Deliverable D2.1

Description of KPI needed and KPI targets

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DOCUMENT REVIEW

Reviewer	Date	Reviewer Name (Short Organisation Name)
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Executive Summary

HEATERNAL develops a Thermal Energy Storage (TESS) System conceived to meet industry needs of constant high temperature heat for continuous and batch processes in the face of climate and geopolitical urgencies.

Project contributes to HORIZON-CL5-2022-D4-01-05 by developing a Thermal Energy Storage to recover industrial waste heat or renewable energy, helping to balance energy demand and supply on a daily basis. HEATERNAL will allow plants that operate continuously needing heat to reduce their natural gas needs or to electrify: plants could convert electricity to heat when it is available in excess and store that heat for use when electricity is not available.

HEATERNAL proposes to develop and validate at TRL 5 an innovative TESS concept able to store high-temperature heat (600-900 °C) generated by renewables or Industrial Waste Heat (IWH) to meet the needs of 3 use-cases of energy-intensive processes, i.e., steel, aluminum and ceramics, thanks to the combination of innovative phase-change materials (PCMs).

Chemical and steel industries are the main energy consumers (about 580 TWh/year each) and 60% of the European industrial heat consumption is allocated to 5 countries: Germany, Italy, France, UK and Spain. Only 52% of the industrial energy consumption (3 196 TWh) is spent usefully while the rest is lost through exhaust and effluents (29%) or other losses (20%). Theoretically, the potential waste heat recoverable (WHRP) is about 920 TWh annually in Europe, but in practice only a part (“practical” or PWHRP) is recoverable, or 279 TWh of which 55% concerns temperature >300ºC.

The present Deliverable (D2.1) contributes to achieve the objectives of WP2, by identifying relevant KPI and process parameters, that will be later used on WP3 and WP4 as well as WP7 for technology assessment.

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1. Introduction

HEATERNAL Thermal Energy Storage Systems (TESS) are based on innovative alloy-based phase change materials (PCM) integrated in tailored refractory concepts. TESS concept will be validated in three industrial demo cases. Environment specifications will be the baseline for the material design in WP3 as well as modelization in WP4. In order to achieve the objectives of the project, main parameters and KPI for analysis have been identified.

The TESS will be designed to satisfy the thermal energy requirements from 3 use-cases:

1. TESS for the aluminium industry [ALCOA]: Installation of TESS in an alumina refinery.
2. TESS for ceramic pigment furnaces [TCID]: Installation of TESS in a ceramic frit smelter to reuse industrial waste heat to reduce the use of natural gas (NG) and CO_2 emissions. WH from a continuous process (smelters) will be stored and reused in a batch process (ceramic pigment furnace) to preheat air between 650 and 900 ºC.
3. TESS for steel furnace [UGIT]: Installation of TESS in stainless steel foundry bloom reheating furnace to improve the thermal efficiency of refractory walls

D2.1 defines the KPI and background status that will be used in WP3, in WP4 for modelization and targets for WP7, techno economic and environmental assessment. D2.1 is public, so key process data values have not been included due to confidentiality issues. D2.1 describes the demo cases, provide a review of KPI for HEATERNAL, and reviews demo cases providing specific KPI and process parameters. It gathers information obtained in WP2 through Task 2.1 on Characterization of use cases and operational environment and Task 2.2 on Accurate specification of KPIs for each use cases and background.

D2.1 will allow to achieve objectives defined in DoA, specifically OBJ#1 “maximise thermal performances”, and OBJ#2 “simulate full TESS integration for 3 use cases”.

2. HEATERNAL use cases and KPI

2.1 Description of use cases

HEATERNAL will address three industrial environments representative of Energy Intensive Industries (EII).

- **ALCOA** - The production of aluminium from bauxite is a two-step process: refining bauxite to obtain alumina and smelting alumina to produce aluminium. Conventional calcination to produce alumina combusts NG and, for example, over 1.100,000 MWh NG is used per year by ALCOA in its San Ciprian alumina refinery's calciner. ALCOA is currently developing an electric calciner powered by renewable energy (RE) to decarbonize alumina refining. The electric calciner use case details are confidential, however, in the San Ciprian use-case, a portion of the calcination heat would be supplied from the HEATERNAL TESS. The calciner requires 14 hours of thermal storage and a TESS storage capacity of 970 MWh. The stored heat for calcination will be from electricity, which typically can be converted into heat at above 1000°C. ALCOA's process runs continuously and requires firm thermal heat. Firm power is very expensive. TESS would enable the use of inexpensive, intermittent, renewable power to provide the continuous thermal heat. The intraday TESS will charge when there is excess RE, and discharge when solar PV or wind produce less energy.

- **TORRECID** - The highly energy-intensive ceramic frit industry uses heat for melting, drying and pigment synthesis. HEATERNAL concerns two processes. Firstly, the continuous furnaces (frit smelters) that melt raw materials at 1500-1580 ºC, and secondly, ceramic pigment furnaces operating at 1300°C. In the VULKANO H2020 project, TORRECID studied a heat exchanger based on molten salts for storage/recovery of energy. The solution was not viable due to corrosion issues. The HEATERNAL use-case will focus on WH recovery from continuous frit smelters to be stored and supplied to ceramic pigment furnaces (batch process) that run 18 hours per batch, 15 times per month. As heat source, fumes coming from the heat recuperator will be used. The heat from the TESS will reduce heat from natural gas combustion by heating up combustion air.

- **UGITECH** - This use-case focuses on a 34 MW continuous walking beam furnace dedicated to stainless steel bar (bloom) reheating before rolling. The heating range of the blooms is between 1100 and 1330°C. The furnace is lined with refractories (ceramic bricks and concrete). Currently, thanks to the refractory lining and existing heat recovery, UGITECH can handle 7h gas shortage (with no impact on production and no furnace damage). The main objective for this use case is to reduce natural gas consumption and CO_2 emissions during the weekend when the rolling mill is stopped, and the furnace maintained at a temperature of 750ºC to avoid potential breaks on the refractory coating inside the furnace. UGITECH focuses the scope of the use case on replacing the existing lining on the walls with HEATERNAL materials with higher thermal density (available volume calculation gives 120 m3 for the 2 walls). The charging phase will allow to store a certain amount of heat during the week. During the weekend, after the burners are cut off, the discharging phase will return some heat to the furnace. The objective is to calculate the volume of NG that can be saved thanks to the heat recovery from HEATERNAL materials in the coating lining of the walls.

HEATERNAL TESS will consist in a metal PCM alloy system enclosed in tailored refractories, in which geometry will be optimized to improve thermal transfer during charge and discharge. Initial modelization will optimize the design.

2.2 HEATERNAL main KPI

The main objectives of HEATERNAL are:

1. OBJ#1 To maximize thermal performance of TESS UNIT, energy, density, heat supply
2. OBJ#2 To simulate full TESS integration in 3 use cases.
3. OBJ#3 To ensure economic viability and environmental sustainability of the system.
4. OBJ#4 To ensure the reliability of the thermal storage unit from 600 to 900 ºC.
5. OBJ#5 To validate a 50 kWh -scale (TRL5).
6. OBJ#6 To minimize system footprint.
7. OBJ#7 To ensure that HEATERNAL R&D leads to a system that can be rapidly manufactured and improved after the project.

In accordance with the main objectives according DoA, Table 1 summarizes the main KPI .

Table 1. HEATERNAL KPI

KPI	Description
[KPI#1]	TESS Unit energy density increased by 350% (compared to stand-alone refractory), to 110 kW/m^3 over temperature change of 50 ºC which would TESS energy density over temperature of 300 C to exceed 400 kwh/m^3 after upscaling.
[KPI#2]	3 novel PCM material formulations with cascading phase transition temperatures from 600 to 900 ºC, enthalpy of phase transition over 150 J/g, stability for more than 1000 h.
[KPI#3]	Improved convective heat transfer coefficient (CHTC) by 30- 50%.
[KPI#4]	TESS model presents a stable efficiency of 90% as per the IRENA road map.
[KPI#5]	TESS model predicting efficiency decrease during test phase < 5%.
[KPI#6]	Accuracy of thermal model versus empirical data from the prototype within 10ºC of outlet temperature.

KPI	Description
[KPI#7]	Accuracy of reduced order model vs Computational Fluid Dynamic (CFD) calculation: a maximum deviation of 20 ºC.
[KPI#8]	Tech-economic assessment (TEA) study showing Return on Investment (RoI) below 3 years for all use-cases and Levelized Cost of Stored Energy (LCOS) below 6€/MWh. Preliminary study shows RoI of 14.4 months and LCOS of 3.5 €/MWh.
[KPI#9]	TEA shows at-scale CAPEX at 20€ per kWh TESS capacity (compared to 30.96 €/kWh for molten salts), 0 €/kWh OPEX for 10 years for IWH recovery, OPEX limited to electricity costs when heat comes from RE.
[KPI#10]	NG reduction.
[KPI#11]	CO_2 emission reduction.
[KPI#12]	Lower life-cycle environmental costs for short-term storage (12 – 48 hours) than hydrogen production via electrolysis followed by H_2 storage and combustion.
[KPI#13]	Volume variation <10% maximum from 600–900°C to prevent stress induced cracking.
[KPI#14]	Stable phase change temperature, evolving < 3% over 1000 hours.
[KPI#15]	No physico-chemical interactions between PCMs & ceramics after 500 h of immersion tests to prevent damage to ceramics and ensure a long lifetime.
KPI#16]	Stable efficiency of 90 % decrease during test phase, below 5 %
[KPI#17]	Design TESS units for: (i) IWH storage and use: height 10m, max 2x2m footprint (TCID, UGIT use-cases);
[KPI#18]	Unit production process shall be able to use existing /commercially viable processes for refractory manufacturing (MRL of 9-10). Ability to begin Unit mass production via existing processes within 2 months following demonstration.
[KPI#19]	Ability to begin PCM alloy mass production via MRL9-10 processes within 6 months following demonstration. Next-generation TESS Unit Manufacturing
[KPI#20]	New routes for additive (3D) manufacturing of TESS Units with TRL of 4 by end of project (including new filament materials).
[KPI#21]	Reduce manufacturing and recyclability costs by up to 70% in contrast to the traditional manufacture of ceramic parts (for 3D-printing)
[KPI#22]	>8 Companies sign engagements before the end of HEATERNAL including 1 PCM supplier,>3 metals and minerals industry end-users, >1 equipment manufacturer,>1 engineering firm, refractory supplier.

2.3 HEATERNAL demo cases KPI and process parameters

In line with the general HEATERNAL KPI , specific KPI and process parameters have been identified for each demo case. The present deliverable displays the description of KPI and parameters. Specific values have been reported internally.

2.3.1 ALCOA use case

The information of ALCOA use case is omitted due to confidentiality concerns.

2.3.2 TORRECID use case

Figure 1 shows HEATERNAL concept associated with the TORRECID use case. It will focus on WH recovery from continuous frit smelters to be stored and supplied to ceramic pigment furnaces.

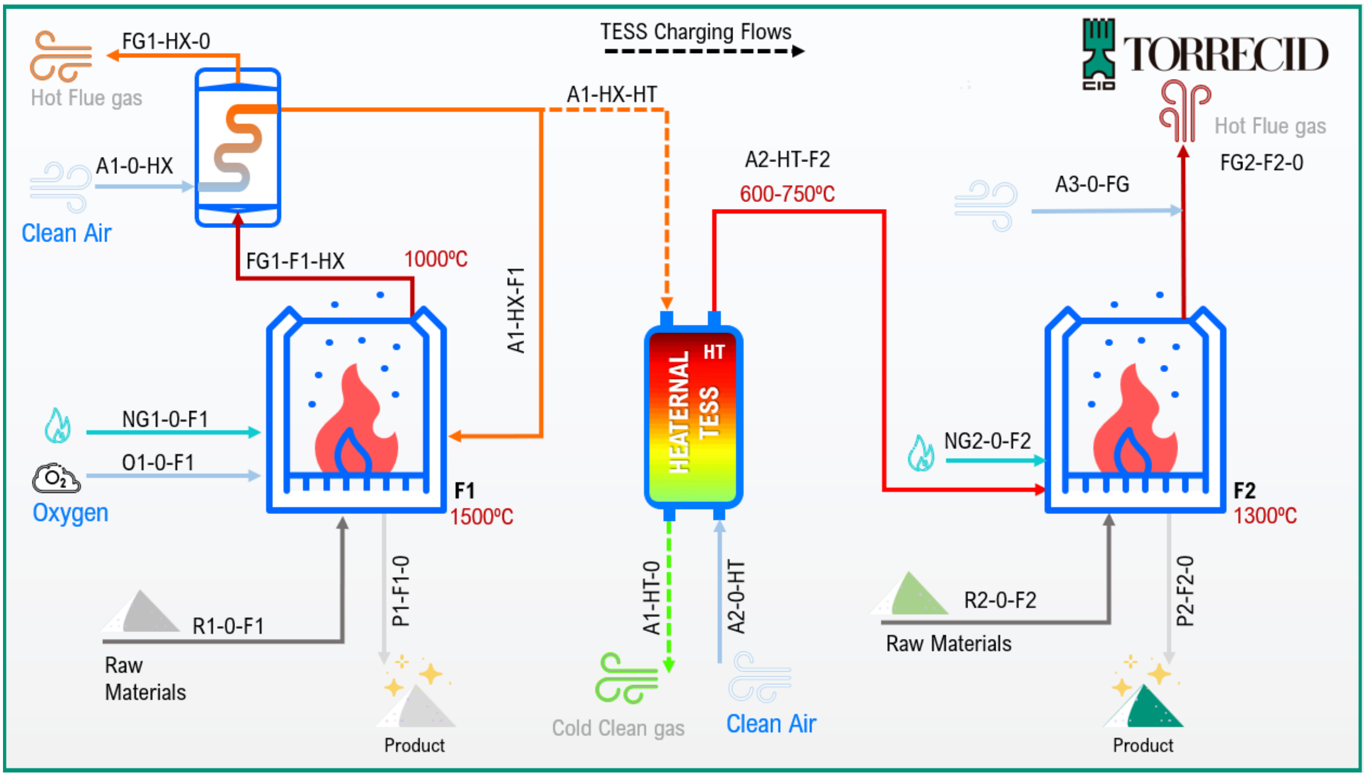

Figure 1. HEATERNAL integration at TORRECID use case

The main energy and materials flows, and design parameters considered in the TESS design for TORRECID are described in Table 2 and Table 3, respectively.

Table 2. Energy and Materials Flow in TORRECID

Id.	Description	Units
A2-HX-HT	Heated up air from heat exchanger in smelter. Part is fed into burner for the smelter, part is sent to TESS	m^3/h
A2-HX-HT - TEMP	Temperature of heated air in the heat exchanger	ºC
A1-0-F1	Combustion air to the main burner of smelter.	m^3/h
A2-HX-HT - A1-0-F1	Heated air entering into the TESS for recovery	m^3/h
A3-HT-F2	Combustion air from TESS for ceramic pigment furnace	m^3/h
A3-HT-F2 - TEMP	Temperature of heated air exiting TESS	ºC
NG2-0-F2	Natural gas for ceramic furnace pigments	m^3/h
R2-0-F2	Ceramic pigment raw batch	Tn/batch
A3-0-HT	Air entering TESS for being preheated	m^3/h
FG1-HT-0	Air exiting TESS after heating up alloys.	m^3/h
A3-HT-F2	Combustion air from TESS for ceramic pigment furnace	m^3/h
FG2-F2-0	Combustion fumes out of ceramic pigment furnace	m^3/h

Table 3. Design parameters for TORRECID use case

Description design parameters	Units
Thermal power needed for ceramic furnace	W/h
Thermal load need of TESS	W
Time for heat discharge	H
Length of heat supply	m
Available room for TESS implantation	m^2
Available height of building	m

Table 4 shows main KPIs affecting the demo case, as well as some specific KPIs due to the peculiarity of TORRECID's process.

Table 4. KPIs identified in TORRECID use case

Id.	Description	Unit	Measurement
[KPI#1]	Thermal output of TESS	W/m^3	Energy transferred into furnace.
[KPI#2]	Lifetime of installed TESS	years	Assessment
[KPI#9]	€/kWh opex for TESS	€/kwh	Assessment
[KPI#8]	€//mWh return on investment	€/MWH in furnace	Assessment
[KPI#10]	Natural gas reduced in the demo case case	m^3/h	Gas consumption
[KPI#11]	CO_2 emissions reduced at demo case	kg/h CO_2	LCA
[KPI#17]	TESS SIZE	m^2/m^3	
Id. specific KPI	**Description**	**Unit**	**Measurement**
[KPI#T23]	Quality acceptance	ceramic acceptance	Quality controls
[KPI#T24]	Productivity of ceramic pigment furnace	Tn/batch	Weighting

Regarding the identified process parameters for TORRECID use case, main variables to be monitored in the TESS are compiled in

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Table 5. Apart from flows indicated in the graphs, process parameters for TESS unit have been identified

Table 5. Process parameters in TORRECID's TESS.

Id.	Description
A2-HX-HT	Temperature of incoming hot air into TESS
FG-1-HT0	Temperature of exit air in TESS
A3-HT-F2	Temperature of exit air heated air into combustion chamber of ceramic demo case
A2-HX-HT	incoming air flow into TESS
FG-1-HT0	Outcoming air of TESS
A3-HT-F2	Outcoming heated air flow into combustion chamber
	Temperature of refractory in TESS
	Temperature of PCM in TESS
A3-HT-F2	Pressure of outcoming air from TESSS into combustion chamber
A2-HX-HT	Pressure of incoming hot air into combustion chamber
	Expansion of TESS system
	Electrical power consumptions fan

2.3.3 UGITECH use case

Figure 2 shows the use case of UGITECH in charge phase (top flowchart) and discharge phase (bottom flowchart). UGITECH focus the scope of the use case on replacing the existing lining on the walls with HEATERNAL materials with higher thermal density (available volume calculation gives 120 m3 for the lateral 2 walls). The charging phase will allow to store a certain amount of heat during the week. During the weekend, after the burners are cut off, the discharging phase will return some heat to the furnace.

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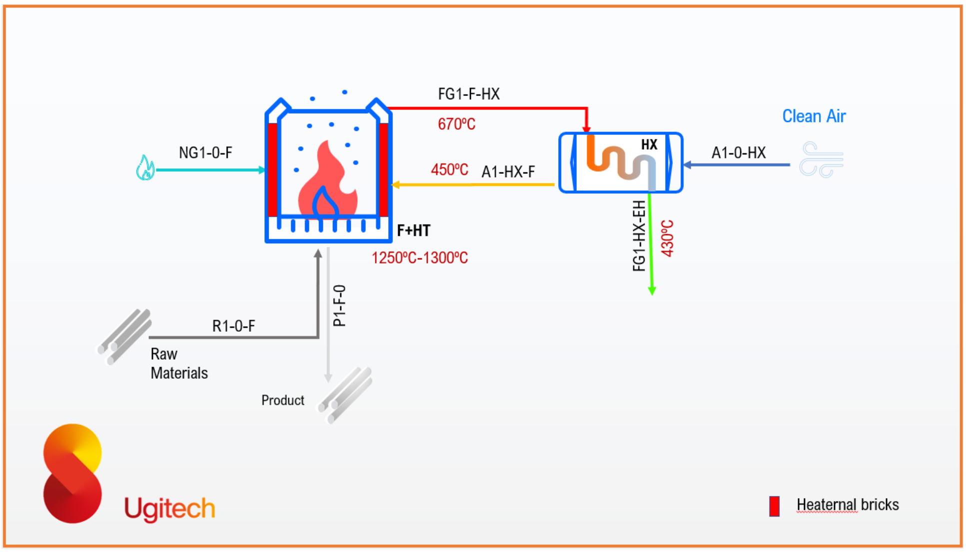
Simplified Flow Diagram (Proposed Operation)

Charge Phase:



Discharge Phase:

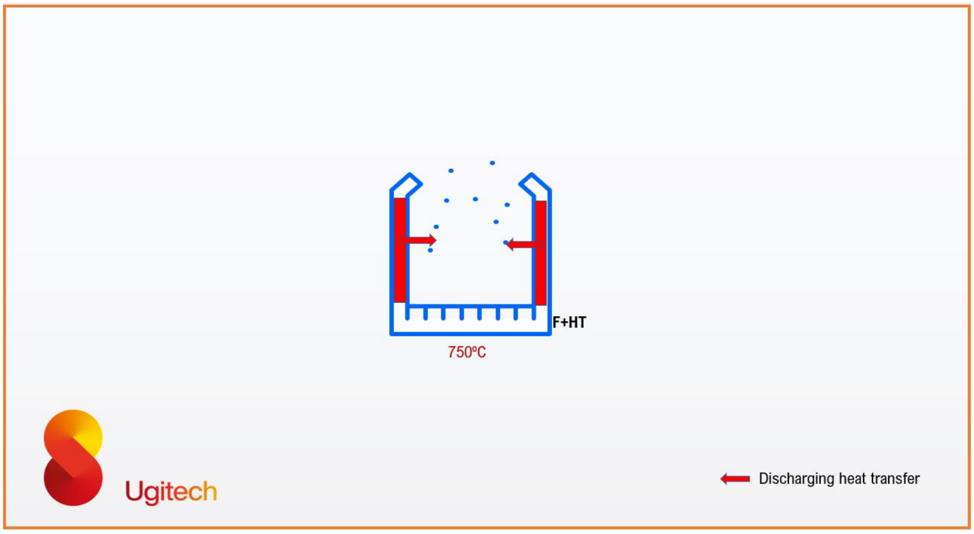


Figure 2. HEATERNAL integration at UGITECH use case.

The energy and material flows related to the UGITECH use case are described in the Table 6.

Table 6. Energy and material flows in UGITECH

Id.	Description	Units
NG1-0-F	Natural gas input on zone 3 and 4	Mass
	Oxygen input on zone 3 and 4	Mass
	Power input on zone 1 and 2	Mass
FG1-F-HX	Flue gases from furnace	Mass
	Thermal output to HEATERNAL material in the refractory lining (walls) => charging phase	
	Thermal HEATERNAL output to other parts of refractories lining (top and ground) => discharging phase	

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Regarding the thermal exchange system designed , HEATERNAL will tailor design to the specific use cases gathering inputs for replicability. HEATERNAL will advance by developing 3D based novel geometries. The main parameters that will be considered during the TESS design are shown in Table 7.

Table 7. Design parameters for UGITECH use case

Description design parameters	Units
Refractory thermal expansion	$^{o}C^{-1}$
Refractory thermal conductivity	W/mk
PCM Alloy thermal expansion	$^{o}C^{-1}$
PCM Alloy thermal conductivity	W/mK
PCM Alloy melting temperature	ºC
PCM J/kg storage	J/kg
PCM alloy heat flow density	W/m^2
PCM Alloy liquid to solid temperature	ºC
PCM Alloy volume	m^3
PCM alloy latent heat	
Refractory to alloy surface ratio / volume ratio	m^2/m^3
TESS size	m^3
TESS internal geometry	m^3

Table 8 shows main KPIs affecting the demo case, as well as some specific KPIs due to the peculiarity of process.

Table 8. KPIs identified in UGITECH demo case.

Id.	Description	Unit	Measurement
[KPI#1]	Thermal output of TESS	W/m^3	energy transferred into furnace.
[KPI#9]	€/kwh opex for TESS relative to natural gas, oxygen and power	€/kwh	assessment
[KPI#8]	€//mWh return on investment	€/MWH in furnace	assessment
[KPI#10]	NG Gas reduction	m^3/h	assessment
[KPI#11]	Emissions	kg CO_2-eq	assessment
Id. specific KPI	**Description**	**Unit**	**Measurement**
[KPI#U29]	Refractory lifetime	kg/year	Quality controls

The main parameters of relevance for the process in UGITECH are compiled in Table 9.

Table 9 Process parameters in UGITEC case

Id.	Description	Units
NG1-0-F	Natural gas input	Nm^3/h
	Oxygen input	Nm^3/h
	Power input	kWh
R1-0-F	Stainless steel blooms	kg/h
P1-F-0	Hot stainless steel blooms	kg/h
FG1-F-HX	Flue gases from furnace	Nm^3/h
NG2-0-F	Natural gas input to maintain the 750ºC during the weekend.	Nm^3/h
	Size of PCM bricks and volume available	m^3

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3. Conclusion

HEATERNAL contributes to roadmap of CL5-2023-D4-01-05 by developing short term thermal storage systems for decoupling the heat generation from the heat use in industrial processes, being assessed in 3 use cases and by developing of economically affordable new materials for heat storage dedicated to medium to high temperature industrial processes. In this line the Deliverable 2.1 defines KPI and processing parameters for heat storage in the relevant industrial sectors.

Deliverable 2.1 has defined relevant key performance indicators for successful project development, including KPIs for the industrial cases and process parameters of relevance for the 3 cases. Specific values for the KPI, energy flows and operational parameters have been identified and shared with involved partners. The procedure involved in assessing KPI and parameters can be replicated to other possible use cases.

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4. List of Acronyms

CFM	Computational Fluid Dynamics
D	Deliverable
IWH	Industrial Waste Heat
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
NG	Natural Gas
PCM	Phase Change Material
RE	Renewable Energy
TCID	TORRECID
TEA	Techno-economic Assessment
TES	Thermal Energy Storage
TESS	Thermal Energy Storage System
TRL	Technology Readiness Level
UGIT	UGITECH
WHRP	Waste Heat Recovery Potential
WP	Workpackage

Table 10 List of acronyms

5. Appendix

N/A