STUDIA UBB CHEMIA, LXX, 3, 2025 (p. 227-241)
(RECOMMENDED CITATION)
DOI:10.24193/subbchem.2025.3.16

AN ENVIRONMENTAL ASSESSMENT OF ENERGY STORAGE USING THE RESTORE CONCEPT: ANALYSIS OF THE GMUNDEN CEMENT PLANT

Alessandra-Diana SELEJAN-CIUBANCAN[a], Letitia PETRESCU[a,*], Stefan Cristian GALUSNYAK[a], Calin-Cristian CORMOS[a]

ABSTRACT. The RESTORE initiative explores an innovative method of energy storage based on the thermochemical cycling of copper sulphate. During periods of surplus renewable electricity, such as for example solar-rich summer months, the system stores energy through the dehydration of copper sulphate. The stored energy is subsequently recovered during colder periods, such as winter, when energy demand increases and renewable availability declines, via the rehydration of the material. The current investigation focuses on the industrial RESTORE application at the Gmunden cement plant in Austria, proposing the integration of Thermochemical Energy Storage (TCES) with an Organic Rankine Cycle (ORC) and a Heat Pump (HP). The sustainability of the system was evaluated through a Life Cycle Assessment (LCA), conducted in accordance with the standard LCA framework, using version 10.8 of the LCA for Experts software. Environmental performance was quantified based on eleven key indicators derived from the ReCiPe 2016 assessment method. The functional unit for this study was set as the generation of 1 kWh of thermal energy, enabling a consistent comparison between the two construction alternatives of storage tanks, relevant to the industrial use case: carbon steel against high-density polyethylene (HDPE). The system boundaries were established to encompass the complete life cycle, segmented into three primary stages: i) Upstream activities; ii) Core operational processes; iii) Downstream operations. The use of HDPE outperformed carbon steel in key impact categories, cutting global warming potential (GWP) by over 55%, while significantly lowering other indicators. However, increased impacts in terms of fossil depletion and freshwater ecotoxicity potential

[a] *Babeş-Bolyai University, Faculty of Chemistry and Chemical Engineering, 11 Arany Janos str., RO-400028, Cluj-Napoca, Romania.*
[*] *Corresponding author: letitia.petrescu@ubbcluj.ro*

are registered, likely due to the petroleum-based nature of HDPE. Several discussions and interpretations of the most relevant environmental key performance indicators are provided, underlining the effectiveness of the proposed concepts.

Keywords: *Life Cycle Assessment (LCA), Thermochemical Energy Storage (TCES), Heat Pump (HP), Organic Rankine Cycle (ORC), District Heating and Cooling (DHC).*

INTRODUCTION

Global efforts to mitigate climate change have intensified in recent years, as the average global temperature continues to rise at a rate of approximately 0.2°C per decade. To address this challenge, international climate targets seek to limit the increase in global mean temperature to below 2°C, and ideally under 1.5°C, above pre-industrial levels [1]. Surpassing these thresholds poses significant risks to human health and the environment, including extreme weather events, rising sea levels, and ecosystem disruptions [2]. One of the primary strategies to combat climate change is the reduction of greenhouse gas (GHG) emissions through improved energy efficiency and the transition to low-carbon energy sources [3]. In this context, domestic heating emerges as a critical sector, representing approximately 78% of the total energy consumption in EU-27 households in 2020 [4]. Currently, around 42% of Europe's energy is still derived from fossil fuels, particularly natural gas. To achieve a sustainable energy transition, the European Commission promotes the adoption of renewable energy sources (RES) such as biomass, solar, wind, and geothermal energy [5,6]. However, the intermittent and seasonal nature of many RES necessitates the development of reliable energy storage technologies to balance energy supply and demand. Among the various storage solutions, Thermochemical Energy Storage (TCES) has gained prominence due to its high energy density and capacity for long-term storage with minimal thermal losses. TCES systems operate by storing heat in thermochemical materials through reversible chemical reactions, making them well-suited both for residential and industrial applications [7]. To facilitate year-round integration of RES, Organic Rankine Cycle (ORC) technology is frequently coupled with TCES. ORC systems are efficient and environmentally friendly technologies that convert low-grade heat, such as waste heat or energy from solar, biomass, or geothermal sources, into electricity [8]. Unlike traditional steam cycles, ORC can effectively utilize low-temperature heat sources, thereby offering a scalable solution for sustainable energy generation in light of dwindling fossil fuel reserves and increasing environmental concerns.

The Renewable Energy-based Seasonal Storage Technology in Order to Raise Economic and Environmental Sustainability of DHC (RESTORE) solution aims to integrate TCES with ORC and HP systems, promoting the large-scale incorporation of RES into District Heating and Cooling (DHC) networks (see Figure 1) [9].

To assess the environmental viability of this integrated system, the project employs Life Cycle Assessment (LCA) as a standardized methodology for evaluating environmental impacts across the full life cycle of a product or technology. LCA enables identification of environmental hotspots and offers guidance for system optimization, thereby supporting sustainable innovation [10].

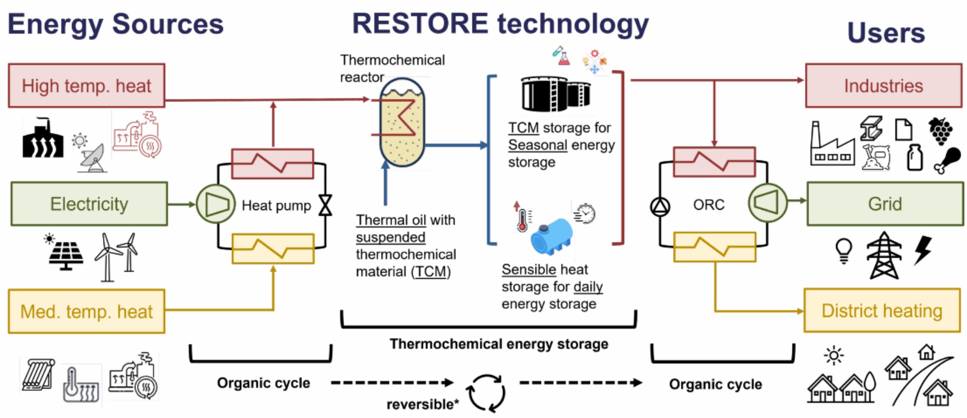


Figure 1. Overview of the RESTORE technology

MATERIALS AND METHODS

The LCA methodology used in this study adheres to ISO 14040:2006 and ISO 14044:2006 standards, which define the principles, framework, and detailed requirements for conducting LCA [11]. The LCA process consists of four interconnected and iterative stages: (1) Goal and Scope Definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation of Results [12].

This study assesses the environmental performance of the RESTORE technology when integrated into a cement production facility located in Gmunden, Austria. As outlined previously, the proposed RESTORE concept combines TCES with ORC and HP technologies. Two design configurations for the construction of the RESTORE plant are evaluated: in Option 1, the storage tanks for charged and non-charged thermochemical material are constructed from carbon steel, whereas in Option 2, they are made of plastic. The system aims to enhance the efficiency and sustainability of DHC networks by enabling the seasonal storage of energy from renewable sources. The assessment covers a 25-year operational period and incorporates location-specific conditions for Austria [13].

The Functional Unit (FU) for the study is defined as 1 kWh of thermal energy output, a standardized reference against which all environmental impacts are measured. The study adopts a cradle-to-gate system boundary, covering stages from raw material production (e.g., Therminol V66, copper sulfate, oil, etc.), system assembly, and energy output generation, as illustrated in Figure 2. Notably, the study excludes decommissioning processes, labor activities, rare catastrophic events, and the construction of transport infrastructure.

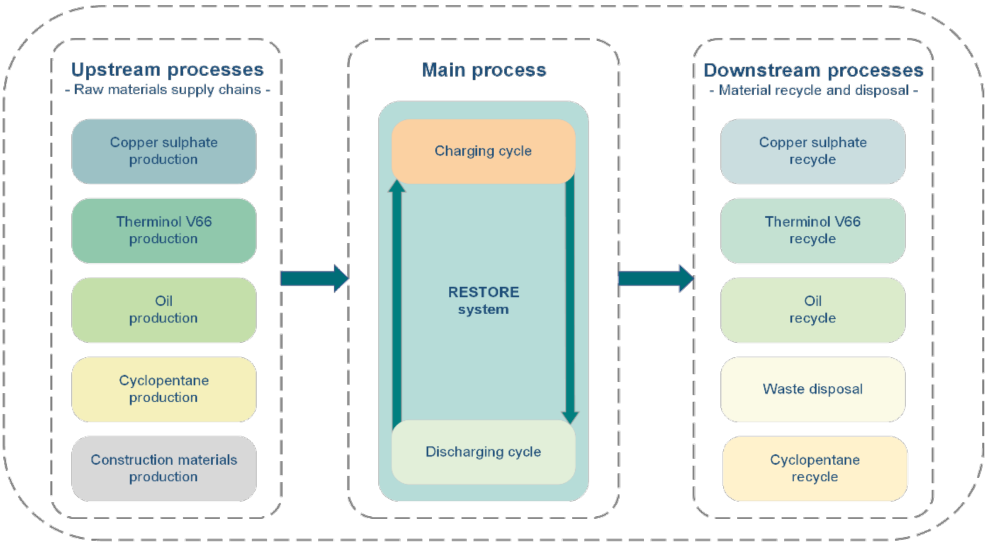
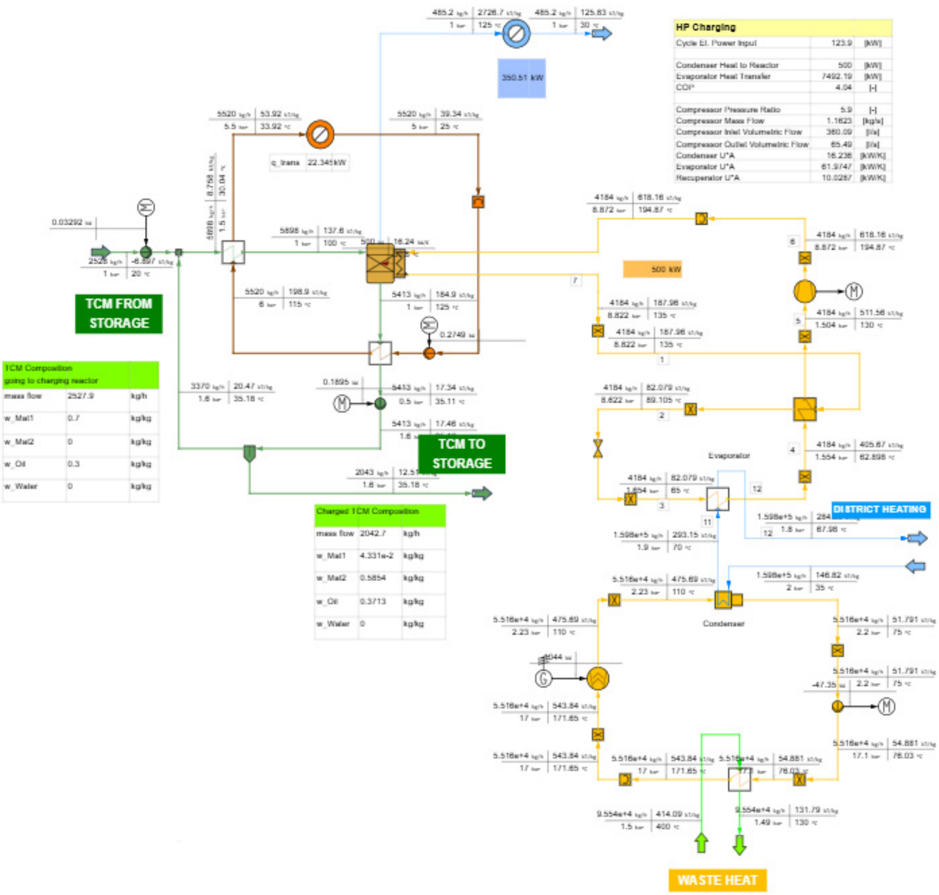


Figure 2. System boundaries for the RESTORE system

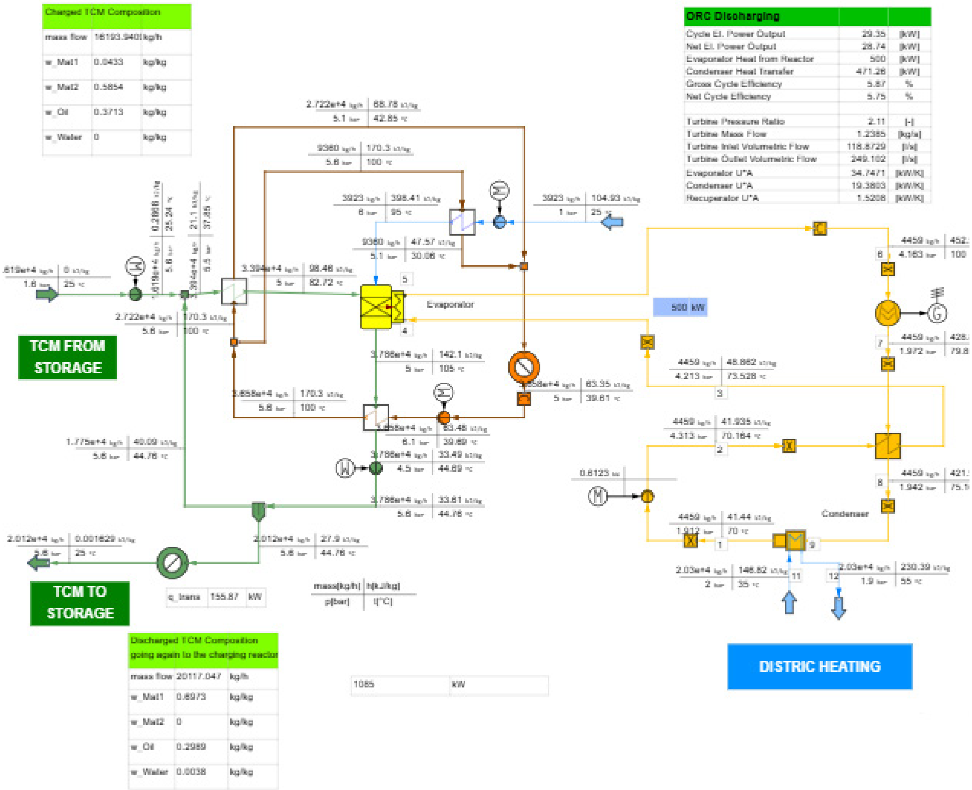
Table 1. Assumptions considered in all chemical compound supply chains

Process	Inputs	Value	Unit
Copper Sulphate	Diesel for transportation	10^{-3}	kg/h
	Copper for production	0.39	kg/h
	Sulphuric acid for production	0.61	kg/h
Oil	Diesel for transportation	$1.50 \cdot 10^{-3}$	kg/h
	Rapeseed oil [14]	1.00	kg/h
Cyclopentane	Crude oil	1.02	kg/h
	Electricity	$2.11 \cdot 10^{-4}$	kW/h

During the LCI phase, the study collects detailed data on all inputs and outputs associated with each unit process in the system [15]. Table 1 lists the comprehensive input-output data for the production of 1 kg of each material. Secondary datasets are utilized as they derive from process simulation activities using IPSE GO software, as seen in Figure 3, and a dedicated RESTORE_Lib model developed specifically for the project [16]. IPSE GO is an online process simulation software that features an integrated flowsheet editor for graphically building and connecting process models with advanced numerical methods for fast and precise calculations, and automatically generates reports of results [17]. For the production of specific materials such as Therminol V66, $CuSO_4$, cyclopentane, etc., existing literature and public life cycle databases provided the necessary information [18,19].



a)



b)

Figure 3. IPSE GO model for the Gmunden (Austria) case:
a) Charging cycle and b) Discharging cycle

In the LCIA stage, the input and output inventory flows are translated into environmental impact categories [10]. This study employs the ReCiPe 2016 methodology, recognized for its capacity to evaluate both midpoint and endpoint indicators through scientifically supported cause-and-effect pathways [15].

The LCA was conducted using the LCA for Experts software [20], a robust platform that supports ISO-compliant assessments and includes extensive databases for modeling material use, energy consumption, emissions, and waste treatment.

RESULTS AND DISCUSSION

Table 2 summarizes the environmental performance of the RESTORE system based on a detailed LCA investigation. The analysis was conducted across three main phases: charging, discharging, and plant construction, which was further analyzed under two alternative scenarios for the storage tank material (carbon steel - Option no.1; and high-density polyethylene - Option no.2), all being reported to the FU of 1 kWh thermal energy output. Part of the LCA plans used for the below-mentioned results are presented in Figure 5 to Figure 7.

Table 2. Environmental key performance indicators (KPIs) according to the ReCiPe impact assessment method

KPIs	Units	Charging	Discharging	Option no.1	Option no.2
GWP	kg CO_2 eq./kWh	$7.68 \cdot 10^{-2}$	$0.92 \cdot 10^{-2}$	$3.21 \cdot 10^{-2}$	$1.35 \cdot 10^{-2}$
FDP	kg oil eq./kWh	$1.90 \cdot 10^{-2}$	$-0.10 \cdot 10^{-2}$	$6.52 \cdot 10^{-3}$	$1.08 \cdot 10^{-2}$
FETP	kg 1,4-DB eq./kWh	$1.53 \cdot 10^{-5}$	$0.12 \cdot 10^{-5}$	$5.44 \cdot 10^{-6}$	$7.63 \cdot 10^{-6}$
FEP	kg P eq./kWh	$1.19 \cdot 10^{-6}$	$0.31 \cdot 10^{-6}$	$1.22 \cdot 10^{-11}$	$1.22 \cdot 10^{-11}$
HTP_{cancer}	kg 1,4-DB eq./kWh	$1.88 \cdot 10^{-4}$	$-1.29 \cdot 10^{-7}$	$1.68 \cdot 10^{-4}$	$1.72 \cdot 10^{-4}$
$HTP_{non\text{-}cancer}$	kg 1,4-DB eq./kWh	$-0.48 \cdot 10^{-3}$	$0.67 \cdot 10^{-3}$	$2.50 \cdot 10^{-3}$	$2.96 \cdot 10^{-3}$
MDP	kg Cu eq./kWh	$1.93 \cdot 10^{-4}$	$3.78 \cdot 10^{-4}$	$9.59 \cdot 10^{-4}$	$1.32 \cdot 10^{-5}$
$POFP_{ecosystem}$	kg NO_x eq./kWh	9.57	0.69	$4.71 \cdot 10^{-5}$	$1.77 \cdot 10^{-5}$
ODP	kg CFC-11 eq./kWh	$2.75 \cdot 10^{-5}$	$3.96 \cdot 10^{-5}$	$1.90 \cdot 10^{-9}$	$2.26 \cdot 10^{-9}$
TAP	kg SO_2 eq./kWh	$2.43 \cdot 10^{-4}$	$1.78 \cdot 10^{-4}$	$4.59 \cdot 10^{-5}$	$1.32 \cdot 10^{-5}$
TETP	kg 1,4-DB eq./kWh	$1.37 \cdot 10^{-2}$	$-3.48 \cdot 10^{-4}$	$2.63 \cdot 10^{-2}$	$1.76 \cdot 10^{-2}$

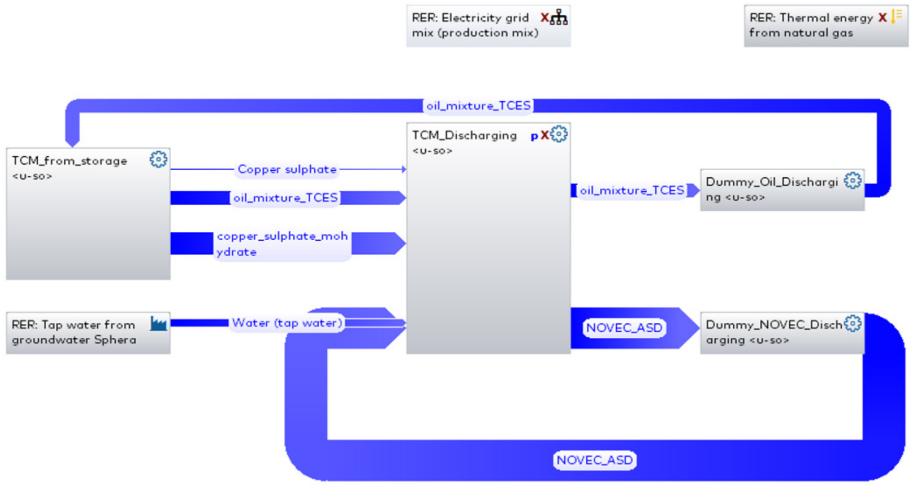


Figure 4. LCA plan for the discharging cycle

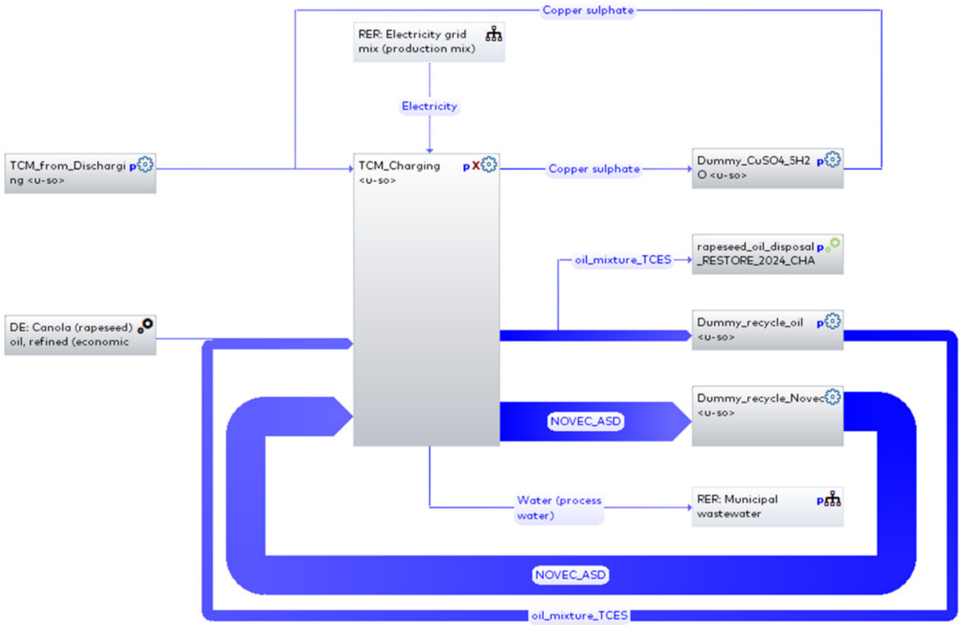


Figure 5. LCA plan for the charging cycle

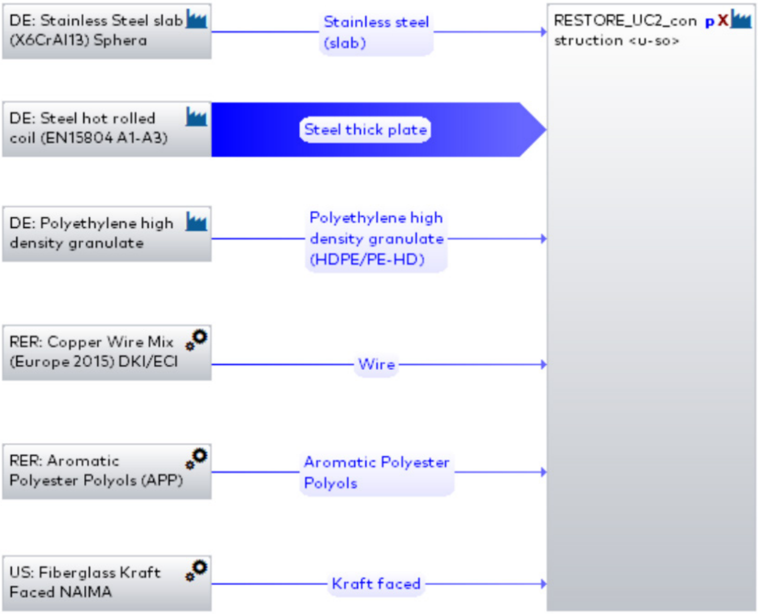


Figure 6. LCA plan for the plant construction

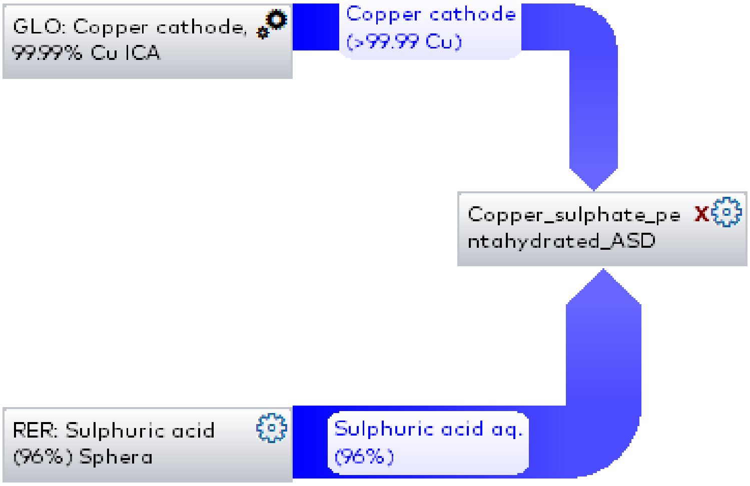


Figure 7. LCA plan for the Copper sulphate production

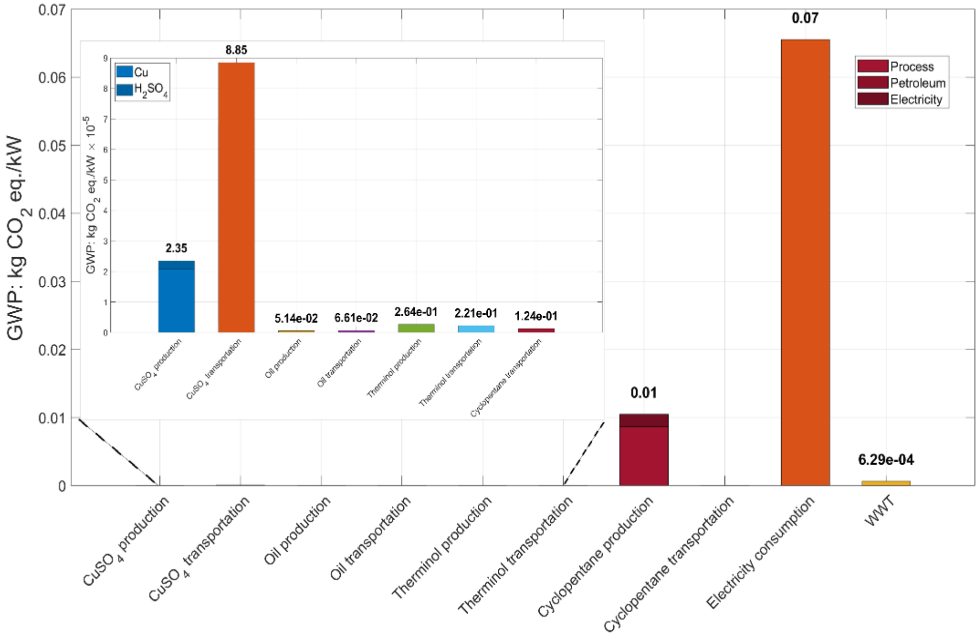


Figure 8. GWP for the Charging phase

During the charging phase, the system exhibited a Global Warming Potential (GWP) of $7.68 \cdot 10^{-2}$ kg CO_2 eq./kWh, significantly higher than that observed during the discharging phase ($9.2 \cdot 10^{-3}$ kg CO_2 eq./kWh), indicating that most of the climate change impact is concentrated in the thermal energy input phase (see Figure 8 and Figure 9). A similar trend was observed for most other impact categories, including Fossil Depletion Potential (FDP), Freshwater Ecotoxicity Potential (FETP), and Terrestrial Acidification Potential (TAP), all of which showed markedly higher values during charging. The FDP and Terrestrial Ecotoxicity Potential (TETP) indicators during the discharging phase registered values of $-1.0 \cdot 10^{-3}$ kg oil eq./kWh and $-3.48 \cdot 10^{-4}$ kg 1,4-DB eq./kWh, respectively. The Human Toxicity Potential cancer (HTP_{cancer}) for charging contributed to $1.88 \cdot 10^{-4}$ kg 1,4-DB eq./kWh, while discharging showed a small negative value ($-1.29 \cdot 10^{-7}$ kg 1,4-DB eq./kWh). Conversely, $HTP_{non\text{-}cancer}$ impacts were higher during discharging ($6.7 \cdot 10^{-4}$ kg 1,4-DB eq./kWh) than charging, suggesting increased exposure to non-carcinogenic toxic agents during this phase.

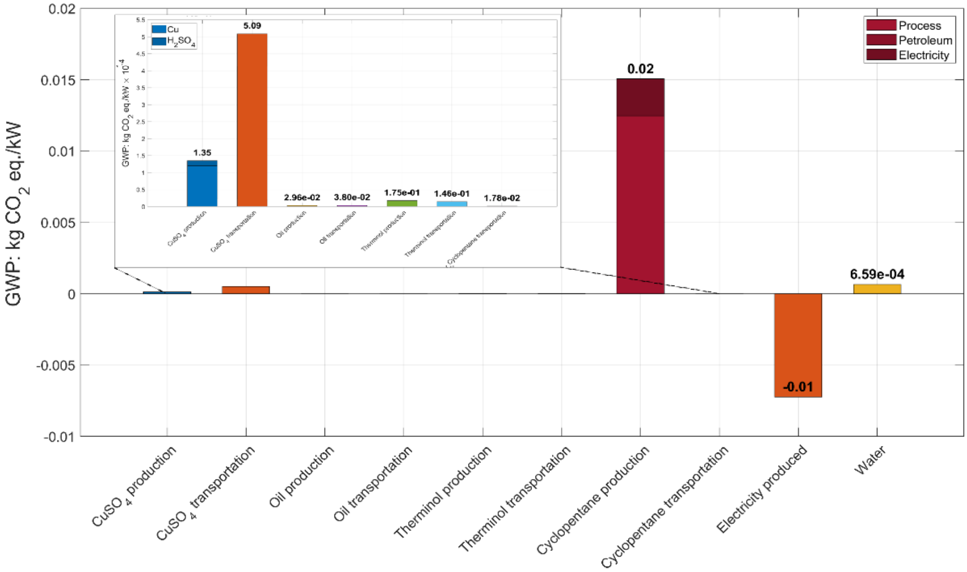


Figure 9. GWP for the Discharging phase

Regarding the environmental impact of plant construction, a notable difference was observed between the two tank material options. Option no.2 (HDPE tanks) consistently showed lower environmental impact across most categories compared to Option no.1 (carbon steel tanks), with the exception of the FEP category, where both options exhibited similar values ($1.22 \cdot 10^{-11}$ kg P eq./kWh). For instance, GWP was reduced from $3.21 \cdot 10^{-2}$ kg CO_2 eq./kWh in Option no.1 to $1.35 \cdot 10^{-2}$ kg CO_2 eq./kWh in Option no.2, indicating a 58% reduction in climate change-related emissions (see Figure 10 and Figure 11).

Similar reductions were evident in categories such as TAP (from $4.59 \cdot 10^{-5}$ to $1.32 \cdot 10^{-5}$ kg SO_2 eq./kWh) and $POFP_{ecosystem}$ (from $4.71 \cdot 10^{-5}$ to $1.77 \cdot 10^{-5}$ kg NO_x eq./kWh), reinforcing the environmental advantage of using HDPE instead of carbon steel. However, some trade-offs emerged since Option no.2 showed a higher impact in categories such as FDP ($1.08 \cdot 10^{-2}$ kg oil eq./kWh vs. $6.52 \cdot 10^{-2}$ in Option no.1), FETP ($7.63 \cdot 10^{-6}$ 1,4-DB eq./kWh vs. $5.44 \cdot 10^{-6}$ kg 1,4-DB eq./kWh), and ODP ($1.90 \cdot 10^{-9}$ kg CFC-11 eq./kWh vs. $2.26 \cdot 10^{-9}$ kg CFC-11 eq./kWh) which reflects the petroleum-based nature of HDPE and the associated toxicity during its production. The most significant divergence occurred in the Mineral Depletion Potential (MDP) category, with Option no.1 exhibiting a substantially higher impact score ($9.59 \cdot 10^{-4}$ kg Cu eq./kWh) compared to Option no.2 ($1.32 \cdot 10^{-5}$ kg Cu eq./kWh), thus highlighting the material intensity and extractive burden of carbon steel manufacturing.

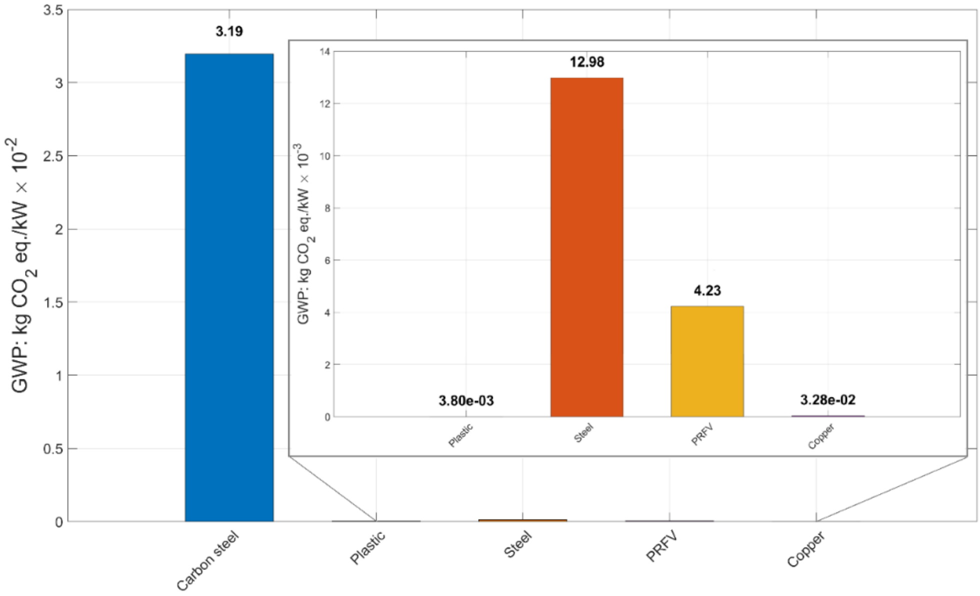


Figure 10. GWP for Plant construction – Option no.1

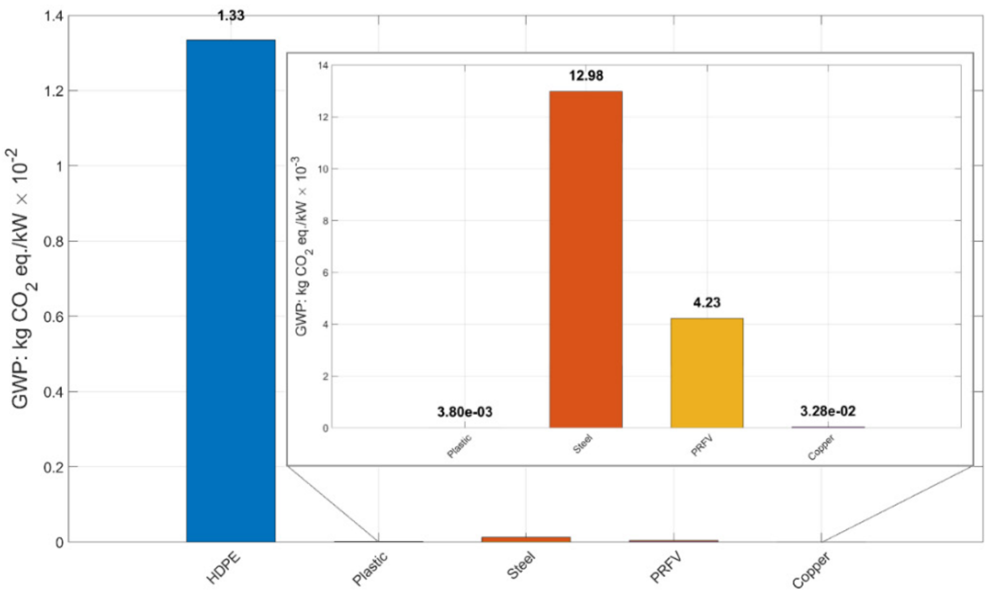


Figure 11. GWP for Plant construction – Option no.2

CONCLUSIONS

This study presented a comprehensive LCA of the RESTORE system, an integrated TCES and ORC/HP solution designed to enhance the environmental sustainability of DHC networks. Conducted over a 25 years operational lifespan and based on a functional unit of 1 kWh of thermal energy output, the assessment focused on three system phases: charging, discharging, and plant construction. Two construction configurations were analyzed, differing in the material used for storage tanks: carbon steel (Option no.1) and high-density polyethylene (HDPE, Option no.2).

The results indicate that the charging phase is the dominant contributor to environmental impacts across most categories, particularly in terms of GWP, FDP, and TAP. In contrast, the discharging phase exhibited considerably lower impacts and even environmental benefits in select categories, such as FDP and TETP.

From a construction perspective, Option no.2 consistently outperformed Option no.1 in several key impact categories. Notably, Option no.2 reduced GWP by approximately 58%, alongside substantial reductions in TAP and POFP. However, trade-offs were observed, as Option no.2 incurred higher impacts in categories such as FDP and FETP, likely due to the petroleum-based origin of HDPE.

These findings underscore the importance of adopting a life cycle perspective in the development of sustainable energy technologies, where both operational performance and construction material selection play critical roles in determining overall environmental outcomes. The RESTORE system, particularly when implemented with HDPE tanks, demonstrates strong potential as a low-impact, long-duration energy storage solution for supporting renewable energy integration in DHC networks. Moreover, this study highlights how combining LCA with performance-based indicators offers valuable guidance for optimizing the design and deployment of TCES technologies in future seasonal storage applications.

ACKNOWLEDGMENTS

The current work has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No. 101036766.

ABBREVIATIONS

DALY – Disability adjusted life years
DHC – District Heating and Cooling
FDP – Fossil Depletion Potential
FEP – Freshwater Eutrophication Potential
FETP – Freshwater Ecotoxicity Potential
GHG – Greenhouse gas emissions
GWP – Global Warming Potential
HDPE – High-Density Polyethylene
HP – Heat Pump
HTP – Human toxicity potential
ISO – International Organization for Standardization
LCA – Life Cycle Assessment
LCI – Life Cycle Inventory
LCIA – Life Cycle Impact Assessment
MDP – Mineral Depletion Potential
ODP – Ozone Depletion Potential
ORC – Organic Rankine Cycle
POFP – Photochemical Ozone Formation Potential, Ecosystem
PRFV – Reinforced Polyester with Fiberglass
RES – Renewable Energy Sources
TAP – Terrestrial Acidification Potential
TETP – Terrestrial Ecotoxicity Potential
TCES – Thermochemical Energy Storage

REFERENCES

1. E. C. Okonkwo; A. AlNouss; M. Shahbaz; T. Al-Ansari, *Energy Convers. Manage.*, **2023**, *296*, 117687.
2. Causes of climate change - European Commission. https://climate.ec.europa.eu/climate-change/causes-climate-change_en (accessed June 23, 2025).
3. Global and European temperatures 2025. https://www.eea.europa.eu/en/analysis/indicators/global-and-european-temperatures (accessed June 23, 2025).
4. Q. Bian, *Environ. Syst. Res.*, **2020**, *9*, 8.
5. Y. Hao; I. Khan, *Energy*, **2025**, *324*, 135863.
6. K. I. Vatalis; G. Avlogiaris; T. A. Tsalis, *J. Environ. Manage.*, **2022**, *309*, 114713.
7. P. Kalita; D. Kashyap; U. Bordoloi, Thermal Energy Storage Systems for Cooling and Heating Applications. In *Energy Storage*; John Wiley & Sons, Ltd: **2021**; pp 149–199.
8. M. Eyidogan; F. Canka Kilic; D. Kaya; V. Coban; S. Cagman, *Renew. Sustain. Energy Rev.*, **2016**, *58*, 885–895.

9. Luis, H2020 RESTORE Project. https://www.restore-dhc.eu/about-us/h2020-restore-project/ (accessed June 23, 2025).
10. O. Jolliet; S. Shaked; A. Jolliet; P. Crettaz; M. Saadé, *Environmental Life Cycle Assessment*; CRC Press: Boca Raton, **2016**.
11. H.-J. Klüppel, *Int. J. Life Cycle Assess.*, **2005**, *10*, 165–165.
12. S. C. Galusnyak; L. Petrescu; D. A. Chisalita; C.-C. Cormos, *Energy*, **2022**, *259*, 124784.
13. E. Perz; S. Kysela; M. Perz, **2025**, https://doi.org/10.5281/zenodo.15341167.
14. L. Schmieder; S. Kuloglija; K. Ilyina-Brunner; S. Jezernik; F. Winter, *Appl. Therm. Eng.*, **2025**, *258*, 124557.
15. M. A. J. Huijbregts; Z. J. N. Steinmann; P. M. F. Elshout; G. Stam; F. Verones; M. Vieira; et al., *Int. J. Life Cycle Assess.*, **2017**, *22*, 138–147.
16. SimTech GmbH, IPSE GO — The Future of Process Simulation. IPSE GO **2022**. https://about.ipsego.app/ (accessed August 11, 2025).
17. IPSE GO — Mass and Energy Balance Process Simulation Online. https://ipsego.app (accessed August 11, 2025).
18. M. Botejara-Antúnez; J. González-Domínguez; F. J. Rebollo-Castillo; J. García-Sanz-Calcedo, *Sustain. Energy Technol. Assess.*, **2025**, *74*, 104188.
19. S. Katz; A. S. Lindner, *J. Air Waste Manage. Assoc.*, **2003**, *53*, 469–477.
20. *LCA for Experts (GaBi) Software*; Sphera™: **2024**.