D4.3 Report of use case analyses and benchmarkings

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Deliverable 4.3 Report of use case analyses and benchmarkings

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TechUPGRADE

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Tech UPGRADE

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1 Summary

This deliverable provides the results of techno-economic simulations that were performed for the defined TechUPGRADE project use cases. The performance of the technologies developed in these cases is evaluated and compared with competing technologies from a technical and economic perspective. The report discusses key performance indicators for industrial process heating applications, such as energy efficiency, levelized cost of heat (LCOH), and operating limits. The results support objective evaluation of the suggested solutions and serve as a basis for benchmarking, decision-making, and future implementation.

2 Introduction

2.1. Introduction to the TechUPGRADE concept

TechUPGRADE develops and demonstrates a thermochemical heat upgrade technology, referred to as a Hydration Heat Transformer, designed to upgrade low-temperature heat to a target temperature of 150-250°C, depending on the heat sink temperature requirements. The system is based on reversible hydration and dehydration reactions of salt hydrates and enables temperature upgrading of industrial waste heat, e.g., datacenters, solar thermal energy, and district heating to output temperatures of 150–250°C [1]. The operating principle is based on thermochemical reactions in which heat is stored and released through chemical bonds. During the dehydration phase, low-grade heat drives an endothermic reaction that removes water from the salt at low water vapor partial pressure, storing heat in the form of chemical bonds. In the hydration phase, water vapor at elevated partial pressure is introduced, triggering an exothermic reaction that releases heat at a higher temperature [2]. The equilibrium temperature of the reaction is governed by the water vapor partial pressure, enabling controlled temperature lifting without mechanical compression, thereby enabling marginal electricity input limited to pumps, fans, etc. The system operates cyclically between two main reactors: a dehydration reactor and a hydration reactor, each equipped with internal heat exchangers and connected via a closed loop of heat transfer fluid (HTF). Low-temperature heat is supplied to the dehydration reactor, while the hydration reactor delivers upgraded heat. Figure 1 shows the TechUPGRADE concept in the black box mode.

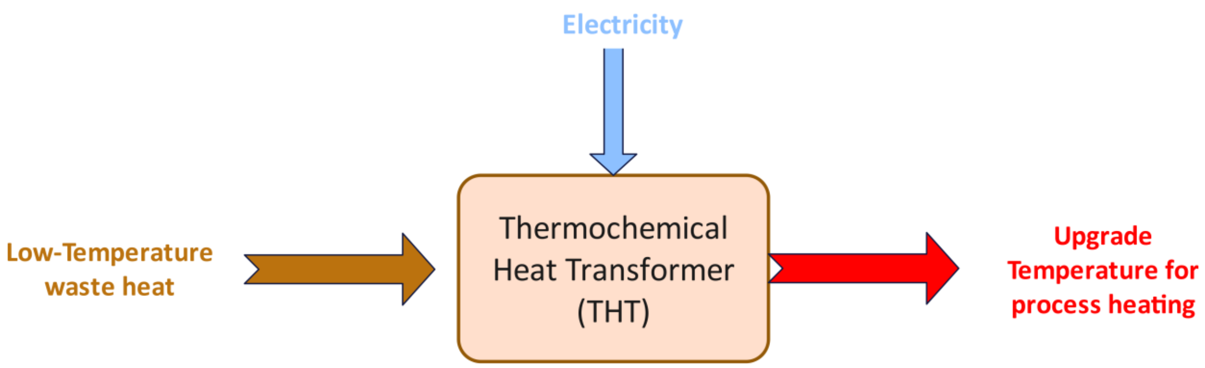


Figure 1. The TechUPGRADE project concept

2.2. Benchmarking on alternative solutions

To assess the techno-economic feasibility of the TechUPGRADE solution, three alternative technologies will be benchmarked against the reference scenario of the current natural gas boiler through a techno-economic analysis. In addition to benchmarking the three alternatives individually, the TechUPGRADE solution with an integrated solar heating system or HTHP will also be analyzed. For the techno-economic analysis, the following key performance indicators (KPI's) were used for benchmarking: Technology efficiencies, LCOH based on CAPEX, and OPEX (fixed and variable) from DEA's process heat technology catalogue [3] and CO_2 savings vs natural gas and LCOH/kg and CO_2 (€/kg) for each technology. A summary of the data assumptions can be found in Table 1, where VAT and taxes are excluded. Furthermore, the natural gas boiler efficiency is estimated to be 73% compared to DEA's 92.5% due to the age and location of the boiler. Economic assumptions not shown in Table 1 are an interest rate of 4% and an economic lifetime of 20 years. A sensitivity analysis of the economic lifetime of 7, 10, and 15 years is performed. For the operation, 4000 hours of operating time, assuming 2 shifts on workdays, including start-up time.

Table 1. A summary of KPI's for different technologies[1]

Technology	CAPEX M€/MW	OPEX (Fixed) k€/MW/y	OPEX (var.) €/MWh	Fuel cost €/MWh	CO_2 e (Kg/MWh)	Efficiency
Natural gas boiler (existing)	0	2.34	1.32	50.5	204.46	73%
TechUPGRADE	0.9	45.63	7.4	194.1	31.02	COPh = 0.6 COP = 14.5
HTHP 150° + MVP 250°	1.43 2.44	1.104 1.16	3.96 5.94	194.1 194.1	31.02 31.02	COP = 3.05 COP = 1.48
Electric boiler 12 bar 150° 40 bar 250°	0.11 0.35	1.3 1.3	1.08 1.08	194.1 194.1	31.02 31.02	94.5 94.5
Biomass boiler (Wood chips) 6-10 bar 150° 40 bar 250°	0.73 0.92	41.76 41.76	3.4 3.4	33.8 33.8	4.92 4.92	88% 89%
Biomass boiler (Wood pellets) 6-10 bar 150° 40 bar 250°	0.58 0.74	43.85 43.85	2.53 2.53	40.3 40.3	4.12 4.12	90 % 90 %

Technological assumptions

Natural gas boiler

The reference scenario includes an existing natural gas boiler with an estimated efficiency of 73% derived from a span of 56-86% depending on the age and location of the boiler. The CAPEX is set to 0 due to the investment already have been made. Natural gas boilers are a common technology in

[1] Please note that building costs and design fees are not included in CAPEX for TechUPGRADE, HTHP or solar, it is estimated that the CAPEX would increase by approximately up to 50% given these costs were included.

industrial heat processes and are a well-proven technology, with the main drawback being the high emission factor of natural gas combustion.

High Temperature Heat Pump

A HTHP that can supply 150°C of steam and 250°C with an added MVR steam compressor will be benchmarked. HTHP's are gaining traction for industrial heat supply due to their high obtainable efficiencies in use-cases with a high temperature glide, where heat is not transferred at a fixed temperature. The main drawback in relation to temperature glide is that in use cases where a constant process temperature is required with a low glide, the efficiency of the HTHP decreases significantly. Therefore, the COP value of 3.05 is potentially overestimated and will be lowered to e.g. 2.00 with the biogas plant use-case which requires near constant temperature levels of 150°C for biogas upgrade.

Electric Boiler

An electric boiler supplying process heat at 150°C and 250°C will be benchmarked. Electric boilers are heating elements using resistance or electrode systems, with smaller-scale boilers in the range of 1-4 MW utilizing resistance heating, and in systems up to 60 MW electrode systems are commonly used. When exceeding 12 bar(g) and 16 bar(g), the investment and maintenance costs increase significantly as shown in Table 1, but these configurations are rarely used in industries. Electric boilers operate at higher efficiency than natural gas boilers and have lower investments and operational costs than HTHPs or biomass boilers.

Biomass boiler

A biomass boiler capable of supplying 150°C and 250°C will be benchmarked. Biomass boilers are associated with low CO_2 eq (kg/MWh) and an efficiency of 88-90 % depending on using wood pellets or wood chips. The drawbacks compared to both electric boilers and HTHPs are the high fixed operational costs.

2.3. Introduction to GreenLab

GreenLab is a green and circular industrial park located in Skive, Denmark, that demonstrates the transformation of the energy system through a colocation of energy production, consumption, and integration across sectors. GreenLab works to develop and demonstrate green transition and circular economy in practice by improving the way renewable energy is produced, transformed, stored, and utilized in proximity-based industrial parks. GreenLab accelerates the green transition of industry through large-scale testing of new technologies, direct connection of industrial production to renewable energy, and mission-driven research.

The 60-hectare industrial park built through a greenfield and curated approach, accommodates 9 industrial site partners that, through innovative pyrolysis, PtX, microwave technology, biogas, etc., technologies, contribute directly to the green energy transition.

Figure 2. GreenLab Skive [4]

In the industrial park, companies can share their surplus energy and resources with each other through the SymbiosisNET™ - an intelligent network of energy and data managed by GreenLab. GreenLab is the site and infrastructure manager and park curator. Furthermore, companies in the park also produce bio-based fuels that can potentially supply other companies in the park with renewable energy.

Figure 3. GreenLab Skive site map [4]

Renewable energy is generated, stored and shared with the companies located in GreenLab's industrial area via a direct connection to the 84 MW wind and solar park just south of GreenLab (56 MW wind farm and 24 MW solar PV capacity). A 40 MW transformer station (with double capacity for further development) secures energy transformation from the wind and solar to the companies in the park. GreenLab is currently installing 10 MW electrical boiler and a 100 kWh thermal storage systems for balancing volatility from renewable energy supply.

Several interconnections and symbiosis exist at GreenLab industrial site and are visualized in figure 4.

GreenLab's infrastructure is provided through the SymbiosisNET, which secures the transportation of energy from renewable energy sources (i.e. the wind turbine and end solar cells park in the vicinity of GreenLab) and connects this with the existing site partners through our own transformer station. GreenLab offers several other services, providing ultra-pure water, nitrogen, and heating to industrial sites. SymbiosisNET goes further and provides possibilities for the interchange of various resources. Currently various resource flows exist among site partners. New resource flows are planned, and few others are analyzed for future partners. This includes the symbiosis potential of a Datacenter with the rest of the existing industries in GreenLab.

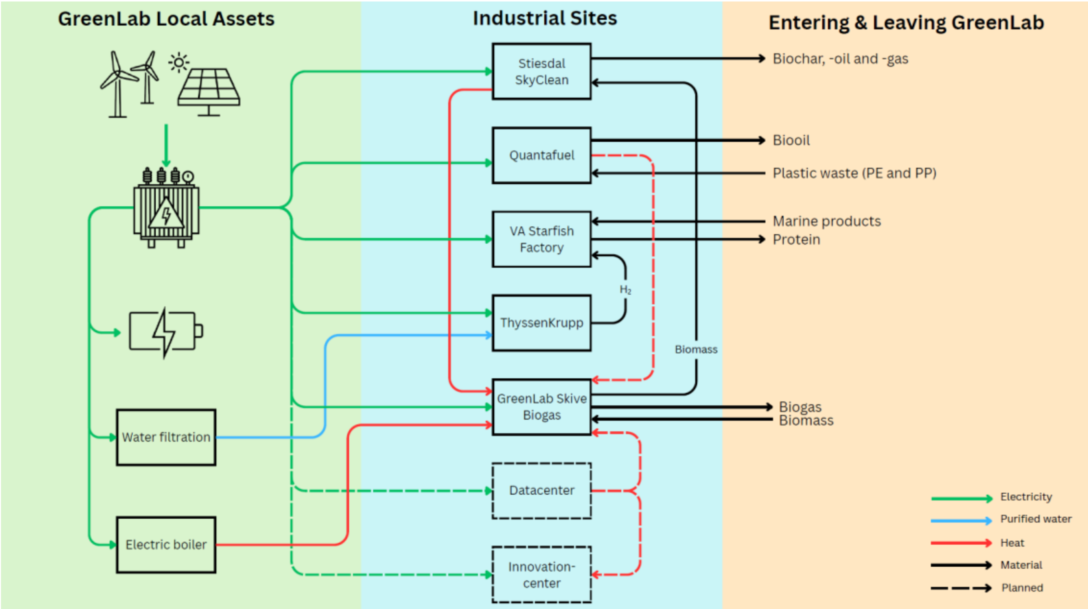


Figure 4. Current and planned GreenLab Skive SymbiosisNET [4]

The GreenLab model seeks to create the energy system of tomorrow and to demonstrate how different energy sectors can be integrated in a unique interplay between different energy forms, industries, and internal energy infrastructure. Therefore, GreenLab is always researching new sectors, new technologies, and new industries to be invited to the park community and become an integrative part of the SymbiosisNET. Datacenters are one of such industries that look promising regarding symbiotic potential, including energy use, heat production (as a byproduct of their operation), water recycling, etc. GreenLab is therefore keen on analyzing the potential of a datacenter for the heat symbiosis established in the park in general, and the interconnection between the datacenter and the site partners in the park, specifically with GreenLab Biogas Plant. Therefore, one of the following cases revolves around this problem.
GreenLab is also keen on developing the park through new symbiotic exchanges where site partners are the main key players. Quantafuel is one of the site partners that presents potential for the collection and use of waste heat, which can be distributed and reused by other site partners. Despite their potential, Quantafuel is not included in the use-case analysis due to data availability.

GreenLab has only these few possibilities for the TechUPGRADE project, and therefore, we use some other cases to exemplify the technology and concept. These are introduced and described under each specific section.

3 Use case analysis

3.1 Case 1: Reuse of surplus heat from a Data Center in GreenLab

3.1.1 Case description

GreenLab is analyzing the potential of heat symbiosis between a datacenter and the GreenLab Biogas Plant in the park.

Figure 5: Datacenter in GreenLab [4]

The datacenter is a 100 MW energy-consuming center, with a potential of 80 MW of waste heat at 70°C (after a heat pump process). The surplus heat can contribute to the Heat Symbiosis system in GreenLab, being an important input for other site partners, such as GreenLab Biogas A/S, if upgraded. The Biogas plant has a necessity of 5 MW of heat covered by natural gas, of which 4 MW is for process heating at 55°C, and 1 MW is needed at a temperature of 150°C, in its upgrading facilities. The rest of the 75 MW of waste heat from the Data Center will be considered for district heating.
The waste heat from the Data Center will only vary a little over the year, with a load factor of 80-90%, so waste heat will be abundant compared to the process heat demand.
As biogas production is practically constant 24/7, the biogas upgrade system also works on a constant, continuous basis. The biogas upgrade will remove CO_2 from the biogas to achieve a gas quality that enables it to be fed into the natural gas grid. The biogas upgrade (CO_2 removal) is based on sorption in an amine solution, which must be regenerated in a continuous process by heating it to 145°C to release the CO_2 for carbon capture. For this, a heat source of at least 150°C is needed, which can be provided with the TechUPGRADE process.

About the GreenLab Biogas Plant (from the home page - Anlægget - GreenLab Skive Biogas)

Two lines: Organic / Conventional
A flexible plant solution that allows adaptation of feedstock input in line with changes in the raw material market.

Plant area: approx. 7.5 hectares

Annual biomass input: 500,000 t/year

Estimated gas production: approx. 200 GWh of methane annually

Number of employees: 9

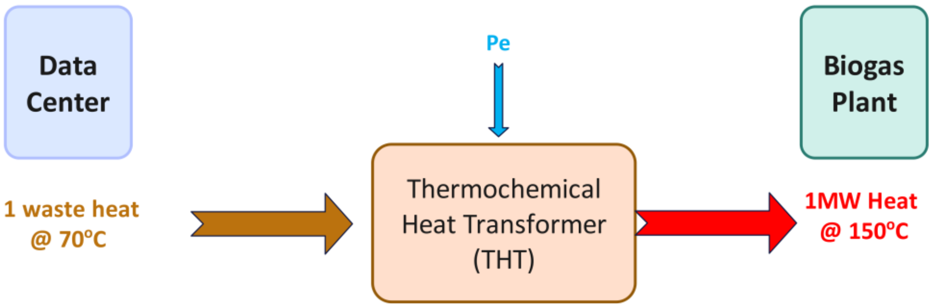
Process type: Thermophilic with organic line (variable ratio)

Upgrading facility

The biogas is upgraded to natural gas quality. The upgrading plant is of the amine type, operating by spraying a cold amine solution into the top of an absorber column, where it trickles down through a high-surface packing material.

3.1.2 Technical, economic, and environmental analysis

Figure 6 shows the schematic of case 1, the reuse of surplus heat from a datacenter in GreenLab to upgrade and use at the Biogas Plant in GreenLab. As can be seen in the schematic, the Thermochemical Heat Transformer (THT) is designed to upgrade the waste heat temperature from 70°C to 150°C. For this temperature range, some alternative materials should be used for the THT system. $SrBr_2.6H_2O$ and $CalCl_2.H_2O$ [5] are two salt hydrates, which can be used in this case. Table 2 summarizes the techno-economic results for case 1. Also, Table 3 provides the environmental results for case 1.



$$SrBr_2\cdot 6H_2O_{(s1)} + 5\Delta H_r^0 \leftrightarrows SrBr_2\cdot 1H_2O_{(s2)} + 5H_2O_{(g)}$$

$$CaCl_2\cdot H_2\ O + H_2\ O \leftrightarrow CaCl_2\cdot 2H_2O$$

Figure 6. Schematic of case 1

Table 2. A summary of techno-economic results for Case 1

Technology / Case	Process Heat Temperature (°C)	Process Heat Demand (MW)	Waste Heat Temperature (°C)	Quantity of Waste Heat (MW)	CAPEX (M€)	OPEX (Fixed) M€	OPEX (var.) M€	LCOH (c€/kWh)	Efficiency
THT/Case 1	150	1	70	80	0.9	0.045	0.03	3.53	COP_h=0.55

Table 3. Environmental results for Case 1

Technology / Case	Fuel	CO_2 in fuel (kg/MWh)	Efficiency	CO_2 for delivered process heat (kg/MWh)
THT/Case 1	Electricity DK	31	COP=14.5	2.14

3.2 Case 2: low- or medium-temperature solar heat

3.2.1 Case description

Our partner (Absolicon) [6] provides two cases for the low- or medium- temperature solar heat. Case 1 is a Food & Beverage Plant. This case examines a large, multi-product industrial facility that is divided into four production areas and operates year-round with seasonal fluctuations. Heating is supplied by several coal-fired boilers (4, 8, 14, and 14 TPH), which typically run two units at a time and consume about 7,700 tons of coal annually. Boiler efficiency is ~80%, contributing to CO_2 emissions of approximately 20,000 tons/year. Steam is delivered at 10 bar(g) (~184°C) with additional sectional steam requiring between 2.5–8 bar(g). Cooling demand is provided by a 1,387 kW ammonia chiller. The average steam demand is ~34,000 MWh/year with strong weekly and hourly variations, and an unused connection point in the steam header provides a promising opportunity for solar thermal integration. Case 2 is a food production plant (EU). The plant produces ~41 tons/day and operates continuously throughout the year, except for a brief shutdown on 31 December. Heating is supplied by a 6 TPH natural gas boiler operating at 5 bar(g) and 94% efficiency (installed in 1974 and refurbished in 2002). Steam at 5 bar(g) (~159°C) is mainly used for sterilization processes, accounting for about 70% of the total steam consumption. Plant expansion plans indicate a future need for steam at 7 bar(g) (~170–175°C) and potentially a second boiler. Condensate is returned throughout the system, except for the batch-type chunk line. The internal process layout includes meat preparation, sterilization, and the chunk line, all supplied from a 4.8 bar(g) steam collector. Figure 7 shows the schematic of case 2. It should be noted that $SrBr_2.6H_2O$ is used as a salt hydrate for this case because of the low- and medium-temperature of the solar system as a dehydration part for the THT system.

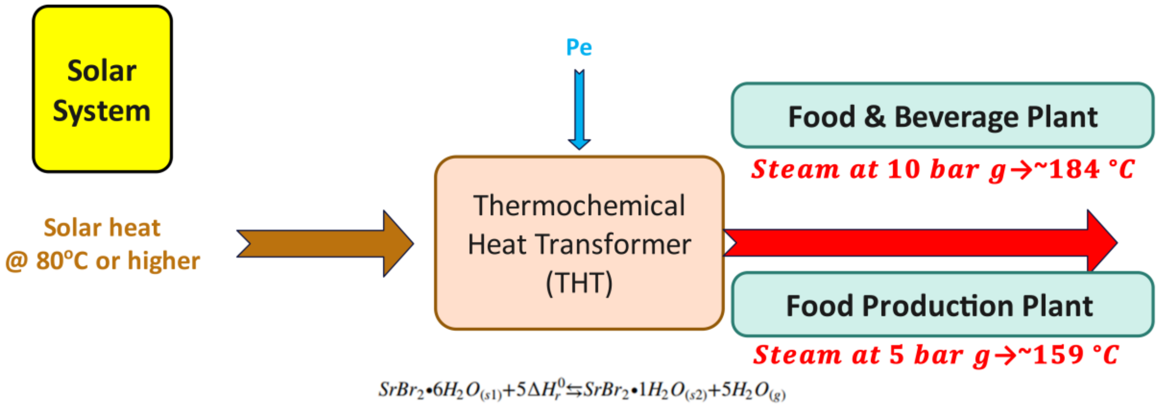


Figure 7. Schematic of case 2

3.2.2 Technical, economic, and environmental analysis

Table 4 summarizes the techno-economic results for case 2. Table 5 also presents the environmental results for case 2. Note that the THT system capacity in this case is assumed to be 4 MW.

Table 4. A summary of techno-economic results for Case 2: food production plant

Technology / Case	Process Heat Temperature (°C)	Process Heat Demand (MW)	Solar Heat Temperature (°C)	Quantity of Waste Heat (MW)	CAPEX (M€)	OPEX (Fixed) M€	OPEX (var.) M€	LCOH (c€/kWh)	Efficiency
THT+Solar/ Case 2	160	4	80	-	8.48	0.18	0.12	5.8	COP_h=0.55

Table 5. Environmental results for Case 2: food production plant

Technology / Case	Fuel	CO_2 in fuel (kg/MWh)	Efficiency	CO_2 for delivered process heat (kg/MWh)
THT+Solar/ Case 2	Electricity DK	31	COP=14.5	5.43

3.3 Case 3: Solar heat system as the primary source for the temperature range of $SrBr_2.H_2O$ (Absolicon 200°C)

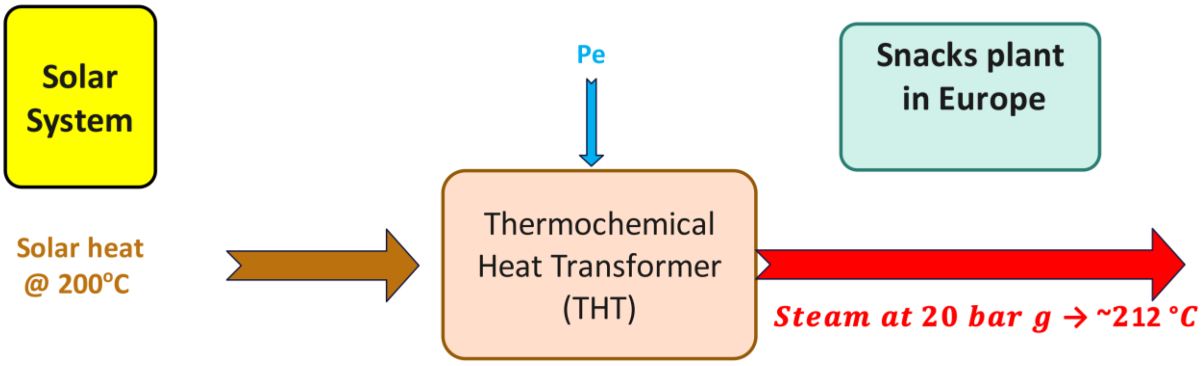
3.3.1 Case description

Our partner (Absolicon) [6] provides us with this case: solar heat system as the primary source for the temperature range of $SrBr_2.H_2O$ (Absolicon 200°C). Figure 8 illustrates the schematic of this case. This case is related to a large snack-processing facility with high-temperature thermal requirements, particularly for multiple industrial fryers. The plant operates a closed-loop thermal oil system delivering heat at 270°C (supply) and 230°C (return), supplying most fryers and ancillary equipment. Steam (20 bar(g) ~212°C) and hot water (90°C) boilers also support secondary processes, including blanching, kettles, pellet fryers, and area-specific hot-water jets.

The production lines (chips, kettle chips, pellets, and indirect products) collectively consume a substantial share of the site's total energy, with chips production alone accounting for ~67% of the total heat use. The thermal demand is dominated by the various fryers, where significant quantities of vapor at ~130°C are released during frying but are currently not recovered. This represents a major opportunity for waste heat recovery, estimated at ~8,054 MWh/year of recoverable heat from vapors. In summary, the snack-processing plant has a total installed thermal capacity of ~31 MW, consisting of:

- 18.6 MW thermal-oil system at 270°C
- 11.5 MW steam boiler at 20 bar(g)
- 1.1 MW hot-water boiler

Here, the THT is designed to produce steam at 20 bar(g) at a temperature of about 212°C, so the capacity of the THT system is 11.5 MW. Figure 8 shows the schematic of Case 3. As can be seen, the solar system temperature is assumed to be 200°C (dehydration temperature). Therefore, the salt hydrate $SrBr_2 \cdot H_2O$, which is appropriate for the temperature range between 150°C-250°C, is chosen for this case.



$$SrBr_2.H_2O\,(s) + \Delta H_R \rightleftharpoons SrBr_2\,(s) + H_2O\,(g)$$

Figure 8. Schematic of case 3

3.3.2 Technical, economic, and environmental analysis

Table 6 summarizes the techno-economic results for case 3. Table 7 also presents the environmental results for case 3.

Table 6. A summary of techno-economic results for Case 3

Technology / Case	Process Heat Temperature (°C)	Process Heat Demand (MW)	Solar Heat Temperature (°C)	Quantity of Waste Heat (MW)	CAPEX (M€)	OPEX (Fixed) M€	OPEX (var.) M€	LCOH (c€/kWh)	Efficiency
THT+Solar/ Case 3	212	11.5	200	-	24.4	0.52	0.34	5.8	COP_h=0.6

Table 7. Environmental results for Case 3

Technology / Case	Fuel	CO_2 in fuel (kg/MWh)	Efficiency	CO_2 for delivered process heat (kg/MWh)
THT+Solar/ Case 3	Electricity DK	31	COP=14.5	5.43

3.4 Case 4: Upgrading heat by a cascade system: Integration of HTHP and TCHT

3.4.1 Case description

Figure 9 describes the schematic of case 4. This case is upgrading from low-temperature (about 70°C) to high-temperature (about 250°C) using a cascade system, a high-temperature heat pump (HTHP), and a THT system. The HTHP is used to upgrade the temperature from 70°C to 180°C. Steam at 180°C is used as input to the THT system. The THT system is used to upgrade the temperature from 180°C to 250°C. As a result, the temperature lift for this case is about 250-70=180°C.

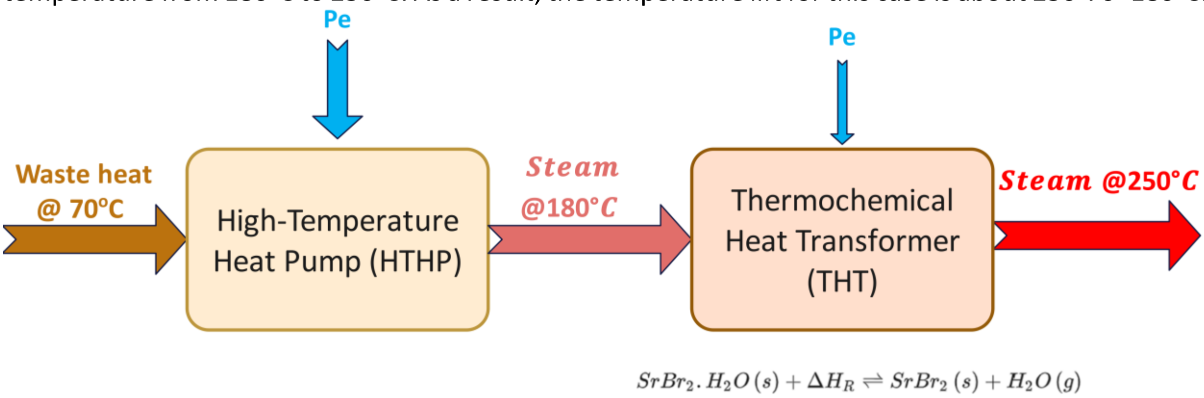


Figure 9. Schematic of case 4

3.4.2 Technical, economic, and environmental analysis

Table 8 summarizes the techno-economic results for case 4. Table 9 also presents the environmental results for case 4. Note that the useful system capacity in this case is assumed to be 1 MW.

Table 8. A summary of techno-economic results for Case 4

Technology / Case	Process Heat Temperature (°C)	Process Heat Demand (MW)	Source Heat Temperature (°C)	Quantity of Waste Heat (MW)	CAPEX	OPEX (Fixed)	OPEX (var.)	Fuel Cost	LCOH (c€/kWh)	Efficiency
					M€	M€	M€	M€		
HTHP+THT	250	1	70	-	4.7	0.047	0.062	0.87	33.2	COP_h=0.6

Table 9. Environmental results for Case 4

Technology / Case	Fuel	CO_2 in fuel (kg/MWh)	Efficiency	CO_2 for delivered process heat (kg/MWh)
HTHP+THT	Electricity DK	31	COP=0.84	36.9

4 Conclusion

This deliverable introduces a comparative techno-economic and environmental assessment to evaluate a wide range of industrial heat-supply technologies, including conventional systems and advanced low-carbon technologies. In addition, a comparison between the existing competing technologies for industrial process heating and our proposed TechUPGRADE solution is presented. The key indicators, such as fuel type, CO_2 emissions, and additional heating costs, are used to provide a comprehensive view of performance. The results are summarized in Table 10. The table introduces the differences in cost, CO_2 intensity, and decarbonization potential across all evaluated options. These results show how the TechUPGRADE solution performs compared to traditional heating options like natural gas and other low-carbon systems. The analysis compares the benefits and limitations of each technology. This information helps inform decisions about the best ways to provide industrial heating in the future and the potential role of TechUPGRADE in this regard.

Table 10. Techno-economic and CO_2 performance indicators for the assessed heat-supply technologies

Technology / Case	Fuel	CO_2 in fuel (kg/MWh)*)	CO_2 for delivered process heat (kg/MWh)	CO_2 savings vs N-gas for process heat (kg/MWh)	LCOH (€/MWh)	Additional cost LCOH (€/MWh)	LCOH/kg CO_2 (€/kg)
Natural gas boiler (existing)	N-gas	204.46	**280.08**	0.00	71.00	**0**	**0**
HTHP up to 150°C	Electricity DK	31.02	10.17	269.91	94.00	23.00	0.09
HTHP+MVP 250°	Electricity DK	31.02	20.96	269.91	188.00	117.00	0.43
Electric boiler up to 150°C	Electricity DK	31.02	32.83	247.26	209.00	138.00	0.56
Electric boiler up to 250°C	Electricity DK	31.02	32.83	247.26	213.00	142.00	0.57
Biomass boiler – Wood Chips up to 150°C	Wood chips	4.92	5.59	274.49	65.00	-6.00	-0.02
Biomass boiler – Wood Chips up to 250°C	Wood chips	4.92	5.53	274.55	68.00	-3.00	-0.01
Biomass boiler – Wood Pellets up to 150°C	Wood pellets	4.92	5.47	274.62	69.00	-2.00	-0.01
Biomass boiler – Wood Pellets up to 250°C	Wood pellets	4.92	5.47	274.62	72.00	1.00	0.00
Our Solution 1: TechUPGRADE Basic	Electricity DK	31	2.14	277.94	35.00	-36.00	-0.13
Our Solution 2: TechUPGRADE + Solar	Electricity DK	31	5.43	274.66	58.00	-13.00	-0.05
Our Solution 3: TechUPGRADE + HTHP Integrated	Electricity DK	31	36.90	243.18	348.00	277.00	1.14

* The CO2 emission does not include the embedded energy.

Figure 10 shows the sensitivity analysis of the LCOH to the system lifetime (7 to 20 years) for all heat-supply technologies. As expected, extending the lifetime significantly reduces LCOH for capital-intensive technologies, while fuel-dominated systems remain almost unchanged. The natural gas boiler shows no decline (0%) because we assumed it is an existing technology, so CAPEX for the natural gas boiler is equal to zero. For the HTHP cases, the HTHP up to 150°C shows a 26.0% reduction (from 127 to 94 €/MWh), while HTHP+MVP 250°C achieves a 25.4%

reduction (252 to 188 €/MWh). Electric boilers only represent marginal sensitivity, with a reduction of 0.9% for 150°C (211 to 209 €/MWh) and 3.6% for 250°C (221 to 213 €/MWh). Biomass boilers show moderate reductions, 20.7% (wood chips, 150°C), 24.4% (wood chips, 250°C), 15.9% (wood bullets, 150°C), and 18.2% (wood bullets, 250°C). TechUPGRADE concepts benefit the most from lifetime extension: TechUPGRADE Basic achieves a 37.5% reduction (56 to 35 €/MWh), TechUPGRADE+ Solar a reduction of 45.8% (107 to 58 €/MWh), and TechUPGRADE integrated with HTHP will reduce 26.9% (476 to 348 €/MWh).

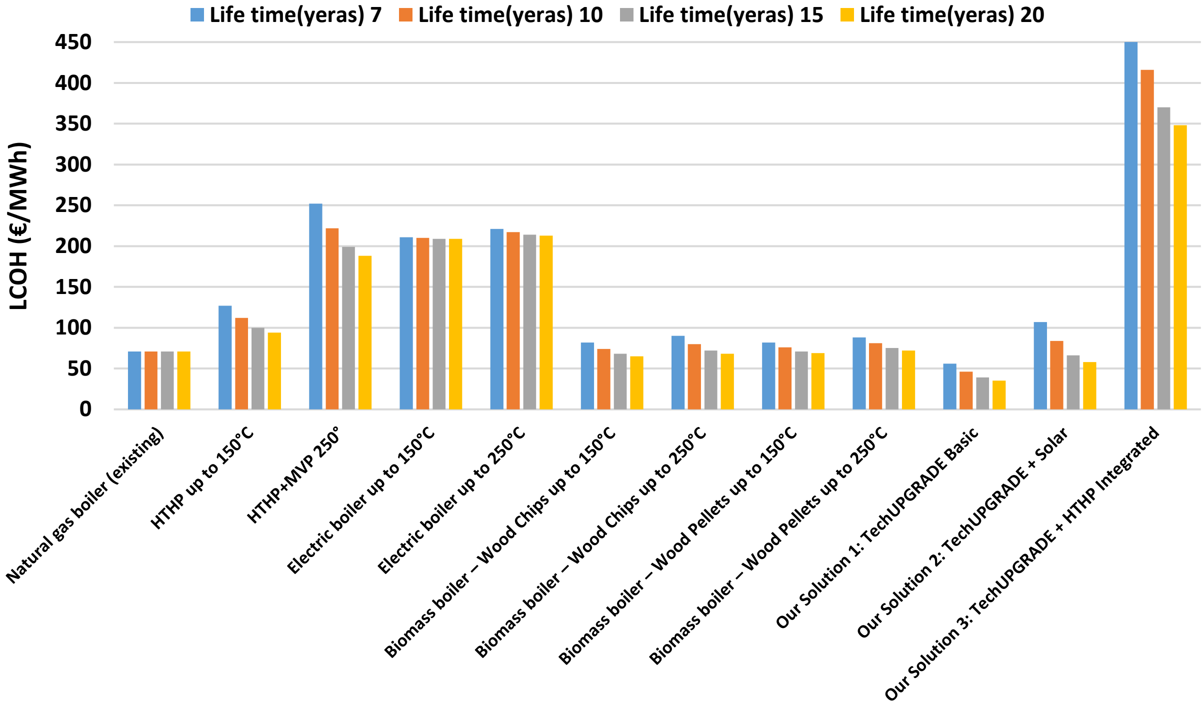


Figure 10. Sensitivity of the LCOH to system lifetime (7–20 years)

Table 11 compares some selected heat-supply technologies against an existing natural gas (NG) boiler (EB). As can be seen, the electric boiler shows a negative cash flow (CF), and so there is no meaningful payback time. HTHP provides only a marginal improvement in annual CF relative to NG. According to this, an extremely long payback time of about 11 years is obtained, which is not economically attractive. The biomass boiler improves the CF and achieves a positive NPV, with a payback time of about 9.6 years. THT with WH provides the strongest economic performance with a large increase in CF and a short payback time of approximately 4.3 years. THT with solar also improves the annual CF related to NG, but requires more investment, and has a longer payback time of about 10.1 years. In general, technologies that have a positive NPV and short payback time (i.e., THT with WH) are the best economically attractive alternatives to existing NG boilers.

Table 11. Payback time, NPV, and IRR for the selected heat-supply technologies

Technology	CAPEX (€)	CF (€/y)	NPV (€)	IRR (stand-alone)	Payback (y)
EB	€108,000.00	−542,870.67	−7,430,789.57	N/A	N/A
HTHP	€1,428,000.00	€12,831.33	−1,198,618.04	N/A	111.3
Wood	€726,000.00	€75,448.33	€354,367.43	10.99%	9.6
THT + WH	€900,000.00	€209,102.33	€1,996,768.90	24.67%	4.3

THT + Solar	€2,120,000.00	€209,102.33	€776,768.90	8.55%	10.1

5 Bibliography

[1] Thermochemical Heat Recovery and Upgrade for Industrial Processes (TechUPGRADE) 2023. https://doi.org/10.3030/101103966.

[2] Yu Y, Zhang P, Wu J, Energy RW-R and S, 2008 undefined. Energy upgrading by solid–gas reaction heat transformer: A critical review. Elsevier n.d.

[3] Technology Data for Industrial Process Heat n.d. https://ens.dk/en/analyses-and-statistics/technology-data-industrial-process-heat (accessed January 1, 2026).

[4] Frontpage | GreenLab n.d. https://www.greenlab.dk/ (accessed January 1, 2026).

[5] Hayatina I, Auckaili A, Farid M. Review on Salt Hydrate Thermochemical Heat Transformer. Energies 2023, Vol 16, Page 4668 2023;16:4668. https://doi.org/10.3390/EN16124668.

[6] Absolicon - Production Line for T160 concentrating solar collector. n.d. https://www.absolicon.com/ (accessed January 1, 2026).

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