate to each other, and organize to meet their needs. It also encompasses cultural impacts, such as changes to the norms, values, and beliefs that guide and shape their understanding of themselves and society [13].

To understand the concept of a social impact assessment, it is essential to explore the key indicators, frameworks, measurement tools, and current methodologies used to assess these impacts.

3.1. Social indicators

3.1.1. Factors to analyse

Several methodologies are available for quantifying and evaluating social impacts. The elements are diverse, so compiling a list of all the essential analytical components for social assessments is challenging. According to the World Bank, a thorough social evaluation typically requires analysing the following factors: sociocultural, institutional, historical, political context, social diversity and genders, institutions, rules, behaviours, stakeholders, equity of participation, and identification of social risks [14].

Nevertheless, there are more indicators to consider, such as the ones proposed by The State of Queensland: community and stakeholder participation, manpower management, accommodation, businesses, health, and community well-being. Furthermore, the United Nations Research Institute for Social Development's Platform on Sustainable Development Performance Indicators identifies six indicators for social economy entities: attendance, cooperative engagement, democratic participation, stakeholder collaboration, vulnerable people, and employment integration [15]. The comprehensive nature of social impact evaluation continues to evolve, influenced by various frameworks, institutions, and targeted outcomes.

3.1.2. Frameworks for Assessing Social Impact

Several robust frameworks are applicable for conducting social impact assessments.

Notably, the **Social Return on Investment (SROI)** framework is prevalent for analysing the efficiency of social economy institutions. This investment strategy seeks to generate financial returns while considering social, environmental, and ethical impacts [16].

The **Sustainable Livelihoods Approach (SLA)** is another key methodology to analyse and enhance the circumstances of individuals experiencing poverty and disadvantage. This participatory approach recognizes the inherent abilities and assets of all individuals, facilitating the development needed to improve their lives. SLA is a project delivery tool established in the UK [17].

The **Local Multiplier (LM3)** framework enables companies, governments, and community organizations to evaluate how their expenditures impact the local economy and benefit their communities. LM3 assists stakeholders in identifying areas requiring adjustments to optimize this impact [18].

Another valuable method is the **Logical Framework Approach (LFA)**, a systematic and analytical project planning and management strategy emphasizing goal orientation. This approach involves the active engagement of all relevant stakeholders [19].

Social Accounting and Auditing (SAA) primarily aims to demonstrate, enhance, and substantiate an organization's impact while assessing its performance concerning its social, environmental, and economic objectives and core values [20].

Finally, the **Social Impact Assessment**, developed by the International Association for Impact Assessment, emphasizes a systematic approach to understanding and managing the social effects of projects [21].

3.1.3. Software Tools for Social Impact Assessment

Currently, there are different software platforms specifically designed to facilitate the measurement of social impact. Table 3.1 provides a comparison of selected tools, their strengths, and their limitations.

The following paragraphs present an overview of some of the most effective tools available and their respective advantages and disadvantages. It is important to recognize that numerous other platforms can be utilized and customized to address the unique needs of the organizations.

These software solutions provide a wide array of features for conducting social impact assessments, thereby accommodating the diverse requirements of organizations within the social sector. Depending on the preferences and goals, it may identify one or more of these tools as particularly advantageous for the required impact assessment.

Table 3.1 Comparison between Social Impact software

Software	Brief Description	Pros	Cons	Price details
Sopact	Offers data collection, analysis, and reporting, helping organizations track their social performance and outcomes effectively.	Provides a user-friendly interface and robust support for organizations.	High price for small organizations/start-ups	$299/year
Salesforce Impact Cloud *(Cloud-based platform)*	Offer tools that provide solutions for managing social impact data, tracking outcomes, and engaging stakeholders.	Integration with other Salesforce products. Strong community and resources	It can take time to see results. High Pricing plans	$25 to $330 per user/month
Survey Monkey *(Not designed for SIA)*	It can be adapted for measuring social outcomes. It offers features for designing surveys, collecting data, and analysing results, making it a versatile tool for impact assessment.	Intuitive data Flexibility Free version to create and send surveys	May require customization Limited features for tracking outcomes	Free for surveys EXTRA: $25 user/month SUPER: $75 user/month
Google Forms	Easily create and share online forms and surveys and analyse responses in real-time.	Free to Use, User-Friendly Interface, Customizable Templates, Real-time collaboration, **Integration with Google Services**	No Offline Access: Making it difficult in developing countries Dependence on Google Account.	Free of charge

3.1.4. Data Collection Methods for Social Impact Assessment

To carry out the social impact assessment, many tools can be taken into account to collect the data, such as interviews (In-depth discussions to gather qualitative insights), observations (Direct monitoring of community interactions and project impacts), questionnaires, and surveys (Structured tools for collecting large-scale quantitative and qualitative data), data analysis with either quantitative or qualitative approaches, case studies (Detailed examinations of specific instances or examples), and evaluations (Systematic assessments of project outcomes). A survey is a broader research process that typically involves using a questionnaire as its tool for data collection. Surveys may include additional elements like sampling, distribution methods, data analysis, and interpretation [22].

3.1.5. Definition of social indicators

The primary performance social indicators proposed for the PVT4EU project consider the dimensions, objectives, and expectations related to solar technologies during this evaluation.

Employment Growth

This part of the survey is tailored to the manufacturers, installers, and designers throughout all areas involved in the production, manufacturing, designing, installation, and operation and maintenance of solar energy systems. Its purpose is to identify employment opportunities within this sector and quantify the number of working hours employees contribute.

Social Acceptance

In this area, stakeholders evaluate the information based on the information about these cutting-edge technologies to determine the feasibility of integrating these solutions into the energy market. The objective is to effectively implement these technologies to achieve more sustainable electricity and heat generation while considering their main concerns. Stakeholders are asked if they would accept implementing these PVT solar systems in their neighbourhoods.

Additionally, an evaluation of the primary concerns associated with implementing these technologies is conducted to include public perceptions across various dimensions, including environmental benefits, economic advantages, job creation, aesthetic considerations, and the reliability of the technology.

Perception Rate

Following the afore mentioned category, it is also foundational to see how households feel about these solar technologies, specifically in terms of their perceived environmental, economic, energy-efficiency, and societal impacts. Here questions about how stakeholders perceive the technologies as environmentally friendly, financially feasible, and energy efficient, and if they believe other people in the society will also accept it.

Energy Access and Affordability

Within this category, households are asked about the main preferences between the regular electric grid and microgrid, following a brief explanation of a hybrid microgrid. This section specifies how many people would like to participate in a decentralized system where everybody is willing to produce heat and electricity in their own houses generated by inexhaustible energy and therefore reduce costs and the main factors contributing to their decision. This key performance indicator (KPI) is essential for raising awareness about current trends in transitioning from non-renewable to sustainable energy sources. **Table 3.2** outlines the primary KPIs and their functional units.

Table 3.2 Social Key Performance Indicators

KPI	Functional Unit
1. Employment Growth	1. Number of people hired (e.g., engineers, designers, technicians) annually.
	2. Duration of employment (months per year).
	3. Number of hours a week of employment needed. Weekly working hours per role.
2. Social Acceptance	1. Percentage of people supporting technology implementation.
	2. Main concerns of this technology among the people.
3. Perception Rate	1. Percentage perceiving technologies as environmentally friendly, energy-efficient, or economically viable.
	2. Social acceptance within communities.
4. Energy Access and Affordability	1. Percentage preferring decentralized systems over traditional grids.
	2. Factors influencing their decision.

3.2. Methodology for the social impact

3.2.1. Framework

The framework selected for this assessment is based on the International Association of Impact Assessments' Guidance for Assessing and Managing the Social Impacts of Projects, with slight modifications to make it more suitable for the project's timelines and goals.

This approach emphasizes stakeholder engagement and the consideration of social dimensions, allowing for a nuanced understanding of the effects on local communities and societal structures.

The methodology's phases and subcategories are represented in **Figure 3.1**.

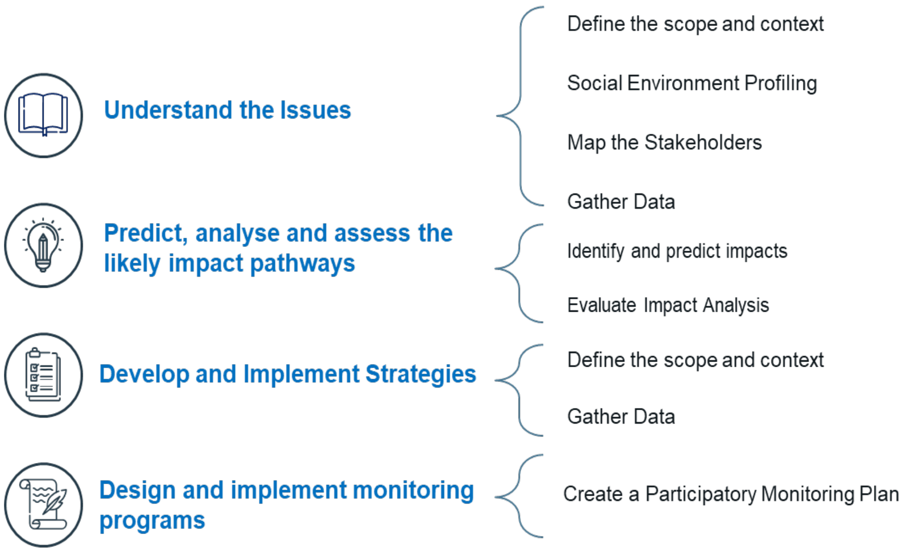

Figure 3.1 Social Impact Assessment Methodology

The methodology for assessing social impacts is divided primarily into the following phases and their sub-categorization.

3.2.2. Understand the Issues

The definition of the scope and context are evaluated in this step to understand the project's socio-economic, cultural, and political context and identify key social issues.

Define the scope and context: Identify the project's key social challenges and goals and determine the assessment's geographical and temporal boundaries.
Social Environment Profiling: the aim is to identify social factors and potential issues by doing research on scientific studies, articles, and reports and the current global acceptance of PVT technology. This will be done through an equity and inclusion analysis, which ensures that marginalised and underrepresented groups are not overlooked. It will examine how decisions, outcomes, and processes promote fairness and equal access while fostering an inclusive environment for diverse stakeholders. This will address barriers to participation, ensure fair distribution of benefits and impacts, inclusive communication, and data collection while putting in place measures for social equity such as the percentage of underrepresented groups participating in decision-making, employment rates for marginalized populations, and the impact of decentralized energy systems on rural or low-income communities.

Map the Stakeholders: Conduct a stakeholder analysis to understand the needs, interests, and potential impacts on different groups. A robust stakeholder engagement strategy also ensures all voices are heard, fostering trust and collaboration while increasing the project's legitimacy and long-term success. The plan will involve mapping stakeholders by influence and interest, identifying primary and secondary stakeholders, and designing tailored engagement activities involving focus groups, workshops, interviews, and surveys to engage stakeholders based on their preferences, continuous feedback mechanisms, and knowledge sharing.

During the project and the development of the solar collectors and PVTs, the participation of different actors is required to maintain an optimal and smooth flow. The main stakeholders are those directly interested in the project and the technologies to be developed within and throughout the program. However, there might be more secondary stakeholders that have an indirect impact on the main goals.

Gather Data: Information about the site where the project is being carried out is collected to foresee how the communities interact.

3.2.3. Predict, analyse, and assess the likely impacts.

Identify and Predict Potential Positive and Negative Impacts

In this section, a collection of social factors is done to highlight the threats, risks, problems, challenges, benefits, and opportunities that new technology brings to society. For this assessment, a SWOT analysis is conducted to understand the social impacts comprehensibly.

Evaluate the significance of each identified impact:

Under this evaluation, following the results from the main impacts in the preceding point, it is necessary to establish the significance and contribution of these cumulative impacts by the stakeholders using this technology. In addition to the already identified impacts, a Multi-Criteria Decision Analysis (MCDA) methodology is incorporated to establish the importance of such areas.

3.2.4. Develop and Implement Strategies

Mitigation Plans: Once the impact's significance is highlighted, a plan is implemented to address and identify ways of addressing potential negative consequences. The other main actions to perform here are developing and implementing ways to enhance benefits and project-related opportunities. Developing and implementing appropriate feedback and grievance mechanisms is also considered.

Ethical Considerations: Ethical considerations underpin the legitimacy of the social impact assessment, ensuring respect for human rights, cultural norms, and community values. This involves informed consent and transparency by making the stakeholders understand the goals of the project, its impacts, and their rights before participating in any study. Privacy and data protection through data protection policies such as GDPR, avoiding exploitation and coercion in the assessments while respecting all cultures and norms and promoting accountability.

3.2.5. Design and implement monitoring programs

Create a Participatory Monitoring Plan: The PVT4EU project lasts 36 months. During the first two years, the collectors are designed and constructed, and the monitoring plan is implemented just after they are finished.

Over the last year, the main project participants have re-evaluated the technology to verify whether it complies with local and regional regulations. This will complement the data obtained from questionnaires by providing in-depth insights about the stakeholders' perceptions, experiences, and attitudes toward the project. It will also allow the exploration of nuanced social impacts that may not be captured through quantitative measures.

The monitoring plan should act as a pathway for tracking impacts over time, and it should be a dynamic meeting to see if all the indicators are still relevant and appropriate, particularly considering technological advancements [23]. This will also be helpful for the market analysis developed in WP6.

3.2.6. Baseline Data Collection

Data from previous social assessments conducted from similar projects will be collected from government agencies, development banks (e.g., World Bank), NGOs, academic institutions, consulting firms, and public repositories. This baseline data will serve as a marker to compare the data obtained from this social assessment and establish a starting point to measure any social changes in the data analysis, considering also the KPIs used in such studies. Baseline indicators for employment levels, energy access, public perceptions, and social acceptance will be established, thus allowing future assessments to compare the progress with these initial metrics.

3.2.7. Data Collection

Structured surveys will be designed around key themes related to the environmental, economic, and social impacts of these PVT4EU solutions. These questionnaires will gather quantitative and qualitative data, as well as demographic information, to enhance the accuracy and depth of data analysis.

Social impact assessments can be conducted at various levels, including macro (society and region), mezzo (institutions and organizations), and micro (individuals, groups, and households). They utilize diverse social research methods such as surveys, interviews, group interviews, and case studies [24]. For this project, we are assessing micro and mezzo levels.

SIA is a learning process that involves gathering and analysing data. As a result, early hypotheses and understandings are needed to evaluate it comprehensively and avoid possible adverse effects. Surveys and questionnaires assess the social impacts and obtain stakeholder information. Google Forms is the most convenient instrument for this, as almost everybody uses a Google account, and it is easy to utilize.

Before dissemination, the proposed technologies will be outlined in a comprehensive document and distributed to the stakeholders. This document will provide them with a detailed overview of the associated benefits, including the economic and technical specifications.

Two different surveys were elaborated. One is specifically for the manufacturers, designers, and experts of PVT Technologies, and it will provide an indicator for employment growth along with their perceptions and level of acceptance of the devices. The other is tailored to citizens and other organizations to collect information on the rest of the KPIs. The answers will allow us to gain insights from both experts and citizens.

The links for the Google Forms surveys are shown in **Table 3.3**.

Table 3.3 Stakeholders Survey links and their respective performance indicators

Stakeholders	Link	Targeted KPI
Manufacturers	Manufacturers Survey	1.Employment Growth 2.Social Acceptance 3.Perception Rate 4.Energy Access and Affordability
Organizations and Citizens	Organizations and Citizens Survey	2.Social Acceptance 3.Perception Rate 4.Energy Access and Affordability

3.2.8. Data Analysis

The forthcoming inquiries will yield both quantitative and qualitative data. The percentages and overall number of respondents for the final KPIs will be obtained by evaluating all the answers; therefore, scales are assigned for each question. For additional clarity, an interpretation of this scalability for each Key Performance Indicator (KPI) and its corresponding subcategories will be provided.

In Google Forms, the types of responses encompass the following categories: short answer, paragraph, multiple choices, check boxes, drop-down, linear scale, rating, multiple-choice grid, tick box grid, date, and time.

Both surveys contain the same questions about basic information about the respondents, such as name, age, gender, location, and occupation, where they must fill the gap with their own words (short answers). This is exclusively additional information that will be helpful for the marketing strategy that will also be carried out in the project.

In addition, familiarity with and general acceptance of solar hybrid technologies will be requested for a more comprehensive insight from the respondents. The surveys associated with each indicator will yield qualitative and quantitative data.

Survey Types and Example Questions

KPI 1. Employment Growth

1.1 Type of question: Checkboxes

- "What technical backgrounds are common for workers during installation?" (Options: Engineers, designers, installers, technicians, supervisors, administrative staff)

1.2 Type of question: Multiple-Choice Grid

- "How many months would service for each role be needed annually?" (Options: <1 month to 12 months)
- "How many hours per week would each role require?" (Options: <10 to 40+ hours)

KPI 2: Social Acceptance

2.1 Type of question: Checkboxes

- "Do you support implementing solar thermal technology in your area?" (Options: Yes, fully supportive; No, not supportive; Neutral)

2.2 Type of question: Multiple-Choice Grid

- "What are your main concerns or reasons for support?" (Options: Environmental, economic, job creation, reliability, aesthetics)

KPI 3: Perception Rate

3.1 Type of Question: Multiple-Choice Grid

- "How do you rate the environmental impact of these technologies?" (Options: Extremely low to Extremely High)
- "How efficient do you find these technologies?" (Options: Not efficient to Highly Efficient)
- "How costly do you think each of them is compared to other similar configurations or those coming from fossil fuel sources? For both technologies" (Options: Very cheap to very expensive)
- "Do you think the long-term savings on energy bills outweigh the initial investment costs of installing solar thermal technology?" (options: Definitely; Yes, to some extent; No; Not sure).
- "Is it important to you to understand how the technology works?" (options: Definitely; Yes, to some extent; No; Not sure).

KPI 4: Energy Access and Affordability

4.1 Type of question: Multiple Choice

- "Do you prefer a decentralized energy system?" (Options: Yes, No, Not Sure)
- "What factors influence your decision?" (Options: Cost savings, environmental benefits, reliability, security, social aspects)

4. Conclusion

This report established the foundation for the future environmental, techno-economic, and social assessments to be conducted in deliverables D6.2, D6.3, and D6.4 of the PVT4EU project. A global approach is fundamental for large-scale projects, and therefore, the environmental, economic, and social analyses are evaluated in conjunction, thanks to a total of 10 indicators.

Environmental indicators play a pivotal role in ensuring that the development of PVT technologies minimizes their ecological footprint while contributing to global sustainability targets. By incorporating indicators such as the Reparability Index (REPA), Recycled Content (RC), Energy Payback Time (EPBT), and Global Warming Potential (GWP), the framework ensures that PVT systems are designed to prioritize resource efficiency, durability, and climate mitigation. These KPIs directly address the need for cleaner technologies and adherence to circular economy principles, supporting the transition to a low-carbon economy.

Economic performance is fundamental to the widespread adoption of PVT systems. This report highlights metrics such as the Levelized Cost of Energy (LCOE) and Payback Period (PBP) to ensure that these technologies are both financially viable and competitive in the market. By evaluating these indicators, stakeholders can make informed decisions regarding investment, pricing strategies, and long-term profitability—factors that are essential for successful commercialization. Moreover, these indicators will serve as the foundation for the forthcoming techno-economic analysis.

The social impact assessment details the stakeholder's preferences and perspectives on the technologies evaluated during this project. This will be useful for further dissemination and for the market approach to make the technology safer and allow the details provided by the surveys to be considered. Prevention is better than remediation. It is always easier to prevent something bad from happening than to deal with it after it has occurred. Therefore, the assessments are fundamental to this project to keep track of the whole process and avoid repercussions. Technological assessment is also essential when developing new technology, so public participation with the stakeholders is necessary to ensure transparency and integrate values of integrity and equality throughout the process.

In conclusion, the defined KPIs and assessments are essential to monitor progress, guide development, and ensure the PVT4EU project adheres to sustainability, market readiness, and societal alignment. This comprehensive framework will support the development and implementation of the innovative PVT technologies targeted within the project.

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