Ref. Ares(2025)2581031 - 31/03/2025

HYPERGRYD

WP5 – TRL5 demonstration in living labs and virtual labs in LEC

Task 5.6 Validation and impact assessment analysis

D5.7 Impact Analysis Study

***HYPERGRYD**. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036656*

DISCLAIMER

The opinion stated in this report reflects the opinion of the authors and not the opinion of the European Commission.

ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement № 101036656.

Project	
Project Acronym	HYPERGRYD
Project Title	Hybrid coupled networks for thermal-electric integrated Smart Energy Districts
Grant Agreement number	101036656
Call identifier	H2020-LC-GD-2020
Topic identifier	LC-GD-2-1-2020 Innovative land-based and offshore renewable energy technologies and their integration into the energy system
Funding Scheme	Research and Innovation Action
Project duration	42 months (From 1 October 2021)
Coordinator	ARCbcn
Website	http://hypergryd.eu
Deliverable	
Deliverable No.	D5.7
Deliverable title	Validation and impact assessment analysis
Description	This task aims at assessing the environmental, economic and social impacts of the HYPERGRYD solutions. The task is divided into 3 sub-tasks, assessing the three pillars of sustainability such as environmental, economic and social impacts. SubTask 5.6.1 Environmental impact study: Life Cycle Assessment (LCA): LCA is the key methodology utilised to perform the environmental study and derive the impacts of the applied technology. LCA is used to analyze given processes and performances of the systems in the Project. The study will also benefit from digital twin simulation study of the living labs as local energy markets with the following KPIs: energy bill cost, self-consumption and self-sufficiency. SubTask 5.6.2 Study on economic impacts and benefits through Life Cycle Costs Analysis (LCC): the economic dimension is another key aspect of the project and will strongly influence the implementation of the targeted technologies in the different scenarios. Life Cycle Cost analysis (LCC) of the developed solutions is performed in accordance with ISO 15686-5:2008 and to the Code of Practice suggested by SETAC "Environmental Life Cycle Costing". The LCC allows estimating the total costs (OPerating Expense, OPEX and CAPital Expenditure, CAPEX) to be incurred in the design, development, construction, production, operation, maintenance over their life cycle. Furthermore, comparison analysis of all the proposed alternatives with benchmarks will be performed in order to quantify the economic savings and potential benefits of the technical solutions. SubTask 5.6.3 Study on social and health impacts and benefits through Social Life Cycle Assessment (S-LCA): Social impacts along the entire value chain have to be also taken into account when developing or installing new technologies/solutions and services under a sustainable approach. S-LCA, based on the UNEP/SETAC guidelines, also follows a life cycle approach, but the impacts in this case are related to socio-economic aspects and comprise human rights, working conditions, health and safety, socio-economic repercussion, and so forth.
WP No.	WP5
Related task	T5.6 – Validation and impact assessment analysis
Lead Beneficiary	12 – RINA-C

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Type	R		
Dissemination	**PU** Public		
Language	English – GB		
Due	31/03/2025	**Submission date**	31/03/2025

Version	Date	Authors	Description
V.0.1	24/03/2025	Corinna Ponti, Gloria Anna Carallo and Giovanni Vaccari (RINA-C) Joel Nadal (ARCbcn)	First issue of the deliverable
V.0.2	25/03/2025	Mauro Cornaglia (ENVI)	Review of the draft version
V.0.3	26/03/2025	Stephan Preisinger (OCHSNER) Gabriele Pennello (SORTEC) Peter Platell (RANOTOR)	General Review and integration of the images of the prototype
V.0.4	28/03/2025	Corinna Ponti (RINA-C)	Implementation of the modifications requested in v0.2 and v0.3
V0.5	28/03/2025	Cintia Escandell (COMET)	Review of v0.4
V.0.6	31/03/2025	Corinna Ponti (RINA-C)	Implementation of the modifications requested in v0.5
V.0.7	31/03/2025	Michał Gliński (IMP PAN) WP Leader	Final deliverable

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Executive Summary

The goal of HYPERGRYD project is the development of a set of replicable and scalable cost effective technical solutions to allow the integration of Renewable Energy Sources (RES) with different dispatchability and intrinsic variability inside Thermal Grids as well as their link with the Electrical Grids, including the development of innovative key components, in parallel with innovative and integrated ICT services formed by a scalable suite of tools for the proper handling of the increased complexity of the systems from building to Local Energy Community (LEC) levels and beyond, and accelerate the sustainable transformation, planning and modernization of District Heating and Cooling (DHC) towards 4th and 5th generation.

HYPERGRYD also aims at developing real time management of both electrical and thermal energy flows in the coupled energy network complex, including the synergies between them. Therefore, HYPERGRYD aims at three over-arching General Objectives:

To prove Smart Energy Networks as the future of Efficient Energy Management in DHC in synergy with the Electrical Grids in LEC/Smart Cities of the future;

To define the roadmap to design and plan future DHC as well as the modernization of the existing ones in different climates and RES penetration levels toward 4th-5th generation,

To demonstrate HYPERGRYD RES-based Enabling Technologies, Smart Energy Grid Solutions empowered by new ICT tools and services as the key for this evolution.

During the project, the HYPERGRYD's solutions will be implemented across four Live-In-Labs cases in three representative climates, with special consideration to their cost effectiveness and potential replicability to finally achieve these three main objectives.

The purpose of this deliverable in short is the assessment and validation of the technologies developed in HYPERGRYD with a life-cycle thinking approach in terms of environmental, economic and social sustainability. This deliverable also received inputs from the charachterization of the performances of developed solutions and the results of simulations to explore **the optimal integration of the technologies in suitable energy districts.**

The **audience** of the present deliverable encompasses :

- investors who are focused on the financial viability and sustainability of HYPERGRYD technologies
- technology developers eager to understand the potential exploitation of the developed solutions
- energy users seeking efficient and sustainable energy solutions.

On behalf of Authors

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1 Introduction

1.1 Scope

The scope of this deliverable is the assessment and validation of the HYPERGRYD technologies by means of the life cycle thinking approach, including LCA, LCC and S-LCA. The LCA and LCC here assess the three technologies developed in the project, namely the reversible micro-CHP, the Sorption-based Thermal Energy Storage and the Modular Heat Pumps with PCM Storage including thei potential integration in selected business cases. The technologies are assessed cuilding specific business case and scenarios, assuming their potential integration in specified Live-in labs selected from the one investigated in the project.

- Business case 1: micro-CHP at Envipark
- Business case 2: Sorption-based Thermal Energy Storage at Sonnenplatz
- Business case 1: Modular Heat Pumps with PCM Storage at Sonnenplatz

The S-LCA on the other hand is performed at the technology level. The studies assumes a 25 years reference period to assess the long term sustainability and viability of the developed solutions.

1.2 Audience

The target audience for this report is extensive and diverse, encompassing various stakeholders from both the private and public sectors. This includes investors who are interested in the financial viability and sustainability of the HYPERGRYD technologies, technology developers who are keen on understanding the technical aspects and potential applications of the innovations, and energy customers who are looking for efficient and sustainable energy solutions. Additionally, the report is relevant to policymakers and regulatory bodies who play a crucial role in shaping the future of energy systems and ensuring compliance with environmental standards.

1.3 Abbreviations

AIT: Austrian Institute of Technology GMBH

AT: Austria

BFD: Block Flow Diagram

CAPEX: Capital Expenditure

CBS: Cost Breakdown Structure

CHP: Combined Heat and Power

CHP & HRES: Combined Heat and Power and High Renewable Energy Share

CNR: Consiglio Nazionale delle Ricerche

DC: District Heating

EF: Environmental Footprint

ENVIPARK: PARCO SCIENTIFICO TECNOLOGICO PER LAMBIENTE ENVIRONMENT PARK TORINO SPA

IA: Impact Assessment

IC: Impact Category

IMP PAN: INSTYTUT MASZYN PRZEPLYWOWYCH IM ROBERTA SZEWALSKIEGO POLSKIEJ AKADEMII NAUK

IT: Italy

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LCT: Life Cycle Thinking

OCHSNER : OCHSNER WARMEPUMPEN GMBH

OPEX: Operational Expenditure

PA: Performance Assessment

PSILCA: Product Social Impact Life Cycle Assessment

RINA-C: Rina Cosulting S.p.a.

R2M: R2M SOLUTION SRL

RES: Renewable Energy Sources

S-LCA: Social Life Cycle Assessment

SONNENPLATZ: SONNENPLATZ GROSSCHONAU GMBH

SORTEC: SORPTION TECHNOLOGIES GMBH

STES: Sorption Thermal Energy Storage

HPsPCM: Heat Pumps with Phase Change Materials Storage

1.4 Contributions of partners

RINA-C coordinated the work behind this deliverable and conducted the LCA and LCC analyses. ARCbcn performed the Social LCA analysys. IMP-PAN and ARC approved the general setting of the analyses. Multiple partners contributed to provide data and estimation of the technical and economic information which are the basis of the life cycle studies:

- ENVIPARK and ENCO helped in defining the business case 1. Envipark also provided energy related data on the envipark district both for the baseline and project Scenarios.
- SONNENPLATZ, CNR and AIT collaborated in defining business case 2 and 3. In particular Sonne provided energy related data and energy expenses for the baseline scenarios, while CNR and AIT built the Project Scenario for the Sorption Storage and HPs with PCM scenarios, respectevely.
- Technology developers provided technical and economic data on the HYPERGRYD technologies : RANOTOR for the CHP units, OCHSNER for the Heat Pumps with PCM storage and SORTEC for the Sorption-based Thermal Energy storage.
- R2M conducted a literature study to retrieve economic data on baseline technologies or additional technologies not developed in the project (e.g. conventional heat pumps, additional PV systems, biomass and gas boilers) or to scale-up capex and opex of HYPERGRYD technologies.

1.5 Relation to other activities

The present study is also based on quantitative and qualitative inputs from the following other tasks of the project:

- **WP2 Enabling Technologies for Smart Hybrid Grids**
- Task 2.1 Modelling and simulation of Enabling Technologies
- Task 2.2 Development and manufacturing of Enabling Technologies (M6-M30)
- Task 2.3 Lab-scale testing of the Enabling Technologies (M12-M30)
- **WP3 - ICT Modules and Simulation Tools**
- **WP5 - TRL5 demonstration in living labs and virtual labs in LEC**
- Task 5.4 Model demonstration and validation of the multi-carrier energy dynamic model at ENVI LIL
- Task 5.5 Model demonstration and validation of the HYPERGRYD ICT

The present study gives inputs to the following task :

- Task 5.3 Demonstration and validation actions of RES-based Enabling technologies

1.6 Structure

The present report is structured as follows:

- Chapter 1 briefly introduces the readers to the premises and approach of the study, as well as to the broader context of the project
- Chapter 2 briefly presents the methodology applied for the study
- Chapter 3 describes the business case and scenarios analysed in the LCA and LCC study
- Chapter 4 focuses on the Goal and Scope, Inventories and Results of the LCA, for each one of the developed business cases.
- Chapter 5 reports the Goal and Scope, Inventories and Results of the LCC, for each one of the developed business cases.
- Chapter 6 depicts the results of the S-LCA at the technology level

- Chapter 7 brings the conclusions of the study, focusing on each one of the applied methodology.
- Chapter 8: References
- Chapter 9: Appendices with additional data and technical details for each business case studied

2 Methodology

The present section discussed the methodological framework of the **sustainability assessment** throught the Life Cycle approach, declined for the three different perspectives which are applied so far to HYPERGRYD systems.

Life Cycle Thinking (LCT) approach is a comprehensive procedure used to assess the environmental (LCA), economical (LCC) and social (S-LCA) viability of a product, a service or a process during its lifecycle. This approach is gaining success in the last decades and it has been applied in several industrial sectors, defining the sustainability performances novel/existing systems. Indeed, The Life Cycle Thinking provides a holistic overview of the sustainability performances of the object of the analyses, with important suggestions on implementation points to be tackled for a better viability of products and services.

The Life Cycle approach is standardized and it is internationally ruled by several standards and guidelines for the different studies, including (ISO14044, 2006) and ILCD Handbook (JRC, 2010) for LCA, (ISO15686, 2008) and (SETAC, 2010) for LCC and (UNEP, 2020) for S-LCA.

The three analyses part of LCT follow the same methodological framework and structure, which is composed of four iterative phases (Figure 1), i.e.

1. Goal and Scope definition;
2. Life Cycle Inventory (LCI);
3. Life Cycle Impact Assessment (LCIA);
4. Interpretation of results.

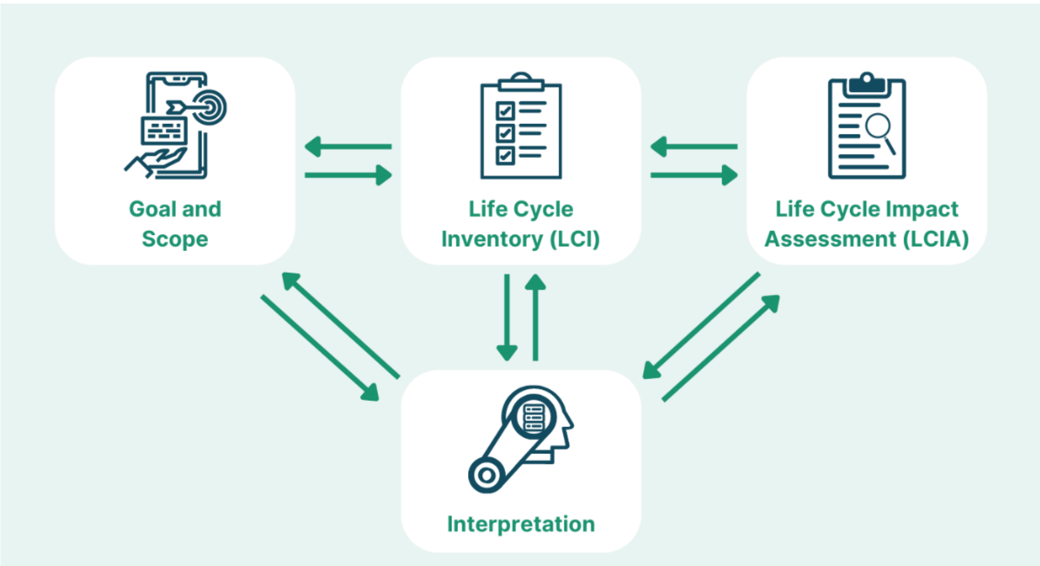

Figure 1. Life Cycle analysis iterative steps

For this reason, these procedural steps are detailed in the next paragraphs with a general, methodological approach valid for all the studies, but some peculiarities regarding the specific analysis are also provided.

Indeed, the application of the sustainability assessment methodologies to HYPERGRYD systems is discussed in Chapter 3 to 6.

2.1 Goal and Scope definition

The first step of a life cycle study is to define the **Goal and Scope**, which is crucial for the whole development of the analysis, since it clearly states and establish a list of parameters and settings which underlay the whole assessment. These methodological choices are then applied all along the study duration; for this reason, the Goal and Scope should be outlined at the beginning of all studies in a clear and precise manner, then all the subsequent steps of the analysis should be consistent with it.
In **Goal** definition, the intended application and the purpose of the study should be clarified; while **Scope** aims to define important parameters which characterise both the object of the study than the methodological procedures of the analysis. For example, the following parameters should be unambiguously stated for all the three assessments:

- the **object** of the study (i.e. a product, a process, a service);
- the **functional unit (FU)**, i.e. the metric (i.e. parameter, value, unit) which represents the reference to which the results of the assessment are reported;
- consequently, the **reference flow**, i.e. the technical description of the metric with its features required to fulfil the function expressed by the functional unit;
- the **system boundaries**, i.e. the framework (as processes, life cycle steps, etc.) within which the study is carried out;
- the **allocation procedures**, i.e. the partitioning of input and/or output flows of a process to the system under study;
- the **data quality requirement** (**DQR**), i.e. relevance of specific (primary) or generic (secondary, e.g. literature) LCA data in accordance with the goal and scope of the study;
- **assumptions** and **limitations,** if any**.**

As anticipated, besides these general parameters that are common to all the 3 life cycle studies, some peculiarities characterize each of the different analyses in the Goal and Scope definition.

For example, among the settings to be defined, for an LCA study is mandatory to declare the **methods for the impact assessment** which are considered for the analysis (e.g. EF, ReCiPe, etc.). Moreover, once methodology is selected, a clear description of the list of **impact indicators** should be provided, with their units and related impact category. On the other hand, for an LCC study it is important to define the **perspective of the study** (e.g. client, end-user or manufacturer point of view): indeed, the point of view is a key-driver of the analysis and the study is carried out taking into account the economic aspects associated to the analyzed perspective, influencing the whole assessment. Finally, for the S-LCA analysis, the definition of **stakeholders** (e.g. workers, local communities, value chain actors, consumers, society, and children) is required. Building on the stakeholder framework S-LCA, **subcategories** (e.g. access to material resources, fair competition, child labour, etc.) provide a detailed lens to evaluate specific social impacts. While stakeholders define the groups affected by a product or service, subcategories focus on measurable aspects relevant to each group, forming a structured approach to addressing social sustainability. Moreover, for S-LCA the definition the **regionality** of the products/services is important for the correct evaluation of their value-chain and social-related aspects.

Once all the methodological parameters and settings of the analyses are clearly stated, the studies enter in their second phase, related to data gathering for within the Life Cycle Inventory (LCI).

2.2 Life Cycle Inventory (LCI)

The **Life Cycle Inventory** (LCI) phase directly involves data provider in the building up of an inventory, which includes a list of flows (inputs/outputs) that characterise the object of the study. Data gathered should be consistent with the purposes of Goal and Scope (e.g. functional unit, boundary conditions, etc.) and they are related with the stages of the life cycle which are decided to be included for the specific assessment.

In order to ease the collection process, the examined system (i.e. a product, process, service) could be divided into main processes, each one including different **inputs** (e.g. energy consumption, raw materials, etc.) and **outputs** (e.g. products, waste, emissions, etc.). To this aim, a block-flow diagram (BFD) could be a useful tool to define the consequentiality of the processes, which is to be replicated in the life cycle inventory structure.

Data to be collected are different for source and purpose and they could be divided into two main categories. ***Background data*** (referring to background processes) is usually secondary data, which is retrieved from literature, databases, data banks, etc.; while ***foreground data*** (referred to foreground processes) are preferably primary data, directly collected from the data providers (e.g. product owners, product developers, end-users, etc.). To have a complete and useful inventory for a sustainability study, both categories of data should be considered, harmonized and well-referenced; however, it is worth to remark that the more primary data is used, the more accurate and reliable is the study.

Along with the necessary input/output flows, which are mandatory for the environmental assessment but they also are required for the two other studies, LCC and S-LCA also involve the use of additional categories of data. In particular, LCC requires all the information regarding the **cost** of the selected input/output flows, in form of aggregate or unitary values. At the same time, economic study also includes the operational costs (OPEX, i.e. maintenance expenses, manpower salaries, etc.) and capital expenditures (CAPEX, for the equipment), which are among the entries of the economic assessment. On the other hand, S-LCA data gathering could be structured across two levels, i.e. country and organisational levels, depending on the type, topic and source of data. In particular, ***country-level*** data are collected from databases, literature studies, data banks and could be considered generic, regionalized and aggregated for a specific value-chain; of course, their quality and recognizeness is very high. On the other hand, ***organisational-level*** inventory is more focused on the specific scenario of a company, a stakeholder group or a project-related partner, hence more direct (but also less generic and less objective) information is drawn. According to the study purposes and on the mark given by the S-LCA practitioners, the combination of the two approaches or the selection of one is applied, due to certain reasons/limitations behind the specific study.

The LCI, made of primary and secondary data, is usually referred to the functional unit of the study and it could be prepared starting from questionnaires, interviews, literature research, spreadsheets. At the end of the data collection, the inventory is reviewed and consolidated, so the process of system model development and, later on, impact assessment could start.

2.3 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is the stage of the analysis in which results are calculated and analyzed. This phase is made of two consequential steps: 1) the realization of a **model** of the object under study (based on the LCI) on a software/tool and 2) the **elaboration of impacts** related to the functional unit, which should be evaluated according to a specific methodology.

Despite the global rationale behind LCIA is common to the three assessments, it is evident that in this stage of the analysis the differences between the three studies are in the approach, methodology and calculation of results, so a specific insight about these features is given so far.

Regarding the environmental analysis, an **LCA model** is developed on a dedicated software (e.g. GaBi™, SimaPro™, etc.) with the aim to re-create the realistic process consequentiality, including all input/output flows collected in the LCI. Consequently, the software elaborates the **environmental impacts** related to one/more life cycle stages of the system considered for the study, being the effective LCIA phase. In this step, the long list of interventions typically found in practice (e.g. energy production, raw materials extraction, etc.) is aggregated into a small set of indicators, aiming to identify processes that contribute most to the overall impact. Indeed, a correlation is established between environmental interventions (e.g. raw materials extractions) and impact categories of midpoint (e.g. Climate change) and endpoint (e.g. Human health) (Margni, 2012). According to the **impact categories** selected in the LCA Goal and Scope, this correlation is expressed through a list of **indicators**, which are related to a specific aspect of environmental affection (e.g. ecotoxicity, ecosystems, resource use, etc.). In HYPERGRYD project, the impact assessment methodology selected for the LCA study is **Environmental Footprint 3.1 (EF 3.1)** (EF3.1, 2025), which encompasses 27 impact indicators related to specific impact categories. The present study is conducted on SimaPro™[1] software (Analyst v9.6.0.1), including ecoinvent[2]© v3.10 library, applying the EF 3.1 impact assessment methodology, whose complete list of indicators is presented in Table 2.1

Table 2.1: EF 3.1 impact indicators selected for the LCA study

Impact category	Unit	Acronym	Impact indicator
Acidification	[mol H+ eq]	ACIDef	Accumulated Exceedance – AE
Climate change	[kg CO_2 eq]	GWP	Radiative forcing as global warming potential – GWP100

[1] SimaPro™ website: https://simapro.com/
[2] Ecoinvent© website: https://ecoinvent.org/database/

Impact category	Unit	Acronym	Impact indicator
Climate change - Biogenic	[kg CO_2 eq]	GWP_b	Radiative forcing as global warming potential – GWP100
Climate change - Fossil	[kg CO_2 eq]	GWP_f	Radiative forcing as global warming potential – GWP100
Climate change - Land use and LU change	[kg CO_2 eq]	GWP_{lu}	Radiative forcing as global warming potential – GWP100
Ecotoxicity, freshwater - part 1	[CTUe]	$FWTOX_1$	Comparative Toxic Unit for ecosystems
Ecotoxicity, freshwater - part 2	[CTUe]	$FWTOX_2$	Comparative Toxic Unit for ecosystems
Ecotoxicity, freshwater - inorganics	[CTUe]	FWTOXi	Comparative Toxic Unit for ecosystems
Ecotoxicity, freshwater - organics - p.1	[CTUe]	$FWTOXo_1$	Comparative Toxic Unit for ecosystems
Ecotoxicity, freshwater - organics - p.2	[CTUe]	$FWTOXo_2$	Comparative Toxic Unit for ecosystems
Particulate matter	[disease incidencies]	PMAT	Impact on human health
Eutrophication, marine	[kg N eq]	MWEUT	Fraction of nutrients reaching marine end compartment
Eutrophication, freshwater	[kg P eq]	FWEUT	Fraction of nutrients reaching freshwater end compartment
Eutrophication, terrestrial	[mol N eq]	TEUT	Accumulated Exceedance – AE
Human toxicity, cancer	[CTUh]	HTOXc	Comparative Toxic Unit for humans
Human toxicity, cancer - inorganics	[CTUh]	$HTOXc_i$	Comparative Toxic Unit for humans
Human toxicity, cancer - organics	[CTUh]	$HTOXc_o$	Comparative Toxic Unit for humans
Human toxicity, non-cancer	[CTUh]	HTOXnc	Comparative Toxic Unit for humans
Human toxicity, non-cancer - inorganics	[CTUh]	$HTOXnc_i$	Comparative Toxic Unit for humans
Human toxicity, non-cancer - organics	[CTUh]	$HTOXnc_o$	Comparative Toxic Unit for humans
Ionising radiation	[kBq U_{235} eq]	IORAD	Human exposure efficiency relative to U_{235}
Land use	[Pt]	LUP	Soil quality index[3]

[3] Representing the aggregated impact of land use on: Biotic production; Erosion resistance; Mechanical filtration; Groundwater replenishment.

Impact category	Unit	Acronym	Impact indicator
Ozone depletion]	[kg CFC_{11} eq	ODEPL	Ozone Depletion Potential – ODP
Photochemical ozone formation	[kg NMVOC eq]	PCHEM	Tropospheric ozone concentration increase
Resource use, fossils	[MJ]	ADEPLf	Abiotic resource depletion, fossil fuels – ADP-fossil
Resource use, minerals and metals	[kg Sb eq]	ADEPLmu	Abiotic resource depletion, fossil fuels – ADP-ultimate reserves
Water use	[m^3 depriv.]	WDEPL	Weighted user deprivation potential

Among these indicators, a selection is applied in order to consider the most relevant for the detailed discussion of results provided in chapter 0: indeed, these 15 indicators (yellow-highligthened) are better correlated with the topic of the analysis (i.e. energy production systems); thus, results of the LCA will be referenced to this selection indicators. Anyway, for a complete overview of the LCA analysis, complete result tables including whole EF 3.1 list of indicators are reported in the Annex section (chapter 9) of this document.

Moreover, in line with (ISO14044, 2006) regulations, the LCIA should include the following calculation actions:

- *Classification*: organisation and combination of LCIA results into impact categories. This action is mandatory;
- *Characterization*: LCIA results are categorized and transformed into impacts, according to a specific methodology selected. This action is mandatory;
- *Normalization*: calculation of the magnitude of category indicator results relative to reference information. This action is optional;
- *Weighing*: conversion of indicator results from different impact categories by using numerical factors. This action is optional.

In the present LCA study, only classification and characterization are applied during LCIA.

Regarding LCC impact assessment, the LCC model is built starting from the inventory analysis, then all costs for each phase of the life cycle should be quantified and related to the functional unit. Thus, cost contributions to the total cost of the analyzed product should be evaluated: the analysis, indeed, may include hotspot identification, net present value (NPV) analysis, calculation of payback period and break-even point as well as sensitivity analysis, depending on the premises defined in the Goal and Scope. In particular, hotspot identification is enabled by a **Cost Breakdown Structure** (CBS), an essential tool which provides a hierarchical framework for categorizing and organising all cost elements associated with a product, system, or structure over its life cycle. CBS helps in understanding the distribution of costs and identifying key-cost drivers.

Finally, the impact assessment in S-LCA starts with the modeling of the system on a dedicated software (e.g. openLCA), using the available libraries or databases (e.g. PSILCA) which correlate the energy and materials flows with cost data. Through an approach similar to LCA correlation, meaningful social performance indicators are put in relation with the **economical value-chain** of input/output flows at country level, expressing the **potential social effects** across the product's lifecycle. From the organisational-level approach, instead, data the inventory sources is processed and transformed into a standardised reference scale (e.g. 1 to 6 ranking or similar), defining the worst and best performances. Then, potential classification, characterization, conversion and, sometimes, normalising and weighting of these impacts are applied to understand their significance in relation to the selected stakeholders. For the present study, a combination of **country- and organisational-level** approaches is applied to the S-LCA analysis, which ensures both broad contextual relevance and precise organizational applicability, addressing potential gaps between general indicators and the unique characteristics of individual organizations.

In conclusion, all the impact assessments could include:

- a *hotspot* (or *contributional*) analysis, i.e. a breakdown evaluation of the most relevant driver in the global impacts,
- a *sensitivity* analysis, i.e. a focused study where some parameters are tuned in order to evaluate their influence on the global impacts.

The obtained results are analyzed and interpreted in the final part of the sustainability study.

2.4 Interpretation of results

The last phase of the impact assessment is the **interpretation of results** obtained by LCIA. The analysis aims to review the results in light of identification, quantification, checking, and validation of information obtained along the study. According to (ISO14044, 2006) standards, the interpretation should consider:

- *Identification*: results should be organized outlining the significant issues, consistently with the goal and scope definition;
- *Evaluation*: results of the evaluation should be presented through a clear and understandable view, which is specific for the type of product analyzed/study performed;
- *Conclusions, limitations, and recommendations*: in the end, the study should draw conclusions, identify limitations, and make recommendations for the LCA addressees.

This phase often draw a set of lessons learnt for improving environmental, economic or social performance, which may involve changes in materials selection, production process, use habits, providers location, sourcing practices, working conditions, or community engagement strategies. By providing a comprehensive analysis and actionable insights, the interpretation phase empowers the stakeholders to implement more sustainable practices.

3 Description of the analysed Business cases for LCA & LCC

In this study the LCA and the LCC methodology are executed to assess the environmental and economic sustainability of the technologies developed in the HYPERGRYD project considering their potential application in the Envipark and Sonneplatz districts, which are two of the LiLs (Live-in labs) studied in the broader scope of the project. The coupling of each technology with the suitable LiL constitutes the **Business case** for the assessments, which sets the geographical and energy boundaries for the analyses.

3.1 Business case 1: Reversible micro-CHP with steam engine and steam buffer - Envipark

The HYPERGRYD technology studied in this use case is the **Reversible CHP with Steam Engine**. This Combined Heat and Power (CHP) system operates in a reversible mode, i.e. it can switch between electricity and thermal energy production based on demand. The steam engine-based configuration enhances efficiency by recovering and exploiting waste heat, reducing energy waste and emissions. The following figure shows a picture of the prototype developed by Ranotor.

Figure 2: the CHP unit developed by RANOTOR

In this study the CHP is virtually applied to the **Envipark District**, located in Turin, Italy. Envipark is an Innovation accelerator hub aiming to partner with enterprises engaged in implementing eco-cleaner and eco-efficient solutions. Shareholders are local institutions and utility companies operating in the energy and cleantech sector. In particular, the complex consists of n.10 buildings, including n.5 office buildings, n.4 laboratories, and a canteen, all interconnected by an internal distribution network for electricity, heating, and cooling.

The assessments adopt a **comparative approach** between three Scenarios: the **Baseline** reflects the current situation at Envipark, in terms of energy assets and energy consumptions, the **CHPs Scenario** considers the potential application of a suitable number of units, while the **CHPs & HRES Scenario** combines the CHPs with a high renewable energy share.

Figure 3: Envipark Technological Park (Environment Park, 2025)

The following table briefly describes the energy assets in the three analysed Scenarios. Additionally numerical details are provided in the LCA and LCC inventory tables in the respective paragraph.

Table 3.1 Details on Energy Supply and Production assets for the different Scenarios analysed in Business case 1.

Scenario	Energy supply and production
Baseline	Heating: provided by the DH (District Heating) network of the City of Turin to the internal heating grid through two heat exchangers. Solar Energy is produced by a PV Totem (16 kW) only for self-consumption. Urban mini-hydroelectric plant (480 kW) producing 1,700 MWh electricity currently sold to the national grid.
CHPs	As in the baseline Scenario, additionally integrating 3 CHPs units with the technical features of the one developed in the project (5kWe 20kWth)
CHP & HRES	Ad in the CHPs Scenario, plus 120 kW PV and using the mini-hydroelectric plant just for self-consumption. In this Scenario the electricity provided by the national gris is drastically reduced.

3.2 Business case 2: Sorption Storage - Sonnenplatz

The assessed HYPERGRYD technology is the **Sorption-based Thermal Energy Storage (STES)**. The STES uses adsorption and desorption processes to store and release heat with minimal energy losses. This technology enhances seasonal energy storage capacity, contributing to greater flexibility in district heating and cooling networks. The developed technology as itw as installed at KEZO Lab (the third LiL of the project, not assessed in the present study) is shown in the next Figure.

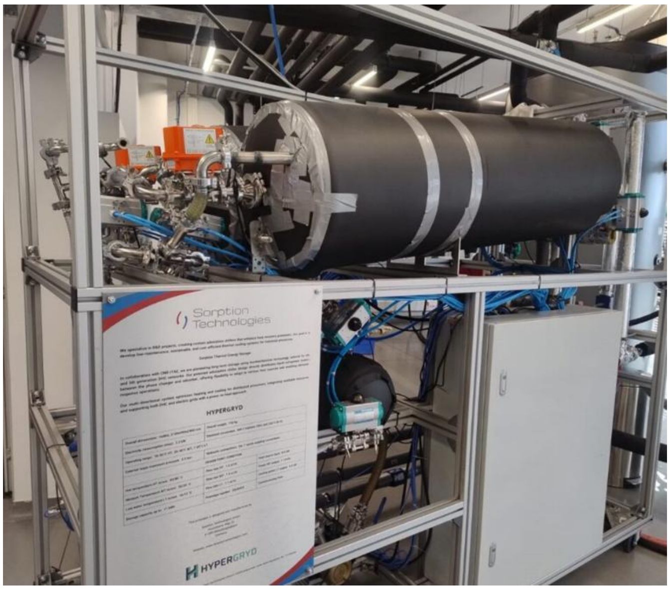

Figure 4: Installation of the STES system at KEZO Lab

The study investigates the potential application of the system in the **Sonnenplatz District**, located in Großschönau, Austria. It is an energy citizenship example with the aim of popularising energy-efficient and sustainable construction and renovation. Customers are residential houses, and commercial and public buildings.

Figure 5: Sonnenplatz, GrossShoenau district (Sonnenplatz, 2025)

Next table reports some information on the destination of each building included in the district, as well as the net and gross floor area.

Table 3.2: Technical information on the Sonnenplatz district

Building N°	GFA of heated area in (m²)	NFA of heated area (m²)	type of building	households	residents	employees	average daily visitors
1.0	683	478	public			4	30
2.0	441	309	public			2	10
3.0	674	472	public			10	60
4.0	2349	1.644	public/commercial			66	110
5.0	160	112	public			4	
6.0	338	237	commercial	1	1	3	40
7.0	1610	1.127	hotel	1	2	2	14
8.0	2292	1.604	office, exhibition			7	136
9.0	226	158	residential	1	1		
10.0	246	172	residential	1	4		
11.0	193	135	residential	1	2		
12.0	408	286	residential/farm	2	6		
13.0	368	258	residential	1	4		
14.0	1.508	1.056	industrial	1	3	6	
15.0	380	266	public	1	1		2
16.0	160	112	public				6
17.0	303	212	residential	2	4		
18.0	187	131	residential	1	2		
19.0	254	178	residential	2	4		
20.0	172	120	residential	1	1		
21.0	212	148	residential	1	1		
22.0	1.309	916	residential	15	24		
23.0	415	291	residential	5	7		
24.0	193	135	residential	1	1		

In this business case the system boundaries are restricted to buildings **7,8,10,11,12,13** because for the other buildings data on the energy production and consumptions with a minute resolution were not available and were needed to perform simulation on the potential adoption of the STES System. A comparative perspective is adopted between a **Baseline Scenario** and the **STES Scenario.** The two are described in the table below.

Table 3.3: Details on Energy Supply and Production assets for the different Scenarios analysed in Business case 2.

Scenario	Energy supply and production
Baseline	Distant heating system of the Municipality of Großschönau based on biomass as heat source Solar Energy is produced by multiple PV plants, which are partially employed for self consumptions and excess energy sold to the grid.

	The heat generation system includes, besides a oil boiler, a back-up heater, a heat pump and a solar heater. Urban mini-hydroelectric plant (480 kW) producing 1,700 MWh electricity currently sold to the national grid.
STES	As in the baseline Scenario, additionally integrating a **STES system** with a total storing capacity of 750 kWh. The STES system is charged employing a series of **high temperature heat pumps** (250 kW) which in turns are powered by the excess of electricity from the PV plants present on site.

3.3 Business case 3: Heat Pump with PCM storage - Sonnenplatz

This business case develops the study of the **Modular Reversible Heat Pumps with Short-Term PCM Storage (HPsPCM).** These heat pumps can operate in both heating and cooling modes, adapting to fluctuating thermal demands. The integration of Phase Change Material (PCM) storage enables efficient short-term thermal energy retention, improving energy management and reducing peak loads.

Figure 6: The modular Heat Pump developed by OCHSNER.

Their are virtually applied to the Sonnenplatz to completely replace the biomass and oil boilers in the heat providing function. In this case the system boundary is fixed at the **whole district level.**

The next tables described the main energy supply and production assets in the business case in the baseline and project scenarios.

Table 3.4: Details on Energy Supply and Production assets for the different Scenarios analysed in Business case 3

Scenario	Energy supply and production
Baseline	As in business case 2.
HPsPCM	The heat consumption from both biomass and the oil-fired boiler are replaced by the HYPERGRYD Heat Pumps with PCM storage. HYPERGRYD HP heating capacity is 1.25 kW under ideal conditions but is reduced to 1.1 kW to account for operational inefficiencies. Each set of 8 HYPERGRYD HPs (10 kW) is paired with 4 latent storage units (PCM RT55), with a total capacity of 2.4 kWh. In total 26 sets for a total of 263 kW are applied.

4 LCA of HYPERGRYD technologies

This chapter reports the Life Cycle Assessment (LCA) applied to the three business cases and Scenarios defined within the HYPERGRYD project. Premises, inventory and results are discussed below per each business case. The results are here shown in aggregated form, additional details on the seasonal variation for each business case can be accessed in the table in Appendix 9.1.1, 9.1.2 and 9.1.3.

4.1 Reversible micro-CHP with steam engine and steam buffer

4.1.1 Goal and scope

Goal: The goal of this LCA study is to evaluate the environmental benefits and burdens arising from the implementation of the micro-CHP units, and eventually a higher share of renewable energy in the Envipark district. A comparative perspective is adopted between a Baseline and the two project Scenarios (CHPs Scenario and CHP & HRES Scenario).

System Boundaries: The LCA focuses exclusively on the use phase of the district's energy consumption. This includes all activities related to the generation, distribution, and consumption of energy within the district.

Functional Unit: The functional unit for this assessment is defined as the total energy consumed by the district over a 25-year period.

Temporal Scope: The assessment will cover a 25-year timeframe, from 2030 to 2055.

Geographical Scope: The geographical scope is limited to the boundaries of the district under study as described in paragraph 3.1.

Assumptions and Limitations: The assessment assumes that the energy consumption patterns remain unchanged over the 25-year period, as well as the energy performance of the technologies where no degradation factors have been applied.

The energy flows which would remain unchanged upon the introduction of the new technology are considered a cut-off.

4.1.2 Inventories

This paragraph reports the LCA Inventory tables for the Business case 1 for the Baseline, CHPs and CHPs & HRES scenarios. The quantification of the seasonal flows for the three Scenarios was provided by Envipark. In particular for the Scenario with the CHPs Envipark performed simulation based on the technical performances attended for the technology developed by RANOTOR.

Table 4.1: LCA Inventory Table of Envipark 'Baseline' Scenario

Flow	Unit	Winter	Spring	Summer	Autumn	Total average year	Total 25 years	Dataset
Energy consumption								
Heat consumption - Urban district heating	kWh	1.613.930	430.740	-	308.630	2.353.300	58.832.500	IT: heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical. Ecoinvent 3.10
Electrical consumption - National Grid	kWh	840.939	779.812	1.044.296	831.820	3.496.867	87.421.675	IT:electricity, low voltage, market for. Ecoinvent 3.10
Energy production on site - Renewable								
Hydro	kWh_e	235.836	391.579	345.704	207.698	1.180.816	29.520.411	IT: electricity production, hydro, run-of-river.Ecoinvent 3.9.1
Hydro self consumption	%	0%	0%	0%	0%	0%	0%	-
Hydro to the grid	%	100%	100%	100%	100%	100%	100%	-
PV	kWh_e	1.890	3.995	3.718	1.868	11.471	286.780	IT: electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted. Ecoinvent 3.10
PV self consumption	%	100%	100%	100%	100%	100%	100%	-
PV to the grid	%	0%	0%	0%	0%	0%	0%	-

Table 4.2: LCA Inventory Table of Envipark 'CHPs' Scenario

Flow	Unit	Winter	Spring	Summer	Autumn	Total average year	Total 25 years	Dataset
Energy consumption								
Heat consumption - Urban district heating	kWh	1.484.330	364.500	-	240.950	2.089.780	52.244.500	IT: heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical. Ecoinvent 3.10
Natural gas consumption - CHP	Smc	21.039	10.753	-	10.987	42.779	1.069.479	Already included in the selected datasets covering electricity and heat production from CHP. Ecoinvent 3.10
Electrical consumption - National Grid	kWh	808.539	763.252	1.044.296	814.900	3.430.987	85.774.675	IT:electricity, low voltage, market for. Ecoinvent 3.10
Energy production on site - Not renewables								
Electricity from CHP	kWh_e	32.400	16.560	-	16.920	65.880	1.647.000	Europe without Switzerland : Electricity, heat and power co-generation, natural gas, mini-plant 2KW electrical. Ecoinvent 3.10
CHP self consumption	%	100%	100%	100%	100%	100%	100%	
Heat from CHP	kWh_{th}	129.600	66.240	-	67.680	263.520	6.588.000	Europe without Switzerland : Heat, heat and power co-generation, natural gas, mini-plant 2KW electrical. Ecoinvent 3.10
CHP self consumption	%	100%	100%	100%	100%	100%	100%	
Energy production on site - Renewable								
Hydro	kWh_e	346.543	350.601	336.641	271.808	1.305.593	32.639.825	IT: electricity production, hydro, run-of-river.Ecoinvent 3.9.1
Hydro self consumption	%	0%	0%	0%	0%	0%	0%	-
Hydro to the grid	%	100%	100%	100%	100%	100%	100%	-
PV	kWh_e	1.890	3.995	3.718	1.868	11.471	286.780	IT: electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted. Ecoinvent 3.10
PV self consumption	%	100%	100%	100%	100%	100%	100%	-
PV to the grid	%	0%	0%	0%	0%	0%	0%	-

Table 4.3: LCA Inventory Table of Envipark 'CHPs & HRES' Scenario

Flow	Unit	Winter	Spring	Summer	Autumn	Total average year	Total 25 years	Dataset
Energy consumption								
Heat consumption - Urban district heating	kWh	1.484.330	364.500	-	240.950	2.089.780	52.244.500	IT: heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical. Ecoinvent 3.10
Natural gas consumption - CHP	Smc	21.039	10.753	-	10.987	42.779	1.069.479	Already included in the selected datasets covering electricity and heat production from CHP. Ecoinvent 3.10
Electrical consumption - National Grid	kWh	414.329	331.440	613.172	491.323	1.850.263	46.256.573	IT:electricity, low voltage, market for. Ecoinvent 3.10
Energy production on site - Not renewables								
Electricity from CHP	kWh_e	32.400	16.560	-	16.920	65.880	1.647.000	Europe without Switzerland : Elrctricity, heat and power co-generation, natural gas, mini-plant 2KW electrical. Ecoinvent 3.10
CHP self consumption	%	100%	100%	100%	100%	100%	100%	
Heat from CHP	kWh_{th}	129.600	66.240	-	67.680	263.520	6.588.000	Europe without Switzerland : Heat, heat and power co-generation, natural gas, mini-plant 2KW electrical. Ecoinvent 3.10
CHP self consumption	%	100%	100%	100%	100%	100%	100%	
Energy production on site - Renewables								
Hydro	kWh_e	346.543	350.601	336.641	271.808	1.305.593	32.639.825	IT: electricity production, hydro, run-of-river.Ecoinvent 3.9.1
Hydro self consumption	%	99%	100%	100%	99%	99%	0%	-
Hydro to the grid	%	0,7%	0,3%	0,2%	0,8%	0,5%	100%	-
PV	kWh_e	41.398	81.211	94.483	50.977	268.069	6.701.725	IT: electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted. Ecoinvent 3.10
PV self consumption	%	100%	100%	100%	100%	100%	100%	-
PV to the grid	%	0%	0%	0%	0%	0%	0%	-

4.1.3 Impact Assessment

This section describes the environmental impact assessment results obtained 1st business case of HYPERGRYD project. In Table 4.4 the results of the LCA study are reported for the three compared scenarios.

Table 4.4: Comparative LCA results of Envipark 'Baseline', 'CHPs' and 'CHPs & HRES' Scenarios (25 years)

Impact Categories	Baseline	CHPs	CHPs & HRES	Delta % CHP-Baseline	Delta % CHP&HRES-Baseline
Acidification [mol H+ eq]	2.04E+05	2.00E+05	1.28E+05	-2%	-38%
Climate change [kg CO2 eq]	6.28E+07	6.10E+07	4.65E+07	-3%	-26%
Climate change - Biogenic [kg CO2 eq]	1.33E+05	1.31E+05	7.42E+04	-2%	-44%
Climate change - Fossil [kg CO2 eq]	6.26E+07	6.09E+07	4.64E+07	-3%	-26%
Climate change - Land use and LU change [kg CO2 eq]	4.37E+04	4.33E+04	2.49E+04	-1%	-43%
Ecotoxicity, freshwater - part 1 [CTUe]	5.45E+07	6.14E+07	4.21E+07	11%	-20%
Ecotoxicity, freshwater - part 2 [CTUe]	4.60E+07	4.59E+07	3.29E+07	0%	-28%
Ecotoxicity, freshwater - inorganics [CTUe]	9.44E+07	1.01E+08	7.12E+07	7%	-23%
Ecotoxicity, freshwater - organics - p.1 [CTUe]	1.17E+06	1.18E+06	8.53E+05	0%	-27%
Ecotoxicity, freshwater - organics - p.2 [CTUe]	4.94E+06	4.92E+06	2.96E+06	0%	-40%
Particulate matter [disease inc.]	7.97E-01	8.03E-01	5.08E-01	1%	-36%
Eutrophication, marine [kg N eq]	3.41E+04	3.33E+04	2.26E+04	-2%	-34%
Eutrophication, freshwater [kg P eq]	1.08E+03	1.06E+03	6.22E+02	-1%	-42%
Eutrophication, terrestrial [mol N eq]	3.82E+05	3.73E+05	2.52E+05	-2%	-34%
Human toxicity, cancer [CTUh]	1.49E-02	1.51E-02	9.70E-03	1%	-34%
Human toxicity, cancer - inorganics [CTUh]	1.04E-02	1.05E-02	6.73E-03	1%	-35%
Human toxicity, cancer - organics [CTUh]	4.56E-03	4.63E-03	2.97E-03	1%	-34%
Human toxicity, non-cancer [CTUh]	3.44E-01	3.42E-01	2.26E-01	-1%	-34%
Human toxicity, non-cancer - inorganics [CTUh]	3.26E-01	3.24E-01	2.13E-01	-1%	-35%
Human toxicity, non-cancer - organics [CTUh]	1.78E-02	1.77E-02	1.27E-02	-1%	-29%
Ionising radiation [kBq U-235 eq]	1.64E+06	1.62E+06	9.14E+05	-1%	-44%
Land use [Pt]	2.18E+08	2.14E+08	1.23E+08	-2%	-44%
Ozone depletion [kg CFC11 eq]	1.15E+01	1.09E+01	8.59E+00	-5%	-25%
Photochemical ozone formation [kg NMVOC eq]	1.15E+05	1.12E+05	7.86E+04	-2%	-31%
Resource use, fossils [MJ]	9.76E+08	9.45E+08	7.15E+08	-3%	-27%
Resource use, minerals and metals [kg Sb eq]	3.35E+02	3.33E+02	2.32E+02	0%	-31%
Water use [m3 depriv.]	3.20E+07	3.13E+07	1.81E+07	-2%	-44%

Results clearly indicates that the two innovative scenarios are advantageous from environmental point of view with respect to the baseline configuration at Envipark. Indeed, CHP system slight reports a reduction of impacts with an average saving of 2%, while the combination of CHP with a HRES system is strongly convenient, determining an average reduction of 34% of impacts with respect to the benchmark scenario. A clear representation of these outcomes is given in the chart of Figure 7.

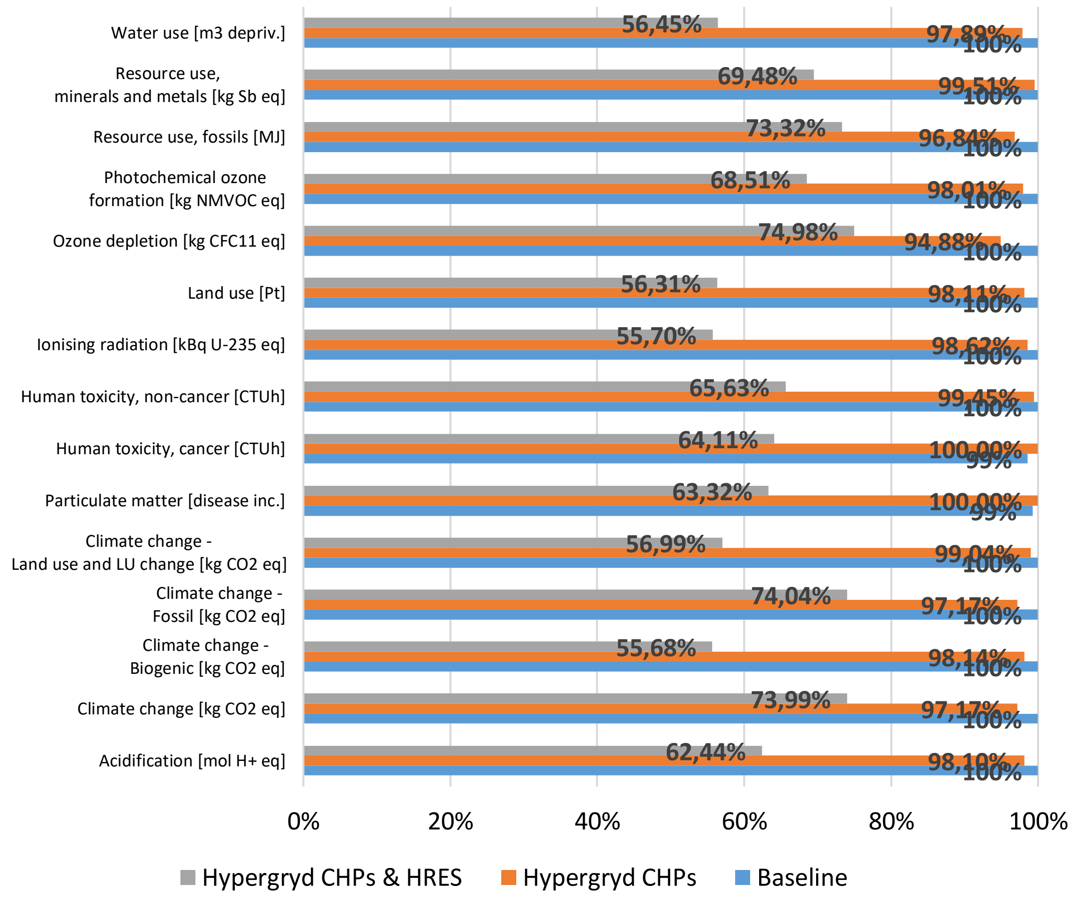

Figure 7: Comparative LCA results of Envipark 'Baseline', 'CHPs' and 'CHPs & HRES' Scenarios

The comparative LCA study for the Envipark business case confirms that introducing innovative HYPERGRYD solutions is proficient in terms of the environmental impacts of the district area. Indeed, all impact indicators report a reduction of burdens associated with the use of novel CHPs. Considering the well-known *Climate Change* indicator, indeed, the CHP system enables a reduction around 3% of impacts, which is even higher when combining this technology with HRES system, achieving 26% of GWP reduction, which is a outstanding result. This reduction trend could be observed in almost all impact indicators selected for the study: in fact, similarly to Climate change, the improvement action of combining CHP novel system with HRES technology enables a global reduction of almost 34% in most all the impact indicators, while the stand-alone CHP determines only a slight reduction (2-3%) of burdens with respect to baseline.

Figure 8 provides a deeper insight into the the breakdown of contributions for Envipark use case. Here, hotspot analysis is applied to the three different scenarios for selected and most relevant impact indicators.

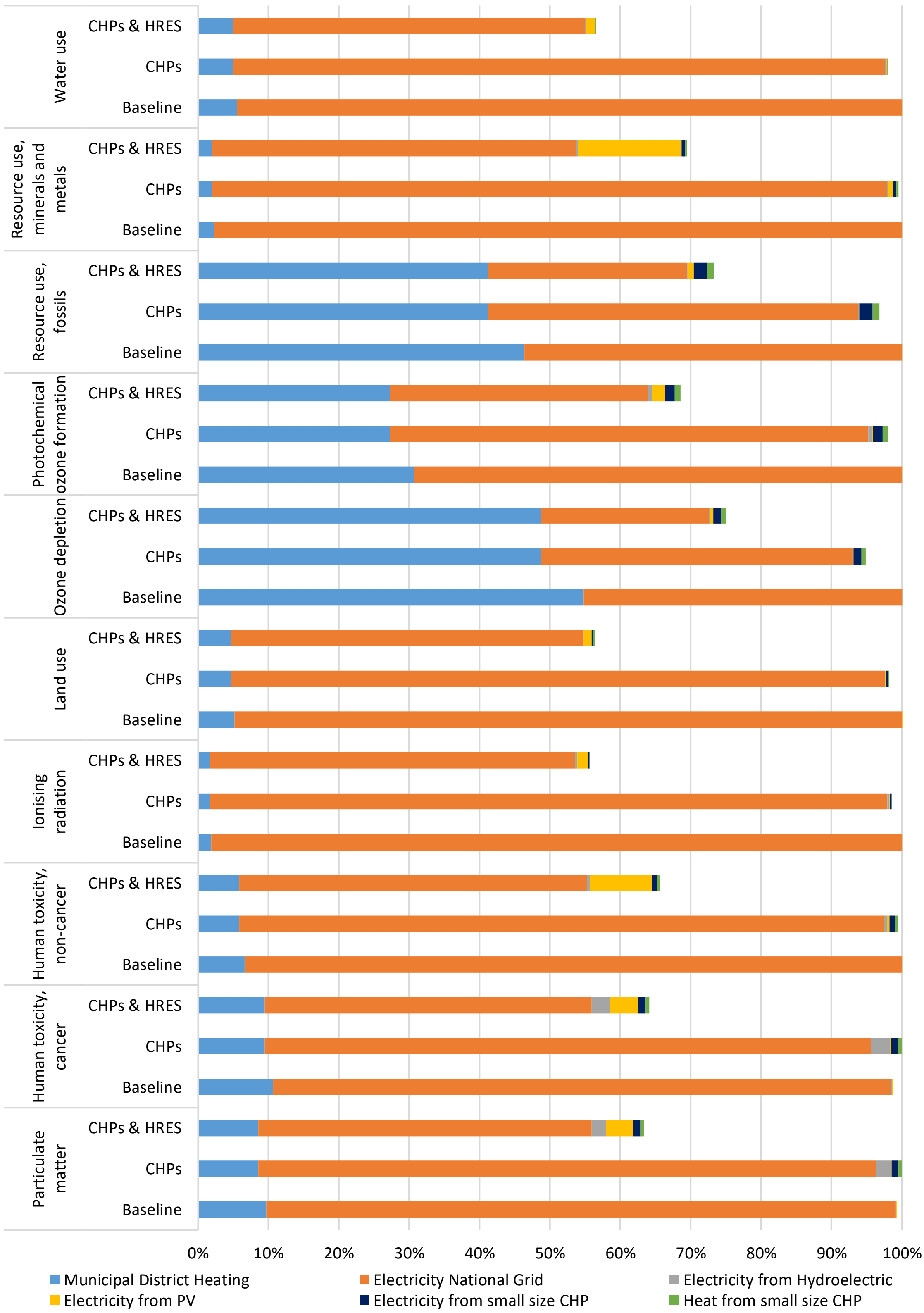

Figure 8 Comparative LCA results of Envipark 'Baseline', 'CHPs' and 'CHPs & HRES' Scenarios with the contribution of the different energy utilities.

The chart points out that the most relevant contribution in all scenarios is *Electricity national grid*, having the highest impact shares for all categories. This result, determined by the specific energy demand in Envipark district, deeply affects the impact indicators. On the other hand, a relevant role is also given to *Municipal district heating* system, which specifically prevails in Ozone depletion indicator, probably because of the role of its value-chain (e.g. use of chemicals).

4.2 Sorption Thermal Energy Storage

4.2.1 Goal and scope

Goal: This LCA study aims to evaluate the environmental benefits and/or burdens arising from the implementation of the Sorption Thermal Energy Storage in the Sonnenplatz district. It adopts a comparative perspective between a Baseline and the project Scenario (STES Scenario).

System Boundaries: The LCA assessment is solely limited to the use phase of the district's energy consumption encompassing all activities related to the generation (e.g. biomass production), distribution, and consumption of energy within the district.

Functional Unit: The functional unit for this assessment is defined as the total energy consumed by the district over a 25-year period.

Temporal Scope: The assessment will cover a 25-years timeframe, from 2030 to 2055.

Geographical Scope: The geographical scope is limited to the portion of the district described in paragraph 3.2 (buildings **7,8,10,11,12,13).**

Assumptions and Limitations: The assessment assumes that the energy consumption patterns remain consistent over 25-years.

The energy flows that would remain unchanged upon the introduction of the new technology are considered a cut-off.

4.2.2 Inventories

In this paragraph the LCA Inventory tables for Business case 2 for the Baseline and STES scenario are disclosed. The quantification of the seasonal flows for the Baseline scenario was provided by Sonnenplatz while the STES scenario was built with the help of CNR and SORTEC.

Table 4.5: LCA Inventory Table of Sonnenplatz 'Baseline' Scenario

Flow	Unit	Winter	Spring	Summer	Autumn	Total average year	Total 25 years	Dataset
Energy consumption								
Heat consumption - Biomass	MJ	248544	143424	70963	199987	662918	16572960	AT: Heat, central or small-scale, other than natural gas | heat and power co-generation, biogas, gas engine | APOS, U. Ecoinvent 3.10
Heat consumption – Oil fired boiler	MJ	288	173	346	7200	8006	200160	Europe without Switzerland: heat production, light fuel oil, at boiler 100kW, non-modulating | APOS, U. Ecoinvent 3.10
Energy production on site - Renewable								
PV	kWh_e	7657	19008	25617	11301	63584	1589592	AT: electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | APOS, U. Ecoinvent 3.10
PV self consumption	%	62	50	48	50	51	51	-
PV to the grid	%	38	50	52	50	49	49	-

Table 4.6: LCA Inventory Table of Sonnenplatz 'Sorption Thermal Energy Storage(STES)' Scenario

Flow	Unit	Winter	Spring	Summer	Autumn	Total average year	Total 25 years	Dataset
Energy consumption								
Heat consumption - Biomass	MJ	215505	109731	45826	155647	526708	13167701	AT: Heat, central or small-scale, other than natural gas | heat and power co-generation, biogas, gas engine | APOS, U. Ecoinvent 3.10
Heat consumption – Oil fired boiler	MJ	250	132	223	5604	6209	155219	Europe without Switzerland: heat production, light fuel oil, at boiler 100kW, non-modulating | APOS, U. Ecoinvent 3.10
Energy production on site - Renewable								
PV	kWh_e	7657	19008	25617	11301	63584	1589592	AT: electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | APOS, U. Ecoinvent 3.10
PV self consumption	%	97	97	96	96	97	97	-
PV to the grid	%	3	3	4	4	3	3	-

4.2.3 Impact Assessment

This section discusses the results of the Life Cycle Assessment on the business case 2, considering baseline and innovative scenarios. The following table shows the environmental results of the two Scenarios over a 25 years period as well as the percentage difference between them.

Table 4.7: Comparative LCA results of Sonnenplatz 'Baseline', 'STES' Scenarios (25 years)

Impact Categories	Baseline	STES	Delta % STES-Baseline
Acidification [mol H+ eq]	2.91E+03	2.56E+03	-12%
Climate change [kg CO2 eq]	3.31E+05	2.96E+05	-10%
Climate change - Biogenic [kg CO2 eq]	2.48E+04	1.98E+04	-20%
Climate change - Fossil [kg CO2 eq]	2.99E+05	2.71E+05	-9%
Climate change - Land use and LU change [kg CO2 eq]	6.56E+03	5.28E+03	-19%
Ecotoxicity, freshwater - part 1 [CTUe]	2.86E+06	2.42E+06	-16%
Ecotoxicity, freshwater - part 2 [CTUe]	1.54E+06	1.40E+06	-10%
Ecotoxicity, freshwater - inorganics [CTUe]	3.90E+06	3.39E+06	-13%
Ecotoxicity, freshwater - organics - p.1 [CTUe]	2.27E+05	1.92E+05	-16%
Ecotoxicity, freshwater - organics - p.2 [CTUe]	2.87E+05	2.36E+05	-18%
Particulate matter [disease inc.]	2.23E-02	1.99E-02	-11%
Eutrophication, marine [kg N eq]	6.71E+02	5.71E+02	-15%
Eutrophication, freshwater [kg P eq]	1.98E+01	1.80E+01	-9%
Eutrophication, terrestrial [mol N eq]	6.98E+03	5.95E+03	-15%
Human toxicity, cancer [CTUh]	4.65E-04	4.18E-04	-10%
Human toxicity, cancer - inorganics [CTUh]	3.35E-04	2.97E-04	-11%
Human toxicity, cancer - organics [CTUh]	1.30E-04	1.21E-04	-7%
Human toxicity, non-cancer [CTUh]	1.45E-02	1.33E-02	-8%
Human toxicity, non-cancer - inorganics [CTUh]	1.40E-02	1.28E-02	-8%
Human toxicity, non-cancer - organics [CTUh]	4.66E-04	4.29E-04	-8%
Ionising radiation [kBq U-235 eq]	1.67E+04	1.47E+04	-12%
Land use [Pt]	8.91E+06	7.23E+06	-19%
Ozone depletion [kg CFC11 eq]	8.48E-02	7.10E-02	-16%
Photochemical ozone formation [kg NMVOC eq]	1.44E+03	1.28E+03	-11%
Resource use, fossils [MJ]	3.60E+06	3.30E+06	-8%
Resource use, minerals and metals [kg Sb eq]	1.52E+01	1.49E+01	-2%
Water use [m3 depriv.]	1.68E+06	1.36E+06	-19%

The LCA data reports that the novel technology (STES) enables a net reduction of environmental impacts for the Sonnenplatz district in all the impact categories selected for the study. In particular, Climate change expresses -10% of burdens and the highest values are outlined for Water use (-19%), Land use (-19%) and Ecotoxicity, freshwater (-18%). Figure 9 clearly represents these results.

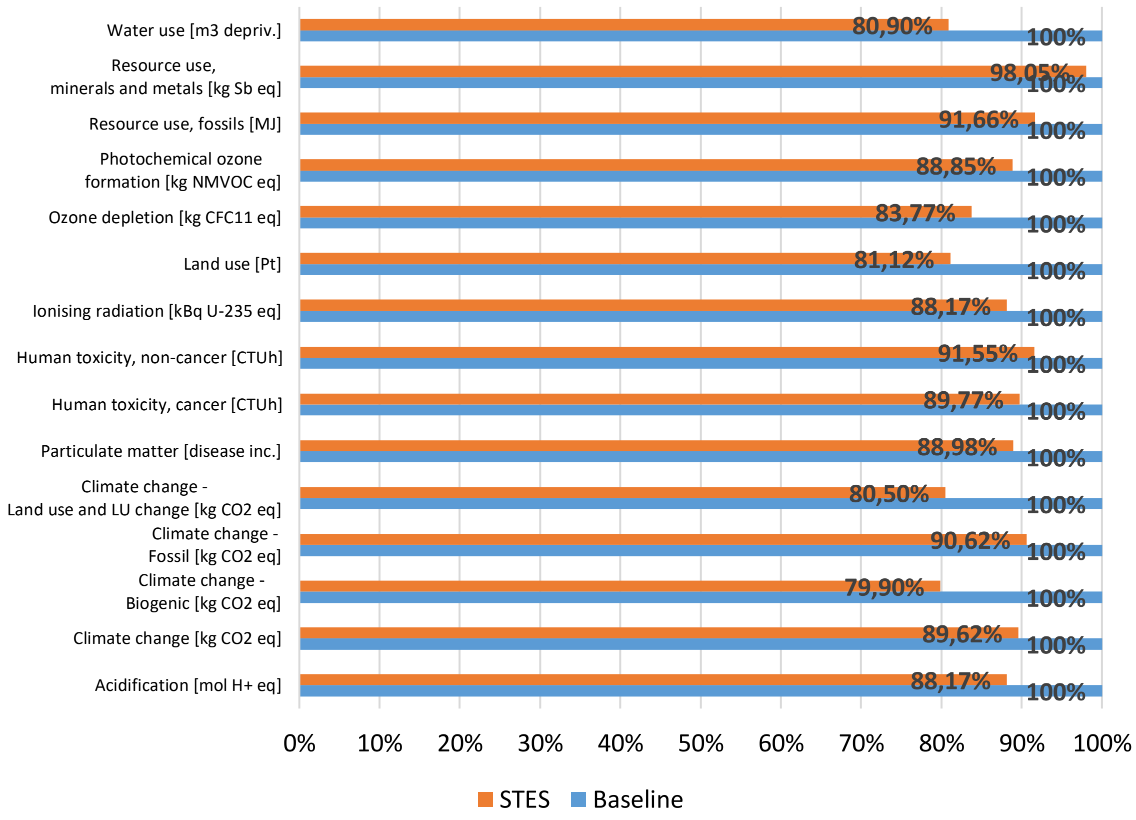

Figure 9: Comparative LCA results of Sonnenplatz 'Baseline'and 'STES' Scenarios

The chart clearly demonstrates that the introduction of the STES system is beneficial for the environment, because it determines an average reduction of 20% of burdens associated with the use phase at Sonnenplatz district. Reduction of impacts, indeed, could be associated with a better selection of energy storage systems and proper management of the energy demand over the entire life cycle.

In order to better highlight the importance of each input in the overall impact distribution, a hotspot analysis is applied in Figure 10.

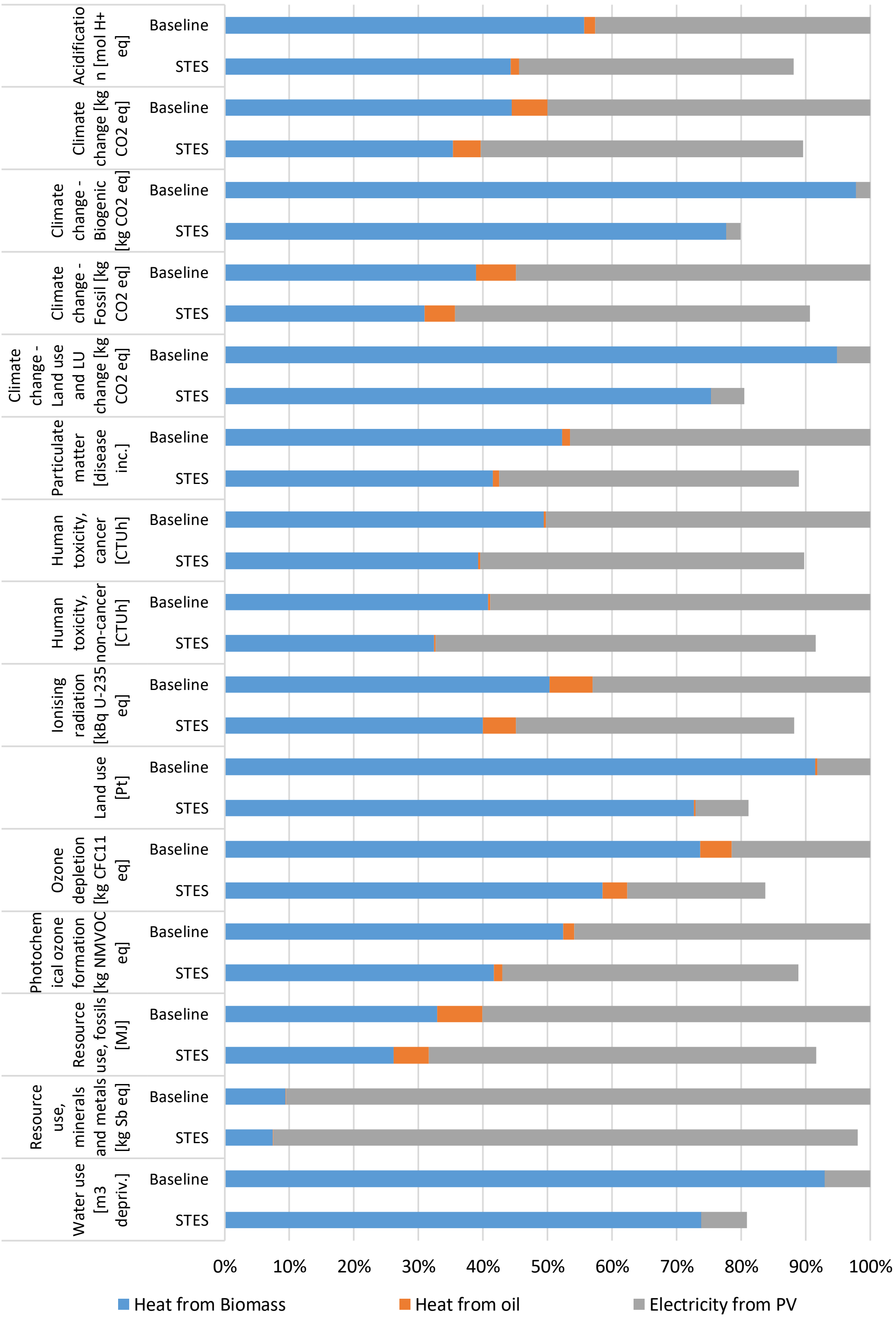

Figure 10: Comparative LCA results of Sonnenplatz 'Baseline' and 'STES' Scenarios with the contribution of the different energy utilities.

The breakdown analysis indicates that the significant contribution for impacts is *Heat produced from biomass*, followed by *Electricity from PV*, having also a high share of burdens. In fact, in all the impact indicators the prevalence of *Biomass heat* is outlined, often counterpaired by the *PV Electricity*: this evidence is due to the input energy mix of Sonnenplatz STES district, in which these two energy sources prevail. In fact, the role of other sources (e.g. *Heat from oil*) is less relevant or, in some categories, quite negligible.

From a general point of view, the hotspot analysis confirms that the consumptions (and, in turn, burdens) of the STES novel systems are lower than those of the benchmark, which is a positive result. Consequently, the LCA study proves that the STES technology is a more convenient and sustainable energy solution for the Sonnenplatz district in baseline scenario.

4.3 Modular Heat Pump with short-term storage

4.3.1 Goal and scope

Goal: The present LCA study evaluates the environmental impacts and benefits arising from the potential integration of the Modular Heat Pumps with PCM storage in Sonnenplatz district. It adopts a comparative perspective between a Baseline and the project Scenario (STES Scenario).

System Boundaries: The LCA exclusively assesses the use phase of the district's energy consumption encompassing all activities related to the generation, distribution, and consumption of energy within the district during the reference period.

Functional Unit: The functional unit for this assessment is defined as the total energy consumed and produced by the district over 25-years.

Temporal Scope: The assessment will cover a 25-years timeframe, from 2030 to 2055.

Geographical Scope: The geographical scope is limited to the whole Sonnenplatz district, described in 3.3.

Assumptions and Limitations: The assessment assumes that the energy consumption patterns remain constant over the 25-year period.

The energy flows that would remain unchanged upon introducing the new technology are considered a cut-off.

4.3.2 Inventories

This paragraph illustrates the LCA Inventories for the business case 3 different Scenarios. The data on the seasonal energy consumptions and production of the Baseline Scenarios were provided by Sonnenplatz, while the 'HPsPCM' scenario was build thanks to the simulations performed by AIT considering the technical features of the HPs developed in the project by OCHSNER. For the estimation of the electricity necessary to power the HPs, AIT assumed a seasonal coefficient of performance (COP) qual to 2.90, 3.40, 3.80 and 3.10 for winter, spring, summer and autumn respectively.

Table 4.8: LCA Inventory Table of Sonnenplatz 'Baseline' Scenario

Flow	Unit	Winter	Spring	Summer	Autumn	Total average year	Total 25 years	Dataset
Energy consumption								
Electricity – Nation grid	kWh	47326	46595	51666	51611	197198	4929938	AT: Market for Electricity, low voltage. Ecoinvent 3.10
Heat consumption - Biomass	MJ	1652400	1189440	471600	829800	4143240	103581.000	AT: Heat, central or small-scale, other than natural gas | heat and power co-generation, biogas, gas engine | APOS, U. Ecoinvent 3.10
Heat consumption – Oil fired boiler	MJ	2880	2880	1440	42840	50040	1251000	Europe without Switzerland: heat production, light fuel oil, at boiler 100kW, non-modulating | APOS, U. Ecoinvent 3.10
Energy production on site - Renewable								
PV – on site	kWh	17981	69591	101196	52441	241209	6030222	AT: electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | APOS, U. Ecoinvent 3.10
PV self consumption	%	62	50	48	50	50	50	-
PV to the grid	%	38	50	52	50	50	50	-

Table 4.9: LCA Inventory Table of Sonnenplatz 'Heat Pumps with PCM' Scenario

Flow	Unit	Winter	Spring	Summer	Autumn	Total average year	Total 25 years	Dataset
Energy consumption								
Electricity – Nation grid	kWh	47326	46595	51666	51611	197198	4929.938	AT: Market for Electricity, low voltage. Ecoinvent 3.10
Heat consumption - Biomass	MJ	0	0	0	0	0	-	-
Heat consumption – Oil fired boiler	MJ	0	0	0	0	0	-	-
Electricity consumption for Heat Pumps	kWh	161723	99360	35271	79757	376111	9402768	AT: Market for Electricity, low voltage. Ecoinvent 3.10
Energy production on site – Not Renewable								
Heat production from Heat Pumps	kWh	468996	337824	134028	247248	1188096	29.702.400	-
Energy production on site - Renewable								
PV – on site	kWh	17981	69591	101196	52441	241209	6030222	AT: electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | APOS, U. Ecoinvent 3.10
PV self consumption	%	62	50	48	50	50	50	-
PV to the grid	%	38	50	52	50	50	50	-

4.3.3 Impact Assessment

This section discusses the results of the Life Cycle Assessment of the Modular Heat Pump technology applied in Sonnenplatz (Großschönau, AT) district, considering baseline and innovative scenarios. The environmental results of this last use case are outlined in Table 4.10.

Table 4.10: Comparative LCA results of Sonnenplatz 'Baseline', 'HPsPCM' Scenarios (25 years)

Impact Categories	Baseline	HPsPCM	Delta % HPsPCM-Baseline
Acidification [mol H+ eq]	2.09E+04	1.86E+04	-11%
Climate change [kg CO2 eq]	3.29E+06	4.55E+06	28%
Climate change - Biogenic [kg CO2 eq]	1.58E+05	1.17E+04	-93%
Climate change - Fossil [kg CO2 eq]	3.09E+06	4.53E+06	32%
Climate change - Land use and LU change [kg CO2 eq]	4.25E+04	6.94E+03	-84%
Ecotoxicity, freshwater - part 1 [CTUe]	1.77E+07	6.27E+06	-65%
Ecotoxicity, freshwater - part 2 [CTUe]	1.14E+07	1.21E+07	6%
Ecotoxicity, freshwater - inorganics [CTUe]	2.60E+07	1.77E+07	-32%
Ecotoxicity, freshwater - organics - p.1 [CTUe]	1.32E+06	2.91E+05	-78%
Ecotoxicity, freshwater - organics - p.2 [CTUe]	1.79E+06	3.98E+05	-78%
Particulate matter [disease inc.]	1.35E-01	8.88E-02	-34%
Eutrophication, marine [kg N eq]	4.71E+03	3.06E+03	-35%
Eutrophication, freshwater [kg P eq]	3.03E+02	5.36E+02	44%
Eutrophication, terrestrial [mol N eq]	5.00E+04	3.46E+04	-31%
Human toxicity, cancer [CTUh]	3.00E-03	2.49E-03	-17%
Human toxicity, cancer - inorganics [CTUh]	2.23E-03	1.78E-03	-20%
Human toxicity, cancer - organics [CTUh]	7.69E-04	7.16E-04	-7%
Human toxicity, non-cancer [CTUh]	8.73E-02	7.49E-02	-14%
Human toxicity, non-cancer - inorganics [CTUh]	8.45E-02	7.25E-02	-14%
Human toxicity, non-cancer - organics [CTUh]	2.81E-03	2.48E-03	-12%
Ionising radiation [kBq U-235 eq]	1.84E+05	2.60E+05	29%
Land use [Pt]	6.20E+07	2.23E+07	-64%
Ozone depletion [kg CFC11 eq]	6.17E-01	3.85E-01	-38%
Photochemical ozone formation [kg NMVOC eq]	1.04E+04	9.69E+03	-7%
Resource use, fossils [MJ]	4.11E+07	6.58E+07	37%
Resource use, minerals and metals [kg Sb eq]	7.81E+01	9.27E+01	16%
Water use [m3 depriv.]	1.06E+07	1.47E+06	-86%

The analysis reports a substantial reduction of impacts in the novel configuration with Modular Heat Pump: indeed, a positive decrease of burdens is observed for several indicators, including *Water use* (-86%), *Ecotoxicity freshwater* (-78%), *Land use* (-64%) and *Ozone depletion* (-38%). However, some indicators report an increase in their impacts for the HYPERGRYD scenario: for example, *Climate change* (+28%), *Resource use, fossils* (+37%) and *Eutrophication, freshwater* (+44%) indicators are affected by this increment. A better overview of the obtained results is reported in Figure 11.

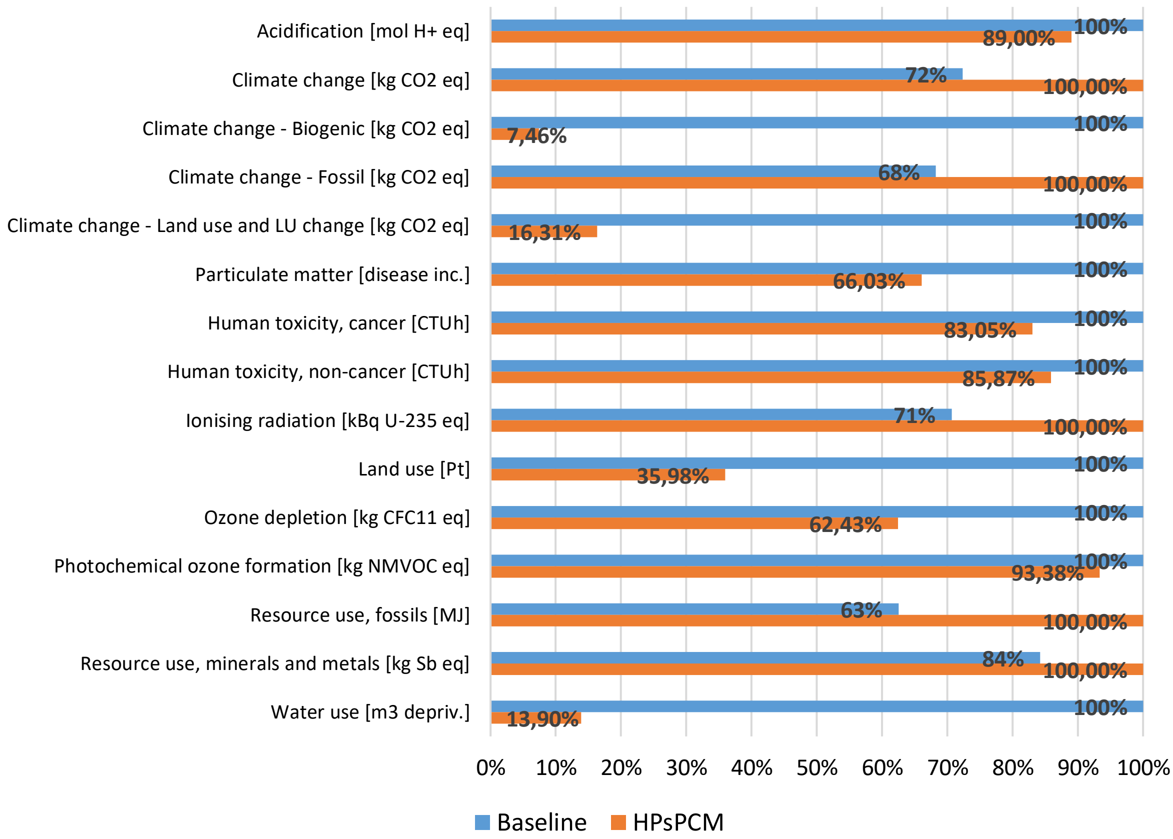

Figure 11: Comparative LCA results of Sonnenplatz 'Baseline', 'HPsPCM' Scenarios

The chart confirms the afore-mentioned overview, with a positive performance of HPsPCM strategy in most of the environmental indicators. At the same time an increase in impacts with respect to the baseline scenario is outlined. The reason behind this evidence could be retrieved in the different energy mixes required for the innovative solutions, which could affect specific indicators. This remark is clearly explained by the breakdown analysis in Figure 12.

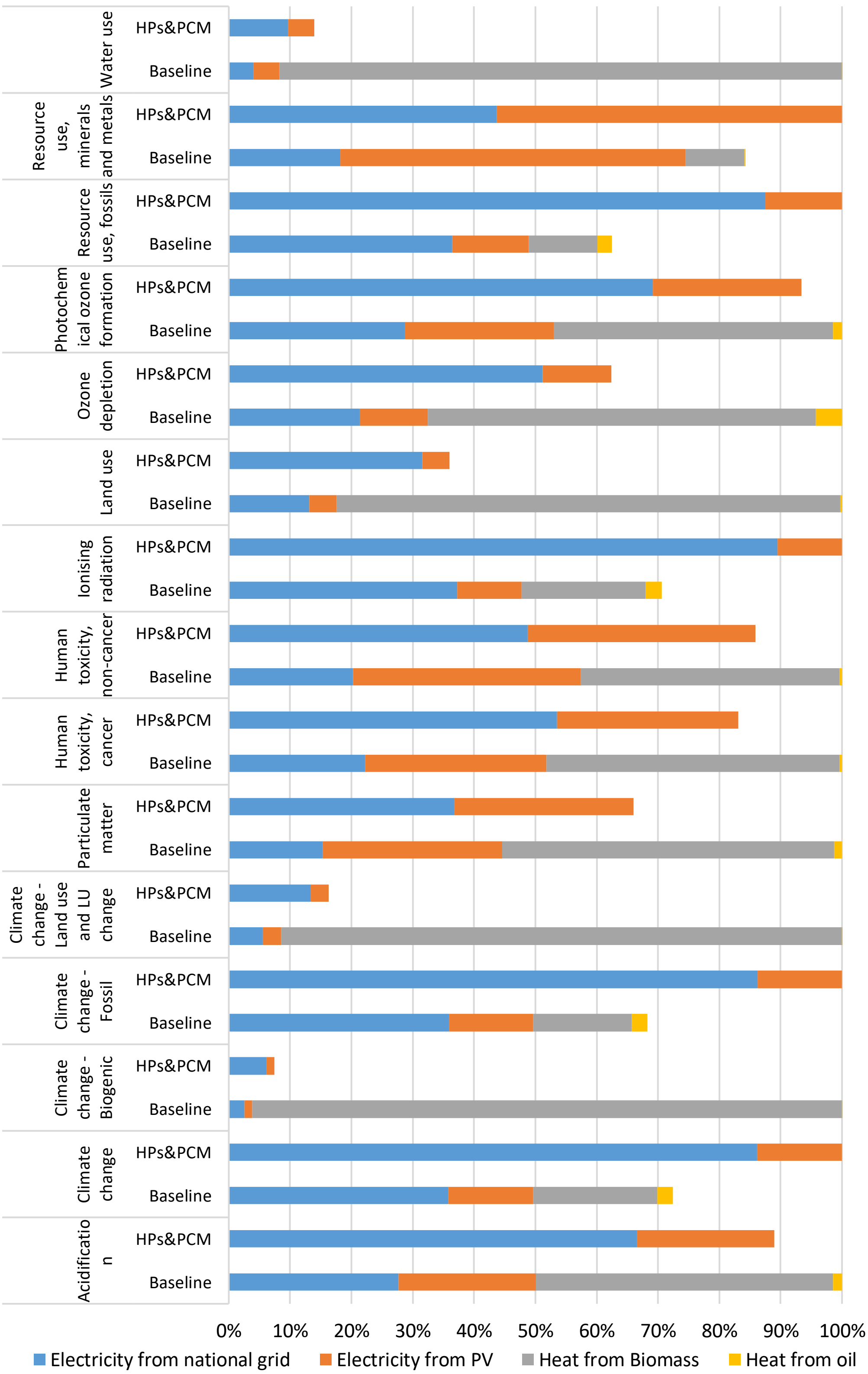

Figure 12: Comparative LCA results of Sonnenplatz 'Baseline'and 'HPs & PCM' Scenarios with the contribution of the different energy utilities

In particular, while the implementation of the HPs ensures a remarkable reduction of the environmental burdens in the Climate Change – Biogenic indicators (by breaking the dependence on the biomass boilers), the electrification causes an excess of electricity consumptions from the grid that in the presented energy mix of Austria causes an increase in the Climate Change – Fossil that is also reflected in the Climate Change – Total indicator. This issue could in part be mitigated by making internal use of the excess PV which today is sold to the national grid today, and expanding the solar park.

5 LCC of HYPERGRYD technologies

This chapter reports the Life Cycle Costing applied to the three business cases of the HYPERGRYD project. Premises, inventory and results are discussed below.

5.1 Reversible micro-CHP with steam engine and steam buffer

5.1.1 Goal and scope

Goal: The Goal of the analysis is to evaluate the economic impacts of implementing the micro-CHP units, and eventually achieving higher share of renewable energy in the Envipark district A comparative perspective is adopted between a Baseline and the two project Scenarios (CHPs Scenario and CHP & HRES Scenario). This comparison aims to provide insights into the economic viability over 25 years.

System Boundaries: The LCC analysis will focus on the financial aspects of the energy district, including CAPEX, OPEX, and revenues, from the supply of new equipments and their use for the reference period. System decomissioning is excluded.

Functional Unit: The functional unit for this assessment is defined as the total energy consumed and produced by the district over 25 years.

The perspective adopted in the one of **the final user.**

Geographical Scope and Temporal Scope: As per the LCA study.

Assumptions and Limitations: The assessment assumes that the energy consumption patterns remain unchanged over the 25-years period.

The energy flows which would remain unchanged upon introducing the new technology are considered a cut-off. The same applies to the Capex and Maintenance cost of the equipment that would stay in place for both Scenarios (pre-existing PV and Hydro-plant, district heating internal network).

Energy prices and feed-in tariffs to the grid are assumed to remain constant over the 25-year period. The reference value is the average energy price over a long period to account for cyclical price fluctuations.

5.1.2 Inventories

This paragraph reports the economic and technical parameters underlying the LCC analysis. RANOTOR provided data on the selling price, installation and maintenance of the CHPs units. Data on additional PV were estimated with the help of R2M.

Table 5.1: LCC Inventory Table of Envipark 'Baseline, 'CHPs' and 'CHP & RES' Scenarios

Flow	Baseline Scenario	CHPs Scenario	CHPs&HRES Scenario	Unit	Note/ Data source
Nominal Power of the CHP	-	5/20	5/20	kWe/kWth	
Number of System to be installed	-	3	3	-	
Life-span of the CHP	-	15	15	years	
Nominal Power of the PV System	-	-	219	kWe	1 System 19 kWe plus 2 Systems 20 kWe
Life-span of the PV	-	-	25	years	
Capex					
Initial Capex 1 CHP	-	12.500	12.500	Eur	It includes installation costs.
Total Capex, 3 CHPs, 25 years		62.500	62.500	Eur	
Initial Capex PV		-	250.000	Eur	
Opex					
Maintenance of the CHPs units, 25 years	-	29.646	29.646	Eur	Yearly Operational hours:4392 (Primary data);Maintenance cost : 0.018 Eur/kWh (Burgis, 2025) ;
Maintenance cost PV	-	-	5.500	Eur	2% of the Initial cost for small size; 1% of the initial cost for big size (SOLAR FAQs, 2025);
Total Cost for energy	15.912.033	15.556.786	10.829.762	Eur	See Annex 9.2.1
Revenues					
Total Revenues	2.940.475	2.940.475	0	Eur	Hydro energy to the grid. See Annex 9.2.1

5.1.3 Impact Assessment

This section reports the economic impact assessment analysis on Envipark (Turin, IT), which is the 1st use case of the HYPERGRYD project. Envipark includes a reversible micro-CHP system with a steam engine and steam buffer. In Figure 13 the global results of the LCC study are reported for the three compared scenarios. The charts presents the total costs for each of the three Envipark scenarios. In particular, the baseline and CHPs configuration have very similar outcomes: indeed, the costs are only inputable to *Opex* and they have similar extent; moreover, these scenarios also include a good share of *Revenues* obtained from the electricity sold to the grid. The other innovative scenario (CHPs &HRES) presents a minor cost for the investment (*Capex*) required for the new technology, while the *Operational costs* are lower than previous scenarios.

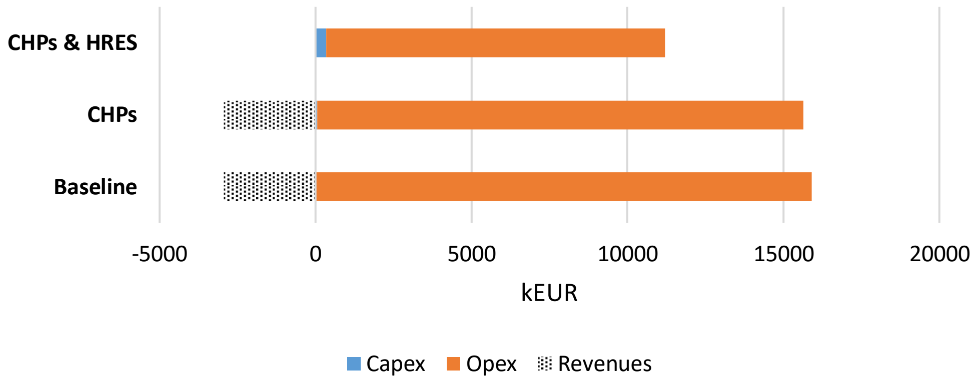

Figure 13: Comparative LCC results of the Envipark use case

To better understand the contribution of entries to the final costs of the three different configurations, a hotspot analysis is applied and reported in Figure 14.

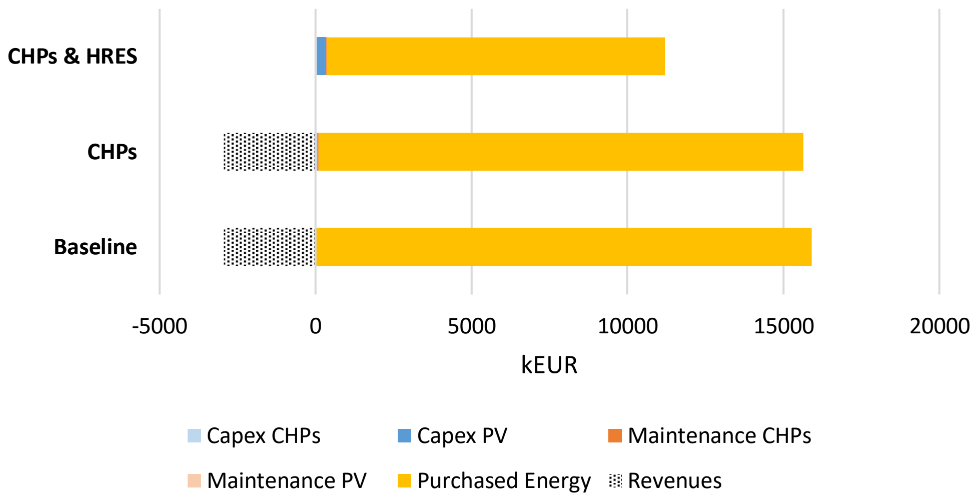

Figure 14: Hotspot analysis on LCC results for Envipark use case

The contribution analysis for Envipark results outlines that the main cost driver is the *Purchased energy*, which is more than 15000 k€ for both CHPs and baseline scenarios and almost 11000 k€ for the combined configuration (CHPs and HRES). The costs related to *Capex* are null or negligible, and m*aintenance* costs are very low and not visible for the scale of the graph. Finally, revenues of more than 2500 k€ are outlined for baseline and CHPs scenarios. In conclusion, the two CHPs innovative scenarios are competitive with respect to baseline: in fact, stand-alone CHPs have same *Revenues* as baseline, with slightly lower *Opex*, while the combination of CHPs & HRES has a minor share of *Capex for PV* systems no *Revenues*, but a very lower cost for the *Purchased energy*. For this reason, they could be considered economically viable and sustainable alternative to the baseline Envipark configuration.

The Investment Pay back time was calculated and reported in the next Table, to better express the economic viability of the two projects scenarios.

Table 5.2: Calculation of the Investment Payback time for the Scenarios investigated in business case 1.

Scenario	Opex – revenues (€)	Opex - revenues/year (€/year)	Delta Project vs. Baseline (€/year)	pay back time (years)
Baseline	12.971.557	518.862	n.a	n.a
CHPs	12.645.956	505.838	-13.024	4.80
CHPs & HRES	10.864.908	434.596	-71.242	4.74

5.2 Sorption Thermal Energy Storage

5.2.1 Goal and scope

Goal: The Goal of the analysis is to evaluate the economic impacts of the implementation of the Sorption storage in the Sonnenplatz district. A comparative perspective is adopted between a Baseline and the project Scenario to provide insights into the financial viability over 25 years.

System Boundaries: The LCC analysis will focus on the financial aspects of the energy district, including CAPEX, OPEX, and revenues, from the supply of the new equipments and their use for the reference period. System decomissioning is excluded.

Functional Unit: The functional unit for this assessment is defined as the total energy consumed and produced by the district over a 25-years period.

Geographical Scope: as per LCA.

Temporal Scope Assumptions and Limitations: as per business case 1.

5.2.2 Inventories

Table 5.3: LCC Inventory Table of Sonnenplatz'Baseline'and 'Sorption Thermal Energy Storage' (STES) Scenario

Flow	Baseline Scenario	Sorption Thermal Storage Scenario	Unit	Note/ Data source
Power Output of the HP	-	250	kW	Calculated in order to cover the the maximum storing capacity of the Sorption Storage (750 KWh_{th}) in 3h.
Life-span of the HP		15	years	
Nominal Power of the STES	-	5	kW	
Storing Capacity needed	-	750	kWh_{th}	Primary data from the project (CNR simulation)
Number of STES needed	-	15		Primary data from the project (CNR simulation): Total storing capacity needed 750 kWh_{th}
Life-span of the STES	-	25	years	
Capex				
Initial Capex HP	-	104.000 (Min) 1.040.000(Max) 572.000(Average)	EUR	Equipment cost at manufacturer: 100 to 1000 EUR/KW. Project cost = 4.16*Equipment cost. (Kosmadakis, 2020).A sensitivity taking into account the variability of the equipment cost was performed
Total Capex, HP, 25 years	-	173.333 (Min) 1.733.333(Max) 953.333(Average)	EUR	Calculated from Initial Capex multiplied per the ratio between the Reference period and technology Life span (25/15=1.67)
Total Capex STES	-	236.250 (Equipment) 6.480 (Installaton)	EUR	Primary data from SORTEC: 17500 EUR + 480 EUR for the installation of a 5 kW System. Total Capex for 75 KW = Cost of 15 Systems with a 10% discount.
Opex				
Maintenance HP	-	34.667 (Min) 3.467(Max) 19.067(Average)	EUR	2% of the Equipment Cost (Kosmadakis, 2020)
Maintenance STES	-	42.000 (Replacements) 54.250 (Man hours)	Eur	Primary data from SORTEC: Replacements:3500 EUR per 5KW System. For 15 Systems, 10% discount. Man hours: 300 EUR/year (0.5h online, 2h in presence) for a 5 kW System. For 15 Systems, 50% discount.
Total Cost for energy	361034	286.798	Eur	See Annex 9.2.2
Revenues				
Total Revenues	131752	92.230	Eur	PV to the grid; See Annex Annex 9.2.2

5.2.3 Impact Assessment

This section reports the economic impact assessment analysis on Sorption Storage for the Sonnenplatz (Großschönau, AT) district, which is the 2nd use case of the HYPERGRYD project. The configuration includes the Sorption Thermal Energy Storage (STES) system. In Figure 15, the global results of the LCC study are reported considering three different scenarios for STES, because of a high cost variability present in the literature for this technology.

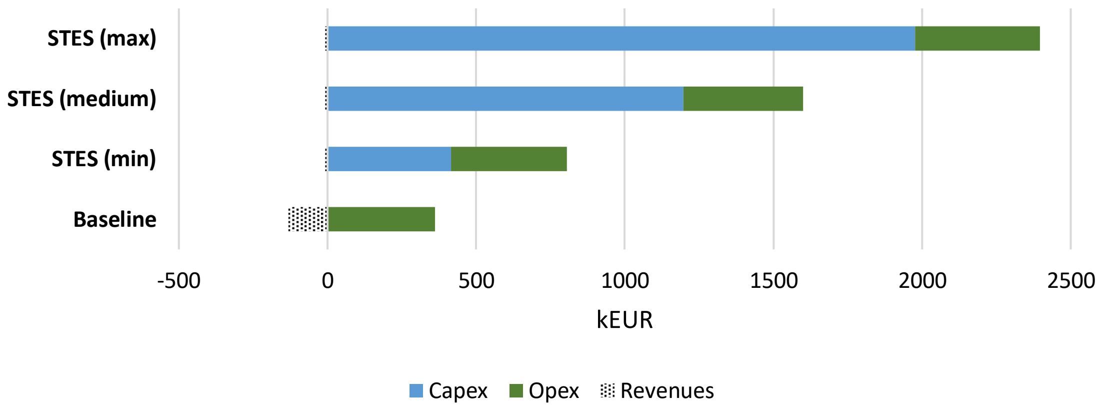

Figure 15: Comparative LCC results of the Sonnenplatz STES use case

Results point out that the innovative solutions are still not competitive with respect to the baseline from an economic perspective. Indeed, the high *Capex* expense for this technology raises the final costs of innovative configurations, making them less sustainable than the benchmark. In this sense, despite the difference between the currently available info, which led to a sensitivity between higher and lower costs reported in the literature, the impact on the final cost is the same. Moreover, at this stage of art, STES scenarios do not enable a remarkable revenue, which is still very low. On the other hand, *Opex* costs are almost similar between all the compared configurations.

The breakdown analysis of Figure 16 reports the contribution cost analysis for Sonnenplatz STES scenarios. In particular, the most relevant entry cost for STES novel solutions is represented by the very high *Capex required for the Heat Pump*. As already observed, the cost variability of this equipment is one of the limitations of the present assessment, which is mitigated by the applied sensitivity analysis (max, average and min cost scenarios).

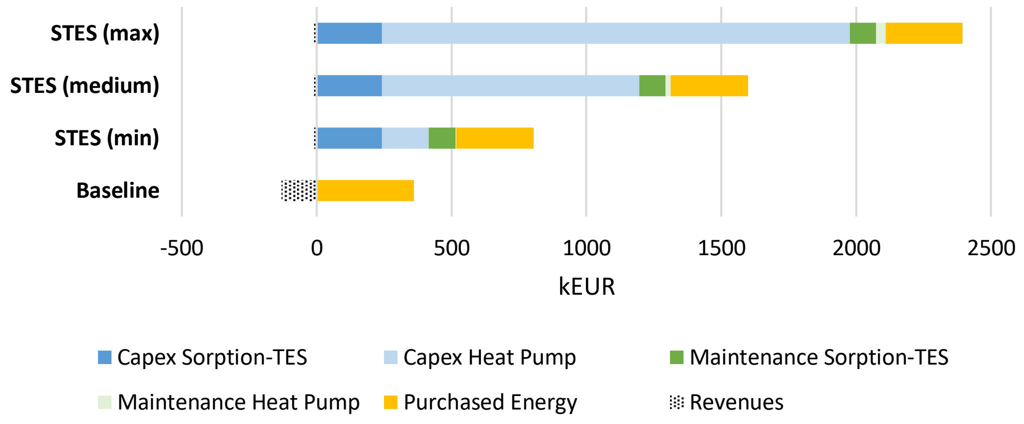

Figure 16: Hotspot analysis on LCC results of the Sonnenplatz STES use case

Novel STES configurations also includes the same share of *Capex for the Sorption-TES* (about 2500 k€), which is close to the cost amount for *Purchased energy* (around 2300 k€). *Maintenance expenses* are quite low, while major revenues are only observed for the baseline scenarios.

In conclusion, the Sonnenplatz STES new configurations, at this stage of art, are not economically viable nor convenient concerning baseline, because of higher costs and no revenues: to improve their viability and sustainability, an increase in the revenue incomes and the implementation of the Heat Pump costs are suggested, so as to reduce the associated expenditures with their provision and installation.

To better express the obtained results are also described in terms of the Yearly Delta between the project Opex + Revenues, and the same quantity normalised for the number of users expressed as the sum of households (5), office (1) and hotel (1) in the buildings which are part of the assessed business case. As evident from the data reported in the following table, the investment is not paid back in any of the analysed analyses in the present hypothesis. Even with the hypothesis of minimum cost of the Heat Pumps, implementating this Scenario would enhance the yearly expenses by a quantity of 4545 EUR.

Table 5.4: Calculation of the Investment Payback time for the Scenarios investigated in business case 2.

Scenario	Cape/year (€/year)	Opex + revenues/year (€/year)	Delta Project vs. Baseline (€/year)	Delta Capex + Opex Project vs. Baseline (€/year per user)	pay back time (years)
Baseline	0	9171			n.a
STES (max)	79.043	16420	+7.248	+13.637	Not payed back
STES (min)	16.643	15172	+6.000	+4.545	Not payed back
STES (medium)	47.843	15.796	+6.624	+9.091	Not payed back

5.3 Modular Heat Pump with short-term storage

5.3.1 Goal and scope

Goal: The Goal of the analysis is to evaluate the economic impacts of implementing Modular Heat Pumps with PCM Storage in the Sonnenplatz district. A comparative perspective is adopted between a Baseline and the project Scenario to provide insights into the economic viability over a 25-year period.

System Boundaries: The LCC analysis will focus on the financial aspects of the energy district, including CAPEX, OPEX, and revenues, from the supply of new equipments and its use for the reference period. System decommissioning is excluded.

Functional Unit: The functional unit for this assessment is defined as the total energy consumed and produced by the district over 25 years.

Geographical Scope: as per LCA

Temporal Scope Assumptions and Limitations: as per business case 1 and 2.

5.3.2 Inventories

Table 5.5: LCC Inventory Table of Sonnenplatz'Baseline'and 'Heat Pumps with PCM' (HPsPCM) Scenarios

Flow	Baseline Scenario	HPsPCM Scenario	Unit	Note/ Data source
N° Biomass Boilers (500 kW)	1	-	-	(500 kW)
N° Biomass Boilers (125 kW)	1	-	-	(125 kW)
N° Gas Fired Boiler (500 kW)	1	-	-	(500 kW)
Lifespan of the Boilers	15	-	-	
Heating Capacity HPsPCM Module	-	10	kW	A module includes 8 Heat pumps (1.25 kW) and it is paired with 2 latent storage units (PCM RT55), with a total capacity of 2.4 kWh
Life-span of the HPsPCM Module		20	years	
N° of HPsPCM Modules needed	-	26		Calculated by AIT assuming a conservative value of the heating capacity of a single Heat Pump equal to 1.1 KW
Capex				
Initial Capex Boilers	281.838	-	EUR	ref
Total Capex, Boilers, 25 years	469.730	-	EUR	Calculated from Initial Capex multiplied per the ratio between the Reference period and technology Life span (25/15=1.67)
Initial Capex HPsPCM	-	374.400 (Equipment) 40.768 (Installaton)		Primary data from OCHSNER: 17500 EUR + 480 EUR for the installation of 1 Module.. Total Capex for 26 Modules = Cost of 1*26 modules with a 20% discount.
Total Capex HPsPCM	-	518.960	EUR	Calculated from Initial Capex multiplied per the ratio between the Reference period and technology Life span (25/20=1.25)
Opex				

Maintenance Boilers	11.743	-)	EUR	2.5% of the Equipment Cost
Maintenance HPsPCM	-	52000 (Replacements) 249600 (Labour)	Eur	Primary data from OCHSNER: Replacements:2500 EUR and Labour 12000 EUR per 1 Module. 20% discount applied for 26 Modules.
Total Cost for energy	2.789.305	1.549.126	Eur	See Annex 9.2.3
Revenues				
Total Revenues	505.961	505.961	Eur	PV to the grid; See Annex Annex 9.2.3

5.3.3 Impact Assessment

This section discusses the economic impact analysis on the Modular Heat Pump for the Sonnenplatz (Großschönau, AT) district, the 3rd and last use case of the HYPERGRYD project. The configuration is characterised by a Modular Heat Pump with a short-term storage system. Figure 17 reports the global results of the LCC study for this 3rd use case.

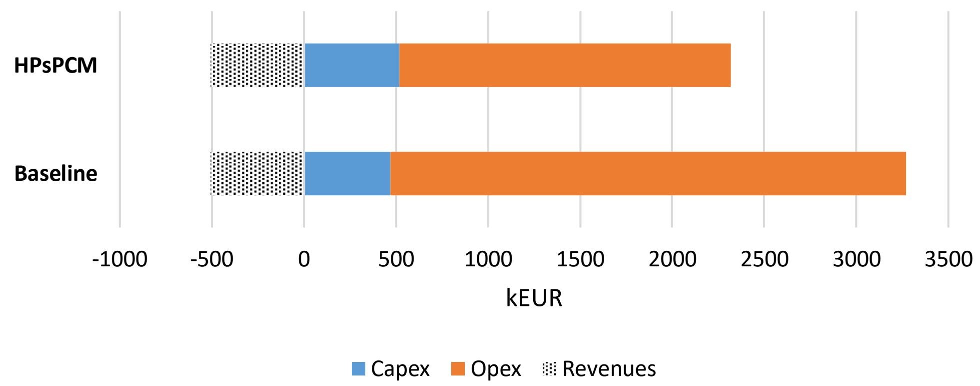

Figure 17: Comparative LCC results of the Sonnenplatz Modular Heat Pump use case

The graph clearly remarks that the costs for the baseline scenario are higher than those required in the innovative HPsPCM system: indeed, the total cost for the baseline is around 3350 k€, while those for the HYPERGRYD solution are 2300 k€. Both scenarios enable a quite good value for *Revenues* (500 k€) and have almost similar amount of *Capex* (around 500 k€), so the main difference is the *Operative cost*, which is positively lower for the novel solutions.

To examine the associated costs, in more detail, the breakdown analysis in Figure 18 reports the contribution of each entry to the final costs.

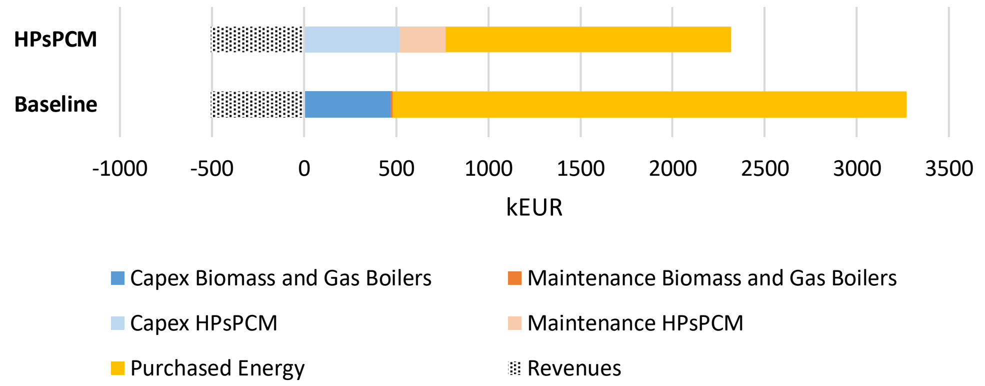

Figure 18: Hotspot analysis on LCC results of the Sonnenplatz Modular Heat Pump use case

The hotspot analysis points out that the most relevant cost contribution is due to the *Purchased energy*, which has the largest cost share in both scenarios. Then, the *Capex for biomass and gas boilers* is also high for the baseline scenario and very close to the *Capex for HPsPCM* required in the HYPERGRYD configuration. The cost for *Maintenance* is minor or null, and, as said, the selected technologies enable the same *revenues* in both scenarios.

In conclusion, the Modular Heat Pump Sonnenplatz configuration with the HPsPCM system is proven to be sustainable from an economic point of view. It is also more convenient than the baseline scenario because it allows for a reduction (-31%) of associated costs and it enables the same revenue value for the electricity sold to the grid.

In order to better express the economic viability of the two project Scenarios, the Investment payback time was calculated and reported in the next Table. The payback in the hypothesis made in this study and with the present analysis system boundaries is 13 years, which is longer than the case of business case 1, but still feasible.

Table 5.6: Calculation of the Investment Payback time for the Scenarios investigated in business case 3.

Scenario	Opex – revenues (€)	Opex - revenues/year (€/year)	Delta Project vs. Baseline (€/year)	pay back time (years)
Baseline	2.295.088	91.804	n.a	n.a
HPsPCM	1.292.765	51.711	-40.093	13

6 S-LCA of HYPERGRYD technologies

The present chapter describes the social life cycle assessment (S-LCA) study applied to the HYPERGRYD technologies. ARCbcn conducts the analysis, and it adheres to the methodological sheets developed by UNEP, initially introduced in 2013 and updated in its latest version released in 2021 (UNEP, 2020). These sheets outline the definition of the subcategories of impact and suggest sources of information and reference points. Also, the methodology used by Ciroth and Franze (A.Ciroth, 2011) and more recent works (E.Borri, 2024) and (M. C. Caruso, 2022) are considered.

The following paragraphs, according to the S-LCA iterative phases, outline the main methodological choices behind the study and its most remarkable outcomes.

6.1 Goal and Scope

The current S-LCA approach follows the steps implemented by Caruso et al. (M. C. Caruso, 2022), derived from the structure of the (ISO14044, 2006) of Life Cycle Assessment. The steps are the following, as from Figure 19:

- *Step 1*: Definition of the objectives and system boundaries, and selection of the stakeholders and the subcategories of impact.
- *Step 2*: Conduction of the inventory data collection at the organisational and country scale.
- *Step 3*: Evaluation of the impact assessment on the society stakeholders, based on the data collected in the inventory step.
- *Step 4*: Interpretation of the results obtained.

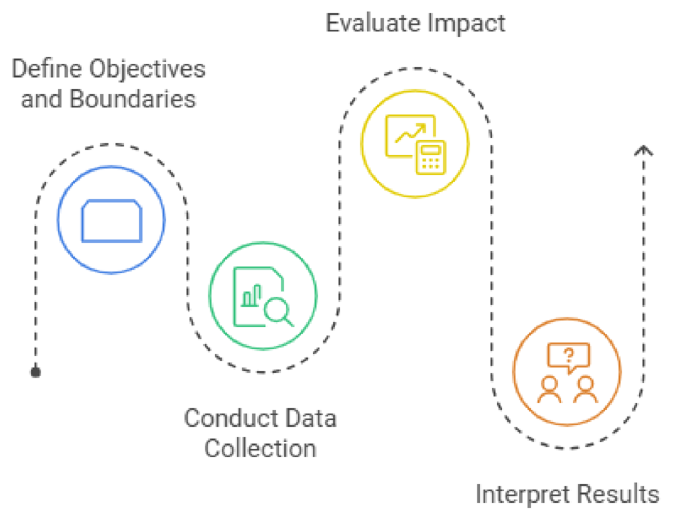

Figure 19. Steps in the S-LCA process

The present S-LCA aims to provide valuable insights into the social hotspots of the three main technologies developed in the HYPERGRYD project. This information will be used alongside the data from the LCA and LCC in the following steps to select the most suitable system for each situation. Moreover, the *scope* of the study includes selecting the functional unit and the RES-based enabling technology. Indeed, the **functional unit** for this S-LCA is defined as:

the Renewable Energy Sources (RES)-based enabling technology developed within the HYPERGRYD project.

Regarding the **study boundaries**, this assessment focuses exclusively on the technology's *development phase*, with system boundaries limited to research, design, and prototype development activities. This targeted assessment ensures a comprehensive evaluation of the social impacts linked to creating and advancing the RES-based enabling technology.

According to (Traverso, 2021), the stakeholders included in the analysis are: *Workers, Local Communities, Value -Chain Actors, Consumers* and *Society*, while the stakeholder group *Children* is excluded from this assessment due to the absence of direct or significant social impacts on this demographic throughout the technology's development phase.

The stakeholder framework provides a foundation for analysing social impacts and understanding the relationship between production processes and societal dynamics. Here's an explanation of each stakeholder category:

- ***Workers***: This group includes people directly involved in the production process, such as employees, contractors, and temporary labour. The focus is on evaluating their working conditions, rights, and well-being, including safety, fair treatment, and access to benefits. Assessing this group ensures that businesses adhere to ethical labour practices and promote worker welfare;
- ***Local Communities***: These communities are geographically close to or directly affected by production activities. Impacts on this group can include access to resources, environmental and social well-being, and overall community development;
- ***Value-Chain Actors***: This group includes suppliers, distributors, and other businesses involved in the product's lifecycle. The focus on fair and ethical practices, like transparency, working fairly with others, and responsibly sharing benefits. This category emphasizes the importance of accountability and ethical business relationships in the supply chain;
- ***Consumers***: Consumers are the end-users of the product or service. For them, assessments focus is on measuring aspects such as product safety, information transparency, and the social implications of consumption;
- ***Society***: This broad category examines how production and consumption affect society. It includes things like public policies, social development, and economic trends. Measuring these impacts helps ensure production supports sustainability and good governance at a larger scale.

After the stakeholder definition, the selection of applicable sub-categories is performed. In this study, 34 subcategories have been identified and analysed, and are presented in Table 6.1: they are related with the Impact Categories, which are Working Conditions (WC), Health & Safety (HS), Human Rights (HR), Socio-Economic Repercussions (SER), Indigenous Rights (IR), and Governance (G).

Table 6.1: Stakeholders, subcategories and Impact Categories

Stakeholder	Subcategory	WC	HS	HR	SER	IR	G
LOCAL COMMUNITY	Access To Immaterial Resources	(x)	(x)	x	x	(x)	x
	Access To Material Resources	-	(x)	x	x	x	(x)
	Community Engagement	(x)	x	(x)	x	(x)	x
	Cultural Heritage	-	-	(x)	x	x	x
	Delocalization And Migration	x	(x)	(x)	x	x	(x)
	Local Employment	x	(x)	(x)	x	x	x
	Safe And Healthy Living Conditions	x	x	x	x	(x)	(x)
	Secure Living Conditions	(x)	x	x	(x)	(x)	(x)
VALUE CHAIN ACTORS	Fair Competition	x	x	x	x	-	x
	Promoting Social Responsibility	x	x	x	(x)	(x)	x
	Respect Of Intellectual Property Rights	(x)	-	-	x	-	x
	Supplier Relationships	(x)	(x)	(x)	x	-	x
	Wealth Distribution	x	(x)	x	x	(x)	x
CONSUMER	Consumer Privacy	-	-	x	(x)	(x)	x
	End-Of-Life Responsibility	x	x	x	x	x	x
	Feedback Mechanism	(x)	(x)	x	x	-	x
	Health And Safety	-	x	(x)	x	-	x
	Privacy	-	-	x	(x)	(x)	x
	Transparency	(x)	x	x	x	(x)	x
WORKERS	Child Labour	x	x	x	x	x	x
	Employment Relationship	x	x	x	(x)	(x)	-
	Equal Opportunities/ Discrimination	x	x	x	x	x	x
	Fair Salary	x	(x)	x	x	-	x
	Forced Labour	x	x	x	x	x	x
	Freedom Of Association And Collective Bargaining	x	x	x	x	x	x
	Health And Safety	x	x	x	x	-	x
	Sexual Harassment	x	x	x	(x)	x	-
	Social Benefit/Social Security	x	x	x	x	x	(x)
SOCIETY	Contribution To Economic Development	x	(x)	(x)	x	(x)	x
	Corruption	x	x	x	x	x	x
	Poverty Allevation	x	(x)	x	x	x	(x)
	Prevention And Mitigation Of Conflicts	(x)	x	x	x	x	x
	Public Commitment To Sustainability Issues	(x)	(x)	-	(x)	-	x
	Technology Development	x	x	(x)	x	-	x

The Performance assessments scores are expressed in values between 1 (best performance) and 6, (worst performance). Once transformed to Impact Categories, values of 1 expressed positive effects and values of 6 express negative effects (M. C. Caruso, 2022).

This study faces several **limitations** inherent to the application of Social Life Cycle Assessment (S-LCA) to the development of the RES-based enabling technology within the HYPERGRYD project. One major challenge is the difference in *stakeholder perspectives* when evaluating social impacts. For example, high wages may be seen as beneficial for workers but could lead to increased product costs, which may negatively impact consumers. These contrasting viewpoints create challenges in interpreting social performance results and highlight the need for more refined assessment frameworks that balance stakeholder interests for a more holistic understanding of social impacts.

Another significant limitation arises from the use of different *scales of assessment*, as data were collected at both the country and organizational levels. This discrepancy complicates the aggregation and comparison of results, potentially leading to inconsistencies in the assessment outcomes.

Additionally, the assignment of a *functional unit* remains a challenge in S-LCA, as it is not feasible to base social impact evaluations on standard physical units (e.g., kWh of energy or kg of product) commonly used in Life Cycle Assessment (LCA) or Life Cycle Costing (LCC), especially during the development phase of enabling technologies.

The study also encountered difficulties in establishing a *baseline for social performance*. This challenge arises from the complexity of comparing existing solutions to innovative technologies and the absence of clear thresholds for performance assessments (e.g., determining what level of child labour constitutes the "worst" performance score).

Moreover, due to the *novelty of the RES-based enabling technology*, it was difficult to obtain reliable and comprehensive data from other life cycle stages, such as raw material extraction, usage, and end-of-life management. Since the technology is still in the development phase, these data are either unavailable or highly uncertain, limiting the ability to fully assess social impacts across the entire product life cycle.

Settled the premises, boundaries (physical and methodological) and parameters of the S-LCA study, the analysis continued with data gathering and LCI building-up.

6.2 Inventories

The data inventory for this S-LCA is structured across two levels, following a combined approach: *country level* and *organizational level*. Indeed:

- *Country-Level Inventory* is primarily based on country-specific indicators sourced from official reports and reputable NGOs, ensuring reliable and widely recognized data. The data sources used for each stakeholder is presented in Table 6.2:

Table 6.2: Data sources for the S-LCA country level inventory

Impact category	Unit
LOCAL COMMUNITY	World Bank (WorldBank, 2025)
	Article 19 (Article19, 2025)
	Organisation for Economic Co-operation and Development (OECD) (OECD, 2025)
	Migrant Integration Policy Index (MIPEX, 2025)
	Eurostat – European Commission (EUROSTAT, 2025)
	Our World in Data (OWID, 2025)
	World Justice Project (WJP, 2025)
	Vision of Humanity (Humanity, 2025)
VALUE-CHAIN ACTORS	Competition Policy – European Commission (Competition, 2025)
CONSUMER	European Environment Agency (EEA, 2025)
	UN Trade and Development (UNCTAD, 2025)
WORKERS	World Bank (WorldBank, 2025)
	UNICEF (UNICEF, 2025)
	World Economic Forum (WEF, 2025)
	Eurostat – European Commission (EUROSTAT, 2025)
	Walk Free (WalkFree, 2025)
SOCIETY	*Transparency International* (Transparency, 2025)

Impact category	Unit
	Eurostat – European Commission (EUROSTAT, 2025)

- *Organizational-Level Inventory* is conducted through a questionnaire distributed to representatives from all partner organizations involved in the project, providing tailored and context-specific information. The questionnaire is mainly based on the level of agreement with around 50 positive -oriented statements related to all the stakeholders, ranging from «*strongly agree*» to «*strongly disagree*», alongside with multiple choice questions.

The combination of these two levels offers a balanced approach. The country-level data provides an objective foundation, while the organizational-level data offers insights specific to the project participants. This dual approach ensures both broad contextual relevance and precise organizational applicability, addressing potential gaps between general indicators and the unique characteristics of individual organizations.

The complete inventory questionnaire for S-LCA is presented in Appendix 9.3.

6.3 Impact Assessment

The present S-LCA study applied a certain impact assessment methodology for the calculation of potential socio-economic impacts of the HYPERGRYD solutions, taking into account a combination of country- and organizational-level data. This information is opportunely processes before obtaining the final social performance, as described in the following methodological section, specific for HYPERGRYD project.

6.3.1 Methodological premise

Data collected from the inventory sources is transformed with a **performance assessment** (PA) into a **standardized reference 1-to-6 scale** (1: best, 6: worst) Since the input data varies across indicators, multiple transformation methods are employed to align the data to this scale according to the following methodology.

Processing Questionnaire Data

Responses from the organizational-level questionnaire, using an «agree/disagree» system," are converted PA scores. Specifically:

- «strongly agree»is assigned a PA score of 1 ;
- «strongly disagree» is assigned a PA score of 6 ;
- Intermediate responses are interpolated proportionally.

Processing Quantitative Country-Level Data

Quantitative indicators from country-level sources are transformed into PA scores using one of the following methods:

– *Reference Point Method*: If a reference point exists, it is assigned a PA score of 3.5. Other values are then adjusted by interpolating between the reference point and the most distant value in the dataset ;

- *Minimum-Maximum Scale Method*: For data with a defined range:
    - If the positive impact increases with higher values, the minimum is assigned a PA score of 6 and the maximum a score of 1 ;
    - If the positive impact decreases with higher values, the reverse is applied ;
    - Intermediate values are interpolated linearly.
- *No Reference or Scale*: When no reference point or clear scale is available, the midpoint is set to the average value for European Union member states, and scores are derived relative to this average.

After calculating the Performance Assessment (PA) at both the country and organisational levels, the overall PA for the functional unit is determined by evaluating the three main technologies developed within the project. A *multi-weight assignment* process is applied to account for the varying levels of partner involvement in the development of each technology to aggregate the PA values across these layers. Indeed, for each development within a layer, *partner-specific weights* are assigned based on their rôle, i.e.:

- A weight of 1 is assigned to the *main development partner*, reflecting their leading role and direct influence on the technology's design and implementation;
- A weight of 0.5 is assigned to *collaborators* who provide significant support but are not directly leading the development;
- Partners with *general or coordination roles* are assigned lower weights of 5% and 10%, respectively, acknowledging their indirect contributions to the technology without hands-on involvement in core development tasks.

These weight values were carefully established following extensive internal discussions to ensure they accurately represent each partner's actual impact and responsibility within the project. This structured approach guarantees a balanced and fair distribution of influence in the overall social performance assessment, reinforcing the transparency and credibility of the results.

Finally, to calculate the total PA for the project, the results from each technology layer are combined using weighted contributions: 65% for Layer 1 (RES-based enabling technologies), 20% for Layer 2 (HYPERGRYD ICT tools), and 15% for Layer 3 (integrated platform and services).

To enhance the evaluation of the project's social impact, the performance assessment is analysed through six defined Social Impact Categories (ICs), as introduced in (A.Ciroth, 2011). These categories include Working Conditions (WC), Health & Safety (HS), Human Rights (HR), Socio-Economic Repercussions (SER), Indigenous Rights (IR), and Governance (G). Each subcategory is evaluated for its relationship with these impact categories, which can be classified as strong, weak, or no relationship. As seen in Table 6.1, strong relationships are marked with an "x," weak relationships with "(x)," and no relationship with a "-".

The subcategories do not have uniform connections with all impact categories. To account for this variation, a transformation from PA to IA has been designed and presented in Table 6.3, ensuring that each subcategory is appropriately weighted according to its relevance to each impact category (M. C. Caruso, 2022). Depending on the aggregated ∑IC, thresholds are defined to adjust the PA score, allowing for an increment or decrement in the final IA score. For instance, a subcategory with a high PA score but strong relationships across all impact categories may result in a lower IA score to reflect its greater overall impact.

Table 6.3: Transformation rules from PA to IA. Each cell represents the new IA score

PA	∑IC<2	2<∑IC<4	4<∑IC<5	5<∑IC<6
PA=1	2	1	1	1
PA=2	3	2	1	1
PA=3	4	3	3	2
PA=4	3	4	4	5
PA=5	4	5	6	6
PA=6	5	6	6	6

6.3.2 Results for S-LCA

After this methodological premise, the impact assessment for S-LCA study in HYPERGRYD project is discussed on two different levels:

- *Performance assessment of the involved countries*, which acts as a sensitivity analysis on the social performance of the countries involved in the project;
- *Impact assessment of HYPERGRYD technologies*, which focuses on the potential socio-economic impacts of the project-developed solutions.

Both analyses are discussed in the next sections of the document.

6.3.2.1 Performance assessment of the involved countries

The country-level performance assessment the present S-LCA study aims to evaluate and compare the social performance of the countries involved in the project, based on various socio-economic indicators reported in Appendix 9.4 of this document. These countries are **Austria, Belgium, Germany, Italy, Poland, Spain** and **Sweden**. The assessment considers the average marks assigned to each country across multiple dimensions relevant to key stakeholders, including Workers, Local Communities, Consumers, and Society at large. The evaluation provides insights into how countries are performing in terms of social sustainability and highlights areas where improvements are needed. It is also useful to compare and visualize results that will be used to calculate the Impact Assessment for the HYPERGRYD solutions.

In the subsequent sections, the average marks for each stakeholder category will be presented through graphical plots. These plots illustrate the comparative performance of countries, offering a clear visual representation of their strengths and weaknesses in addressing social impacts. This analysis is crucial for identifying best practices and areas requiring policy intervention to enhance social outcomes globally.

<u>Local Community</u>

The performance assessment for the **Local Community** stakeholder indicates significant impacts across all countries participating in the project. The impact values (pictured in Figure 20)range from 2.3 in Sweden to 3.4 in Spain. While these findings suggest that there is room for improvement, they also indicate that the overall impact on local communities at the country level is relatively moderate.

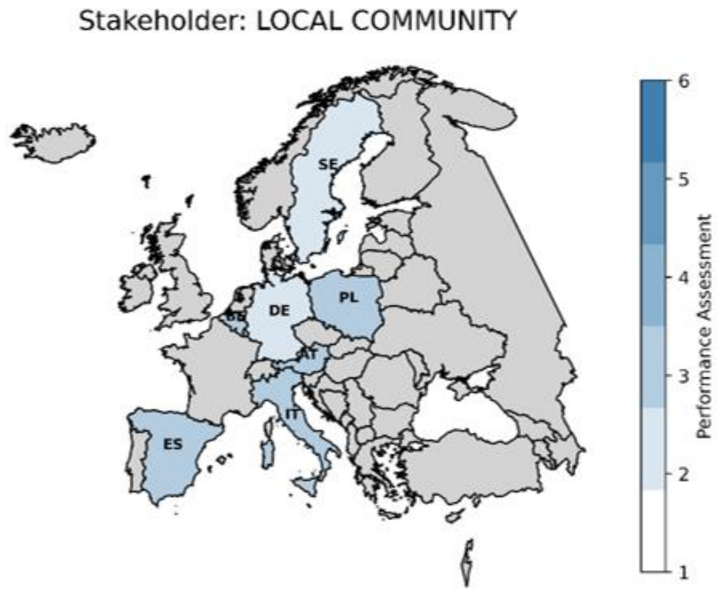

Figure 20. Performance Assessment per countries to the stakeholder Local Community

Consumer

The performance assessment of impacts on the **Consumer** stakeholder indicates consistently low values across the seven countries involved in the project. Specifically, the average impact scores range between 1 and 2, which represents the best-case scenario according to the rating scale employed, where 1 signifies the least negative impact and 6 signifies the most negative impact. This uniform low impact suggests that the project has minimal to no negative effects on consumers across all evaluated countries. The map presented in *Figure 21* visually illustrates these findings, highlighting the range of impact values across the assessed countries.

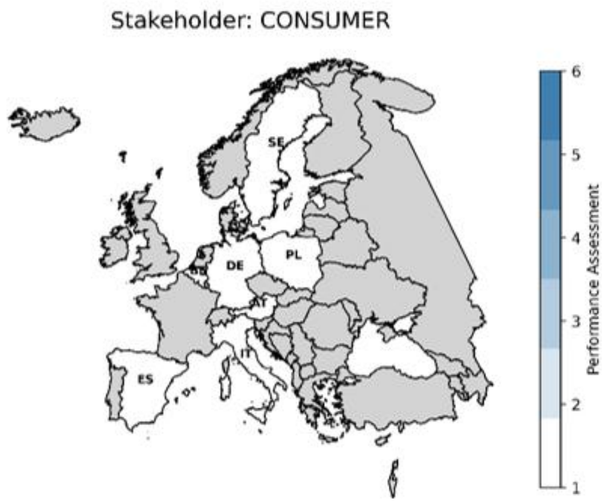

Figure 21. Performance Assessment per countries to the stakeholder Consumer

The consistently favourable ratings across all countries underscore the project's effectiveness at the national level in safeguarding consumer interests, showcasing a high level of social responsibility towards this stakeholder group.

Worker

The performance assessment for the **Worker** stakeholder reveals substantial impacts across all participating countries, indicating negative effects according to the applied scale. Notably, Germany, Sweden, and Belgium are exceptions, with their performance assessments scoring below 3. In contrast, all other countries exhibit scores higher than 3, highlighting significant areas for improvement in worker-related impacts. Figure 22 presents a map of the assessed countries, illustrating these findings.

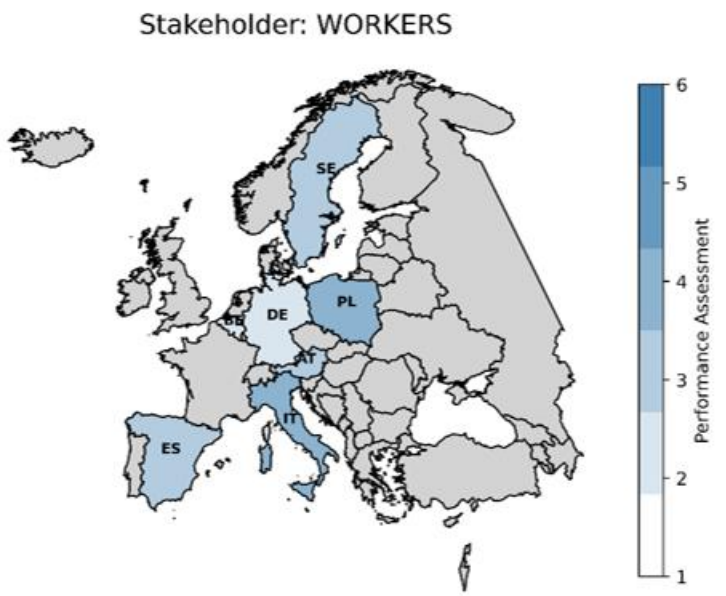

Figure 22. Performance Assessment per countries to the stakeholder Workers

Society

In the performance assessment of the **Society** stakeholder there are two clear clusters of countries. In one hand, Austria, Belgium, Germany and Sweden perform very well in the effects on this particular stakeholder, with values close to 1 in all cases. On the other hand, Italy, Poland and Spain present opportunities for enhancement in this field, with values around 3.5 in all the cases. These differences can be observed in the map presented inFigure 23.

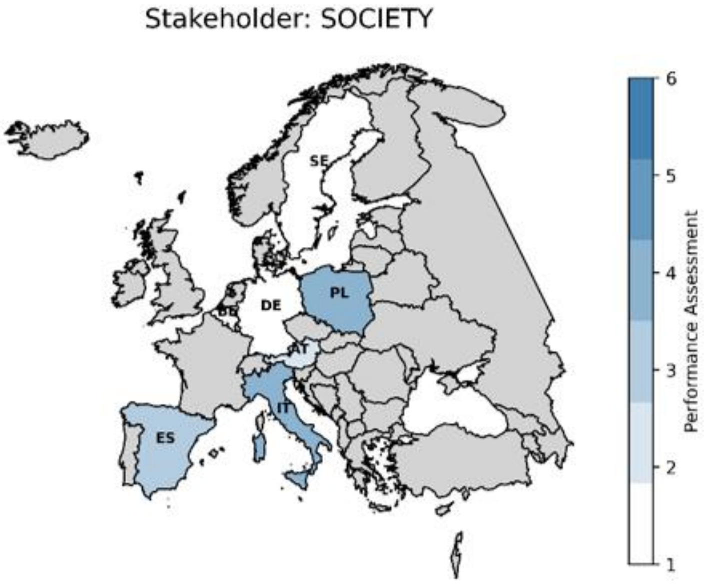

Figure 23. Performance Assessment per countries to the stakeholder Society

Value-Chain Actors

In the case of ***Value-Chain Actors***, the results are not presented because there is only one subcategory analysed, and all countries perform the best with an indicator of 1.

6.3.2.2 Impact assessment of HYPERGRYD technologies

The impact assessment (IA) of HYPERGRYD technologies is structured in three different parts: first of all, a preliminary ***overview*** is presented, then a focus on the ***stakeholder*** IA is discussed and finally the IA for ***organizations and countries*** is examined.

Overview

To provide a comprehensive overview of the impact of the technologies involved in HYPERGRYD, distribution of the Impact Assessment (IA) has been studied. This visualization has been constructed through a series of systematic steps. First, the IA values (ranging from 1 to 6) were counted for each stakeholder: these counts were then normalized to allow for comparative analysis. Following normalization, the percentage distribution for each IA value was calculated. It is important to notice that the total area represented by each stakeholder in the plot remains constant, ensuring an equitable comparison across different stakeholders.

The stakeholders considered in this assessment include *Consumers, Local Community, Society, Value Chain Actors,* and *Workers*. Each segment within the bar plot in Figure 24 corresponds to a specific stakeholder's contribution to the overall impact at each IA value, providing a clear visual representation of how impacts are distributed among different groups.

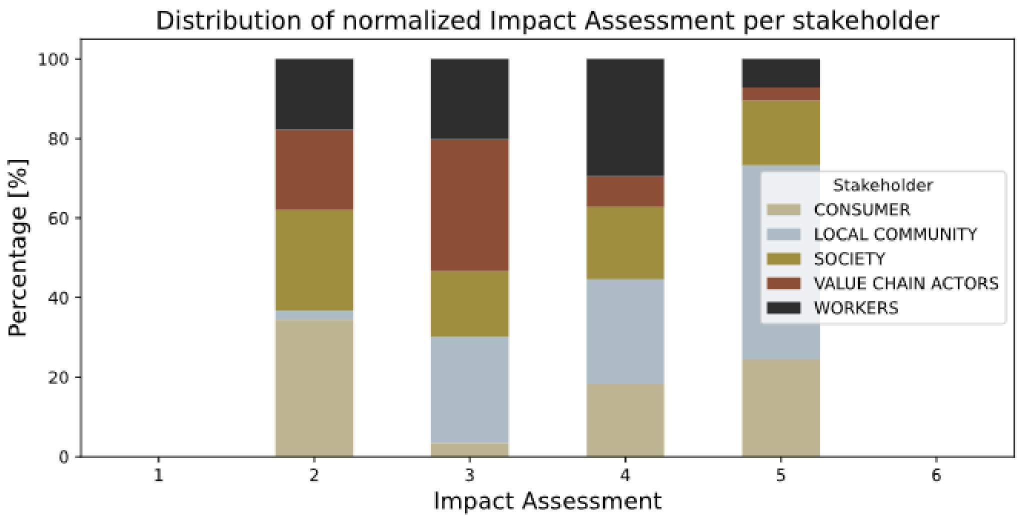

Figure 24. Distribution of the Impact Assessment per categories and stakeholders normalized

Notable differences can be observed among the stakeholders. It is important to highlight that, following the conversion from Performance Assessment (PA) to IA, there are no instances of IA values 1 and 6, which represent the best and worst possible values, respectively.

In this project, the *Consumer* stakeholder exhibits a larger percentage of IA value 2, indicating relatively better protection. However, this stakeholder also has significant proportions of IA values 4 and 5. Conversely, the *Local Community* stakeholder has the highest fraction of IA value 5 and almost no indicators at IA value 2, indicating greater vulnerability. The *Society* stakeholder shows a uniform distribution of IA values between 2 and 5, suggesting that while the impacts are not excessively negative, there is still considerable room for improvement. *Value Chain Actors* appear to be relatively well-protected, with the majority of indicators falling at IA values 2 and 3. Lastly, the *Worker* stakeholder has a more diverse distribution across all IA values, with a noticeable presence at IA value 4 and a lesser presence at IA value 5. This distribution indicates a moderate to high level of impact on *Workers*, necessitating targeted interventions to mitigate these effects.

Stakeholder Impact Assessment

Local Community

The Impact Assessment for the stakeholder ***Local Community*** is presented in Figure 25.

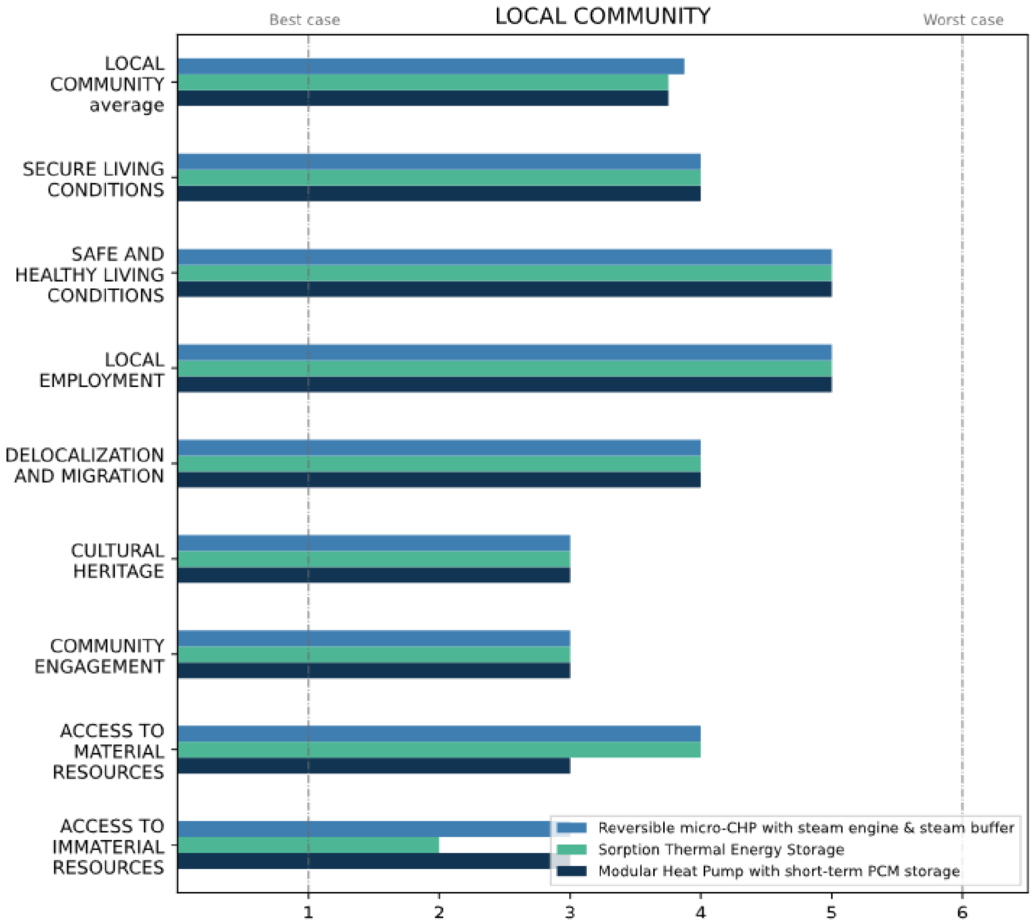

Figure 25. Impact Assessment for stakeholder Local Community

As observed, the results for the three technologies are similar across almost all subcategories, except for *Access to Material and Immaterial Resources*. In these subcategories, only three subcategories show a slightly positive impact, while the others range from slightly negative to negative impacts. The average result for all three technologies is approximately 3.5 on the Impact Assessment (IA) scale, indicating a neutral impact overall. This suggests that there is still room for improvement, particularly in the subcategories *Safe and Healthy Living Conditions* and *Local Employment*.

Value-Chain Actors

The social impact assessment for all technologies concerning the stakeholder ***Value Chain Actors*** indicates a slightly positive overall impact, with a notable positive effect in the subcategory *Respect for Intellectual Property Rights*. As illustrated in Figure 26, the results range from positive to slightly positive, with a slightly negative impact observed in the subcategory *Promotion of Social Responsibility* caused by the Reversible Micro-CHP and Modular Heat Pump technologies.

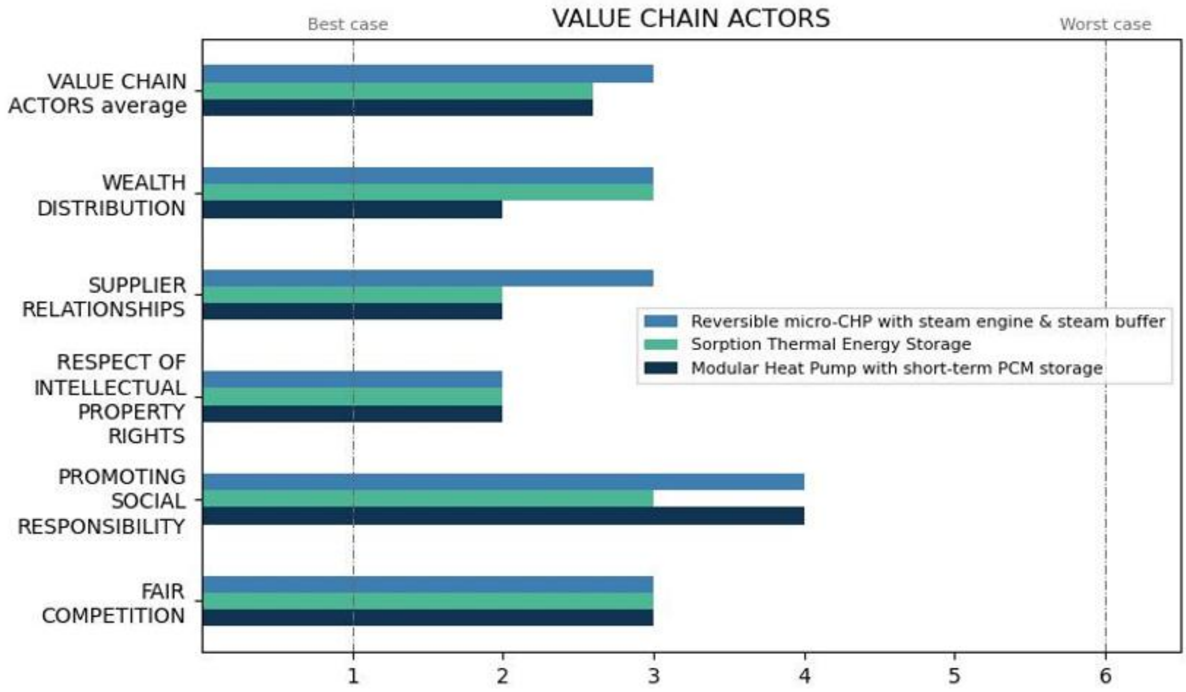

Figure 26. Impact Assessment for stakeholder Value-Chain Actors

Consumer

The social impact assessment for the stakeholder ***Consumer*** is presented in Figure 27. The three technologies demonstrate a positive impact across most subcategories. However, the subcategories *Transparency* and *End-of-life Responsibility* show slightly negative to negative impacts for all three technologies, resulting in an overall average Impact Assessment (IA) that is only slightly positive. These areas represent clear hotspots for improvement, indicating a need for targeted actions to enhance performance in these specific subcategories.

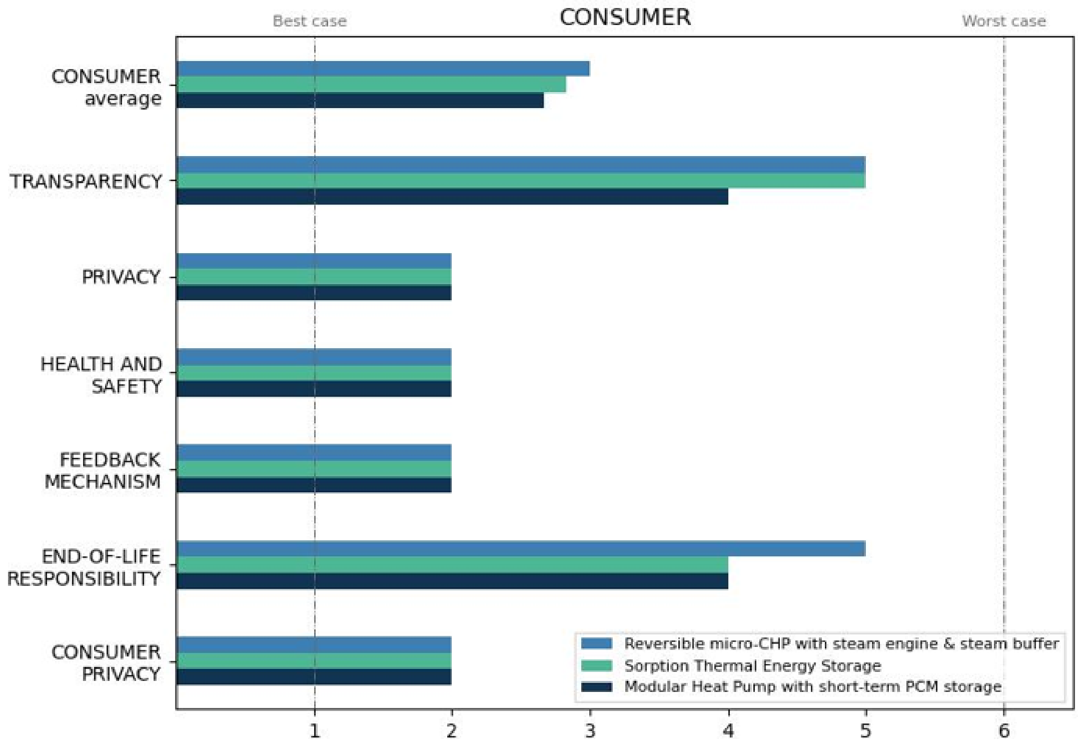

Figure 27. Impact Assessment for stakeholder Consumer

Workers

The social impact assessment for the stakeholder ***Workers*** is presented in Figure 28. This stakeholder includes the largest number of subcategories, and on average, the three technologies show a slightly positive impact. Compared to the other stakeholders assessed so far, the technologies display more variation in their impacts across subcategories. However, most impacts remain around neutral. Notably, the subcategory *Health and Safety* stands out as an area of concern, representing a clear hotspot where further improvements are necessary to ensure better outcomes for workers.

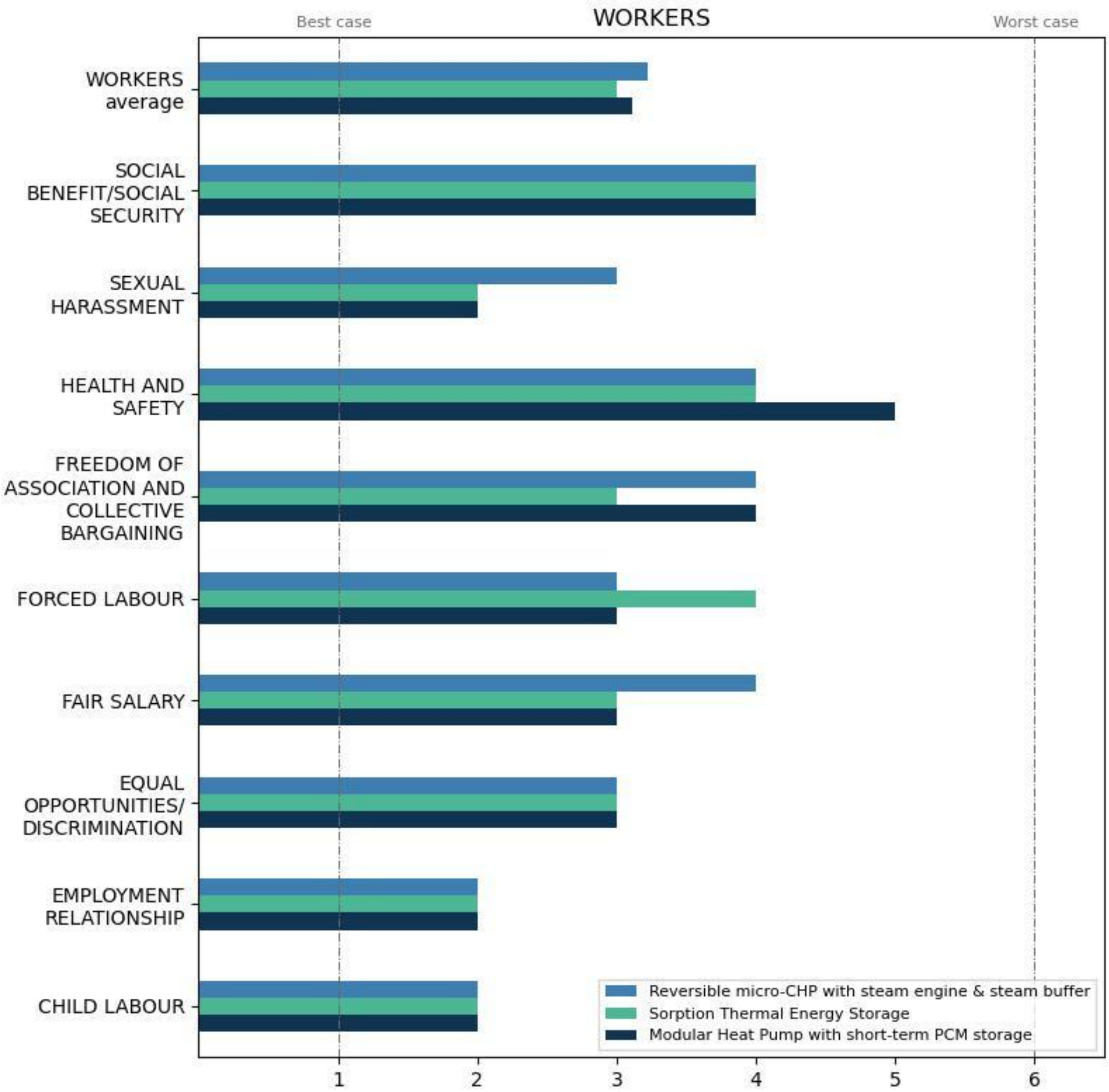

Figure 28. Impact Assessment for stakeholder Workers

Society

The social impact assessment for the stakeholder ***Society*** is presented in Figure 29. While the overall impact is slightly positive, specific subcategories, such as *Poverty Alleviation* and *Corruption*, reveal negative and slightly negative social impacts, raising areas of concern. For most other subcategories, the three technologies show positive to slightly positive impacts. However, the Modular Heat Pump presents a slightly negative impact in the subcategory *Prevention and Mitigation of Conflicts*. These results highlight key areas where improvements are necessary, particularly in addressing systemic societal challenges such as poverty reduction and governance integrity. Enhanced focus on these hotspots could substantially improve the overall societal performance of these technologies.

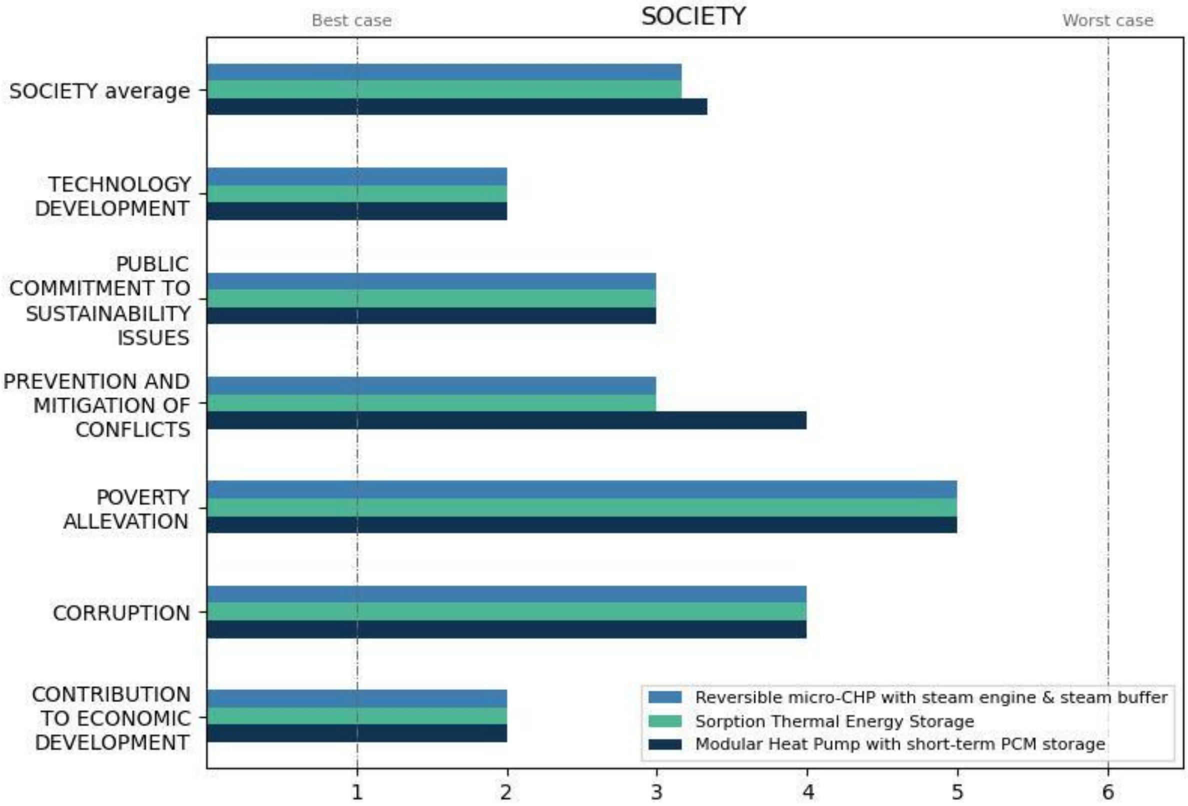

Figure 29. Impact Assessment for stakeholder Society

Impact Assessment for organizations and countries

As previously explained, social impact assessment is influenced by a combination of country-specific characteristics and regulations, as well as internal organizational procedures. Figure 30 illustrates the **Impact Assessment** (IA) scores for the three technologies, highlighting the contributions of both country-level factors and organizational practices. Due to the conversion from **Performance Assessment** (PA) to IA, the results for the three technologies are relatively similar, with only minor differences.

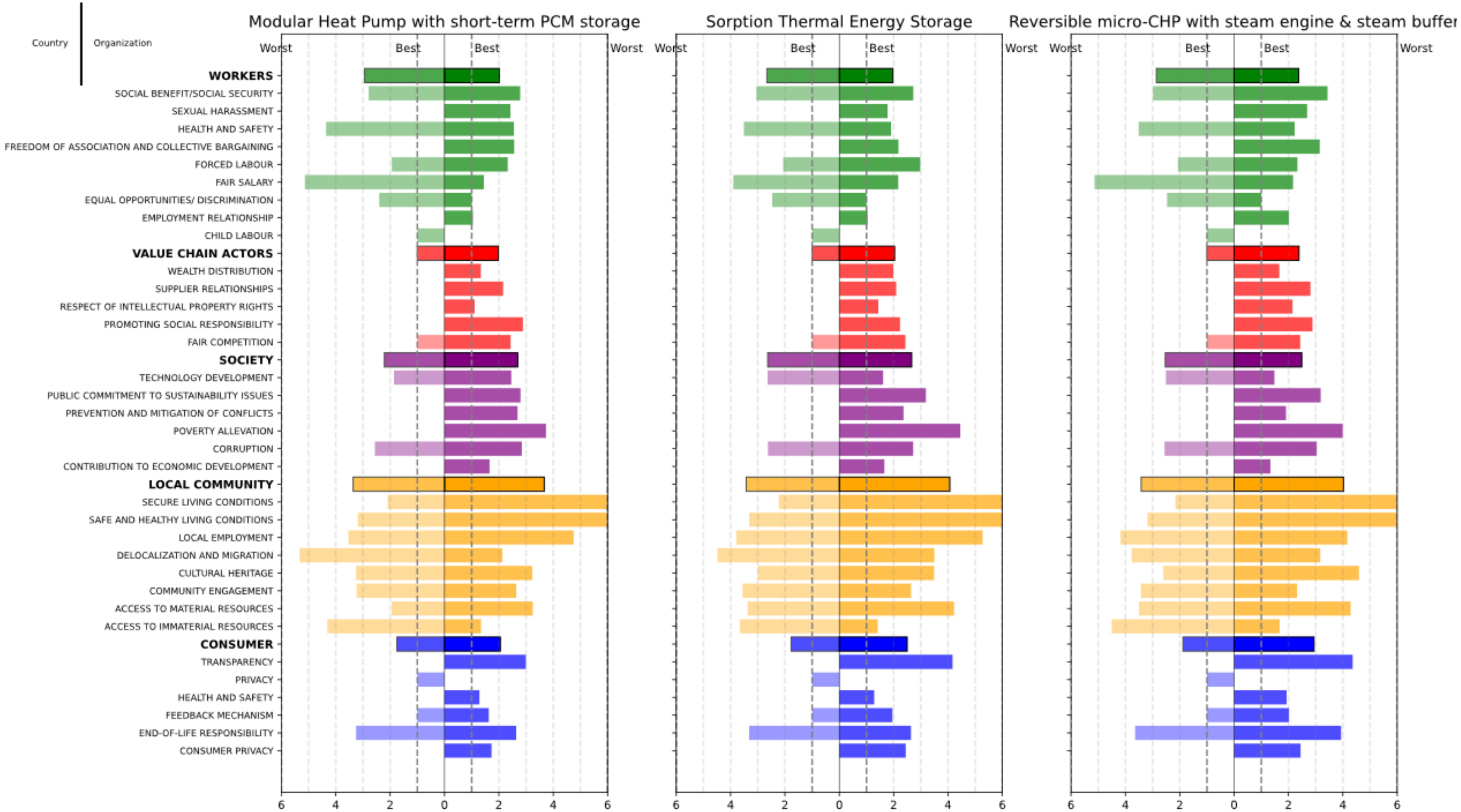

Figure 30. Comparison of the IA of the three HYPERGRYD technologies

For the ***Workers*** stakeholder group, the overall social impact at the country level is slightly positive, while at the organizational level it is consistently positive. However, a significant hotspot is identified across all technologies regarding *Fair Salaries*, which shows a strongly negative impact. This is partially offset by the positive contributions of organizational practices within this subcategory. Overall, organizations demonstrate better performance compared to their respective countries for this stakeholder, with positive impacts across all technologies.

The social impact for ***Value Chain Actors*** is generally positive, with only one subcategory at the country level presenting a minor concern. Similarly, the impact on ***Society*** is positive both at the organizational and country levels, with only two subcategories at the country level showing potential issues. A major hotspot observed across all technologies is *Poverty Alleviation*, which has a varying degree of negative impact.

The impacts on the ***Local Community*** are the most negative among all stakeholder groups, with overall negative or slightly negative scores in all cases. The primary hotspots are tied to organizational performance, specifically in *Secure Living Conditions* and *Safe and Healthy Living Conditions*. Additional concerns include *Local Employment* and *Access to Material Resources*, which also emerge as potential hotspots at the country level.

Finally, the impacts on the ***Consumer*** stakeholder group are positive at both the country and organizational levels. However, there are notable potential hotspots. At the organizational level, issues with *Transparency* are identified for the Sorption Thermal Energy Storage and Reversible Micro-CHP technologies. Additionally, at the country level, concerns are raised regarding *End-of-Life Responsibility*.

In conclusion, while some positive trends are evident, significant hotspots require targeted attention to improve social sustainability across specific subcategories and stakeholder groups.

6.4 Main conclusions for S-LCA

The Social Life Cycle Assessment (S-LCA) performed for HYPERGRYD project has provided valuable insights into the social impacts associated with the development of the Renewable Energy Sources (RES)-based enabling technology within the HYPERGRYD project. By evaluating the technology across various stakeholder groups—*Workers, Local Communities, Value Chain Actors, Consumers,* and *Society*—the study identified both positive contributions and critical social hotspots. Notably, the project demonstrated positive social performance in areas such as consumer safety and value chain ethics, while areas like worker health and safety, fair salaries, and local community well-being require further attention. The multi-layered analysis, covering the RES technologies, ICT tools, and integrated platform, allowed for a comprehensive understanding of the social dynamics throughout the technology development process.

However, the assessment also highlighted several methodological and data-related challenges that limit the full capture of social impacts. These include the difficulty in balancing diverse stakeholder perspectives, handling different scales of assessment, and the challenge of assigning a suitable functional unit during the development phase. Additionally, the lack of comprehensive data on the raw material sourcing, usage, and end-of-life stages due to the novelty of the technology restricted the scope of the assessment. Addressing these limitations in future research—through more refined frameworks, improved data collection across life cycle stages, and stakeholder engagement—will be essential for enhancing the accuracy and depth of S-LCA in evaluating emerging energy technologies.

7 Conclusions

7.1 Main conclusions for LCA

- Business case 1: The comparative LCA study for Envipark business case confirms that the introduction of innovative HYPERGRYD solutions is proficient in terms of environmental impacts of the district area. Indeed, all impact indicators reports a reduction of burdens associated with the implementation of the innovative scenarios. combining the CHP novel system with HRES technology enables a reduction of the impacts from a minimum of 20% up to 44% in specific indicators like *Water use* and *Climate Change biogenic*, while the stand-alone CHP determines only a slight reduction (2-3%) of burdens with respect to baseline.
- Business case 2 : The LCA data reports that the novel technology (STES) enables a net reduction of environmental impacts for Sonnenplatz district in respect to the baseline scenario in all the impact categories selected for the study. In particular, Climate change expresses -10% of burdens and also highest values are outlined for Water use (-19%), Land use (-19%) and Ecotoxicity, freshwater (-18%).
- Business case 3 : The analysis confirms a substantial reduction of impacts in the novel configuration with Modular Heat Pump: indeed, a positive decrease of burdens is observed for several indicators, including *Water use* (-86%), *Ecotoxicity freshwater* (-78%), *Land use* (-64%) and *Ozone depletion* (-38%). However, some indicators report an increase of their impacts for the HYPERGRYD scenario: for example, *Climate change* (+28%), *Resource use, fossils* (+37%) and *Eutrophication, freshwater* (+44%) indicators are affected by this increment. In particular while the implementation of the HPs ensures a remarkable reduction of the environmental burdens in the Climate Change – Biogenic indicators (by breaking the dependence on the biomass boilers), the electrification causes an excess of electricity consumptions from the grid that in the present energy mix of Austria causes an increase in the Climate Change – Fossil that is also reflected in the Climate Change – Total indicator. This issue could in part be mitigated by making internal use of the excess PV which today is sold to the national grid and expanding the solar park.

It is worth mentioning that the present assessment has a restricted system boundary, focused on the use phase. The approach is justified by the lack of comprehensive data on the raw material sourcing, usage, and end-of-life stages due to the novelty of the technologies. Dedicated studies could expand the sustainability assessment by focusing on the ecodesign of the prototypes. However when taking into account the context of the analyses, that is the one of energy related equipments, the great parts of environmental impacts is generally associated with their use phase and therefore even the expansion of the system Boundaries should not alter significantly the presents results.

7.2 Main conclusions for LCC

- Business case 1: the implementation of the two innovative scenarios in the assumptions of the present study resulted economically viable. The bay back time of the investment Capex is around 5 years for both the 'CHPs' and 'CHPs & HRES' scenarios. After this time the innovative energy assets configurations ensure net economic savings in terms of maintenance costs and energy expenses greater than 13000 €/year and 71000 €/year respectively.

- Business case 2: the implementation of the investigated scenario in the hypothesis of this study is not economically feasible nor convenient with respect to baseline, because of the higher costs in term of Capex are not compensated by the potential savings achievable in terms of maintenance and energy expenses. It is also worth mentioning that the higher Capex Cost is mainly associated with the implementation of the high temperature Heat Pumps rather than with the Sorption Storage it self. **Different results may therefore be obtained building a different configuration for the integration of the novel technology in a similar energy community.**
- Business case 3: the integration of the Modular Heat Pump with the PCM storage is proven to be sustainable from economic point of view and it is more convenient than baseline scenario, because it allows a reduction of the Opex cost greater than 40000 €/year ensuring an investment pay-back time around 13 years.

The conclusions of the LCA study are strictly dependent on the assumptions that were necessary to estimate the Capex and Opex of the novel and baseline technologies, but also on the energy purchase and selling price. Regarding the last point the mid and long-term future scenarios will be strongly effected by the real trend in the energy market prices that today are difficulty predictable.

7.3 Main conclusions for S-LCA

The Social Life Cycle Assessment (S-LCA) performed for HYPERGRYD project has provided valuable insights into the social impacts associated with the development of the Renewable Energy Sources (RES)-based enabling technology within the HYPERGRYD project. By evaluating the technology across various stakeholder groups—*Workers, Local Communities, Value Chain Actors, Consumers,* and *Society*—the study identified both positive contributions and critical social hotspots. Notably, the project demonstrated positive social performance in areas such as consumer safety and value chain ethics, while areas like worker health and safety, fair salaries, and local community well-being require further attention. The multi-layered analysis, covering the RES technologies, ICT tools, and integrated platform, allowed for a comprehensive understanding of the social dynamics throughout the technology development process.

However, the assessment also highlighted several methodological and data-related challenges that limit the full capture of social impacts. These include the difficulty in balancing diverse stakeholder perspectives, handling different scales of assessment, and the challenge of assigning a suitable functional unit during the development phase. Additionally, the lack of comprehensive data on the raw material sourcing, usage, and end-of-life stages due to the novelty of the technology restricted the scope of the assessment. Addressing these limitations in future research—through more refined frameworks, improved data collection across life cycle stages, and stakeholder engagement—will be essential for enhancing the accuracy and depth of S-LCA in evaluating emerging energy technologies.

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9 Appendices

The present Annex encloses the additional information that have been used to perform the sustainability assessment in HYPERGRYD project.

9.1 HYPERGRYD LCA Impact Assessment (LCIA)

9.1.1 Business case 1: LCIA Reversible micro-CHP with Steam Buffer at Envipark (Turin, IT)

Table 9.1: Comparative LCA Results of the Baseline, CHPs and CHP & HRES Scenario. Results disclosed for the total and different seasons for 25 years

Impact Categories	Total 25 years			Winter 25 years			Spring 25 years			Summer 25 years			Autumn years		
	Baseline	CHPs	CHPs & HRES	Baseline	CHPs	CHPs & HRES	Baseline	CHPs	CHPs & HRES	Baseline	CHPs	CHPs & HRES	Baseline	CHPs	CHPs & HRES
Acidification [mol H+ eq]	2.04E+05	2.00E+05	1.28E+05	6.46E+04	6.23E+04	4.38E+04	4.42E+04	4.32E+04	2.35E+04	5.08E+04	5.10E+04	3.14E+04	4.49E+04	4.39E+04	2.89E+04
Climate change [kg CO2 eq]	6.28E+07	6.10E+07	4.65E+07	2.82E+07	2.73E+07	2.36E+07	1.28E+07	1.24E+07	8.42E+06	9.97E+06	1.00E+07	6.08E+06	1.18E+07	1.13E+07	8.35E+06
Climate change - Biogenic [kg CO2 eq]	1.33E+05	1.31E+05	7.42E+04	3.40E+04	3.27E+04	1.84E+04	2.95E+04	2.89E+04	1.35E+04	3.85E+04	3.86E+04	2.33E+04	3.12E+04	3.06E+04	1.90E+04
Climate change - Fossil [kg CO2 eq]	6.26E+07	6.09E+07	4.64E+07	2.82E+07	2.73E+07	2.36E+07	1.28E+07	1.23E+07	8.41E+06	9.92E+06	9.96E+06	6.05E+06	1.18E+07	1.13E+07	8.32E+06
Climate change - Land use and LU change [kg CO2 eq]	4.37E+04	4.33E+04	2.49E+04	1.10E+04	1.07E+04	6.01E+03	9.71E+03	9.62E+03	4.62E+03	1.28E+04	1.28E+04	7.89E+03	1.03E+04	1.02E+04	6.41E+03
Ecotoxicity, freshwater - part 1 [CTUe]	5.45E+07	6.14E+07	4.21E+07	1.62E+07	1.94E+07	1.44E+07	1.19E+07	1.36E+07	8.43E+06	1.43E+07	1.44E+07	9.28E+06	1.22E+07	1.40E+07	1.00E+07
Ecotoxicity, freshwater - part 2 [CTUe]	4.60E+07	4.59E+07	3.29E+07	1.61E+07	1.59E+07	1.24E+07	9.81E+06	9.82E+06	6.33E+06	1.04E+07	1.05E+07	7.16E+06	9.75E+06	9.72E+06	7.02E+06
Ecotoxicity, freshwater - inorganics [CTUe]	9.44E+07	1.01E+08	7.12E+07	3.06E+07	3.37E+07	2.58E+07	2.03E+07	2.21E+07	1.40E+07	2.30E+07	2.31E+07	1.53E+07	2.06E+07	2.23E+07	1.61E+07
Ecotoxicity, freshwater - organics - p.1 [CTUe]	1.17E+06	1.18E+06	8.53E+05	3.01E+05	2.98E+05	1.99E+05	2.60E+05	2.62E+05	1.79E+05	3.39E+05	3.42E+05	2.69E+05	2.75E+05	2.75E+05	2.06E+05
Ecotoxicity, freshwater - organics - p.2 [CTUe]	4.94E+06	4.92E+06	2.96E+06	1.34E+06	1.31E+06	8.04E+05	1.09E+06	1.09E+06	5.53E+05	1.38E+06	1.39E+06	8.70E+05	1.14E+06	1.13E+06	7.31E+05
Particulate matter [disease inc.]	7.97E-01	8.03E-01	5.08E-01	2.30E-01	2.25E-01	1.49E-01	1.75E-01	1.77E-01	9.69E-02	2.15E-01	2.19E-01	1.41E-01	1.81E-01	1.82E-01	1.21E-01
Eutrophication, marine [kg N eq]	3.41E+04	3.33E+04	2.26E+04	1.23E+04	1.18E+04	9.06E+03	7.24E+03	7.04E+03	4.13E+03	7.47E+03	7.53E+03	4.65E+03	7.14E+03	6.92E+03	4.72E+03
Eutrophication, freshwater [kg P eq]	1.08E+03	1.06E+03	6.22E+02	2.71E+02	2.62E+02	1.49E+02	2.39E+02	2.36E+02	1.17E+02	3.14E+02	3.15E+02	1.98E+02	2.53E+02	2.49E+02	1.59E+02
Eutrophication, terrestrial [mol N eq]	3.82E+05	3.73E+05	2.52E+05	1.37E+05	1.31E+05	1.00E+05	8.12E+04	7.90E+04	4.60E+04	8.45E+04	8.51E+04	5.24E+04	8.03E+04	7.78E+04	5.29E+04
Human toxicity, cancer [CTUh]	1.49E-02	1.51E-02	9.70E-03	4.41E-03	4.31E-03	2.90E-03	3.26E-03	3.32E-03	1.86E-03	3.97E-03	4.08E-03	2.65E-03	3.38E-03	3.41E-03	2.29E-03
Human toxicity, cancer - inorganics [CTUh]	1.04E-02	1.05E-02	6.73E-03	3.02E-03	2.94E-03	1.96E-03	2.27E-03	2.31E-03	1.30E-03	2.79E-03	2.87E-03	1.88E-03	2.35E-03	2.38E-03	1.60E-03
Human toxicity, cancer - organics [CTUh]	4.56E-03	4.63E-03	2.97E-03	1.39E-03	1.37E-03	9.44E-04	9.93E-04	1.01E-03	5.62E-04	1.18E-03	1.21E-03	7.69E-04	1.02E-03	1.03E-03	6.91E-04
Human toxicity, non-cancer [CTUh]	3.44E-01	3.42E-01	2.26E-01	9.33E-02	9.11E-02	5.94E-02	7.57E-02	7.54E-02	4.45E-02	9.58E-02	9.66E-02	6.72E-02	7.93E-02	7.86E-02	5.45E-02
Human toxicity, non-cancer - inorganics [CTUh]	3.26E-01	3.24E-01	2.13E-01	8.70E-02	8.48E-02	5.44E-02	7.20E-02	7.16E-02	4.20E-02	9.19E-02	9.27E-02	6.46E-02	7.56E-02	7.49E-02	5.18E-02
Human toxicity, non-cancer - organics [CTUh]	1.78E-02	1.77E-02	1.27E-02	6.36E-03	6.27E-03	4.93E-03	3.78E-03	3.76E-03	2.43E-03	3.93E-03	3.95E-03	2.67E-03	3.74E-03	3.70E-03	2.67E-03
Ionising radiation [kBq U-235 eq]	1.64E+06	1.62E+06	9.14E+05	4.10E+05	3.96E+05	2.18E+05	3.65E+05	3.59E+05	1.67E+05	4.81E+05	4.82E+05	2.92E+05	3.87E+05	3.81E+05	2.36E+05
Land use [Pt]	2.18E+08	2.14E+08	1.23E+08	5.74E+07	5.54E+07	3.24E+07	4.81E+07	4.71E+07	2.23E+07	6.17E+07	6.17E+07	3.70E+07	5.06E+07	4.95E+07	3.09E+07
Ozone depletion [kg CFC11 eq]	1.15E+01	1.09E+01	8.59E+00	5.56E+00	5.26E+00	4.69E+00	2.31E+00	2.16E+00	1.54E+00	1.55E+00	1.55E+00	9.33E-01	2.06E+00	1.90E+00	1.44E+00
Photochemical ozone formation [kg NMVOC eq]	1.15E+05	1.12E+05	7.86E+04	4.34E+04	4.20E+04	3.33E+04	2.42E+04	2.36E+04	1.44E+04	2.37E+04	2.39E+04	1.49E+04	2.35E+04	2.29E+04	1.60E+04
Resource use, fossils [MJ]	9.76E+08	9.45E+08	7.15E+08	4.37E+08	4.21E+08	3.63E+08	2.00E+08	1.92E+08	1.29E+08	1.56E+08	1.57E+08	9.46E+07	1.84E+08	1.76E+08	1.29E+08
Resource use, minerals and metals [kg Sb eq]	3.35E+02	3.33E+02	2.32E+02	8.43E+01	8.22E+01	5.26E+01	7.43E+01	7.41E+01	4.80E+01	9.76E+01	9.85E+01	7.49E+01	7.88E+01	7.81E+01	5.69E+01
Water use [m3 depriv.]	3.20E+07	3.13E+07	1.81E+07	8.50E+06	8.14E+06	4.79E+06	7.06E+06	6.90E+06	3.29E+06	9.02E+06	9.04E+06	5.46E+06	7.42E+06	7.24E+06	4.52E+06

9.1.2 Business case 2: LCIA Sorption based Thermal Energy Storage at Sonnenplatz

Table 9.2: Comparative LCA Results of the Baseline and STES Scenario. Results disclosed for the total and different seasons for 25 years

Impact Categories	Total 25 years		Winter 25 years		Spring 25 years		Summer 25 years		Autumn 25 years	
	Baseline	STES	Baseline	STES	Baseline	STES	Baseline	STES	Baseline	STES
Acidification [mol H+ eq]	2.91E+03	2.56E+03	7.58E+02	6.77E+02	7.21E+02	6.39E+02	6.74E+02	6.12E+02	7.52E+02	6.34E+02
Climate change [kg CO2 eq]	3.31E+05	2.96E+05	7.57E+04	6.83E+04	8.16E+04	7.40E+04	8.31E+04	7.73E+04	9.03E+04	7.68E+04
Climate change - Biogenic [kg CO2 eq]	2.48E+04	1.98E+04	9.15E+03	7.94E+03	5.40E+03	4.17E+03	2.81E+03	1.89E+03	7.41E+03	5.79E+03
Climate change - Fossil [kg CO2 eq]	2.99E+05	2.71E+05	6.41E+04	5.82E+04	7.48E+04	6.87E+04	7.95E+04	7.48E+04	8.09E+04	6.94E+04
Climate change - Land use and LU change [kg CO2 eq]	6.56E+03	5.28E+03	2.37E+03	2.06E+03	1.45E+03	1.13E+03	8.01E+02	5.65E+02	1.94E+03	1.52E+03
Ecotoxicity, freshwater - part 1 [CTUe]	2.86E+06	2.42E+06	8.84E+05	7.77E+05	6.68E+05	5.59E+05	5.07E+05	4.26E+05	8.06E+05	6.54E+05
Ecotoxicity, freshwater - part 2 [CTUe]	1.54E+06	1.40E+06	3.59E+05	3.25E+05	3.97E+05	3.62E+05	4.08E+05	3.82E+05	3.80E+05	3.28E+05
Ecotoxicity, freshwater - inorganics [CTUe]	3.90E+06	3.39E+06	1.08E+06	9.59E+05	9.49E+05	8.26E+05	8.33E+05	7.40E+05	1.03E+06	8.60E+05
Ecotoxicity, freshwater - organics - p.1 [CTUe]	2.27E+05	1.92E+05	7.11E+04	6.26E+04	5.37E+04	4.50E+04	4.06E+04	3.41E+04	6.18E+04	5.02E+04
Ecotoxicity, freshwater - organics - p.2 [CTUe]	2.87E+05	2.36E+05	9.14E+04	8.00E+04	6.23E+04	5.06E+04	4.19E+04	3.30E+04	9.11E+04	7.25E+04
Particulate matter [disease inc.]	2.23E-02	1.99E-02	5.63E-03	5.05E-03	5.63E-03	5.04E-03	5.44E-03	4.99E-03	5.61E-03	4.78E-03
Eutrophication, marine [kg N eq]	6.71E+02	5.71E+02	2.02E+02	1.78E+02	1.59E+02	1.35E+02	1.26E+02	1.08E+02	1.83E+02	1.50E+02
Eutrophication, freshwater [kg P eq]	1.98E+01	1.80E+01	4.63E+00	4.19E+00	5.19E+00	4.74E+00	5.36E+00	5.03E+00	4.65E+00	4.05E+00
Eutrophication, terrestrial [mol N eq]	6.98E+03	5.95E+03	2.09E+03	1.84E+03	1.66E+03	1.41E+03	1.33E+03	1.14E+03	1.90E+03	1.56E+03
Human toxicity, cancer [CTUh]	4.65E-04	4.18E-04	1.14E-04	1.03E-04	1.20E-04	1.08E-04	1.19E-04	1.10E-04	1.12E-04	9.67E-05
Human toxicity, cancer - inorganics [CTUh]	3.35E-04	2.97E-04	8.73E-05	7.81E-05	8.46E-05	7.52E-05	7.99E-05	7.28E-05	8.34E-05	7.08E-05
Human toxicity, cancer - organics [CTUh]	1.30E-04	1.21E-04	2.71E-05	2.48E-05	3.51E-05	3.28E-05	3.90E-05	3.73E-05	2.91E-05	2.60E-05
Human toxicity, non-cancer [CTUh]	1.45E-02	1.33E-02	3.24E-03	2.95E-03	3.83E-03	3.53E-03	4.07E-03	3.85E-03	3.34E-03	2.94E-03
Human toxicity, non-cancer - inorganics [CTUh]	1.40E-02	1.28E-02	3.14E-03	2.86E-03	3.71E-03	3.41E-03	3.94E-03	3.72E-03	3.23E-03	2.84E-03
Human toxicity, non-cancer - organics [CTUh]	4.66E-04	4.29E-04	1.01E-04	9.22E-05	1.23E-04	1.14E-04	1.33E-04	1.26E-04	1.09E-04	9.58E-05
Ionising radiation [kBq U-235 eq]	1.67E+04	1.47E+04	4.06E+03	3.64E+03	4.00E+03	3.56E+03	3.85E+03	3.51E+03	4.82E+03	4.03E+03
Land use [Pt]	8.91E+06	7.23E+06	3.14E+06	2.74E+06	1.98E+06	1.57E+06	1.17E+06	8.57E+05	2.62E+06	2.06E+06
Ozone depletion [kg CFC11 eq]	8.48E-02	7.10E-02	2.58E-02	2.26E-02	1.90E-02	1.58E-02	1.42E-02	1.18E-02	2.58E-02	2.08E-02
Photochemical ozone formation [kg NMVOC eq]	1.44E+03	1.28E+03	3.64E+02	3.26E+02	3.62E+02	3.23E+02	3.49E+02	3.20E+02	3.68E+02	3.12E+02
Resource use, fossils [MJ]	3.60E+06	3.30E+06	7.13E+05	6.52E+05	9.07E+05	8.46E+05	1.01E+06	9.59E+05	9.69E+05	8.39E+05
Resource use, minerals and metals [kg Sb eq]	1.52E+01	1.49E+01	2.19E+00	2.12E+00	4.42E+00	4.35E+00	5.70E+00	5.64E+00	2.89E+00	2.79E+00
Water use [m3 depriv.]	1.68E+06	1.36E+06	5.98E+05	5.20E+05	3.72E+05	2.93E+05	2.14E+05	1.55E+05	4.91E+05	3.87E+05

9.1.3 Business case 3: LCIA Heat Pumps with PCM storage at Sonnenplatz

Table 9.3: Comparative LCA Results of the Baseline and HPsPCM Scenario. Results disclosed for the total and different seasons for 25 years

Impact Categories	Total 25 years		Winter 25 years		Spring 25 years		Summer 25 years		Autumn 25 years	
	Baseline	HPsPCM	Baseline	HPsPCM	Baseline	HPsPCM	Baseline	HPsPCM	Baseline	HPsPCM
Acidification [mol H+ eq]	2.09E+04	1.86E+04	5.79E+03	6.48E+03	5.64E+03	2.72E+03	4.65E+03	4.52E+03	4.82E+03	4.88E+03
Climate change [kg CO2 eq]	3.29E+06	4.55E+06	8.11E+05	1.77E+06	8.36E+05	5.67E+05	7.98E+05	9.82E+05	8.45E+05	1.22E+06
Climate change - Biogenic [kg CO2 eq]	1.58E+05	1.17E+04	6.15E+04	4.44E+03	4.50E+04	1.54E+03	1.92E+04	2.63E+03	3.18E+04	3.13E+03
Climate change - Fossil [kg CO2 eq]	3.09E+06	4.53E+06	7.33E+05	1.77E+06	7.79E+05	5.64E+05	7.73E+05	9.77E+05	8.05E+05	1.22E+06
Climate change - Land use and LU change [kg CO2 eq]	4.25E+04	6.94E+03	1.62E+04	2.59E+03	1.21E+04	9.25E+02	5.58E+03	1.57E+03	8.69E+03	1.85E+03
Ecotoxicity, freshwater - part 1 [CTUe]	1.77E+07	6.27E+06	5.89E+06	1.81E+06	4.95E+06	1.11E+06	3.02E+06	1.77E+06	3.87E+06	1.58E+06
Ecotoxicity, freshwater - part 2 [CTUe]	1.14E+07	1.21E+07	2.86E+06	4.20E+06	3.04E+06	1.79E+06	2.79E+06	2.96E+06	2.67E+06	3.17E+06
Ecotoxicity, freshwater - inorganics [CTUe]	2.60E+07	1.77E+07	7.68E+06	5.84E+06	7.13E+06	2.77E+06	5.33E+06	4.52E+06	5.84E+06	4.59E+06
Ecotoxicity, freshwater - organics - p.1 [CTUe]	1.32E+06	2.91E+05	4.53E+05	5.19E+04	3.77E+05	6.84E+04	2.19E+05	1.03E+05	2.70E+05	6.83E+04
Ecotoxicity, freshwater - organics - p.2 [CTUe]	1.79E+06	3.98E+05	6.12E+05	1.18E+05	4.86E+05	6.91E+04	2.58E+05	1.10E+05	4.34E+05	1.01E+05
Particulate matter [disease inc.]	1.35E-01	8.88E-02	3.70E-02	2.47E-02	3.72E-02	1.62E-02	3.02E-02	2.56E-02	3.00E-02	2.23E-02
Eutrophication, marine [kg N eq]	4.71E+03	3.06E+03	1.48E+03	1.09E+03	1.30E+03	4.36E+02	8.94E+02	7.28E+02	1.04E+03	8.06E+02
Eutrophication, freshwater [kg P eq]	3.03E+02	5.36E+02	7.45E+01	2.21E+02	7.65E+01	6.07E+01	7.76E+01	1.08E+02	7.42E+01	1.46E+02
Eutrophication, terrestrial [mol N eq]	5.00E+04	3.46E+04	1.56E+04	1.25E+04	1.37E+04	4.85E+03	9.63E+03	8.13E+03	1.11E+04	9.15E+03
Human toxicity, cancer [CTUh]	3.00E-03	2.49E-03	8.00E-04	7.75E-04	8.27E-04	4.14E-04	7.11E-04	6.67E-04	6.65E-04	6.38E-04
Human toxicity, cancer - inorganics [CTUh]	2.23E-03	1.78E-03	6.24E-04	5.77E-04	6.14E-04	2.82E-04	5.01E-04	4.59E-04	4.93E-04	4.59E-04
Human toxicity, cancer - organics [CTUh]	7.69E-04	7.16E-04	1.75E-04	1.98E-04	2.12E-04	1.32E-04	2.10E-04	2.07E-04	1.72E-04	1.79E-04
Human toxicity, non-cancer [CTUh]	8.73E-02	7.49E-02	2.14E-02	2.12E-02	2.41E-02	1.35E-02	2.24E-02	2.14E-02	1.93E-02	1.88E-02
Human toxicity, non-cancer - inorganics [CTUh]	8.45E-02	7.25E-02	2.07E-02	2.05E-02	2.34E-02	1.31E-02	2.17E-02	2.07E-02	1.87E-02	1.82E-02
Human toxicity, non-cancer - organics [CTUh]	2.81E-03	2.48E-03	6.67E-04	7.00E-04	7.70E-04	4.48E-04	7.31E-04	7.08E-04	6.38E-04	6.23E-04
Ionising radiation [kBq U-235 eq]	1.84E+05	2.60E+05	4.66E+04	1.05E+05	4.62E+04	3.08E+04	4.30E+04	5.41E+04	4.77E+04	7.04E+04
Land use [Pt]	6.20E+07	2.23E+07	2.25E+07	8.83E+06	1.73E+07	2.72E+06	9.09E+06	4.74E+06	1.31E+07	6.02E+06
Ozone depletion [kg CFC11 eq]	6.17E-01	3.85E-01	1.94E-01	1.44E-01	1.65E-01	5.10E-02	1.09E-01	8.69E-02	1.50E-01	1.03E-01
Photochemical ozone formation [kg NMVOC eq]	1.04E+04	9.69E+03	2.80E+03	3.35E+03	2.80E+03	1.43E+03	2.38E+03	2.37E+03	2.40E+03	2.54E+03
Resource use, fossils [MJ]	4.11E+07	6.58E+07	9.40E+06	2.60E+07	1.02E+07	8.04E+06	1.06E+07	1.40E+07	1.09E+07	1.77E+07
Resource use, minerals and metals [kg Sb eq]	7.81E+01	9.27E+01	1.15E+01	2.17E+01	2.16E+01	1.90E+01	2.73E+01	2.93E+01	1.76E+01	2.26E+01
Water use [m3 depriv.]	1.06E+07	1.47E+06	4.02E+06	4.86E+05	3.02E+06	2.31E+05	1.41E+06	3.76E+05	2.16E+06	3.82E+05

9.2 HYPERGRYD LCC Inventories

9.2.1 Inventories Business case 1- CHPs

Table 9.4: LCC Inventory Table of Envipark 'Baseline' Scenario – Energy flows

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/ Data source
Expenses for Energy Consumptions								
Heat consumption - Urban district heating	0.093 EUR/kWh	149.643	39.938	-	28.616	218.198	5.454.944	Average unit price in the period 2013-2024 as per Italian local distributor to 'Non households' users. (IlTeleriscaldamento.eu, 2025)
Electrical consumption - National Grid	0.120 EUR/kWh	100.590	93.279	124.915	99.500	418.284	10.457.089	Average unit price of electricity in the period 2013-2024 for Italy 'Non households' users. (Eurostat, 2025)
Revenues for Energy fed into the grid								
Hydro	0.090 EUR/kWh	31.220	31.585	30.327	24.487	117.619	2.940.475	Average zonal feed-in price in the period 2013-2024 for Italy market. (GME, 2025)
PV	0.090 EUR/kWh	-	-	-	-	-	-	Self consumed.

Table 9.5: LCC Inventory Table of Envipark 'CHPs' Scenario – Energy flows

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/Data source
Expenses for Energy Consumptions								
Heat consumption - Urban district heating	0.093 EUR/kWh	137.627	33.796	-	22.341	193.764	4.844.105	Average unit price in the period 2013-2024 as per italian local distributor to 'Non households' users. (IlTeleriscaldamento.eu, 2025)
Electrical consumption - National Grid	0.120 EUR/kWh	96.715	91.298	124.915	97.476	410.403	10.260.081	Average unit price of electricity in the period 2013-2024 for Italy 'Non households' users. (Eurostat, 2025)
Natural Gas	0.423 EUR/Smc	8.904	4.551	-	4.650	18.104	452.600	Average unit price of natural gas in the period 2013-2024 for Italy 'Non households' users. (Eurostat, 2025)
Revenues for Energy fed into the grid								

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/Data source
Hydro	0.090 EUR/kWh	31.220	31.585	30.327	24.487	117.619	2.940.475	Average zonal feed-in price in the period 2013-2024 for Italian market. (GME, 2025)
PV	0.090 EUR/kWh	-	-	-	-	-	-	Self consumed.

Table 9.6: LCC Inventory Table of Envipark 'CHPs & HRES' Scenario – Energy flows

Flow	Average Unit price	Price Unit	Spring	Summer	Autumn	Total average year	Total 25 years	Note/Data source
Expenses for Energy Consumptions								
Heat consumption - Urban district heating	0.093 EUR/kWh	137.627	33.796	-	22.341	193.764	4.844.105	Average unit price in the period 2013-2024 as per italian local distributor to 'Non households' users. (IlTeleriscaldamento.eu, 2025)
Electrical consumption - National Grid	0.120 EUR/kWh	96.715	49.561	39.646	73.346	58.770	221.322	Average unit price of electricity in the period 2013-2024 for Italy 'Non households' users. (Eurostat, 2025)
Natural Gas	0.423 EUR/Smc	8.904	4.551	-	4.650	18.104	452.600	Average unit price of natural gas in the period 2013-2024 for Italy 'Non households' users. (Eurostat, 2025)
Revenues for Energy fed into the grid								
Hydro	0.090 EUR/KWh	-	-	-	-	-	-	Self consumed.
PV	0.090 EUR/KWh	-	-	-	-	-	-	Self consumed.

9.2.2 Business case 2- Sorption Thermal Energy Storage

Table 9.7: LCC Inventory Table of Sonnenplatz 'Baseline' Scenario – Energy flows

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/ Data source
Expenses for Energy Consumptions								

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/ Data source
Heat consumption from biomass	0.078 EUR/kWh	5.732	3.100	1.534	4.323	14.329	358.218	Average unit price of pellets in the period 2005-2024 for Austria: 0.249 EUR/KWh (Heiz_pellets24, 2025). 3.20 kWh/kg (Calculated from Primary Data from sonnenplatz, 2023)
Heat consumption from oil fired boiler	0.051 EUR/kWh	4	2	5	101	112	2816	Average unit price in the period 2003-2024 for Austria Gas oil (industry). (Statistik_Austria, 2025)
Revenues for Energy fed into the grid								
PV	0.169 EUR/kWh	486	1.593	2.235	956	5.270	131.752	Average monthly selling prices in 2023 for generated PV energy (Primary Data from the project)

Table 9.8: LCC Inventory Table of Sonnenplatz 'Sorption Thermal Storage' Scenario – Energy flows

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/Data source
Expenses for Energy Consumptions								
Heat consumption from biomass	0.078 EUR/kWh	4.658	2.372	991	3.364	11.385	284.614	Average unit price of pellets in the period 2005-2024 for Austria: 0.249 EUR/KWh (Heiz_pellets24, 2025). 3.20 kWh/kg (Calculated from Primary Data from sonnenplatz, 2023)
Heat consumption from oil fired boiler	0.051 EUR/kWh	4	2	3	79	87	2.184	Average unit price in the period 2003-2024 for Austria Gas oil (industry). ((Statistik_Austria, 2025))
Revenues for Energy fed into the grid								
PV	0.169 EUR/kWh	34	112	156	67	369	9.223	Average monthly selling prices in 2023 for generated PV energy (Primary Data from the project)

9.2.3 Business case 3 - Modular Heat Pump with short term storage

Table 9.9: LCC Inventory Table of Sonnenplatz 'Baseline' Scenario – Energy flows

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/ Data source
Expenses for Energy Consumptions								
Electrical consumption - National Grid	0.108 EUR/kWh	5.115	5.036	5.584	5.578	21.314	532.844	XXXX
Heat consumption from biomass	0.078 EUR/kWh	35.716	25.709	10.193	17.936	89.554	2.238.860	Average unit price of pellets in the period 2005-2024 for Austria: 0.249 EUR/KWh (Heiz_pellets24, 2025). 3.20 kWh/kg (Calculated from Primary Data from sonnenplatz, 2023)
Heat consumption from oil fired boiler	0.051 EUR/kWh	41	41	20	603	705	17.601	Average unit price in the period 2003-2024 for Austria Gas oil (industry). ((Statistik_Austria, 2025))
Revenues for Energy fed into the grid								
PV	0.169 EUR/kWh	1.142	5.833	8.828	4.435	20.238	505.961	Average monthly selling prices in 2023 for generated PV energy (Primary Data from the project)

Table 9.10: LCC Inventory Table of Sonnenplatz 'Heat Pumps with PCM' Scenario – Energy flows

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/Data source
Expenses for Energy Consumptions								
Electrical consumption - National Grid	0.108 EUR/kWh	5.115	5.036	5.584	5.578	21.314	532.844	Average unit price of electricity in the period 2013-2024 for Austria 'Non households' users. (Eurostat, 2025)
Additional electrical consumptions for HPsPCM	0.108 EUR/kWh	17.480	10.739	3.812	8.620	40.651	1.016.282	Average unit price of electricity in the period 2013-2024 for Austria 'Non households' users. (Eurostat, 2025)
Revenues for Energy fed into the grid								

Flow	Average Unit price	Winter [EUR]	Spring [EUR]	Summer [EUR]	Autumn [EUR]	Total average year [EUR]	Total 25 years [EUR]	Note/Data source
PV	0.169 EUR/kWh	1.142	5.833	8.828	4.435	20.238	505.961	Average monthly selling prices in 2023 for generated PV energy (Primary Data from the project)

9.3 HYPERGRYD S-LCA Inventory Questionnaire

The following questionnaire was used to collect data for the **Social Life Cycle Assessment (S-LCA)** of the HYPERGRYD project. It is structured around key stakeholder groups, assessing various aspects of social sustainability within the organization and its broader impact.

1. Workers

This section evaluates the organization's policies and practices related to employment conditions, worker rights, and well-being, covering aspects such as:

- Contractual transparency and formalization of employment agreements.
- Accessibility of job opportunities and recruitment fairness.
- Equal opportunities and non-discrimination policies in the workplace.
- Wage fairness and alignment with recognized living wage standards.
- Transparency in salary and wage records.
- Protection of worker identity documents and rights.
- Clarity and enforcement of resignation policies and notice periods.
- Assistance provided to workers in understanding contract terms.
- Freedom of association and the right to unionize without repercussions.
- Availability of dispute resolution mechanisms for collective bargaining.
- Workplace health and safety policies and their accessibility to workers.
- Inclusion of specific workplace health and safety risks in company policies.
- Availability of first aid kits and emergency equipment in workplaces.
- Existence of an emergency response plan and evacuation procedures.
- Worker awareness and training on emergency protocols.
- Policies addressing workplace harassment, including sexual harassment.
- Provision of social benefits such as health insurance, pension funds, and other worker support programs.

2. Consumers

This section focuses on how the organization ensures consumer protection, safety, and transparency in product-related information, including:

- Labelling and instructions for safe product use.

- Mechanisms for consumer feedback and complaint resolution.
- Internal policies for handling consumer data and privacy protection.
- Frequency and transparency of sustainability reporting.
- Communication of end-of-life options for products, if applicable.

3. Local Communities

This section assesses the organization's engagement with and impact on the communities where it operates, focusing on:

- Collaboration with educational institutions and training programs.
- Adoption of certified environmental management systems.
- Employee participation in community volunteer programs.
- Support for local non-governmental organizations (NGOs) and social initiatives.
- Contributions to preserving cultural heritage and historical sites.
- Presence of cultural heritage sites that could benefit from organizational activities.
- Assistance provided to migrant workers for integration and communication.
- Policies promoting local hiring and workforce development.
- Percentage of spending allocated to local suppliers and service providers.

4. Value Chain Actors (Suppliers, Partners, and Business Ethics)

This section examines the organization's approach to ethical sourcing, supplier relations, and fair competition, including:

- Market competitiveness and absence of monopolistic control.
- Social responsibility expectations within the supply chain.
- Training and resources provided to employees for understanding ethical sourcing and corporate social responsibility.
- Fair treatment and collaboration with suppliers without power imbalances.
- Engagement with universities, research institutions, or start-ups for intellectual property and technology development.
- Active participation in industry advocacy groups and professional associations.

5. Society and Governance

This section explores the broader societal impact of the organization, including governance, sustainability commitments, and contributions to economic development:

- Job creation and economic contribution at local and national levels.
- Skill level requirements for newly created job positions.
- Anti-corruption policies and ethical business practices.
- Social responsibility strategies with a focus on poverty alleviation.
- Business operations in regions affected by conflicts.
- Public commitment to sustainability and corporate responsibility.
- Mechanisms for monitoring and ensuring compliance with sustainability commitments.
- Participation in technology transfer initiatives and innovation projects.
- Investment in research and development activities.

9.4 Country-Level Social Impact Indicators

This appendix presents key social impact indicators at the country level, categorized by stakeholder groups. These indicators help assess the broader socio-economic context in which the HYPERGRYD project operates, providing insight into national-level regulations, policies, and socio-economic conditions that may influence the project's social sustainability performance.

1. Consumer

- **End-of-Life Responsibility** – Strength of national legislation covering product disposal and recycling.
- **Feedback Mechanisms** – Presence of feedback mechanisms (e.g., after-sales services) at the sector or national level.
- **Privacy Regulations** – Country ranking related to regulations on data-sharing.
- **Data Protection** – Strength of laws protecting privacy against organizations and government.

2. Local Community

- **Access to Immaterial Resources** – Patent filings and intellectual property rights.
- **Freedom of Expression** – National policies and rankings related to freedom of speech.
- **Access to Material Resources** – Percentage of population with access to improved sanitation facilities.

- **Community Trust** – Public trust in political institutions.
- **Cultural Heritage Protection** – Prevalence of racial discrimination and inclusivity measures.
- **Migration & Relocation Trends** – Percentage of international migrants in the population.
- **Employment & Economic Stability** – National unemployment statistics and poverty levels.
- **Public Health & Safety** – Burden of disease and national pollution levels.
- **Construction Safety & Housing** – Strength of laws on building safety regulations.
- **Security & Human Rights** – National security rankings and public safety perception.

3. Society & Governance

- **Corruption & Transparency** – Risk of corruption at the country and regional levels.
- **Technology & Innovation Development** – National investment in research and development (R&D).

4. Value Chain Actors

- **Fair Competition & Market Regulation** – Presence of national laws and regulations ensuring fair competition.

5. Workers & Labor Rights

- **Child Labor Incidence** – Percentage of children working by country and sector.
- **Gender Equality & Non-Discrimination** – Gender equality index and female labor force participation rate.
- **Wage Fairness & Income Standards** – Minimum wage levels and purchasing power parity.
- **Forced Labor Risks** – Estimated percentage of forced labor occurrences by region.
- **Freedom of Association** – Evidence of restrictions on unionization and collective bargaining rights.
- **Workplace Health & Safety** – National occupational accident rates.
- **Social Security & Worker Benefits** – Social security expenditure across sectors, covering healthcare, maternity, and unemployment.