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Energy, exergy, economic and exergoeconomic (4E) multicriteria analysis of an industrial waste heat valorization system through district heating

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Abstract

The purpose of this article is to determine the multicriteria-optimal design of an industrial waste heat recovery system for district heating in Grenoble (France). Energy, exergy and cost flow balances were applied unit by unit allowing to assess the process performance based on two innovative methods. First, the performance assessment includes all units involved in the heat valorization process, not only focusing on the recovery system. Second, the yearly management of energy flows was optimized through mixed-integer linear programming, anticipating fluctuations in residential demands and waste heat availability. This multicriteria analysis with a systemic-anticipative approach allowed to select the appropriate inlet temperature and storage capacity. It was found that the most promising inlet temperature and heat storage capacity are 35 °C and 30 MWh, respectively. With this design, the system recovers 41% of industrial waste heat, covers 48% of residential needs, has an estimated net present value of 11.7 million euros over 20 years, and reduces the district's overall exergy destruction and exergy destruction costs by 20% (4.2 GWh/year) and 9% (286 k€/year), respectively. Remarkably, none of the mono-criterion analyses prioritized this design. Therefore, the multicriteria analysis with systemic-anticipative approach was of utmost importance for detecting the most promising solution.

Keywords: District heating, Waste heat recovery, Exergy, Exergo-economics, 4E Analysis.

Highlights

- Systemic approach englobing the industry, recovery system and district network.
- Anticipative optimization of yearly energy management depending on availability.
- Promising storage capacity and inlet temperature determined by overall indicators.
- Distinct optimum for each criterion, leading to five dual-criteria Pareto fronts.
- Most suitable multi-criteria design not detected by mono-criteria assessments.

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33 **Nomenclature**

34

Names and Variables		Subscripts and Superscripts	
C	Capital cost (k€)	BEP	Breakeven Point
\dot{C}	Cost flow (k€/year)	C	Carnot cycle
c	Specific exergy cost (k€/GW _{ex})	ch	Chemical
CF	Coverage Factor (%)	chrg	Heat charge of the thermal storage unit
COM	Costs of Operation and Maintenance (k€)	CI	Related to capital investment
COP	Coefficient Of Performance (GW _{th} /GW _{el})	cooling	Magnet's cooling process
E	Exergy (GWh)	D	Destruction
\dot{E}	Exergy flow (GW)	dchg	Heat discharge of the thermal storage unit
ECON	Economic criterion	DHN	District Heating Network
ENER	Energetic criterion	DISS	Dissipation
EXER	Exergetic criterion	elec	Electrical
EXEC	Exergo-economic criterion	ex	Exergetic
f	Exergoeconomic factor (k€/k€)	exo	Exogenous
i	Effective rate of return (%/year)	F	Fuel
n	Economic lifespan of the equipment (years)	f	Final
NPV	Net Present Value (k€)	OM	Related to operation and maintenance
Q	Heat (kWh, MWh or GWh)	out	Outlet
\dot{Q}	Thermal power (GW)	Q	Heat
PEC	Purchased Equipment Cost (k€)	GLOB	Overall
r	Relative cost difference (%)	HP	Heat pump
RACF	Recovery And Coverage Factor	HS	Heat supplier
RF	Recovery Factor	in	Inlet
T	Temperature (K)	ini	Initial
T ₀	Temperature of the dead state (K)	L	Losses
t	Time (h)	LNCMI	Laboratoire National des Champs Magnétiques Intenses
TCI	Total Capital Investment (k€)	magnets	LNCMI's high-intensity magnets
U	Internal energy (GWh)	max	Maximal
\dot{W}	Work (electric) power (GW)	min	Minimal
Z	Annuity (k€/year)	mono	Mono-criterion
		multi	Multi-criterion
Greek Symbols		out	Outlet
Δt	Time step (h)	P	Product
ε	Exergy efficiency (%)	pipng	Overall pipeline layout
ξ	Electricity-to-heat conversion ratio (GW _{th} /GW _{el})	q	Related to heat
θ	Exergy factor	REF	Reference scenario
ψ	Relative performance amongst all solutions	SST	Network sub-stations
χ	Value of the performance indicator	TES	Thermal Energy Storage
		u	Related to internal energy
		use	Useful exergy destruction
		wh	Waste heat
		WHRS	Waste Heat Recovery System

35

36 **1. Introduction**

37 Space heating represents a non-negligible amount of end-user energy consumption, especially in the urban
38 residential sector, where district heating is more and more commonly used [1]. In particular, low-temperature district
39 heating has been identified by the International Energy Agency as a key enabling technology to increase the
40 integration of renewable sources, including waste energy [2]. Recovery of industrial waste heat and its integration in
41 district heating are more and more encouraged globally [3]. For instance, McKenna et al [4] evaluated around 90 %
42 of energy-intensive sectors in UK and estimated a potential of 10 TWh to 20 TWh for technically feasible waste heat
43 recovery. Svensson et al [5,6] evaluated the trade-off between using waste heat, sometimes called excess heat,
44 internally for the industrial process itself, or externally for district heating. They concluded that both of them are
45 profitable strategies, and that external use, i.e. industry/district network cooperation, tends to give lower CO₂
46 emissions than internal use. Miró et al [7] identified some aspects that need further development in the integration of
47 industrial waste heat into district heating. Such aspects included (but not limited to) a lack of large scope and high
48 spatial resolution in the analyses, and an apparent reluctance by some industrial actors to publish useful data about
49 their waste streams.

50 Based on this information, one could say that waste heat is an abundant source with integration opportunities, but it
51 is under-documented and under-utilized for the moment [8]. New research contributions to the field can directly solve
52 the first issue, and help solving the second one. Investigations based on mixed electric-thermal models are emerging
53 in countries and areas where heat districts are historically developed, like eastern and northern Europe [9]. Such
54 kinds of projects can benefit from a diversity of criteria, because they involve energy flows of different types and
55 qualities. Thus, conventional techno-economic analyses may not suffice to identify the best opportunities. Energy
56 analysis alone is also insufficient to provide information on the quality of energy streams in a system [10]. Fortunately,
57 thermodynamics has yielded in the recent decades some applicable and easily interpretable criteria to further improve
58 energy systems.

59 One of them is exergy. It gives information on how to optimally transform energy [11], and it can either confirm or be
60 in contrast with energy-based analysis [12]. The interest of exergy is claimed by many specialists [11,13–15], not
61 only for engineering but also in energy policy making [16]. Besides, exergy destruction is an indicator that does not
62 encounter a direct equivalent in first-law analyses. That makes it interesting because it can suggest unique alternative
63 solutions. Exergy analysis has been applied in several studies on district heating and waste heat utilization. For
64 instance, Bühler et al [17] applied exergy analysis on the Danish industry sector to improve its efficiency and identify
65 the potential for waste heat recovery within industrial processes. Solheimslid et al [18] performed the first-law and
66 second-law analyses of a Norwegian combined heat and power facility driven by municipal waste incineration. Wang
67 et al [19] sustained exergy as a crucial optimization criterion for heat pumps that aim to recover industrial waste heat
68 for utilization in district heating. It has also been used successfully as an objective function in control algorithms for
69 district energy networks [10]. The other interesting criterion is exergoeconomics. Exergoeconomics is defended by
70 thermodynamic experts as the proper way of accounting monetarily for thermodynamic inefficiencies within energy
71 systems [11,14]. Exergoeconomics are becoming relevant for district energy networks analysis. For instance,
72 Baldvinsson and Nakata [20] applied the LowEx and SPECO methods on a local source-based district heating system
73 in Japan. Their study was carried out from a single user perspective. Zhang et al [21] developed a novel cost-pricing
74 model based on exergy analysis, for a more efficient evaluation of the district heating market. Čož et al [22] used the
75 exergetic product cost as objective function to optimize the diameter and insulation thickness of a 1000 m-long

76 pipeline for district cooling. Although not abundant, some studies exist on the exergoeconomic analysis of heat pumps
77 at a district scale, but many of them focus on geothermal technologies [23,24].

78 The above comments justify the need and interest of applying exergy and exergoeconomic analyses in design
79 projects. When combined with conventional energy, economic or environmental analyses, they lead to a 3E or 4E
80 multicriteria analysis. These analyses excel in finding better ways to manage energy resources, especially if each
81 criterion suggest a non-redundant solution with respect to the others. Consequently, it is no surprise that 3E and 4E
82 multicriteria analyses are becoming a common procedure in assessing renewable energy integrations, energy
83 recovery within conventional processes, or waste-to-energy systems [25–27]. For instance, Liu et al [28] applied
84 multicriteria analysis to assess waste heat recovery within a syngas process with carbon capture and storage. Ameri
85 et al [29] applied 4E analysis with genetic algorithm to optimize a large steam power plant, increasing its energy and
86 exergy efficiencies by 9.7% and 16.8%. Wang et al [30] performed a 4E analysis on a distributed generation solar-
87 assisted combined cooling, heating and power gas turbine system, achieving 41% less carbon emissions with respect
88 to the non-solar system. Further, their off-design analysis demonstrated that energy and exergy efficiencies alone
89 would not have sufficed to prove the advantages of the solar integration. This means that both the exergoeconomic
90 and the environmental criteria were relevant. Elbar et al [31] applied 4E analysis for the integration of a solar still with
91 photovoltaic panels. Multicriteria analyses have also been used to assess chemical engineering processes. For
92 example, Wang et al [32] combined thermodynamic, thermo-economic and life cycle environmental analyses to
93 assess ketone ammoximation production. Meng et al [33] selected the best design of a distillation-pervaporation
94 process based on energy, economic and environmental evaluations.

95 Multicriteria analyses are also being applied to district heating projects. For example, Ajah et al [34] studied the
96 technical, economic, institutional and environmental feasibilities of a robust industrial waste heat-driven district
97 heating system including recycle of exhaust residential heat after end-user utilization. Baldvinsson and Nakata [20]
98 considered in their study exergy efficiency, monetary costs and exergoeconomic costs to compare the current heat
99 supply system paradigm in Japan with an innovative one integrating several renewable and waste sources.
100 Ghafghazi et al [35] evaluated different types of district heating options through multicriteria analysis. Their study did
101 not consider industrial waste heat recovery, but it did include other interesting renewable options such as biomass,
102 geothermal heat exchange, and sewer heat recovery. More recently, Dorotić et al [36] performed a multi-objective
103 optimization of district heating systems through economic, environmental and exergetic indicators. Their study
104 yielded a 3-D Pareto front that shows the need for compromise between the three criteria, since each one suggested
105 a unique optimal solution.

106 Further, the search for new approaches in district heating with industrial waste heat recovery is still active. Dénarié
107 et al [37] proposed an assessment methodology based on multicriteria decision analysis in order to cope with
108 uncertainties related to input data quality in these kinds of projects. They exemplified the use of their methodology
109 with a real study case in Milano, Italy. Wang et al [38] developed a multicriteria decision support framework for district
110 heating based on combined heat and power systems. Fang et al [39] analyzed key issues in district heating using
111 low-grade industrial heat, and proposed an approach based on “tangency technology” to facilitate integration of
112 multiple waste heat sources. Recently, Woolley et al [40] proposed a 4-step systematic approach including exergy
113 balances, in order to assess industrial waste heat recovery opportunities. They suggested the approach as a support
114 tool for industrial decision-makers. Some of the recent studies consider mixed-integer linear programming for the
115 optimization, like the work of Oluleye et al [41], which uses it for integrating thermodynamic cycles in process sites
116 with the purpose of waste heat exploitation.

117 Many studies on decision aiding for district heating focus on a single decision-maker or, at most, a small group of
118 decision-makers from a same organization. However, district heating projects with several heat sources can involve
119 different stakeholders, that would prefer different optimal designs. Ghafghazi et al [35] demonstrated with their study
120 that communication between those stakeholders can lead to consensus and change the final design significantly.
121 There do not seem to be abundant studies in literature that evaluate industrial waste heat recovery for district heating
122 through multicriteria analysis assuming perfect consensus between the stakeholders. Besides, not many multicriteria
123 studies on industrial waste heat recovery for district heating utilization use the exergo-economic criterion.

124 Our article contributes to that niche. We analyze the integration of industrial waste heat in a district heating network
125 by approaching the industrial process, the heat recovery system, the district network and its auxiliary facilities all as
126 one same system. The aim of this systemic approach is to determine the most suitable inlet temperature and thermal
127 storage capacity of the recovery system. We apply local balances, but define overall performance indicators that
128 involve all parties affected by the project, and assume perfect consensus between the stakeholders. In addition, we
129 support our yearly simulation with a mixed-integer linear programming tool that allows to anticipate the district's needs
130 and the waste heat's availability. As the mono-criterion and multi-criteria results show, each one of the four criteria
131 (energy, exergy, economy and exergoeconomics) suggests a different optimal solution, and so does the multi-criteria
132 assessment. We also point out that a decision based only on the recovery system's performance would have led to
133 another design. Therefore, both the multicriteria analysis and our systemic approach were necessary to identify the
134 most promising solution.

135

136 **2. Materials and method**

137 The selected method consists in applying 4E analyses (energy, exergy, economic and exergoeconomic) on different
138 scenarios where yearly management of energy flows has been previously optimized by means of Mixed-Integer
139 Linear Programming (MILP). The MILP-assisted optimization of the system's yearly operation consisted in
140 determining the best management of energy flows depending on the objective. The aim of the 4E analyses is to
141 determine the most suitable inlet temperature and storage capacity of the waste heat recovery system. Although the
142 design parameters are local, each scenario has been approached englobing all units involved in the heat valorization
143 process.

144

145 **2.1. System description and modelling tool**

146 Figure 1 shows the exergo-diagram of the system. The position of each arrow within the y-axis indicates the quality
147 (i.e. exergy) of that energy stream. Continuous lines represent the existing system. Dashed lines represent the
148 prospective system and its different possible temperature levels.

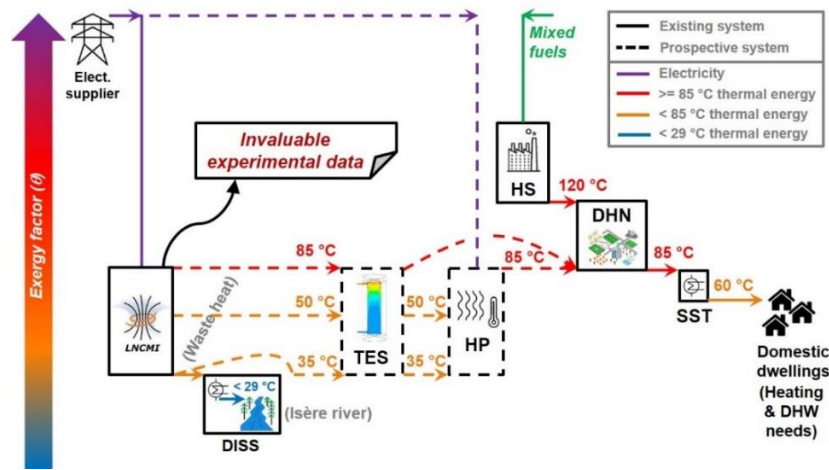


Figure 1. Exergo-diagram of the case study with the existing and prospective units.

149

150 The current scenario (solid lines in Fig. 1) is made up of the following units, described by the associated abbreviations:

- 151 • LNCMI: LNCMI is the French national laboratory for high-intensity magnetic fields in Grenoble (*Laboratoire*
152 *National des Champs Magnétiques Intenses*). It provides high magnetic fields for worldwide researchers.
153 Their electro-intensive activities generate important amounts of low-temperature waste heat.
- 154 • DISS: This unit is used to dissipate LNCMI's waste heat in a nearby river (Isère).
- 155 • DHN: The local District Heating Network in the proximities of the LNCMI, provide residential users with low-
156 temperature heat.
- 157 • SST: The substations associated to the DHN provide residential users with low-temperature heat for space
158 heating and Domestic Hot Water production.
- 159 • HS: A nearby Heat Supplier that currently covers all the needs of the DHN.

160 The studied scenario aims at recovering LNCMI's waste heat for utilization in the DHN. This would be done through
161 a Waste Heat Recovery System (WHRS) represented by dashed lines in fig. 1 and made up of:

- 162 • HP: An electrically-driven mechanical Heat Pump has to be used to upgrade heat's temperature whenever
163 necessary. Its inlet temperature depends on the scenario, but the outlet temperature has to reach 85 °C for
164 injecting heat into the DHN. Mechanical heat pumps are a mature technology whose technical details are
165 available to the general public.
- 166 • TES: A Thermal Energy Storage unit is additionally considered to compensate for short-term temporal
167 mismatch and absorb the highest power peaks of waste heat. Well-documented studies [42] have stated that
168 this component allows to overcome the intermittence and distance between the waste heat source and the
169 application site. Stratified thermal storage and thermocline modelling are interesting research topics in the
170 recent years [43]. The TES considered in this study is a non-pressurized thermocline storage containing
171 liquid water.

172 The sections below describe the 4E (energy, exergy, economic and exergoeconomic) models developed for multi-
173 criteria analysis, and the preliminary approach to determine the most suitable design for the heat recovery system.

174 These analyses were applied after optimizing the yearly management of energy flows through mixed-integer linear
 175 programming. The tool used in the present article is an open-source tool called OMEGAlpes [44].

176

177 2.2. Input data

178 Figure 2a shows the power tranches of both the LNCMI and the DHN. Figure 2b shows the model hourly profile used
 179 for the LNCMI's yearly electricity consumption. It has been constructed from different fragments of several operating
 180 years, aiming at defining a representative operation profile. Therefore, each and every point is a real datum, but the
 181 profile does not correspond integrally with any operating year. The hourly profile of residential heat demand at the
 182 DHN is protected by confidentiality clauses against diffusion to the general public. This critical issue is stated by Miró
 183 et al [7] in their conclusions: industrial actors do not usually publish their waste streams characteristics, which could
 184 facilitate very accurate analyses.

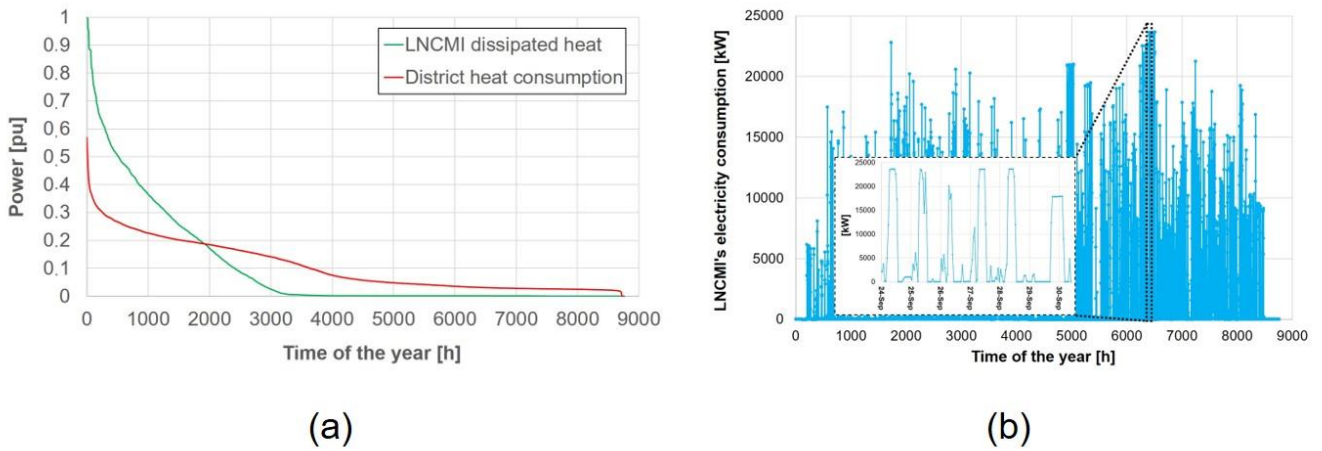


Figure 2. a) LNCMI's and Heat Supplier's power tranches; b) Estimated LNCMI's electricity consumption profile.

185

186 Table 1 contains the values used for the 4E model's input parameters, classified with respect to the model they are
 187 related to. Parameters that have a range of values are optimization parameters and their value was changed from
 188 one scenario to another. In addition, some other parameters varied depending on the waste heat's temperature. It is
 189 the case of electricity-to-heat conversion ratio within the LNCMI (ξ), or the heat pump's COP, for instance.

190

Table 1. Input parameters of the simulations.

Model	Magnitude	Value(s) or limit(s)	Units	Reference
	Initial time of simulation (t_{ini})	0	h	[12]
	Final time of simulation (t_f)	8760	h	[12]
	Time step (Δt)	1	h	[12]
	Electricity-to-heat conversion ratio with waste heat at 35 °C (ξ (35 °C))	0.85	kW_{th} / kW_{el}	[12]
	Electricity-to-heat conversion ratio with waste heat at 50 °C (ξ (50 °C))	0.80	kW_{th} / kW_{el}	[12]
	Electricity-to-heat conversion ratio with waste heat at 85 °C (ξ (85 °C))	0.70	kW_{th} / kW_{el}	[12]
Energy	Heat pump's performance ($COP_{HP}(T_{HP}^{in} = 35 \text{ °C})$)	3	kW_{th} / kW_{el}	[12]
	Heat pump's performance ($COP_{HP}(T_{HP}^{in} = 50 \text{ °C})$)	4.29	kW_{th} / kW_{el}	[12]
	Heat pump's maximum inlet power ($W_{HP}^{el,max}(T_{HP}^{in} = 35 \text{ °C})$)	1260	kW_{el}	[12]
	Heat pump's maximum inlet power ($W_{HP}^{el,max}(T_{HP}^{in} = 50 \text{ °C})$)	881	kW_{el}	[12]
	Thermal storage's maximum capacity (U_{TES}^{max})	[0, 10, 20, 30, 40]	MWh	[12]
	Thermal storage's maximum charging power ($\dot{Q}_{TES}^{in,max}$)	$= U_{TES}^{max} / 3$	MW	[12]
	Thermal storage's maximum discharging power ($\dot{Q}_{TES}^{out,max}$)	$= U_{TES}^{max} / 3$	MW	[12]
Exergy	Dead state temperature (T_0)	8	°C	[12]
	Heat supply unit's exergy efficiency (ϵ_{HS})	0.4	kW_{ex} / kW_{ex}	[12]

	Temperature difference for magnets' cooling ($\Delta T_{cooling}$)	60	°C	[45]
	Waste heat temperature (T_{wh})	[35, 50, 85]	°C	[12]
	Heat pump's inlet temperature (T_{HP}^{in})	[35, 50]	°C	[12]
	Heat pump's outlet temperature (T_{HP}^{out})	85	°C	[12]
	Heat supply unit's service temperature ($T_{HS}^{q,out}$)	120	°C	[12]
	End-users heat temperature	60	°C	[12]
	Heat pump's purchase equipment cost ($PEC_{HP}(T_{HP}^{q,in} = 35 \text{ °C})$)	810	k€	[36]
	Heat pump's purchase equipment cost ($PEC_{HP}(T_{HP}^{q,in} = 50 \text{ °C})$)	526	k€	[36]
	Coefficient of thermal storage's purchase cost (c_{TES}^{PEC})	90	k€/MWh-capacity	[46]
Economy	Coefficient of piping costs (c_k^{pipe})	0.7	k€/(k€ of PEC)	[11]
	Coefficient of operation and maintenance costs (c_k^{OM})	0.1	k€/(k€ of TCI)	[11]
	Economic observation period (n)	20	years	[11]
	Effective rate of return (i)	0.06	-	[11]
	Specific buy cost of electricity from the grid (c^{elec})	120	€/MWh _{elec}	[47]
	Specific sell cost of heat for residential end-users ($c_{SST}^{q,out}$)	80	€/MWh _{heat}	[47]

191

192 2.3. Governing equations and main hypotheses

193 The simulations were based on applying a thermodynamic analysis with energy, exergy and their corresponding cost
194 flow balances unit by unit. The four models are internally correlated. The exergy and economy models are built on
195 the energy model, and the exergoeconomic model is built on the exergy and economy model. Therefore, many of
196 the energetic and economic parameters are shared between the models. A change in any energy parameter has an
197 impact on the rest of the models. Economic parameters, especially the costs of energy streams, also influence
198 exergoeconomic results.

199

200 **ENER: Energy model**

201 The energy model relies on energy balance applied to each unit of the recovery system. The following hypotheses
202 were used in the energy model:

- 203 • Potential and kinetic energy are neglected.
- 204 • Temperature levels of the units remain constant throughout the year.
- 205 • Pressure, temperature and heat losses across the pipelines are neglected.
- 206 • Perfect stratification is assumed in the thermal storage unit.
- 207 • The initial and final state of charge of the thermal energy storage are the same.
- 208 • Heat losses across the different components of the heat pump are neglected.
- 209 • The heat production process by the heat supplier has a constant exergetic efficiency (ε_{HS}).

210

211 In its general form (eq. 1), a non-steady energy balance on a unit at each time step (Δt) accounts for heat inlets (\dot{Q}^{in}),
212 heat outlets (\dot{Q}^{out}), power inlets (\dot{W}^{in}), power outlets (\dot{W}^{out}) and energy accumulations (ΔU) within the unit. Refer to
213 Table A.1 in Appendix A for concretized unit-by-unit energy balances. Most of the units in this study case have no
214 accumulation within them (i.e. $\Delta U = 0$), except for the thermal storage unit.

$$215 \quad \Delta t \cdot \sum(\dot{Q}^{in} + \dot{W}^{in}) = \Delta t \cdot \sum(\dot{Q}^{out} + \dot{W}^{out}) + \Delta U \quad (1)$$

216

217

218 **EXER: Exergy model**

219 Similarly to the energy model, the exergy model results from exergy balances applied to each of the unit. The
220 following hypotheses were used in the exergy model:

- 221 • Potential and kinetic exergy are neglected.
- 222 • The heat production process by the heat supplier has a constant exergetic efficiency (ε_{HS}).

223 The non-steady exergy balance (eq. 2) accounts for the abovementioned power inlets and outlets, the exergy inlets
224 (\dot{E}^{in}) and outlets (\dot{E}^{out}), exergy destruction (\dot{E}^D) and exergy accumulation (ΔE^u) within the unit. Refer to Table A.2 in
225 Appendix A for concretized unit-by-unit exergy balances. The accumulation term is only considered for the thermal
226 storage unit, like in the energy model. The exergy of thermal flows (\dot{E}^q) was determined as a function of their
227 temperature (eq. 2.a). The dead state temperature (T_0) was kept constant, for thermodynamic consistency [48].
228 Electric power can be included directly in the balance because its exergy factor is equal to 1.

229
$$\Delta t \cdot \sum(\dot{E}^{in} + \dot{W}^{in}) = \Delta t \cdot [\sum(\dot{E}^{out} + \dot{W}^{out}) + \dot{E}^D] + \Delta E^u \quad (2)$$

230
$$\text{With } \dot{E}^q = \dot{Q} \cdot \left(1 - \frac{T_0}{T_q}\right) \quad (2.a)$$

231 **ECON: Economic model**

232 The economic model aims to evaluate profitability of the project and the product's final price. The economic model is
233 sustained on the following hypotheses:

- 234 • The analysis is done with 'constant dollars' (i.e. no inflation). This approach is best suited for analyses
235 involving economic periods longer than 10 years [11].
- 236 • Prices of fuels and products are not subject to escalation or changes in the contracts.
- 237 • Capital investments on all existing equipment of the LNCMI, the HS and the DHN owner are completely
238 recovered. Thus, the only capital investment to assess relates to the WHRS.
- 239 • The purchased equipment cost and the cost of piping are the only contributions to the fixed capital
240 investments. Other contributions (offsite costs, indirect costs...) are dismissed.
- 241 • The two potential investors (i.e. the LNCMI and the HS) form a joint Consortium. Both agree to the price of
242 LNCMI's waste heat and respect it for the whole economic life of the equipment. All profits obtained through
243 the WHRS are mutualized proportionally to each one's initial investment.

244 Heat sold by the DHN to the residential end-users remains at the same price (its current price) throughout the
245 equipment's economic life.

246 The cost flow balance (eq. 3) states that the yearly product sales revenues (\dot{C}^P) should compensate the fuel costs
247 (\dot{C}^F) and amortize the annuities (\dot{Z}) related to capital expenditures. Refer to Table A.3 in Appendix A for concretized
248 unit-by-unit formulations of the cost flow balance. In this study, the cost flow balance was applied downstream in
249 most cases, in order to determine product costs from known fuel costs and annuities. The only 3 exceptions took
250 place at the reference scenario, in the balances on the SST, the DHN and the HS. Those balances were applied
251 upstream, starting at the SST with a known sell price for the heat, fixed by a contract with the residential end-users.
252 The aim of those upstream balances was to determine the specific fuel and product costs, both energetic and
253 exergetic, of the HS's combustion process. Those two last costs were kept as input parameters for the rest of the
254 scenarios.

$$\sum \dot{C}^F + \dot{Z} = \sum \dot{C}^P \quad (3)$$

Two types of annuities were assessed (eq. 4). One type (\dot{Z}^{CI}) is related to the Total Capital Investment (TCI), which is the sum (eq. 4.a) of the Purchase Equipment Cost (PEC) and the costs of piping (c^{pipe}). The costs of piping were relevant to this case study because district heating requires long pipelines with relatively big diameters. The other type of annuity (\dot{Z}^{OM}) is related to the Costs of Operation and Maintenance (COM), which were assumed as a fraction (c^{OM}) of the total capital investment (eq. 4.b). All capital costs were transformed into annuities through The Capital Recovery Factor (CRF , eq. 4.c), which accounts for the economic observation period (n) and the interest rate (i).

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM} = (TCI \cdot COM) \cdot CRF \quad (4)$$

$$\text{With } TCI = PEC \cdot (1 + c^{pipe}) \quad (4.a)$$

$$COM = c^{OM} \cdot TCI \quad (4.b)$$

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \quad (4.c)$$

266

267 **EXEC: Exergo-economic model**

268 Exergo-economics claims that exergy is the only rational basis for assigning monetary costs to the interactions of a
269 system with its surroundings and to the sources of thermodynamic inefficiencies within it [13]. The exergoeconomic
270 approach in this study followed the SPecific Exergy COsting method (SPECOC) [14]. After the exergy and economic
271 analyses have been performed, the application of this method is almost straightforward. The average specific exergy
272 costs of the inlets (c^F) and outlets (c^P) of each unit were determined through the Fuel principle (eq. 5) and the Product
273 principle (eq. 6), respectively.

$$c^F = C^F / E^F \quad (5)$$

$$c^P = C^P / E^P \quad (6)$$

276

277 **2.4. Performance indicators**

278 Given the multi-temporal architecture of the model, performance indicators are best assessed by integration of the
279 hourly profiles throughout the year. Three energy-based indicators were used in this study. The Recovery Factor
280 (RF , eq. 7) is the ratio between the total yearly intake of waste heat (Q_{WHRS}^{in}) and the total waste heat available
281 (Q_{LNMCI}^{out}). The Coverage Factor (CF , eq. 8) is the ratio between the total heat injected to the district network (Q_{WHRS}^{out})
282 and the total residential demands (Q_{DHN}^{out}). The Recovery And Coverage Factor ($RACF$, eq. 9) looks for balance
283 between heat recovery and residential coverage.

$$RF = \frac{Q_{WHRS}^{in}}{Q_{LNMCI}^{out}} = \frac{\sum_{t=t_{ini}}^{t=t_f} \dot{Q}_{WHRS}^{in} \cdot \Delta t}{\sum_{t=t_{ini}}^{t=t_f} \dot{Q}_{LNMCI}^{out} \cdot \Delta t} \quad (7)$$

$$CF = \frac{Q_{WHRS}^{out}}{Q_{DHN}^{out}} = \frac{\sum_{t=t_{ini}}^{t=t_f} \dot{Q}_{WHRS}^{out} \cdot \Delta t}{\sum_{t=t_{ini}}^{t=t_f} \dot{Q}_{DHN}^{out} \cdot \Delta t} \quad (8)$$

$$RACF = RF \cdot CF \quad (9)$$

286

287 The exergy indicator is the district's overall efficiency (ε_{GLOB}). To determine it, all exergy destructions (E_{GLOB}^D) and the
 288 district's exergy inlets (E_{GLOB}^{in}) were taken into account (eq. 10). This includes the LNCMI's process, the heat
 289 dissipation, the thermal storage, the heat pump, the Heat Supplier's process, the district network and the residential
 290 dwellings (eq. 11). The exergy inlets of the overall district (eq. 12) are the LNCMI's electricity consumption (\dot{W}_{LNCMI}^{el}),
 291 the heat pump's electricity consumption (\dot{W}_{HP}^{el}), and the Heat Supplier's exergy input (\dot{E}_{HS}^{in}).

$$292 \quad \varepsilon_{GLOB} = 1 - \frac{E_{GLOB}^D}{E_{GLOB}^{in}} \quad (10)$$

$$293 \quad \text{With } E_{GLOB}^D = \sum_{t=t_{ini}}^{t=t_f} (\dot{E}_{LNCMI}^D + \dot{E}_{DISS}^D + \dot{E}_{TES}^L + \dot{E}_{HP}^D + \dot{E}_{HS}^D + \dot{E}_{DHN}^D + \dot{E}_{SST}^D) \cdot \Delta t \quad (11)$$

$$294 \quad E_{GLOB}^{in} = \sum_{t=t_{ini}}^{t=t_f} [\dot{W}_{LNCMI}^{el} + \dot{W}_{HP}^{el} + \dot{E}_{HS}^{in}] \cdot \Delta t \quad (12)$$

295 The Net Present Value of the project (NPV) was the main economic indicator (eq. 13). It is the difference between
 296 the revenues from selling heat to the residential end-users (\dot{C}_{WHRs}^P) and the breakeven revenues ($\dot{C}_{WHRs}^{P,BEP}$). The
 297 BreakEven Point (BEP) is the point at which the sales revenues equal the total costs of production. In this study, the
 298 breakeven revenues (eq. 14) have to compensate the cost of waste heat ($\dot{C}_{LNCMI}^{q,out}$), the cost of electricity to run the
 299 heat pump ($\dot{C}_{HP}^{elec,in}$), and the amortization costs for the heat pump (\dot{Z}_{HP}) and the storage (\dot{Z}_{TES}). Fuel savings by the
 300 district's Heat Supplier ($\dot{C}_{HS,REF}^F - \dot{C}_{HS}^F$) were considered as a collateral profit, because a Consortium is assumed
 301 between all stakeholders involved in the heat valorization process.

$$302 \quad NPV = \frac{\dot{C}_{WHRs}^P - \dot{C}_{WHRs}^{P,BEP}}{CRF} \quad (13)$$

$$303 \quad \text{With } \dot{C}_{WHRs}^{P,BEP} = \dot{C}_{LNCMI}^{q,out} + \dot{C}_{HP}^{elec,in} + \dot{Z}_{HP} + \dot{Z}_{TES} - (\dot{C}_{HS,REF}^F - \dot{C}_{HS}^F) \quad (14)$$

304 If the sales revenues exceed the breakeven revenues, the project yields net benefits ($NPV > 0$). If both are equal,
 305 the investments (including interest) and the production costs are recovered ($NPV = 0$). If the actual revenues are
 306 below the breakeven revenues, the NPV becomes negative and the project yields net economic losses.

307 An additional economic indicator was defined for a more detailed analysis: the relative Revenue Requirement of each
 308 unit (RR). It indicates which amount of the product's final cost (\dot{C}_{WHRs}^P) amortizes expenditures on which unit (eq. 15).
 309 Those expenditures are capital investments (\dot{Z}) plus exogenous consumption of fuel ($\dot{C}^{F,exo}$), i.e. external to the
 310 overall district's boundaries. The total revenue requirement for a system is the revenue that must be collected through
 311 the sale of all products to compensate for all expenditures incurred and to ensure sound economic operation [11].

$$312 \quad RR = (\dot{Z} + \sum \dot{C}^{F,exo}) / \dot{C}_{WHRs}^P \quad (15)$$

313 The overall costs of the irreversibilities (\dot{C}_{GLOB}^D) were chosen as exergoeconomic indicator (eq. 16). They are the sum
 314 of exergy destruction costs of all units (\dot{C}^D , eq. 17). Note how these costs do not appear explicitly in the cost flow
 315 balance (eq. 3). They are usually referred to as *hidden costs* [11].

$$316 \quad \dot{C}_{GLOB}^D = \sum \dot{C}^D \quad (16)$$

$$317 \quad \text{With } \dot{C}^D = c^F \dot{E}^D \quad (17)$$

318

319

320 **2.6. Preliminary assessment of multi-criteria optimality**

321 The preliminary multi-criteria Pareto-optimal solution was determined by quantifying and comparing the relative
 322 performances of all possible solutions. The relative mono-criteria performance of each solution assessed its proximity
 323 to the optimal value of the indicator amongst all available solutions. The equation applied was either 18 when the
 324 indicator's value had to be maximized, or 19 when it had to be minimized. The relative multi-criteria performance was
 325 assessed through an equally-weighted average of all relative mono-criteria performances (eq. 20).

326
$$\psi_j^{mono}(maximize) = 1 - \frac{\chi^{max} - \chi_j}{\chi^{max} - \chi^{min}} \quad (18)$$

327
$$\psi_j^{mono}(minimize) = 1 - \frac{\chi_j - \chi^{min}}{\chi^{max} - \chi^{min}} \quad (19)$$

328
$$\psi^{multi} = \sum_j (w_j \cdot \psi_j^{mono}) \quad \{\sum_j w_j = 1\} \quad (20)$$

329

330 **3. Results and discussion**

331 **3.1. Mono-criterion analyses and optimal conceptions**

332 This study aims to identify the most promising design of a waste heat recovery system through multi-criteria analysis.
 333 The four criteria considered are energy, exergy, economy and exergo-economy. The two design parameters under
 334 analysis are inlet temperature and thermal storage capacity. There are three inlet temperatures to choose from: 35
 335 °C, 50 °C and 85 °C. There are five storage capacities to choose from: 0 MWh, 10 MWh, 20 MWh, 30 MWh and 40
 336 MWh.

337 Figure 3 shows the evolution of the energetic and economic indicators (*RACF* and *NPV*, respectively) as a function
 338 of the storage capacity and the waste heat's temperature. The color transition along the green arrows (from light to dark)
 339 indicates the objective of the optimization, i.e. either to maximize or to minimize. Thus, in Fig. 3 the objectives
 340 are to maximize both indicators. The energetic indicator recommends the highest possible temperature (85 °C) and
 341 storage capacity (40 MWh). On the other hand, the economic indicator suggests 50 °C and points out that there is
 342 no further profit beyond the optimal capacity of 20 MWh.

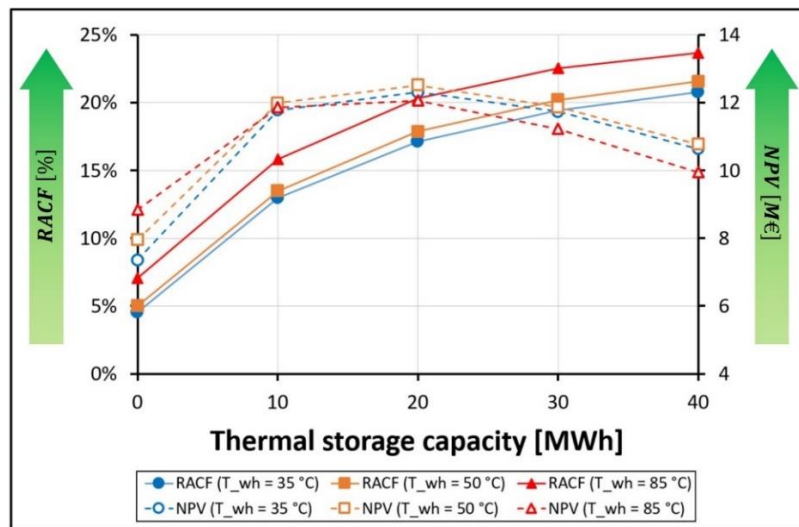


Figure 3. Recovery And Coverage Factor (*RACF*) and Net Present Value (*NPV*) as a function of thermal storage capacity, for the three input temperatures.

343 Any scenario with heat recovery is better than the base scenario, both energy-wise and economy-wise. Additional
 344 heat recovery is asymptotic with respect to additional storage capacity, because of temporal mismatch between the
 345 source and the district network. The asymptote is slightly visible on the *RACF*'s evolution. Meanwhile, marginal
 346 investment costs increase linearly with additional storage capacity. Beyond 20 MWh, the marginal profit does not
 347 outweigh marginal investment costs, at any temperature. This energy/economy divergence confirms the need for a
 348 compromise that was already forecasted in the conclusions of the author's previous study.

349 From the energy standpoint, 85 °C is better because the recovery system takes in more waste heat than the heat
 350 pump, and can inject to the district network the same thermal power or even more, because it is not limited by the
 351 heat pump's maximal power output. From an economic standpoint, the scenarios at 50 °C are the best for the majority
 352 of storage capacities. They are better than those at 35 °C because the heat pump consumes less electricity, the most
 353 expensive 'fuel' in this case study. As an added benefit it takes in more waste heat, thus the *RACF* is higher. At 85
 354 °C, only the case without storage is more profitable than the other temperatures. The reason for this is that no
 355 investment on a heat pump is necessary. But at 10 MWh and beyond, the costs of waste heat outweigh the profits.
 356 This happens because LNCMI's waste heat has a much higher price at 85 °C than at 35 °C or 50 °C, due to the
 357 decreased electricity-to-heat conversion ratio (refer to Table 1).

358 Figure 4 presents the evolution of the exergetic and exergoeconomic indicators (E_{GLOB}^D and C_{GLOB}^D , respectively).
 359 Unlike the energy/economy pair, these indicators recommend 35 °C as input temperature. Waste heat at higher
 360 temperatures is not optimal exergy-wise because of the increased electric consumption of the LNCMI's magnets and
 361 the increased losses. The same reasoning applies in exergo-economics, aggravated by higher costs of LNCMI's
 362 waste heat at higher temperatures. This increases other specific costs downstream in the district. In the reference
 363 case, the overall exergy destruction is 20.6 GWh/year and the overall exergy destruction cost is 3.09 M€/year. By
 364 comparing those data with the points in Fig. 4, it can be seen that all designs except those at 85 °C are better. Refer
 365 to the tables in Appendix B for detailed results of the reference and optimal scenarios.

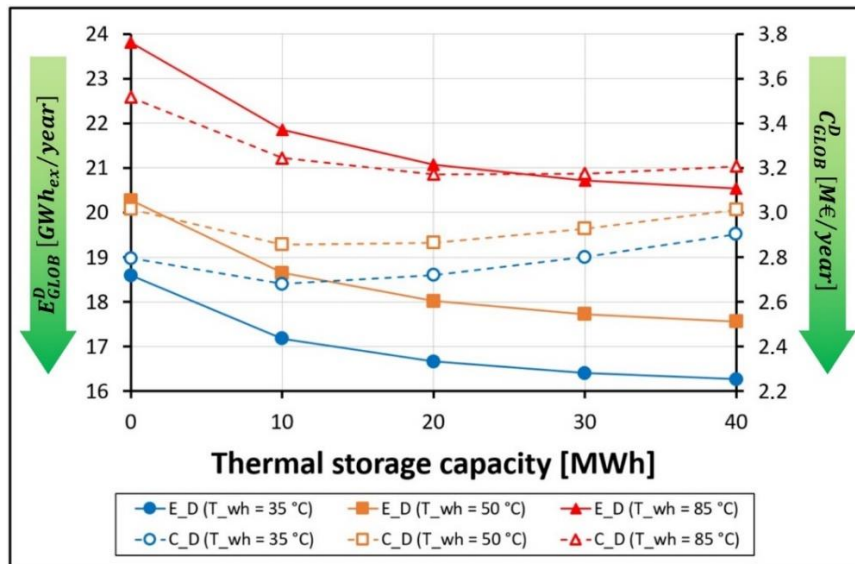


Figure 4. Overall annual irreversibilities (E_{GLOB}^D) and annual cost of irreversibilities (C_{GLOB}^D) as a function of thermal storage capacity, for the three input heat temperatures.

366 As for the storage capacity, a discrepancy similar to that observed in Fig. 3 is observed here. The exergetic indicator
 367 suggests the largest possible storage (40 MWh), while exergo-economy finds its optimum at 10 MWh. Beyond 10
 368 MWh, the benefits of recovering more waste heat are outweighed by the marginal investment costs. At $T_{wh} = 85$ °C,

369 the turning point exists at 20 MWh instead. The explanation for this is the absence of a heat pump and its associated
 370 exergy destruction costs.

371 Table 2 shows the values of the performance indicators for each monocriterion-optimal scenario. For the sake of
 372 comparison, the exergetic and exergoeconomic metrics of the recovery system alone are also shown. It is worth
 373 mentioning that if the assessment was applied only on the recovery system, the selected design would be different:
 374 The exergy-focused optimization would prefer $T_{wh} = 85\text{ }^{\circ}\text{C}$ with $U_{TES}^{max} = 40\text{ MWh}$ instead of $T_{wh} = 35\text{ }^{\circ}\text{C}$ with $U_{TES}^{max} = 40$
 375 MWh. Furthermore, an optimization focused on exergoeconomics would prefer $T_{wh} = 85\text{ }^{\circ}\text{C}$ with $U_{TES}^{max} = 40\text{ MWh}$
 376 instead of $T_{wh} = 35\text{ }^{\circ}\text{C}$ with $U_{TES}^{max} = 10\text{ MWh}$. This reflects the importance of the systemic approach considering all
 377 units affected by the heat recovery, even those that do not belong to the industrial process itself.

378 Table 2. Values of the performance indicators for each mono-criterion optimal design.

Design	RACF (%)	NPV (M€)	E_{GLOB}^D (GWh _{ex} /year)	C_{GLOB}^D (M€/year)	$[E_{WHRS}^D]$ (GWh _{ex} /year)	$[C_{WHRS}^D]$ (k€/year)
ENER-optimal { $T_{wh} = 85\text{ }^{\circ}\text{C}$, $U_{TES}^{max} = 40\text{ MWh}$ }	23.7	9.95	20.55	3.21	0.006	1.23
ECON-optimal { $T_{wh} = 50\text{ }^{\circ}\text{C}$, $U_{TES}^{max} = 20\text{ MWh}$ }	17.9	12.5	18.02	2.87	1.180	266
EXER-optimal { $T_{wh} = 35\text{ }^{\circ}\text{C}$, $U_{TES}^{max} = 40\text{ MWh}$ }	20.8	10.6	16.27	2.90	2.047	525
EXEC-optimal { $T_{wh} = 35\text{ }^{\circ}\text{C}$, $U_{TES}^{max} = 10\text{ MWh}$ }	13.0	11.8	17.18	2.28	1.618	272

379

380 Figure 5 presents a detailed trace of the overall process from the exergetic, exergoeconomic and economic points
 381 of view. All these indicators are represented per MWh of heat delivered to the residential end-users, and the
 382 optimization objective was to minimize their values.

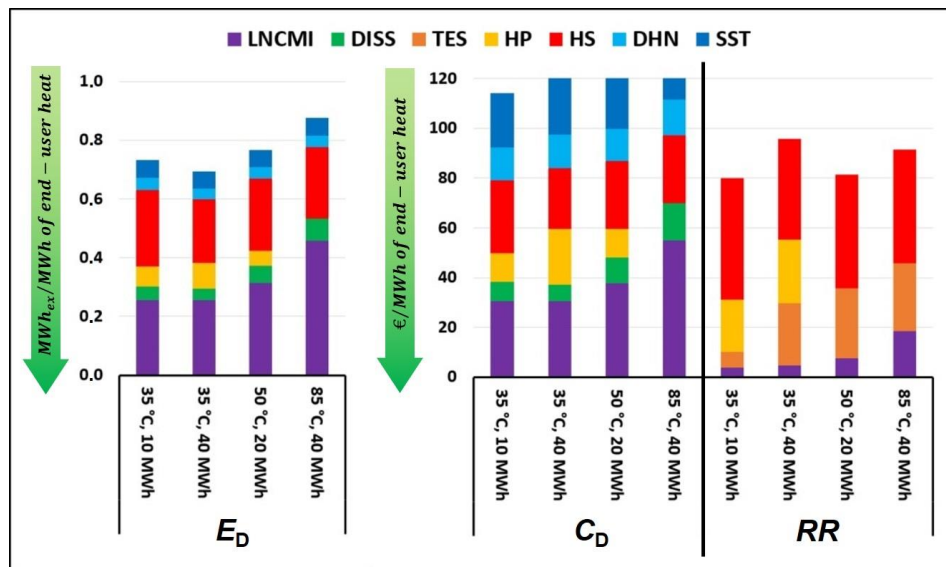


Figure 5. Detailed “4E pathway” of the overall system. All indicators are expressed per MWh of heat delivered to the residential end-users.

383 This can be considered a “4E pathway” of the overall system, as if all units in the district were part of a same process
 384 meant to deliver heat to end-users. From waste heat rejection at the LNCMI up to the residential clients, each unit
 385 increases irreversibility, the cost of irreversibility, and in most cases the product’s final cost. The bar charts in the

386 figure allow to identify each contribution. Although no energetic indicator is presented, energy is implicit in all other
387 criteria, since the four models are internally correlated. It is also important to bear in mind that the $C_{\text{GLOB}}^{\text{D}}$ and the sum
388 of all RR_k must not be directly contrasted in this figure. The first one refers to the overall scenario and includes
389 irreversibilities that do not need to be amortized by the heat sold to residential end-users. Likewise, exergy destruction
390 is accounted for all units in the scenario, not only those involved in the injection of heat to the district network. That
391 explains its relatively high values.

392 The “4E pathway” contains useful information. For instance, almost half of the contributions to the irreversibilities and
393 their costs are related to the LNCMI’s activities. Moreover, note how LNCMI’s influence on those indicators increases
394 at higher temperatures. The effect of waste heat temperature at 85 °C is slightly noticeable at the dissipation unit,
395 too. Another effect is that the influence of the HP is not there anymore. This is especially noticeable in the revenue
396 requirement, since the heat pump represents a high investment whenever it is included. The effect of increasing the
397 storage capacity is quite noticeable on the revenue requirement, too: the RR related to the storage increases by 4-
398 fold. Meanwhile, the thermal storage unit has barely any influence on the other two indicators. Note also that the
399 dissipation unit, the district heating and the substations do not have any influence on the RR , because they use no
400 external paid-for fuel nor require any additional investment.

401 The RR also gives an idea of how profitable the project can be. As mentioned in the hypotheses, the final price of
402 heat for the consumers is set at 80 €/MWh. If the aggregated RR is below that mark, the difference means benefits.
403 The larger the difference, the more the profit. Note that with some of the designs, the heat’s revenue requirement
404 exceeds 80 €/MWh. Thus, that design has a positive NPV (Fig. 3) only thanks to the Heat Supplier’s indirect benefit
405 due to less fuel consumption. As mentioned in the hypotheses, that benefit was mutualized between all of the project’s
406 stakeholders, respecting a Consortium.

407 A general conclusion from Fig. 5 is that a component does not necessarily have the same influence on every criterion.
408 For example, at 35 °C note how the LNCMI’s process has the considerable weights of around 40 % and 30 % in the
409 exergy and exergo-economic criteria, respectively, but only of 5-20 % in the revenue requirement. This is because
410 the electro-intensive process has important irreversibilities, but its waste heat is sold at relatively low prices. As
411 another example, note how the heat supplier’s influence is prominent on the revenue requirement (between 40 %
412 and 50 %), but smaller on the costs of irreversibilities (around 20%). This may be explained because their fuel is
413 relatively expensive, but their process is rather exergy-efficient. For the sake of information, Appendix B shows
414 detailed metrics unit by unit for all mono- and multi-criteria optimal scenarios.

415 **3.2. Dual-criteria Pareto-optimal conceptions**

416 This analysis aims to clarify which compromises can be achieved between mono-criterion optimal conceptions. As a
417 reminder, the following non-redundant optimal solutions have been identified in the previous section:

- 418 • $T_{wh} = 85 \text{ °C}$ and $U_{TES}^{max} = 40 \text{ MWh}$ is the energetically (ENER) optimal design.
- 419 • $T_{wh} = 35 \text{ °C}$ and $U_{TES}^{max} = 40 \text{ MWh}$ is the exergetically (EXER) optimal design.
- 420 • $T_{wh} = 50 \text{ °C}$ and $U_{TES}^{max} = 20 \text{ MWh}$ is the economically (ECON) optimal design.
- 421 • $T_{wh} = 35 \text{ °C}$ and $U_{TES}^{max} = 10 \text{ MWh}$ is the exergo-economically (EXEC) optimal design.

422 These results have two main consequences for the multi-criteria analyses. First, none of the criteria are redundant.
423 Second, there exist two types of Pareto fronts: as a function of T_{wh} and as a function of U_{TES}^{max} . Although both types
424 are scientifically interesting, only those related to U_{TES}^{max} were studied here. The fronts related to T_{wh} are somewhat

discouraging to analyze for this case, because: 1) The gap between $T_{wh} = 50\text{ }^{\circ}\text{C}$ and $T_{wh} = 85\text{ }^{\circ}\text{C}$ does not find practical application due to technological constraints of the magnets' cooling loop; 2) The case at $T_{wh} = 85\text{ }^{\circ}\text{C}$ has important technological differences, and belongs therefore to a different Pareto front of which only 1 point ($T_{wh} = 85\text{ }^{\circ}\text{C}$) finds practical application.

The 4 non-redundant criteria can lead to up to 6 dual-criteria Pareto fronts. Those are presented in the following figures. Like in the previous figures, arrows with color transition from light green to dark green indicate the optimization objectives. Figure 6 introduces the energy-economy and exergoeconomics-economy relationships.

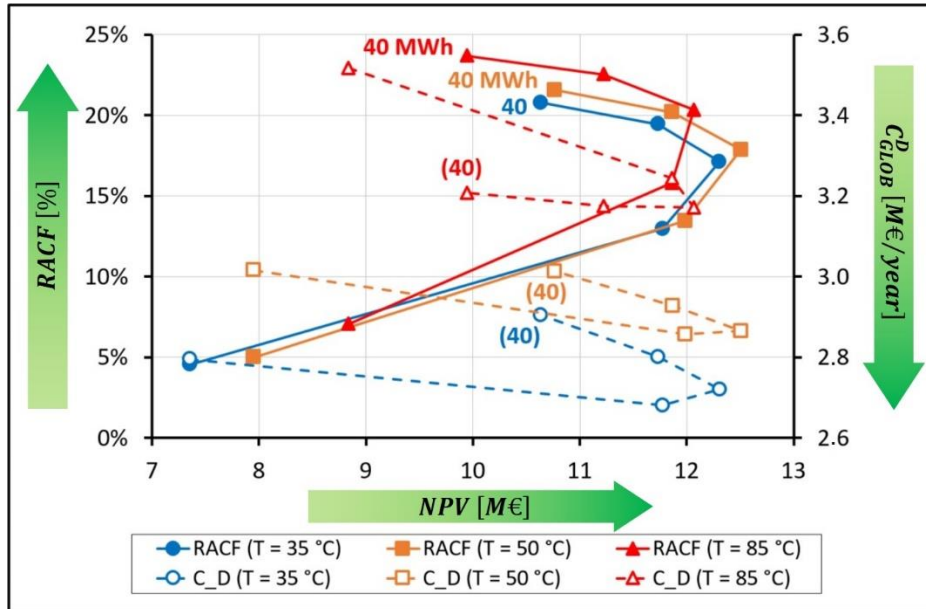


Figure 6. Energy-economy Pareto front ($RACF$ vs NPV) and exergoeconomics-economy Pareto front (C_{GLOB}^D vs NPV) as a function of thermal storage capacity, for the three input heat temperatures.

The energy-economy Pareto-optimal frontier is made up by the designs at $85\text{ }^{\circ}\text{C}$ between 20 MWh and 40 MWh, plus the design at $50\text{ }^{\circ}\text{C}$ with 20 MWh. These four solutions dominate all other solutions. Increasing thermal storage capacity has consistent energetic benefits at the expense of profitability. Switching from $50\text{ }^{\circ}\text{C}$ - 20 MWh to $85\text{ }^{\circ}\text{C}$ - 20 MWh increases the $RACF$ from 17.9% to 20.3% in exchange for only 3.6% less profit. Then, keeping $T = 85\text{ }^{\circ}\text{C}$ while increasing storage capacity from 20 MWh to 30 MWh increases the $RACF$ further to 22.5%, but in exchange for a further drop of 7% in profitability already. In the final increase from 30 MWh to 40 MWh, the margins look discouraging: a further drop of 11% in profits, for only a slight increase in the $RACF$ to 23.7%.

The exergoeconomics-economy analysis presents as most promising the following solutions: $\{50\text{ }^{\circ}\text{C} - 20\text{ MWh}\}$, $\{35\text{ }^{\circ}\text{C} - 10\text{ MWh}\}$ and $\{35\text{ }^{\circ}\text{C} - 20\text{ MWh}\}$. The economic indicator prioritizes the solution at $\{50\text{ }^{\circ}\text{C} - 20\text{ MWh}\}$, while the exergoeconomic indicator prioritizes the $\{35\text{ }^{\circ}\text{C} - 10\text{ MWh}\}$ solution. The $\{35\text{ }^{\circ}\text{C} - 20\text{ MWh}\}$ solution seems like a healthy compromise between the two. None of the solutions at $85\text{ }^{\circ}\text{C}$ is promising in the exergoeconomics-economy analysis. Besides, at $85\text{ }^{\circ}\text{C}$ the evolution of the exergoeconomic indicator is opposite with respect to the other temperatures because of the absence of heat pump, and because the turning point is different (Fig. 4).

Figure 7 presents the energy-exergy and economy-exergy analyses. In the first one, there is actually no storage-dependent Pareto front. Greater storage capacities lead to a better $RACF$ and less irreversibility, straightforwardly. However, their marginal improvement slows down at each increase in capacity. Depending on the unfavorable evolution of other indicators, it may be sensible to not pursue the largest storage unit. This has been observed in the

449 energy-economy comparison from Fig. 6, for instance. The design temperature of 50 °C is surpassed exergy-wise
 450 by $T = 35$ °C and energy-wise by $T = 85$ °C, but it might yield good compromises between those two temperatures.

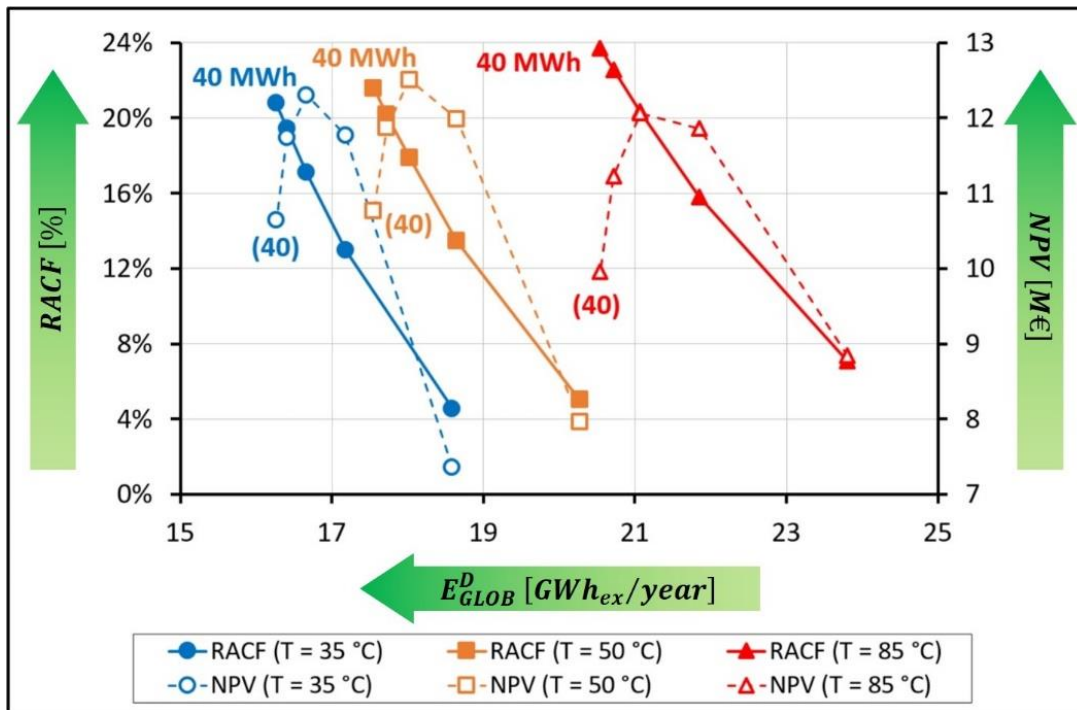


Figure 7. Energy-exergy Pareto front ($RACF$ vs E_{GLOB}^D) and economy-exergy Pareto front (NPV vs E_{GLOB}^D) as a function of thermal storage capacity, for the three industrial waste heat temperatures.

451

452 The economy-exergy analysis, on the contrary, has tendencies that are less intuitive. The {35 °C - 40 MWh}, {35 °C
 453 - 30 MWh} and {35 °C - 20 MWh} solutions outperform any other solution exergy-wise. Meanwhile, the {50 °C - 20
 454 MWh} solution outperforms any other solution economy-wise. Switching successively from {35 °C - 40 MWh} to the
 455 next designs in the Pareto frontier yields marginal increases in net profit at the expense of exergy efficiency. The
 456 inlet temperature of 85 °C is dominated by the other temperatures in the economy-exergy analysis. With respect to
 457 Fig. 6, this figure adds 2 new candidates to the list of promising designs.

458 The results found for 20 MWh reinforce a perspective mentioned in the Conclusions of the authors' previous article.
 459 In theory, it is feasible for the LNCMI to adjust dynamically the temperature of their waste heat, as a function of
 460 temporal mismatch between their activities and the district's thermal needs. A storage capacity of 20 MWh may fit
 461 well in such strategy, because the recovery system would always operate on its economy-exergy Pareto front at
 462 either 35 °C or 50 °C. The same consideration applies on the economy-exergoeconomics Pareto frontier shown in
 463 Fig. 6. For extensive results, Figure B.1 in Appendix B contains additional Pareto fronts.

464 Table 3 summarizes the main conclusions from analyzing the Pareto fronts generated through analyses based on
 465 energy (ENER), exergy (EXER), economy (ECON) and exergoeconomics (EXEC). Solutions displayed in bold font
 466 are monocriterion-optimal, while the rest are Pareto-optimal. Among the Pareto-optimal solutions, those which
 467 prioritize one of the criteria are indicated with the suffix "Promising". If a Pareto-optimal solution is nearly halfway
 468 between the two optimal values, it is labeled as a "Compromise". The cells with no information in them mean that the
 469 design is not interesting with respect to that front. The energy-exergy analysis is not included in the table because it
 470 has no Pareto front and optimality is straightforward.

Table 3. Performance of each possible design with respect to each dual-criteria Pareto front.

Solution \ Front	ENER-ECON	ENER-EXEC	ECON-EXER	ECON-EXEC	EXER-EXEC
{35 °C, 0 MWh}	-	-	-	-	-
{35 °C, 10 MWh}	-	EXEC-Optimal	-	EXEC-Optimal	EXEC-Optimal
{35 °C, 20 MWh}	-	EXEC-Promising	ECON-Promising	Compromise	EXEC-Promising
{35 °C, 30 MWh}	-	EXEC-Promising	EXER-Promising	-	EXER-Promising
{35 °C, 40 MWh}	-	Compromise	EXER-Optimal	-	EXER-Optimal
{50 °C, 0 MWh}	-	-	-	-	-
{50 °C, 10 MWh}	-	-	-	-	-
{50 °C, 20 MWh}	ECON-Optimal	-	ECON-Optimal	ECON-Optimal	-
{50 °C, 30 MWh}	-	-	-	-	-
{50 °C, 40 MWh}	-	Compromise	-	-	-
{85 °C, 0 MWh}	-	-	-	-	-
{85 °C, 10 MWh}	-	-	-	-	-
{85 °C, 20 MWh}	ECON-Promising	-	ECON-Promising	ECON-Promising	-
{85 °C, 30 MWh}	ENER-Promising	ENER-Promising	-	-	-
{85 °C, 40 MWh}	ENER-Optimal	ENER-Optimal	-	-	-

472

473 The semi-qualitative analysis allowed to discard a few solutions that are not promising from any point of view. On the
474 other hand, those that are optimal or Pareto-optimal in at least one front have a chance of becoming multi-criteria
475 optimal. Especially, the {35 °C – 20 MWh} and {35 °C – 30 MWh} solutions have some fair chances. Despite not
476 being optimal in any criterion, they are Pareto-optimal in at least 3 out of 5 different fronts. Thus, they seem the
477 strongest candidates for multicriteria optimality. Of course, the concept of ‘optimality’ depends on criteria weights.

478 In addition to information on the designs, this analysis has given information about the fronts, too. Namely, the exergy-
479 exergoeconomics front is the most restrictive one in terms of temperature, since it only accepts 35 °C as promising.
480 That can make this front hard to conciliate with others. In terms of storage capacity, the economy-exergoeconomics
481 front is clearly the most restrictive, since it restricts promising solutions to a storage capacity of either 10 MWh or 20
482 MWh. The rest of the fronts are quite flexible in temperature or in storage capacity, with the energy-exergoeconomics
483 front being the most flexible.

484 Next section shows results for the quantitative multicriteria analysis. Those results may or may not confirm the {35
485 °C – 20 MWh} and {35 °C – 30 MWh} solutions as the most promising ones, as pointed out by the semi-qualitative
486 analysis.

487

488 3.3. Preliminary results about multi-criteria optimality

489 Table 4 shows multi-criteria optimality for each scenario, assuming that all criteria are equally important to the
490 decision-maker. The table confirms quantitatively what was perceived semi-qualitatively in the dual-criteria analysis.
491 The {35 °C – 30 MWh} design shows high performance in almost every criterion, and that sets it apart as optimal
492 solution. The {35 °C – 20 MWh} design is almost as suitable, but more inclined towards economy and
493 exergoeconomics. Remarkably, none of the two were in the list of mono-criteria optimal designs. It is also remarkable
494 that the 3 highest multi-criteria performances involve waste heat at 35 °C. This means that the multicriteria optimum
495 in this case study is strongly influenced by exergy and exergoeconomics. In terms of thermal storage capacity, the
496 multicriteria optimum is a compromise between economic and non-economic criteria.

Table 4. Proximity of each scenario to multi-criterion optimality.

Design	Mono/Dual-criteria optimality	ψ_{ENER}^{mono}	ψ_{EXER}^{mono}	ψ_{ECON}^{mono}	ψ_{EXEC}^{mono}	ψ^{multi}
		(w = 0.25)	(w = 0.25)	(w = 0.25)	(w = 0.25)	
35 °C. REF	None	0%	62%	0%	73%	33.7%
35 °C. 0 MWh	None	19%	80%	59%	92%	62.5%
35 °C. 10 MWh	EXEC-Optimal	55%	92%	94%	100%	85.2%
35 °C. 20 MWh	Multicriteria-Suboptimal	72%	97%	98%	97%	91.2%
35 °C. 30 MWh	Multicriteria-Optimal	82%	99%	94%	92%	91.7%
35 °C. 40 MWh	EXER-Optimal	88%	100%	85%	85%	89.5%
50 °C. REF	None	0%	43%	0%	51%	23.6%
50 °C. 0 MWh	None	21%	65%	64%	78%	56.9%
50 °C. 10 MWh	None	57%	79%	96%	88%	80.1%
50 °C. 20 MWh	ECON-Optimal	75%	85%	100%	88%	87.0%
50 °C. 30 MWh	None	85%	87%	95%	83%	87.7%
50 °C. 40 MWh	ENER/EXEC-Compromise	91%	89%	86%	78%	85.9%
85 °C. REF	None	0%	0%	0%	0%	0.0%
85 °C. 0 MWh	None	30%	34%	71%	44%	44.7%
85 °C. 10 MWh	None	67%	51%	95%	62%	68.8%
85 °C. 20 MWh	ECON-Promising	86%	58%	96%	67%	76.9%
85 °C. 30 MWh	ENER-Promising	95%	61%	90%	67%	78.3%
85 °C. 40 MWh	ENER-Optimal	100%	63%	80%	65%	76.8%

498

499 If each criterion had a different weight, it might be easier to decide between {35 °C – 20 MWh} or {35 °C – 30 MWh}.
500 But in this case all of them have the same importance, so the final decision would be in the investors' hands. This
501 result serves as a reminder that multi-criteria analyses are just support tools, and final decisions belong to human
502 choices. Of course, there exist more robust (and complex) methods for multi-criteria decision making, such as the
503 ELECTRE family of methods [49].

504

505 4. Conclusions and perspectives

506 This study has determined the most promising inlet temperature and thermal storage capacity of an industrial waste
507 heat recovery system for district heating, by means of a systemic-anticipative approach with 4E analyses (energy,
508 exergy, economy and exergoeconomics) based on local balances. These 4E analyses have been applied on an
509 operating scenario where the management of energy flows had been previously optimized on an hourly time step for
510 a whole year, using Mixed-Integer Linear Programming. The main conclusions of this study are:

- 511 • The most promising design is an inlet temperature of 35 °C and a storage capacity of 30 MWh.
- 512 • With that design, the system recovers 41% of the total waste heat, covers 48% of the total residential heat
513 demands, and has an estimated Net Present Value of 11.7 M€ over 20 years. In comparison to the base
514 scenario, the heat recovery system reduces the district's overall exergy destruction and exergy destruction
515 costs by 20% (4.2 GWh/year) and 9% (286 k€/year), respectively.

- 516 • None of the mono-criterion assessments pointed out this design as optimal. Therefore, the multicriteria
517 systemic assessment was of utmost importance to detect the most promising solution.
- 518 • Fundamental discrepancies between indicators have been identified. Exergy and exergoeconomics
519 recommend the lowest possible temperature (35 °C), while energy-based indicators tend to recommend the
520 highest possible temperature (85 °C). Meanwhile, the economic indicator recommended 50 °C in this case
521 study. This reinforces the interest of including exergy-based indicators in the analyses, since they suggest
522 non-redundant solutions. In addition, technical indicators recommend the largest possible storage capacity
523 (40 MWh) while economy-related indicators advise to stay around 10-20 MWh.
- 524 • The most promising design implies a temperature of 35 °C. Therefore, the exergy-related indicators had a
525 strong presence in the final solution, despite being assigned the same weight as other criteria. This reinforces
526 the interest of exergy and exergoeconomics as criteria for decision-making in waste heat recovery, district
527 heating and urban planning.

528 Two main perspectives have been identified after this study. The first one is to explore two advanced strategies for
529 better heat valorization: 1) Re-schedule the LNCMI laboratory's yearly calendar of experiments, to synchronize them
530 with the periods of highest residential heat demands; 2) Adjust the magnets' cooling loop to reject heat at higher
531 temperatures when there are residential demands, and at lower temperatures the rest of the time. The storage
532 capacity of 20 MWh seems a good candidate for the second strategy, because the system can operate at Pareto-
533 optimality at any of the three temperatures.

534 The second perspective is to use a multi-actor approach to model more realistic scenarios. Indeed, this article
535 assumed a consortium between all potential investors, but in reality the recovery system may belong solely to the
536 industrial actor, the district network operator, or even a third stakeholder. Depending on ownership of the heat
537 recovery system, the most suitable design can change significantly.

538

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656

Appendix A. Detailed equations of the 4E model

658

Table A.1 contains the concretized energy balances unit by unit, as well as the auxiliary equations.

659

Table A.1. Concretized formulation of the energy balance for each unit.

Unit	Energy balance	Auxiliary equations
LNCMI	$\dot{W}_{LNCMI}^{in} \cdot \xi = \dot{Q}_{LNCMI}^{out}$	$\xi = 0.85$
DISS	$\dot{Q}_{LNCMI}^{out} = \dot{Q}_{DISS}^{in} + \dot{Q}_{TES}^{in}$	$\dot{Q}_{TES}^{in,max} \leq U_{TES}^{max} / \Delta t_{TES}^{min,chg}$
TES	$\Delta U_{TES} = \dot{Q}_{TES}^{in} - \dot{Q}_{TES}^{out} - \dot{Q}_{TES}^L$	$\dot{Q}_{TES}^{out,max} \leq U_{TES}^{max} / \Delta t_{TES}^{min,dchg}$
HP	$\dot{Q}_{HP}^{in} + \dot{W}_{HP}^{in} = \dot{Q}_{HP}^{out}$ $\dot{Q}_{HP}^{in} = \dot{Q}_{TES}^{out}$ $COP_{HP} = \dot{Q}_{HP}^{out} / \dot{W}_{HP}^{in,elec}$	$COP_{HP}(T_{HP}^{in} = 35^\circ C) = 3$ $\frac{COP_{HP}(T_{HP}^{in} = 50^\circ C)}{COP_C(T_{HP}^{in} = 50^\circ C)} = \frac{COP_{HP}(T_{HP}^{in} = 35^\circ C)}{COP_C(T_{HP}^{in} = 35^\circ C)}$ $COP_C = T_{HP}^{out} / (T_{HP}^{out} - T_{HP}^{in})$ $\dot{Q}_{HP}^{out,max}(T_{HP}^{in} = 50^\circ C) = \dot{Q}_{HP}^{out,max}(T_{HP}^{in} = 35^\circ C)$
HS	$\dot{E}_{HS}^{in} \cdot \eta_{HS} = \dot{Q}_{HS}^{out}$	$\eta_{HS} = \frac{\dot{Q}_{HS}^{out} / \theta_q(T = T_{HS}^{q,out})}{\dot{E}_{HS}^{in} / \theta_{ch}}$ $\theta_q(T = T_{HS}^{q,out}) = 1 - \frac{T_0}{T_{HS}^{q,out}}$ $(\theta_{ch} \approx 1, T_0 = 8^\circ C)$
DHN	$\dot{Q}_{DHN}^{in} = \dot{Q}_{DHN}^{out}$	$\dot{Q}_{HP}^{out} + \dot{Q}_{HS}^{out} = \dot{Q}_{DHN}^{in}$
SST	$\dot{Q}_{SST}^{in} = \dot{Q}_{SST}^{out}$	$\dot{Q}_{DHN}^{out} = \dot{Q}_{SST}^{in}$

660

661

Table A.2 compiles the concretized formulations of the exergy balance unit by unit. Further details about the energy

662

and exergy models are available in the previous article [12]. The total exergy consumption by the LNCMI's processes

663

is dissociated in 3 main terms: 1) "Useful" exergy destruction by the electromagnets ($\dot{E}_{LNCMI}^{D,use}$) in order to provide

664

experimental data; 2) Recoverable outlet exergy in the form of waste heat ($\dot{E}_{LNCMI}^{out,q}$); 3) Exergy destruction (\dot{E}_{LNCMI}^D)

665

mainly due to mechanical friction and heat losses. Only the third term was considered an irreversibility within LNCMI's

666 process. The temperature difference between the magnets and the waste heat ($\Delta T_{cooling}$) is constant and imposed by
 667 the magnets' cooling process [45].

668

Table A.2. Concretized formulation of the exergy balance for each unit.

Unit	Exergy balance	Auxiliary equations
LNCMI	$\dot{E}_{LNCMI}^{in} = \dot{E}_{LNCMI}^{D,use} + \dot{E}_{LNCMI}^{out,q} + \dot{E}_{LNCMI}^D$	$\dot{E}_{LNCMI}^{in} = \dot{W}_{LNCMI}^{in}$ $\dot{E}_{LNCMI}^{out,q} = \dot{W}_{LNCMI}^{in} \cdot \xi \cdot \theta_q(T = T_{LNCMI}^{out,q})$ $\dot{E}_{LNCMI}^{D,use} = \dot{W}_{LNCMI}^{in} \cdot \xi \cdot (\theta_{elec} - \theta_q(T = T_{LNCMI}^{magnets}))$ $T_{LNCMI}^{magnets} = T_{LNCMI}^{out,q} + \Delta T_{cooling}$
DISS	$\dot{E}_{DISS}^D = \dot{E}_{DISS}^{in,q}$	$\dot{E}_{LNCMI}^{out,q} = \dot{E}_{DISS}^{in,q} + \dot{E}_{TES}^{in,q}$
TES	$\dot{E}_{TES}^{in,q} = \dot{E}_{TES}^{out,q} + \Delta E_{TES}^u + \dot{E}_{TES}^L$	$\dot{E}_{TES}^L = \dot{Q}_{TES}^L \cdot \theta_q(T = T_{TES}^{in,q})$
HP	$\dot{E}_{HP}^{in,q} + \dot{W}_{HP}^{in} = \dot{E}_{HP}^{out,q} + \dot{E}_{HP}^D$	$\dot{E}_{HP}^{in,q} = \dot{Q}_{HP}^{in} \cdot \theta_q(T = T_{HP}^{in,q})$ $\dot{E}_{HP}^{out,q} = \dot{Q}_{HP}^{out} \cdot \theta_q(T = T_{HP}^{out,q})$
HS	$\dot{E}_{HS}^{in,ch} \cdot \varepsilon_{HS} = \dot{E}_{HS}^{out,q}$	$\varepsilon_{HS} = 0.4$ $\dot{E}_{HS}^D = \dot{Q}_{HS}^{out} \cdot \theta_q(T = T_{HS}^{q,out}) \cdot \left(\frac{1}{\varepsilon_{HS}} - 1\right)$
DHN	$\dot{E}_{HS}^{out,q} + \dot{E}_{HP}^{out,q} = \dot{E}_{DHN}^{out,q} + \dot{E}_{DHN}^D$	-
SST	$\dot{E}_{SST}^{in,q} = \dot{E}_{SST}^{out,q} + \dot{E}_{SST}^D$	$\dot{E}_{DHN}^{out,q} = \dot{E}_{SST}^{in,q}$

669

670 Table A.3 presents the concretized formulations of the cost flow balance unit by unit.

671

Table A.3. Concretized formulations of the cost flow balance unit by unit and their auxiliary equations.

Unit	Cost flow balance	Auxiliary equations
LNCMI	$\dot{C}_{LNCMI}^D = \dot{C}_{LNCMI}^{q,out}$	$c_{LNCMI}^{W,in} = c^{elec}$
DISS	$\dot{C}_{DISS}^{q,in} = \dot{C}_{DISS}^D$	$c_{DISS}^{q,in} = c_{LNCMI}^{q,out}$
TES	$c_{TES}^{q,in} + \dot{Z}_{TES} = c_{TES}^{q,out}$	$c_{TES}^{q,in} = c_{LNCMI}^{q,out}$
HP	$\dot{C}_{HP}^{q,in} + \dot{C}_{HP}^{elec,in} + \dot{Z}_{HP} = \dot{C}_{HP}^{q,out}$	$c_{HP}^{q,in} = c_{TES}^{q,out}$
HS	$\dot{C}_{HS}^F = \dot{C}_{HS}^{q,out}$	$C_{HS}^F = c_{SST}^{out,REF} \cdot \dot{E}_{SST,REF}^{q,out} / \dot{E}_{HS,REF}^{F,in}$ $c_{HS}^{q,out} = (c_{SST}^{q,in} \cdot \dot{E}_{SST,REF}^{in}) / \dot{E}_{HS,REF}^{q,out}$ $C_{HS}^F = (c_{HS}^{q,out} \cdot \dot{E}_{HS,REF}^{q,out}) / \dot{E}_{HS,REF}^F$
DHN	$\dot{C}_{HP}^{q,out} + \dot{C}_{HS}^{q,out} = \dot{C}_{DHN}^{q,out}$	-
SST	$\dot{C}_{SST}^{q,in} = \dot{C}_{SST}^{P,BEP}$	$c_{SST}^{q,in} = c_{DHN}^{q,out}$ $c_{SST}^{q,in} = \dot{C}_{SST,REF}^{q,out} / \dot{E}_{SST,REF}^{q,in}$

672

673 Appendix B. Extended results of the 4E model

674 Figure B.1 shows the energy-exergoeconomics and exergy-exergoeconomics analyses. The most promising designs
 675 are: {35 °C - 10 MWh to 40 MWh}, {50 °C, 40 MWh}, and {85 °C, 30 MWh to 40 MWh}. The {35 °C - 10 MWh} design
 676 is EXEC-optimal and the {85 °C - 40 MWh} design is ENER-optimal. Switching from EXEC-optimal to ENER-optimal
 677 passing through the Pareto-optimal solutions causes marginal increases in C_{GLOB}^D but marginal improvements in the
 678 RACF as a compensation.

679 Cases at 35 °C and from 10 MWh to 40 MWh are indisputable exergy-exergoeconomics Pareto-optimal solutions.
 680 The design with 10 MWh is EXEC-optimal as mentioned before, and the design with 40 MWh is EXER-optimal. The
 681 designs with 20 MWh or 30 MWh seem interesting as a compromise.

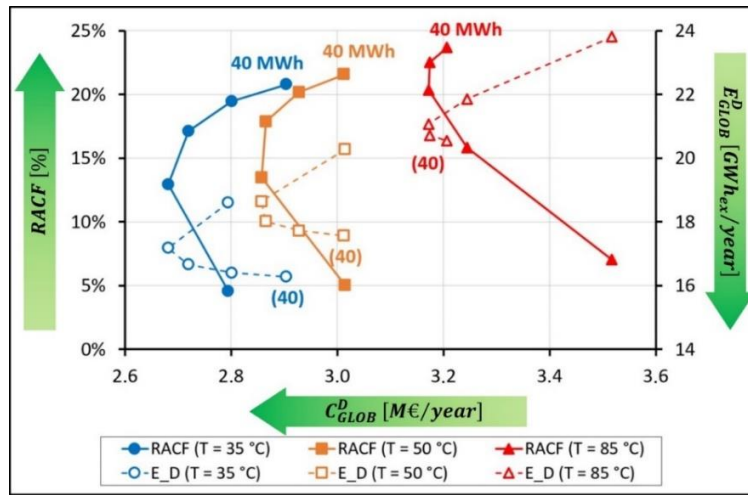


Figure B.1. Energy-exergoeconomics ($RACF$ vs C_{GLOB}^D) and exergy-exergoeconomics Pareto fronts (E_{GLOB}^D vs C_{GLOB}^D) as function of storage capacity and inlet temperature.

682 Tables B.1 to B.8 show detailed results for each reference scenario, each monocriterion-optimal scenario and the
 683 multicriteria-optimal scenario. This study assessed two other well-known indicators, despite not using them as
 684 objective functions: the relative cost difference r (eq. A.1) and the exergoeconomic factor f (eq. A.2). The first
 685 expresses the increase in the average cost per exergy unit between fuel and product. The second defines the relative
 686 significance of the capital investment with respect to the total exergoeconomic expenses of the unit [11].

$$687 \quad r = \frac{c^P - c^F}{c^F} \quad (A.1)$$

$$688 \quad f = \frac{\dot{Z}}{\dot{Z} + \dot{C}^D} \quad (A.2)$$

690 Table B.1. Detailed metrics for the reference scenario at 35 °C (i.e. no waste heat recovery).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	18.4	-	-	0.0	23.5	23.5	41.9	-
W^{in} (GWh/year)	21.6	0.0	-	-	0.0	0.0	0.0	0.0	-
Q^{out} (GWh/year)	18.4	18.4	-	-	23.5	23.5	23.5	41.9	-
E^{in} (GWh _{ex} /year)	21.6	1.6	-	-	16.7	6.7	5.0	18.3	-
E^D (GWh _{ex} /year)	6.0	1.6	-	-	10.0	1.6	1.4	20.6	-
E^{out} (GWh _{ex} /year)	1.6	0.0	-	-	6.7	5.0	3.7	3.7	-
\dot{C}^F (k€/year)	2596.8	267.3	-	-	1877.7	1877.7	1877.7	4474.5	-
\dot{Z} (k€/year)	0.0	0.0	-	-	0.0	0.0	0.0	0.0	-
\dot{C}^P (k€/year)	0.0	0.0	-	-	1877.7	1877.7	1877.7	1877.7	-
\dot{C}^D (k€/year)	717.7	267.3	-	-	1126.6	460.6	514.5	3086.7	-
RR (€/MWh _{th})	0.0	0.0	-	-	80.0	0.0	0.0	80.0	-
f (%)	-	-	-	-	0	0	0	-	-
r (%)	-	-	-	-	0	0	0	-	-

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692 Table B.2. Detailed metrics for the reference scenario at 50 °C (i.e. no waste heat recovery).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	18.4	-	-	0.0	23.5	23.5	41.9	-
W^{in} (GWh/year)	23.3	0.0	-	-	0.0	0.0	0.0	0.0	-
Q^{out} (GWh/year)	18.4	18.4	-	-	23.5	23.5	23.5	41.9	-
E^{in} (GWh _{ex} /year)	23.3	2.4	-	-	16.7	6.7	5.0	19.1	-
E^D (GWh _{ex} /year)	7.4	2.4	-	-	10.0	1.6	1.4	22.8	-
E^{out} (GWh _{ex} /year)	2.4	0.0	-	-	6.7	5.0	3.7	3.7	-
\dot{C}^F (k€/year)	2791.6	420.0	-	-	1877.7	1877.7	1877.7	4669.2	-
\dot{Z} (k€/year)	0.0	0.0	-	-	0.0	0.0	0.0	0.0	-
\dot{C}^P (k€/year)	0.0	0.0	-	-	1877.7	1877.7	1877.7	1877.7	-
\dot{C}^D (k€/year)	885.0	420.0	-	-	1126.6	460.6	514.5	3406.8	-
RR (€/MWh _{th})	0.0	0.0	-	-	80.0	0.0	0.0	80.0	-
f (%)	-	-	-	-	0	0	0	-	-
r (%)	-	-	-	-	0	0	0	-	-

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Table B.3. Detailed metrics for the reference scenario at 85 °C (i.e. no waste heat recovery).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	18.4	0.0	0.0	0.0	23.5	23.5	41.9	0.0
W^{in} (GWh/year)	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Q^{out} (GWh/year)	18.4	18.4	0.0	0.0	23.5	23.5	23.5	41.9	0.0
E^{in} (GWh _{ex} /year)	27.1	4.0	0.0	0.0	16.7	6.7	5.0	20.7	0.0
E^D (GWh _{ex} /year)	10.7	4.0	0.0	0.0	10.0	1.6	1.4	27.7	0.0
E^{out} (GWh _{ex} /year)	4.0	0.0	0.0	0.0	6.7	5.0	3.7	3.7	0.0
\dot{C}^F (k€/year)	3246.0	786.5	0.0	0.0	1877.7	1877.7	1877.7	5123.7	0.0
\dot{Z} (k€/year)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
\dot{C}^P (k€/year)	0.0	0.0	0.0	0.0	1877.7	1877.7	1877.7	1877.7	0.0
\dot{C}^D (k€/year)	1287.3	786.5	0.0	0.0	1126.6	460.6	514.5	4175.5	0.0
RR (€/MWh _{th})	0.0	0.0	0.0	0.0	80.0	0.0	0.0	80.0	0.0
f (%)	-	-	0%	0%	0	0	0	-	0%
r (%)	-	-	0%	0%	0	0	0	-	0%

Table B.4. Detailed metrics for the {85 °C - 40 MWh} scenario (energy-optimal scenario).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	8.3	10.1	0.0	0.0	23.5	23.5	31.8	10.1
W^{in} (GWh/year)	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Q^{out} (GWh/year)	18.4	8.3	10.1	0.0	13.4	23.5	23.5	31.7	0.0
E^{in} (GWh _{ex} /year)	27.1	1.8	2.2	0.0	9.5	3.8	5.0	11.3	2.2
E^D (GWh _{ex} /year)	10.7	1.8	0.0	0.0	5.7	0.9	1.4	20.5	0.0
E^{out} (GWh _{ex} /year)	4.0	0.0	2.2	0.0	3.8	5.0	3.7	3.7	2.2
\dot{C}^F (k€/year)	3246.0	353.6	346.3	0.0	1070.1	2144.2	2144.2	4316.1	346.3
\dot{Z} (k€/year)	0.0	0.0	586.9	54.4	0.0	0.0	0.0	641.3	641.3
\dot{C}^P (k€/year)	346.3	0.0	933.2	54.4	1070.1	2144.2	2144.2	2144.2	987.6
\dot{C}^D (k€/year)	1287.3	353.6	1.2	0.0	642.0	335.1	587.5	3206.8	1.2
RR (€/MWh _{th})	18.4	0.1	25.0	2.3	45.6	0.0	0.0	91.4	27.3
f (%)	-	-	100%	100%	0	0	0	-	100%
r (%)	-	-	136%	5%	0	0	0	-	185%

Table B.5. Detailed metrics for the {50 °C, 20 MWh} scenario (economy-optimal scenario).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	10.7	7.7	7.7	0.0	23.5	23.5	31.9	7.7
W^{in} (GWh/year)	23.3	0.0	0.0	2.3	0.0	0.0	0.0	2.3	2.3
Q^{out} (GWh/year)	18.4	10.7	7.7	10.0	13.5	23.5	23.5	34.2	10.0
E^{in} (GWh _{ex} /year)	23.3	1.4	1.0	3.3	9.6	6.0	5.0	14.3	4.3
E^D (GWh _{ex} /year)	7.4	1.4	0.0	1.2	5.8	0.9	1.4	18.0	1.2
E^{out} (GWh _{ex} /year)	2.4	0.0	1.0	2.2	3.8	5.0	3.7	3.7	3.2
\dot{C}^F (k€/year)	2791.6	244.1	163.7	249.4	1076.6	1911.9	1911.9	3868.2	413.1
\dot{Z} (k€/year)	0.0	0.0	293.5	85.8	0.0	0.0	0.0	379.2	379.2
\dot{C}^P (k€/year)	163.7	0.0	457.1	335.2	1076.6	1911.9	1911.9	1911.9	792.3
\dot{C}^D (k€/year)	885.0	244.1	0.6	265.3	646.0	300.4	523.8	2865.2	265.8
RR (€/MWh _{th})	7.5	0.3	12.5	15.6	45.9	0.0	0.0	81.8	28.1
f (%)	-	-	100%	24%	0	0	0	-	59%
r (%)	-	-	168%	72%	0	0	0	-	92%

Table B.6. Detailed metrics for the {35 °C, 40 MWh} scenario (exergy-optimal scenario).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	10.6	7.8	7.7	0.0	23.5	23.5	30.3	7.8
W^{in} (GWh/year)	21.6	0.0	0.0	3.8	0.0	0.0	0.0	3.8	3.8
Q^{out} (GWh/year)	18.4	10.6	7.7	11.5	11.9	23.5	23.5	34.1	11.5
E^{in} (GWh _{ex} /year)	21.6	0.9	0.7	4.5	8.5	5.9	5.0	13.9	5.2
E^D (GWh _{ex} /year)	6.0	0.9	0.0	2.0	5.1	0.8	1.4	16.3	2.0
E^{out} (GWh _{ex} /year)	1.6	0.0	0.7	2.5	3.4	5.0	3.7	3.7	3.2
\dot{C}^F (k€/year)	2596.8	154.5	112.8	455.1	953.8	2247.6	2247.6	3550.6	567.9
\dot{Z} (k€/year)	0.0	0.0	586.9	132.1	0.0	0.0	0.0	719.0	719.0
\dot{C}^P (k€/year)	112.8	0.0	699.7	587.1	953.8	2247.6	2247.6	2247.6	1286.9
\dot{C}^D (k€/year)	717.7	154.5	1.0	524.1	572.3	318.5	615.8	2903.9	525.1
RR (€/MWh _{th})	4.8	0.1	25.0	25.3	40.6	0.0	0.0	95.8	50.3
f (%)	-	-	100%	20%	0	0	0	-	58%
r (%)	-	-	526%	103%	0	0	0	-	127%

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Table B.7. Detailed metrics for the {35 °C - 10 MWh} scenario (exergoeconomics-optimal scenario).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	12.3	6.1	6.1	0.0	23.5	23.5	32.7	6.1
W^{in} (GWh/year)	21.6	0.0	0.0	3.1	0.0	0.0	0.0	3.1	3.1
Q^{out} (GWh/year)	18.4	12.3	6.1	9.2	14.3	23.5	23.5	35.8	9.2
E^{in} (GWh _{ex} /year)	21.6	1.1	0.5	3.6	10.2	6.0	5.0	14.9	4.1
E^D (GWh _{ex} /year)	6.0	1.1	0.0	1.6	6.1	1.0	1.4	17.2	1.6
E^{out} (GWh _{ex} /year)	1.6	0.0	0.5	2.0	4.1	5.0	3.7	3.7	2.5
\dot{C}^F (k€/year)	2596.8	178.4	88.8	235.7	1145.6	1879.3	1879.3	3742.4	324.5
\dot{Z} (k€/year)	0.0	0.0	146.7	132.1	0.0	0.0	0.0	278.8	278.8
\dot{C}^P (k€/year)	88.8	0.0	235.6	367.7	1145.6	1879.3	1879.3	1879.3	603.3
\dot{C}^D (k€/year)	717.7	178.4	0.2	271.4	687.4	311.0	514.9	2681.1	271.6
RR (€/MWh _{th})	3.8	1.9	6.3	21.2	48.8	0.0	0.0	81.9	27.5
f (%)	-	-	100%	33%	0	0	0	-	51%
r (%)	-	-	166%	122%	0	0	0	-	86%

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Table B.8. Detailed metrics for the {35 °C - 30 MWh} scenario (multicriteria-optimal scenario).

Parameter	LNCMI	DISS	TES	HP	HS	DHN	SST	GLOB	WHRS
Q^{in} (GWh/year)	0.0	10.9	7.5	7.5	0.0	23.5	23.5	30.7	7.5
W^{in} (GWh/year)	21.6	0.0	0.0	3.7	0.0	0.0	0.0	3.7	3.7
Q^{out} (GWh/year)	18.4	10.9	7.5	11.2	12.3	23.5	23.5	34.4	11.2
E^{in} (GWh _{ex} /year)	21.6	1.0	0.7	4.4	8.7	5.9	5.0	14.1	5.0
E^D (GWh _{ex} /year)	6.0	1.0	0.0	2.0	5.2	0.9	1.4	16.4	2.0
E^{out} (GWh _{ex} /year)	1.6	0.0	0.7	2.4	3.5	5.0	3.7	3.7	3.1
\dot{C}^F (k€/year)	2596.8	158.2	109.0	390.5	982.7	2111.5	2111.5	3579.5	499.5
\dot{Z} (k€/year)	0.0	0.0	440.2	132.1	0.0	0.0	0.0	572.3	572.3
\dot{C}^P (k€/year)	109.0	0.0	549.2	522.5	982.7	2111.5	2111.5	2111.5	1071.8
\dot{C}^D (k€/year)	717.7	158.2	0.7	449.7	589.6	307.0	578.5	2801.5	450.4
RR (€/MWh _{th})	4.6	0.1	18.8	24.7	41.9	0.0	0.0	90.1	43.4
f (%)	-	-	100%	23%	0	0	0	-	56%
r (%)	-	-	407%	106%	0	0	0	-	115%

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