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Competitiveness of renewable energies for heat production in individual housing: A multicriteria assessment in a low-carbon energy market

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26 **Keywords:** 1) Renewable energy; 2) Multicriteria analysis; 3) Techno-economic assessment; 4)
27 Environmental assessment; 5) Space heating; 6) Domestic Hot Water; 7) Solar energy; 8) CO₂ mitigation.

28

29 **Highlights**

30

- 31 • Multicriteria comparison of technical solutions for residential heat production.
- 32 • Energy, exergy, economic, exergoeconomic and environmental indicators.
- 33 • Sensitivity study on solar matching, LCOE and exergy destruction cost.
- 34 • Extended qualitative discussion including more technical and operational criteria.
- 35 • Some grid-driven solutions are competitive (efficient, de-carbonized French grid).

36

NOMENCLATURE

$CAPEX$	Capital expenditure (€)
CC_{CO_2}	Carbon credits earner (€/year)
C^D	Cost of exergy destruction (€)
c_{elec}^{sell}	Selling price of excess electricity from PV panels (€/kWh)
C_{elec}^{excess}	Revenues from excess electricity, produced by PV panels, sold to the grid (€)
c^F	Specific energy cost of fuel (€/kWh)
$\bar{c}^{F,ex}$	Specific exergy cost of fuel (€/kWh)
C^F	Total fuel cost (€)
COP	Coefficient Of Performance of the heat production system (kW_{th}/kW_{el})
CRF	Capital Recovery Factor (-)
En^{in}	Total input energy (kWh)
$En^{in,heat}$	Low-temperature heat contribution in the total input energy (kWh)

$E_n^{in,primary}$	Primary energy contribution in the total input energy (kWh)
$E_n^{in,solar}$	Solar energy contribution in the total input energy (kWh)
Ex^{in}	Total input exergy (kWh)
$Ex^{in,heat}$	Low-temperature heat contribution in the total input exergy (kWh)
$Ex^{in,primary}$	Primary energy contribution in the total input exergy (kWh)
$Ex^{in,solar}$	Solar energy contribution in the total input exergy (kWh)
Ex^{out}	Total output exergy (kWh)
i	Effective rate of economic return
$LCOE$	Levelized cost of energy (€/kWh)
n	System's lifespan (years)
$O\&M$	Operation and maintenance costs (€)
$OPEX$	Operating expenditure (€)
p_{CO_2}	Environmental cost (€/tCO ₂)
PER_{Grid}	Primary energy ratio of the grid (kW _{primary} /kW _{final})
Q^{DHW}	Domestic hot water demand of the dwelling (kWh)
Q^{SH}	Space heating demand of the dwelling (kWh)
SCI	Solar self-consumption index (-)
SPI	Solar self-production index (-)
T_0	Dead state temperature (K)
T_{DHW}	Domestic hot water temperature (K)
T_{SH}	Space heating temperature (K)
T_{Sun}	Surface temperature of the Sun (K)
x^{CO_2}	Specific CO ₂ emission (kg/kWh)
z^{CI}	Specific investment cost (€/kW _{peak})
Greek Symbols	
Δ^{CO_2}	CO ₂ mitigation (tCO ₂ /year)

ε	Exergy efficiency (-)
η	Energy efficiency (-)
θ_{chem}	Exergy factor of chemical fuels input to the grid (-)
ϕ	Maintenance cost factor (-)
φ^{CO_2}	CO ₂ emissions (tCO ₂ /year)
ϕ^{peak}	Thermal or electrical peak power produced by the unit (kW _{peak})

Superscripts

F	Fuel (for exergoeconomic analysis)
grid	French national electric grid
HeatUnit	Heat production unit (boiler/heat pump/solar collector)
P	Product (for exergoeconomic analysis)
panels	Solar panels (photovoltaic/solar thermal)
SH	Space Heating
DHW	Domestic Hot Water

Abbreviations

ASHP	Air-Source Heat Pump
BB	Biomass Boiler
EB	Electric boiler
GFB	Gas-fired boiler
Grid	National electric grid
GSHP	Ground-Source Heat Pump
PV	Solar photovoltaic panels
ST	Solar Thermal collector

40 1. INTRODUCTION

41

42 Nuclear power covers around 11% of global electricity production [1] and roughly 71% of electricity
43 production in France [2]. As a matter of fact, France has the world's highest share of nuclear power in
44 electricity generation [3]. Out of France's 58 nuclear power plants, 37 of them will start ageing within
45 the next 15 years [3]. Retrofitting these plants can prolong their lifetime, but this is only a short-term
46 solution. Moreover, the public's negative opinion on nuclear power [4,5] and issues related to waste
47 disposal [6] heat up the debates on a gradual phase-out of this technology.

48 For a country that relies on nuclear power as strongly as France, a phase-out is a very complex decision.
49 Like many other countries, France is committed to keeping CO₂ emissions as low as possible, and this is
50 enforced by political pressure and carbon taxes. Typical efficiencies of nuclear power plants are
51 comparable to those of fossil fueled power plants (33-37% [7]), and their carbon emissions are lower. As
52 a matter of fact, the inclusion of nuclear in the energy mix has been proposed in some countries that are
53 heavily reliant on fossil fuels [8,9]. From the viewpoint of carbon emissions, it can be tricky to phase out
54 a technology that outperforms other technologies. Renewable sources should be the candidate. But
55 even renewables have their own issues, if they are to cover high shares of energy production. Due to
56 their intermittency, hundreds of GWh of storage batteries would be necessary to match the demands.
57 Their construction would have a non-negligible ecological impact that is yet to be assessed [10].

58 Moreover, a very high economic cost is estimated for substituting nuclear power with renewables.
59 Percebois and Pommeret estimated marginal costs between 5.5 and 16.6 billion euros per year, only to
60 reduce France's nuclear generation from its current 71% to 50% by means of solar-PV and wind power
61 production [10]. They pointed out that a fair share of those costs would come from the need for storage
62 units. Malischek and Trüby estimated marginal costs of 76 billion €₂₀₁₀ for a complete phase-out of

63 nuclear power in France [3], which after scale adjustment is very similar to the estimation from
64 Percebois and Pommeret. Therefore, a large scale substitution of nuclear generation by renewables
65 seems a costly decision, and other opportunities should be explored.

66 In 2019, the residential sector was responsible for roughly 36% (170 TWh) of the final electricity
67 consumption in France, the second highest share in the country [11]. Of those 170 TWh consumed,
68 space heating and domestic hot water accounted for 28% and 12% respectively, i.e. the highest and
69 third highest shares among the different residential usages. This means that residential heat needs
70 totaled 68 TWh of electricity consumed in France in 2019. Thus, it could be stated that if the entire
71 residential heat needs in France were covered by renewable sources, the share of nuclear power in the
72 French energy mix could drop from 380 TWh (70.6%) to 312 TWh (57.9%).

73 Based on the data above, it can be affirmed that the residential sector has a relevant weight for cutting
74 back the French dependence on nuclear power. A massive introduction of renewables in this sector
75 would also reduce the use of other non-renewable systems. According to the French ADEME, in 2014
76 about 57% of residential heating systems in France were gas-fired, while 42% were grid-driven electric
77 boilers [12]. Besides, the residential sector may be the most appropriate for a small scale phase-out. As
78 suggested by Busic-Sontic and Fuerst [13], the diffusion of solar panels in residential districts can be fast,
79 thanks mainly to peer effects. They pointed out that peer effects are stronger in districts where
80 homeowners have a higher conscientiousness and openness to the experience of installing solar panels.

81 Performance of renewable energies in domestic thermal applications depends on several intrinsic and
82 extrinsic factors. For instance, these sources are intermittent and typically mismatched with residential
83 thermal demands. Weather conditions are usually a limiting factor too, tightly bound to the location.
84 The crucial extrinsic factor is the market in which renewable solutions must compete. The high efficiency
85 of nuclear power leads to low revenue requirements on the electricity produced, making any grid-driven
86 solution economically competitive in this country. A comparative assessment between renewable and
87 non-renewable solutions needs to account for several criteria.

88 In the literature, the advantages of renewable sources have been proven in front of fossil-fueled
89 national energy grids. However, the French grid has a high share of non-carbon electricity. The main
90 novelty of this study is evaluating the potential competitiveness of renewable-driven solutions against a
91 highly decarbonized national energy grid. Since many countries are evolving towards low-carbon
92 electricity, the case of France is relevant to future conditions for those countries.

93 Many existing studies in the literature investigate different types of heat production systems which
94 could be used in residential heating applications. Esen et al. [14] evaluated and compared a ground-
95 source heat pump (GSHP) system to conventional heating mechanisms such as electric resistance, fuel
96 oil, liquid petrol gas, coal, diesel oil and natural gas for space heating. The GSHP system was reported to
97 have a lower annualized lifecycle cost, i.e. economically favorable, when compared to all the considered
98 systems except natural gas heating. Furthermore, GSHP systems were found preferable to air-source
99 heat pump (ASHP) systems, as a result of a higher coefficient of performance (COP) and lower
100 annualized lifecycle cost [15].

101 Ayadi and Al-Dahidi [16] compared the performance of solar thermal and solar PV systems for space
102 heating, space cooling and domestic hot water production in 5 different climatic regions. The study
103 proposed a systematic methodology for comparing the solar systems with multiple combinations of
104 conventional systems: a reversible heat pump, an air-to-water heat pump, a diesel-fired hot water
105 boiler, an electrically-driven vapour compression chiller, and combined cooling heat and power (CCHP).
106 The comparison was done in terms of primary energy savings and Levelized Cost Of Energy (LCOE). Their
107 results showed that both the solar thermal solution and the solar PV solution reduce primary energy
108 consumption and the LCOE with respect to the most efficient reference system. Nevertheless, the solar
109 PV solution outperformed the solar thermal solution. They also point out that DHW demands represent
110 a significant share of total energy consumption of buildings (7% - 15%). They state that a solar thermal
111 system designed to meet both heating and DHW demands maximizes the utilization of the collected
112 solar energy and improves the non-renewable primary energy ratio.

113 Sustar et al [17] compared the performance of a solar combisystem (for heating and DHW) and a solar
114 water heater. It was found that the combisystem led to more savings than the solar water heater,
115 thanks to providing space heating in addition to DHW production. It was also found that the incremental
116 savings supplied by the combisystem as compared to the solar water heater were 0.5%, 7% and 18.6%
117 for collector areas of 3 m², 6 m² and 9 m² respectively, i.e. they increased with collector area. The study
118 also found out that the incremental savings were highly sensitive to the shares of DHW loads and space
119 heating loads. Highest savings occurred when the shares of DHW demands were low.

120 Lohani and Schmidt [18] compared the energy and exergy performances of a fossil plant heating system,
121 an air source heat pump heating system and a ground source heat pump heating system. In their results,
122 the ground source heat pump outperformed the two other systems. Specifically, the ground source heat
123 pump had roughly 25% less demand of absolute primary energy and exergy, and about 50% higher
124 overall primary COP than the conventional system. The study also found that, although the energy flow
125 in the building was the biggest of the energy chain, the biggest exergy losses occurred in the energy
126 conversion systems, rather than in the building itself. This shows why exergy analysis is very important
127 to get more insight of these processes.

128 Saloux et al [19] compared a solar assisted heat pump and a PV-driven ambient air heat pump through
129 energy, economic and exergoeconomic analysis. It was found that the ambient air heat pump is optimal
130 from energy and economic perspectives, while the solar assisted heat pump provided the best exergy
131 performance. The study puts a special focus on the exergoeconomic analysis, by differentiating between
132 renewable and non-renewable exergy flows/destructions. The optimization led to different optimal
133 solutions if the energy or the exergy criteria were followed. Moreover, different optimal solutions were
134 found if exergy destruction of non-renewable energy flows was used as criteria instead of total exergy
135 destruction. The authors concluded that the choice of performance indicators is important and can
136 change the configuration of the optimal system, especially with exergy indicators.

137 Tolga Balta [20] carried out an exergetic cost and sustainability assessment of 3 different low exergy
138 heating systems. The options were a standard boiler driven by fuel-oil, a condensing boiler driven by
139 natural gas, and an air heat pump driven by electricity. Results from the study pointed out that the
140 condensing boiler driven by natural gas was the most cost-effective system, due to the low costs of
141 natural gas with respect to fuel-oil and electricity.

142 Most of the studies in the literature cover either a large range of different solutions, or a large range of
143 performance criteria. In order to enrich the discussion, we propose here a multicriteria study on a total
144 of 9 different solutions for heating and DHW production, based on 5 different performance criteria. Six
145 heat production units were considered: gas-fired boilers, electric boilers, biomass boilers, solar thermal
146 collectors, air source heat pumps and ground source heat pumps. We also consider the possibility of
147 running the heat pumps and the electric boiler with either the grid or PV panels. This gave a total of 9
148 different solutions under study.

149 A few other multicriteria studies exist in literature for renewable-based domestic heating. Some of them
150 focus on a specific system, like the study from Chen et al [21], which focuses on a hybrid ground source
151 heat pump system integrated with concentrated photovoltaic thermal solar collectors. Other
152 multicriteria analyses use a comparative approach like ours, typically focusing on technical, economic
153 and environmental indicators, like the study from Yang et al on several renewable energy home heating
154 technologies, including boilers, heat pumps and solar collectors among others [22]. Other multicriteria
155 comparative studies use the aforementioned criteria and include social and usability criteria, too, like
156 the study from Kontu et al [23] on several systems, including electric heating, biomass boilers, pellet
157 boilers and ground source heat pumps, among others. In addition to energy, economy and environment,
158 our study includes the exergy and exergoeconomic criteria, in order to assess thermodynamic
159 irreversibilities and the associated costs. We also analyze the influence of extrinsic factors, such as
160 production/consumption mismatch, market prices or the possibility of selling excess PV-electricity to the
161 national grid. After the 5-criteria and sensitivity analyses, we discuss other factors qualitatively

162 (technical, operational, climatic...), and opportunities for further breakthrough of renewable-based
163 solutions.

164 The first stage of this study consisted in determining the self-production and self-consumption indices of
165 solar thermal collectors and photovoltaic panels. To this end, annual profiles were defined (Section 2.2)
166 for space heating and domestic hot water needs of a single dwelling in the city of Chambéry (France).
167 Based on the maximum instantaneous demands, the sizing was determined for each type of panel,
168 taking into account the use of an electric boiler or a heat pump for PV-driven solutions. Along with all
169 this information, relevant economic data were retrieved for the different systems in the French energy
170 market. After this stage of modeling and data gathering, performance analyses were applied solution by
171 solution through 5 different criteria (Section 2.3): energy, exergy, economy, exergoeconomy and
172 environment. This allowed to compare the solutions quantitatively in the nominal scenario (Section 3.1).
173 That comparison was explored further for the economic and exergoeconomic criteria, by the mean of a
174 sensitivity analysis with respect to investment costs and fuel costs (Section 3.2). This allowed to
175 compare the solutions in other favorable/unfavorable scenarios, all of them relevant to the French
176 energy market. At this point, and to close the study as comprehensively as possible, a qualitative
177 discussion was pursued (Section 4) covering several parameters, factors and constraints not accounted
178 for in the quantitative analysis. Finally, the major conclusions of this study were reported qualitatively
179 (Section 5).

180

181 **2. MATERIALS AND METHOD**

182 This study assesses and compares yearly performance of several solutions that aim to satisfy space
183 heating and domestic hot water production in a residential dwelling. Some of the proposed solutions
184 consist in a single unit that produces heat directly, while others are an assembly of a power production
185 unit with a power-to-heat conversion unit. For the sake of a fair comparison, all solutions were

186 evaluated against exactly the same heat load. Then, the required energy inputs for each system were
 187 determined upstream, by means of their operating parameters. As stated in the Introduction, a
 188 multicriteria comparison was deemed appropriate to compare the systems. Five indicators were used:
 189 energy efficiency, exergy efficiency, Levelized Cost Of Energy, exergy destruction cost and CO₂
 190 mitigation. The following subsections offer details on how the scenario was modeled.

191

192 2.1. Systems

193 The study includes the most commonly used heat production systems for individual residential dwellings
 194 (Table 1). The most common types of boilers in the French residential sector are gas-fired boilers and
 195 electric boilers (the latter connected to the electric grid). Biomass boilers were considered as direct
 196 competitors. In addition, air source and ground source heat pumps were considered as competitors to
 197 the electric boiler. For every electric-driven heat production system, PV panels were evaluated as
 198 competitors to the electric grid. Lastly, solar thermal collectors (ST) were also considered. This led to a
 199 total of 9 different solutions, encompassing both renewable and non-renewable sources. Due to
 200 temporal mismatch, the systems driven by the solar resource use the electric grid as a backup.

201

Table 1. Systems considered in this study.

Heating solution (acronym)	System(s)	Temporal mismatch	Backup
GFB	Gas-Fired Boiler (GFB)	No	-
BB	Biomass Boiler (BB)	No	-
Grid + EB	National electric grid (Grid) + Electric Boiler (EB)	No	-
PV + EB	Photovoltaic panels (PV) + Electric Boiler (EB)	Yes	Grid + EB
Grid + ASHP	National electric grid (Grid) + Air Source Heat Pump (ASHP)	No	-
PV + ASHP	Photovoltaic panels (PV) + Air Source Heat Pump (ASHP)	Yes	Grid + ASHP
Grid + GSHP	National electric grid (Grid) + Ground Source Heat Pump (GSHP)	No	-
PV + GSHP	Photovoltaic panels (PV) + Ground Source Heat Pump (GSHP)	Yes	Grid + GSHP
ST	Solar Thermal collectors (ST)	Yes	Grid + EB

202

203 Table 2 presents the technical and economic parameters considered for each system. The self-
 204 production indices (SPI) and the self-consumption indices (SCI) were estimated from the area of panels,
 205 solar irradiation data for the city of Chambéry (France), and the demand profiles (refer to section 2.2).
 206 Further, the amount of CO₂ emitted (kg/kWh) from the grid was evaluated considering the shares of gas,
 207 coal and fuel oil in the French energy mix (7.7%, 1.8% and 0.7%, respectively [24]) and the respective
 208 carbon emissions from each of these sectors [25]. The dead state temperature (T_0) for exergy analysis is
 209 set to the reference temperature for Chambéry [26].

210

211

Table 2. Technical and economic parameters unit by unit.

Unit	Parameter	Value	Units	Source
Gas-fired boiler (GFB)	Energy efficiency (η)	90	%	[12,27]
	Maintenance factor (ϕ)	10	%	[28]
	Economic lifespan (n)	15	years	[12,28]
	Specific investment cost (z^{CI})	344	€/kWpeak	[12,29]
	Specific fuel cost (c^F)	0.074	€/kWh	[12,29]
	CO ₂ emitted (x_{CO_2})	0.38	kg/kWh	[30]
Biomass boiler (BB)	Energy efficiency (η)	90	%	[12,27]
	Maintenance factor (ϕ)	10	%	[12,28]
	Economic lifespan (n)	15	years	[12,28]
	Specific investment cost (z^{CI})	350	€/kWpeak	[12,29]
	Specific fuel cost (c^F)	0.058	€/kWh	[12,29]
	CO ₂ emitted (x_{CO_2})	0.035	kg/kWh	[30]
National electric grid (Grid)	Primary energy ratio (PER_{Grid})	2.58	kWprimary/kWfinal	[31]
	Maintenance factor (ϕ)	10	%	[28]
	Economic lifespan (n)	25	years	[28]
	Specific investment cost (z^{CI})	0	€/kWpeak	Assumed
	Specific fuel cost (c^F)	0.050	€/kWh	[12,29,32]
	CO ₂ emitted (x_{CO_2})	0.056	kg/kWh	[24,25]
Solar photovoltaic panels (PV)	Specific peak production (ϕ^{peak})	0.15	kW_elec_peak/m ²	Section 2.2
	Energy efficiency (η)	15	%	[33]
	Self-consumption, heating (SCI^{SH})	49	%	Section 2.2
	Self-consumption, DHW (SCI^{DHW})	87	%	Section 2.2

	Self-production, heating (SPI^{SH})	25	%	Section 2.2
	Self-production, DHW (SPI^{DHW})	43	%	Section 2.2
	Maintenance factor (ϕ)	2	%	[28]
	Economic lifespan (n)	25	years	[28]
	Specific investment cost (z^{CI})	3110	€/kWpeak	[32]
	Specific fuel cost (c^F)	0	€/kWh	[32]
	Excess electricity sell price (c_{elec}^{sell})	0.10	€/kWh	[32]
	CO ₂ emitted (x_{CO_2})	0	kg/kWh	Hypothesis
Electric boiler (EB)	Maintenance factor (ϕ)	10	%	[28]
	Economic lifespan (n)	15	years	[28]
	Specific investment cost (z^{CI})	188	€/kWpeak	[12,29]
	Specific fuel cost (c^F)	0.130 (Grid)	€/kWh	[12,29]
		0 (Solar)	€/kWh	[32]
	CO ₂ emitted (x_{CO_2})	0 (Solar-source)	kg/kWh	Hypothesis
		0.056 (Grid-source)	kg/kWh	[24,25]
Air source heat pump (ASHP)	COP for space heating (COP^{SH})	3	kWh/kWh	[34]
	COP for DHW production (COP^{DHW})	2	kWh/kWh	[34]
	Maintenance factor (ϕ)	10	%	[28]
	Economic lifespan (n)	17	years	[28]
	Specific investment cost (z^{CI})	1250	€/kWpeak	[12,29]
	Specific fuel cost (c^F)	0.130 (Grid)	€/kWh	[12,29]
		0 (Solar)	€/kWh	[32]
	CO ₂ emitted (x_{CO_2})	0 (Solar-source)	kg/kWh	Hypothesis
		0.056 (Grid-source)	kg/kWh	[24,25]
Ground source heat pump (GSHP)	COP for space heating (COP^{SH})	4	kWh/kWh	[35]
	COP for DHW production (COP^{DHW})	3	kWh/kWh	[35]
	Maintenance factor (ϕ)	10	%	[28]
	Economic lifespan (n)	17	years	[12,29]
	Specific investment cost (z^{CI})	1400	€/kWpeak	[12]
	Specific fuel cost (c^F)	0.130 (Grid)	€/kWh	[12,29]
		0 (Solar)	€/kWh	[32]
	CO ₂ emitted (x_{CO_2})	0 (Solar-source)	kg/kWh	Hypothesis
		0.056 (Grid-source)	kg/kWh	[24,25]
Solar thermal collectors (ST)	Specific peak production (ϕ^{peak})	0.8	kW _{heat_peak} /m ²	Section 2.2
	Energy efficiency (η)	80	%	[12,27,32]
	Self-consumption, heating (SCI^{SH})	34	%	Section 2.2
	Self-consumption, DHW (SCI^{DHW})	61	%	Section 2.2

	Self-production, heating (SPI^{SH})	31	%	Section 2.2
	Self-production, DHW (SPI^{DHW})	55	%	Section 2.2
	Specific investment cost (z^{CI})	1060	€/kWpeak	[32]
	Specific fuel cost (c^F)	0	€/kWh	[32]
	Maintenance factor (ϕ)	2	%	[28]
	Economic lifespan (n)	20	years	[28]
	CO ₂ emitted (x_{CO_2})	0	kg/kWh	Hypothesis
All	Dead state temperature (T_0)	262.15	K	[26]
	Domestic Hot Water temperature (T_{DHW})	338	K	[26]
	Space heating temperature (T_{SH})	308	K	[26]
	Sun's surface temperature (T_{Sun})	5773	K	[33]
	Exergy factor of chemical fuels (θ_{chem})	1	-	[28]
	Effective rate of economic return (i)	3	%	[28]

212

213 2.2. Load profiles and solar matching indices

214

215 A dwelling of 120 m² and built after 2012 was assumed in the H1 Zone, i.e. the RT2012 climatic zone for
 216 Chambéry (France). The dwelling's profiles of thermal demand were calculated through data from the
 217 PHEBUS investigation [36] and from the French ADEME's report on the topic [37]. An hourly profile of
 218 solar irradiation was retrieved from the PVGIS-SARAH database [38] for the year 2016. The latitude and
 219 longitude were 45,567 and 5,922 decimal degrees, respectively. The elevation was 282 m, the slope was
 220 35 degrees (optimum) and the azimuth was 1 degree (optimum).

221 Figures 1a and 1b present samples of the resulting hourly profiles for one winter day and one summer
 222 day, respectively. The total yearly demand was quantified at 2872 kWh for DHW production, and 2232
 223 kWh for space heating. The peak thermal demand (heating + DHW production) was quantified at 1.35
 224 kW.

225

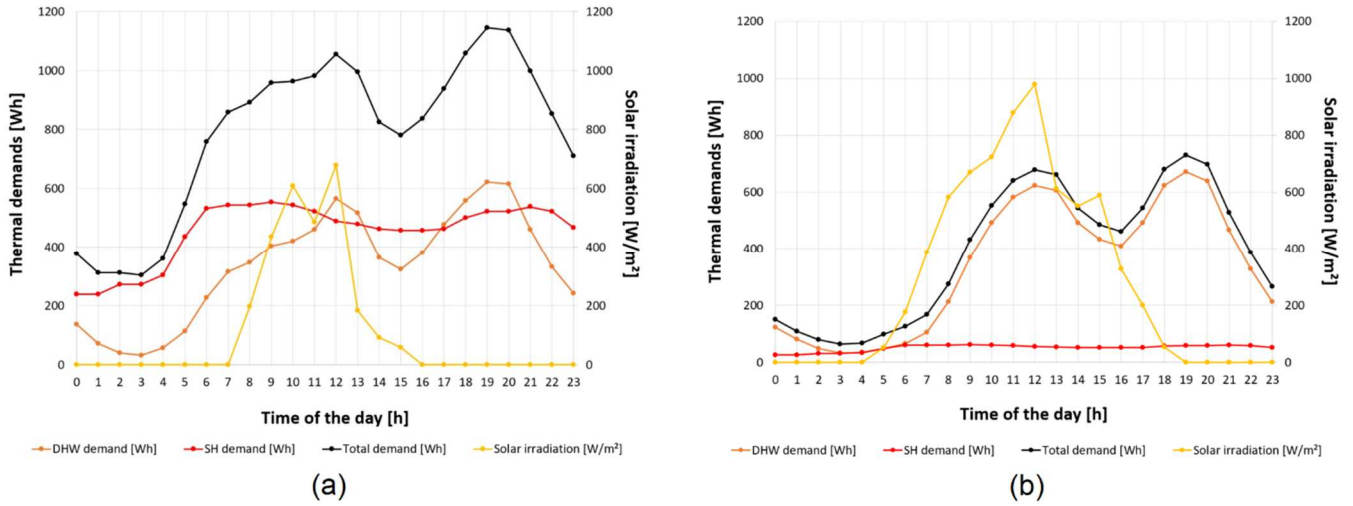


Figure 1. (a) Hourly solar irradiation and thermal needs in one winter day (15th of January). (b) Hourly solar irradiation and thermal needs in one summer day (15th of July).

226

227 Production/consumption temporal mismatch is a classic issue in systems driven by renewable energies.

228 To account for this phenomenon properly, hourly profiles were used in the assessment. It is visible on

229 the profiles given in Figure 1 that the production of solar systems will be partially mismatched with the

230 dwelling's needs. In order to quantify solar matching, the Self-Production Index (*SPI*) and the Self-

231 Consumption Index (*SCI*) were used. Both indicators assess the energy demands covered by the

232 renewable system (Q^{match}), but the *SPI* (eq. 1) compares them to the total demands (Q^{demand}) while

233 the *SCI* (eq. 2) compares them to the system's total production (Q^{prod}).

$$234 \quad SPI = \frac{Q^{match}}{Q^{demand}} \quad (1)$$

$$235 \quad SCI = \frac{Q^{match}}{Q^{prod}} \quad (2)$$

236 Figure 2 shows the evolution of the solar self-production and self-consumption indices as a function of

237 the annual thermal energy generation ratio.

238

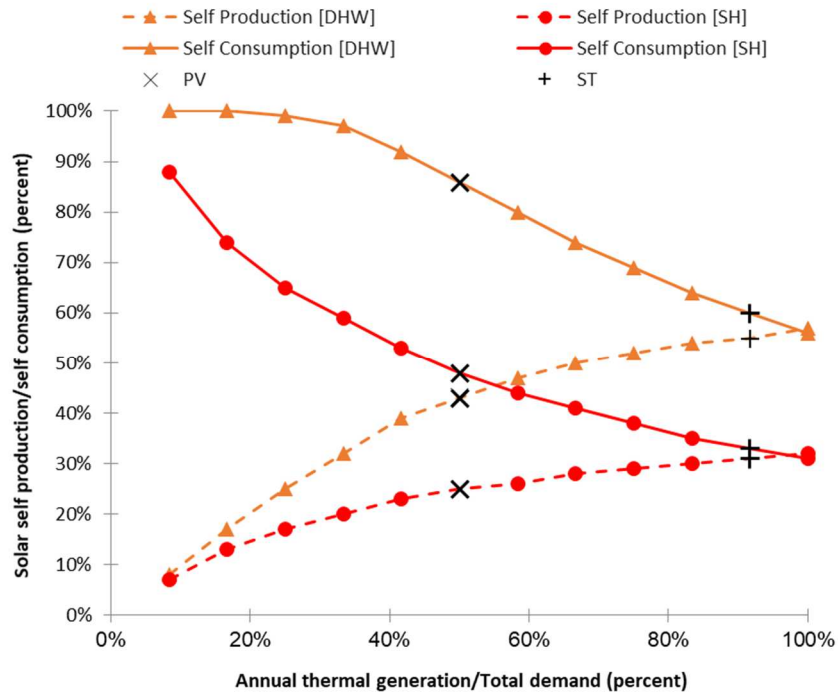


Figure 2. Sensitivity analysis of self-production and self-consumption indices.

239 The annual thermal energy generation ratio is defined as a ratio of the panels' yearly energy production
 240 to the total annual heating demand (in percent). The value 100% does not mean that the system is self-
 241 sufficient since it leads to overproduction in summers and during peak sunshine hours and
 242 underproduction during winters and non-sunshine hours. Moreover, as the annual thermal generation
 243 ratio increases, the required solar panel area, peak power and the cost would also increase. Therefore,
 244 the aim of a good solar panel sizing is to achieve the maximum possible self-production and self-
 245 consumption, without significantly escalating the investment cost. It is interesting to note that for a
 246 given annual thermal energy generation ratio, the required panel area (and consequently, peak power)
 247 would be the highest for PV + electric boiler, followed by PV + ASHP and PV + GSHP. This is due to the
 248 difference in COPs, wherein the GSHP has the highest COP. Further, the ST panels require the lowest
 249 area, among all the solar panel-based systems, owing to the highest energy efficiency (i.e. 80%). For the
 250 sake of analysis, the indices are dissociated into space heating and domestic hot water production.
 251 Low energy production ensures that most of it is consumed, granting high self-consumption indices.
 252 Such high self-consumption can in fact make PV systems profitable [39,40], even in the absence of

253 regulatory support policies for them [41]. On the other hand, it causes low self-production indices with
254 respect to the dwelling's needs. Increasing the self-production only comes at the cost of a high drop in
255 self-consumption. It can also be observed that indices for domestic hot water production are better
256 than for space heating. The reason is simple: space heating is needed mostly in the evening/night and
257 more predominantly in winters, when solar irradiation is not available. On the other hand, domestic hot
258 water may be needed at any time of the day, in any season of the year. Hence, the demand profile of
259 domestic hot water facilitates solar matching. In the present study, peak power sizing method has been
260 utilized to determine the required area of solar panels (in order to meet the dwelling's peak hourly
261 demand over the year) and consequently, the self-production and self-consumption indices. The self-
262 production and self-consumption indices, thus obtained, for both PV (marked as ×) and ST (marked as +)
263 panels are highlighted in Figure 2. With the sizing rules used, the peak electric productions of the solar
264 PV panels were estimated at: 1.78 kWp to run the electric boiler; 0.76 kWp to run the air source heat
265 pump; and 0.53 kWp to run the ground source heat pump. The peak thermal production of the ST
266 collectors was estimated at 3.2 kWp. These values are used for the nominal scenario presented below.

267

268 **2.3. Performance criteria**

269 For each system, 5 criteria were assessed: overall energy efficiency (η), overall exergy efficiency (ϵ),
270 Levelized Cost Of Energy (*LCOE*), cost of exergy destruction (C_D) and CO₂ mitigation (Δ^{CO_2}). The evaluation
271 of each criterion is developed in the following paragraphs.

272

273 **2.3.1 Energy criteria**

274 All solutions were evaluated with respect to the same residential demands, i.e. space heating (Q^{SH}) and
275 domestic hot water (Q^{DHW}) demands. The overall energy input (En^{in}) was determined for every system

276 through an overall energy balance (eq. 3a). The balance accounted for the inlets, outlets and losses. The
 277 losses ($\sum En^{loss}$) were determined (eq. 3b) through the system overall efficiency (η).

$$278 \quad En^{in} = Q^{SH} + Q^{DHW} + \sum En^{loss} \quad (3a)$$

$$279 \quad \text{With } En^{loss} = En^{in} \cdot (1 - \eta) \quad (3b)$$

280 The system's energy efficiency (η , eq. 4) is the ratio of its useful output to its total energy input. For the
 281 biomass and gas-driven boilers, this first criterion is straightforward and presented in Table 2.

$$282 \quad \eta = \frac{Q^{SH} + Q^{DHW}}{En^{in}} \quad (4)$$

283 The energy input (En^{in} , eq. 5) may include a solar contribution if the system includes solar panels
 284 ($En^{in,solar}$), a primary energy contribution if the system is connected to the electric grid ($En^{in,primary}$),
 285 and an environmental, low-temperature heat input if the system includes a heat pump ($En^{in,heat}$).

$$286 \quad En^{in} = En^{in,solar} + En^{in,primary} + En^{in,heat} \quad (5)$$

287 Calculation of the solar contribution proceeds only if the solution includes solar panels. In the rest of
 288 cases, the solar contribution is null. The solar contribution ($En^{in,solar}$, eq. 6a) depends on the energy
 289 issued by the panels for the purposes of heating ($En^{panels,SH}$, eq. 6b) and DHW production
 290 ($En^{panels,DHW}$, eq. 6c). It also depends on the solar panels efficiency (η^{panels}). The energy issued by the
 291 panels depends on their self-production index (SPI) and their self-consumption index (SCI). Refer to
 292 subsection 2.2 for the calculation of the SPI and the SCI . If solar thermal collectors are used, the energy
 293 issued is heat. If PV panels are used, the energy issued is electricity and the calculation requires the COP
 294 of the electricity-to-heat conversion unit. Different COP values were assumed for the purposes of space
 295 heating (COP^{SH}) and DHW production (COP^{DHW}). Note that for the electric boiler, the COP is 1. No
 296 thermal storage or electric batteries were assumed in this study.

$$297 \quad En^{in,solar} = \frac{1}{\eta^{panels}} \cdot (En^{panels,SH} + En^{panels,DHW}) \quad (6a)$$

$$298 \quad En^{panels,SH} = \begin{cases} Q^{SH} \cdot \frac{SPI_{ST}^{SH}}{SCI_{ST}^{SH}} & (\text{with } ST \text{ collectors}) \\ \frac{Q^{SH}}{COP^{SH}} \cdot \frac{SPI_{PV}^{SH}}{SCI_{PV}^{SH}} & (\text{with } PV \text{ panels}) \end{cases} \quad (6b)$$

$$299 \quad En^{panels,DHW} = \begin{cases} Q^{DHW} \cdot \frac{SPI_{ST}^{DHW}}{SCI_{ST}^{DHW}} & (\text{with } ST \text{ collectors}) \\ \frac{Q^{DHW}}{COP^{DHW}} \cdot \frac{SPI_{PV}^{DHW}}{SCI_{PV}^{DHW}} & (\text{with } PV \text{ panels}) \end{cases} \quad (6c)$$

300 Excess electricity produced by PV panels was also assessed (W_{PV}^{excess} , eq. 7). It increases if the self-
 301 consumption indexes decrease. Determining this excess electricity is relevant for the economic analysis.
 302 Indeed, excess electricity is sold to the national Grid, generating some additional revenues (refer to
 303 subsection 2.3.3).

$$304 \quad W_{PV}^{excess} = En_{PV}^{panels,SH} \cdot (1 - SCI_{PV}^{SH}) + En_{PV}^{panels,DHW} \cdot (1 - SCI_{PV}^{DHW}) \quad (7)$$

305 All solutions in this study require some input of primary energy, even solar-driven solutions (due to
 306 temporal mismatch). The primary energy input ($En^{in,primary}$, eq. 8a) refers to the grid's energy inlet in
 307 order to produce electricity. This input depends on the electricity issued by the Grid for the purposes of
 308 space heating ($W^{Grid,SH}$, eq. 8b) and domestic hot water production ($W^{Grid,DHW}$, eq. 8c). The primary
 309 energy input evolves conversely to the solar self-production index (SPI), because the Grid is a backup for
 310 solar-driven systems. It also depends on the COP of the electricity-to-heat conversion system.

$$311 \quad En^{in,primary} = PER_{Grid} \cdot (W^{Grid,SH} + W^{Grid,DHW}) \quad (8a)$$

$$312 \quad W^{Grid,SH} = \frac{Q^{SH}}{COP^{SH}} \cdot (1 - SPI^{SH}) \quad (8b)$$

$$313 \quad W^{Grid,DHW} = \frac{Q^{DHW}}{COP^{DHW}} \cdot (1 - SPI^{DHW}) \quad (8c)$$

314 Calculation of the low-temperature heat input ($En^{in,heat}$, eq. 9a) proceeds only if the solution includes a
 315 heat pump. The heat pump's heat input was assessed for the purposes of space heating ($Q_{HP}^{in,SH}$, eq. 9b)

316 and domestic hot water production ($Q_{HP}^{in,DHW}$, eq. 9c). Each input depends on the heat pump's COP for
 317 that application.

$$318 \quad En^{in,heat} = Q_{HP}^{in,SH} + Q_{HP}^{in,DHW} \quad (9a)$$

$$319 \quad Q_{HP}^{in,SH} = Q^{SH} \cdot \left(1 - \frac{1}{COP^{SH}}\right) \quad (9b)$$

$$320 \quad Q_{HP}^{in,DHW} = Q^{DHW} \cdot \left(1 - \frac{1}{COP^{DHW}}\right) \quad (9c)$$

321 It was assumed that the GSHP runs in reverse mode whenever heat is not needed, in order to
 322 regenerate the ground's heat. Since there are summer periods where neither heating nor DHW are
 323 needed, the GSHP can cover domestic hot water demands even in summer.

324

325 **2.3.2 Exergy criteria**

326 An overall exergy balance (eq. 10a) was applied to each solution by accounting for exergy inlets (Ex^{in}),
 327 outlets (Ex^{out}) and overall destructions ($\sum Ex^D$). Overall destructions were assessed through the inlets
 328 and the system exergy efficiency (eq. 10b). The main utility of the overall exergy balance was to
 329 determine exergy destruction. It was required for calculating the exergy destruction costs in the
 330 exergoeconomic assessment (refer to subsection 2.3.4).

$$331 \quad Ex^{in} = Ex^{out} + \sum Ex^D \quad (10a)$$

$$332 \quad \text{With } \sum Ex^D = Ex^{in} \cdot (1 - \varepsilon) \quad (10b)$$

333 Exergy efficiency (ε) was assessed similarly to energy efficiency (eqs. 11 and 13a), by previously
 334 converting every energy flow to an exergy flow. Thus, every heat flow was multiplied by its exergy factor
 335 (eq. 12), which depends on its temperature (i.e. $1 - T_0/T$). The solar input was treated as a heat flow
 336 too (eq. 13b), although coming from a source at such high temperature (T_{sun}) that its exergy factor nears
 337 1 (refer to Table 2). In order to keep thermodynamic consistency, the same dead state temperature (T_0)

338 was assumed for every flow, and its value was kept constant throughout the year [42]. The selected
 339 value was -11 °C, which corresponds to the reference temperature used in the French building code
 340 RT2012 [26]. Primary energy was assumed as chemical energy, thus with an exergy factor set to $\theta_{chem} =$
 341 1.

$$342 \quad \varepsilon = \frac{Ex^{out}}{Ex^{in}} \quad (11)$$

$$343 \quad Ex^{out} = Q^{SH} \cdot \left(1 - \frac{T_0}{T_{SH}}\right) + Q^{DHW} \cdot \left(1 - \frac{T_0}{T_{DHW}}\right) \quad (12)$$

$$344 \quad Ex^{in} = Ex^{in,solar} + Ex^{in,primary} + Ex^{in,heat} \quad (13a)$$

$$345 \quad Ex^{in,solar} = En^{in,solar} \cdot \left(1 - \frac{T_0}{T_{Sun}}\right) \quad (13b)$$

$$346 \quad Ex^{in,primary} = En^{in,primary} \quad (13c)$$

$$347 \quad Ex^{in,heat} = En^{in,heat} \cdot \left(1 - \frac{T_0}{T_{heat}}\right) \quad (13d)$$

348 Including the exergy efficiency as criteria helps choose the system that implies less degradation of the
 349 available energy. The interest of this criterion is to account for the thermodynamic value of energy
 350 flows, independently of other factors like their availability or their costs.

351

352 **2.3.3 Economic criteria**

353 Total costs of each solution were determined through a techno-economic balance (eq. 14). It comprises
 354 capital expenditures (*CAPEX*) and operating expenses (*OPEX*). The *CAPEX* (eq. 15a) are the sum of
 355 investment costs of all units, transformed into annuities by means of the Capital Recovery Factor (*CRF*,
 356 eq. 15b). The investment cost of a unit is a function of the peak power ϕ^{peak} (thermal or electric) to be
 357 produced by the unit. The *OPEX* (eq. 16a) considers fuel costs (eq. 16b), and operation and maintenance
 358 costs (*O&M*), expressed as a fraction (ϕ) of the *CAPEX* (eq. 16c). If the system includes PV panels, the

359 revenues from selling excess electricity to the grid (C_{elec}^{excess} , eq. 16d) are discounted from the operating
 360 expenses.

$$361 \quad C^{TOT} = CAPEX + OPEX \quad (14)$$

$$362 \quad CAPEX = \sum z^{CI} \cdot \phi^{peak} \cdot CRF \quad (15a)$$

$$363 \quad CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \quad (15b)$$

$$364 \quad OPEX = C_{fuel} + O\&M - C_{elec}^{excess} \quad (16a)$$

$$365 \quad C_{fuel} = c^F \cdot (Q^{SH} + Q^{DHW}) / \eta \quad (16b)$$

$$366 \quad O\&M = \phi \cdot CAPEX \quad (16c)$$

$$367 \quad C_{elec}^{excess} = c_{elec}^{sell} \cdot W_{PV}^{excess} \quad (16d)$$

368 The Levelized Cost Of Energy (LCOE, eq. 17) was used as economic indicator. This indicator determines
 369 the product's price (heat in this case) in order to recover the overall system costs.

$$370 \quad LCOE = \frac{C^{TOT}}{Q^{SH} + Q^{DHW}} \quad (17)$$

371

372 **2.3.4 Exergoeconomic criteria**

373 The overall exergoeconomic balance on a system is the same as the techno-economic balance, but
 374 expressed on an exergy costing basis (eq. 18). Exergy costing means that the inputs and outputs are
 375 computed in exergy (Ex^{in} and Ex^{out}), with their specific exergy costs ($\bar{c}^{F,ex}$ and $\bar{c}^{P,ex}$). The rest of the
 376 components are the same as in the techno-economic balance. The main utility of the exergoeconomic
 377 balance is to determine product costs of each component, which become the fuel costs of other
 378 downstream components.

$$379 \quad \bar{c}^{P,ex} \cdot Ex^{out} = CAPEX + \bar{c}^{F,ex} \cdot Ex^{in} + O\&M - C_{elec}^{excess} \quad (18)$$

380 The exergy destruction cost C^D was used as exergoeconomic indicator (eq. 19). This indicator determines
 381 the operating expenditures related to the system's thermodynamic inefficiencies. For each system,
 382 equation 15 was applied unit by unit and C^D was assessed for each unit and then for the global system
 383 (the sum of all units).

$$384 \quad C^D = \bar{c}^{F,ex} \cdot E^D \quad (19)$$

385 For each unit, the specific exergy cost of fuel ($\bar{c}^{F,ex}$) was derived from the total fuel costs C^F and the
 386 total exergy input Ex^{in} (eq. 20). For those units that receive several inputs of energy, the average fuel
 387 cost is the weighted average of the costs of all inputs, following the F-Principle described in the SPECO
 388 method (SPecific Exergy COsting) [43]. It is also affected indirectly by the systems' exergy efficiencies.
 389 Note that investment costs are taken into account implicitly, since investment on a unit increases the
 390 price of its product, and that product is the fuel of other units downstream in the process. Accordingly,
 391 the C^D of solar panels is 0 because their fuel (solar irradiation) is cost-free.

$$392 \quad \bar{c}^{F,ex} = \frac{\sum C^F}{\sum Ex^{in}} \quad (20)$$

393 Accounting for exergy destruction costs helps choose the system that implies less economic losses due
 394 to degradation of the available energy. Since this criterion focuses on the costs of sources (eq. 15), solar-
 395 driven systems have a theoretical advantage (cost-free source). Still, overall performance in this
 396 criterion depends on other factors like source availability, or the intrinsic efficiency of the
 397 production/conversion systems. Thus, it is difficult to predict whether solar-driven systems will
 398 outperform grid-driven systems straightforwardly.

399

400 **2.3.5 Environmental criteria**

401 For the environmental assessment, the net CO₂ mitigation (Δ^{CO_2}) for each of the 9 considered solutions
 402 was evaluated compared to a gas-fired boiler, i.e. the solution with the highest CO₂ emissions.

$$403 \quad \Delta^{CO_2} = \varphi_{GFB}^{CO_2} - \varphi^{CO_2} \quad (21)$$

404 where, $\varphi_{GFB}^{CO_2}$ and φ^{CO_2} represent the CO₂ emissions from the gas-fired boiler and the analyzed system,
 405 respectively.

406 The CO₂ emissions (φ^{CO_2}) were obtained as (in tonnes):

$$407 \quad \varphi^{CO_2} = \begin{cases} \left[\frac{1}{1-L_{td}} \right] \left[\frac{1}{1-L_a} \right] \frac{x^{CO_2}}{1000} \cdot \frac{En^{in,primary}}{PER_{Grid}} & \text{(grid, including backup requirements)} \\ \frac{x^{CO_2}}{1000} \cdot [Q^{SH} + Q^{DHW}] & \text{(gas – fired/biomass boiler)} \end{cases} \quad (22)$$

408 where, L_{td} and L_a are the transmission and distribution losses, and appliance losses, respectively, and

409 x_{CO_2} (in kg/kWh) is the amount of CO₂ emitted per kWh of energy produced (Table 2) [30]. L_{td} and L_a

410 were assumed to be 40% and 20%, respectively [44,45]. It should be noted that $\frac{En^{in,primary}}{PER_{Grid}}$ represents the

411 total electricity produced by the grid (in kWh).

412 Subsequently, the carbon credits earned (€/year) can be computed, as an enviro-economic indicator,

413 from the CO₂ mitigation using the relation given below.

$$414 \quad CC_{CO_2} = p_{CO_2} \cdot \Delta^{CO_2} \quad (23)$$

415 where, p_{CO_2} represents the environmental cost (€/tCO₂). The value of p_{CO_2} can range from 13\$/tCO₂ to

416 16\$/tCO₂ [46]. Mostly, an average value of 14.5 \$/tCO₂ is adopted by researchers [44,45,47]. In the

417 present study, we do not consider the enviro-economic aspect (CC_{CO_2}) and focus on the environmental

418 indicator i.e. CO₂ mitigation (Δ^{CO_2}).

419

420 3. RESULTS

421 This section includes analytic descriptions of results in this study. Any further discussions on the
 422 implications of these results are presented in Section 4 (Discussion).

423

424 3.1. Nominal scenario

425

426 Table 3 presents monocriterion performances for each system, with optimal values highlighted with
 427 bold font. For the sake of analysis, some major intermediate results are also included: the CAPEX, the
 428 OPEX, the exergy destruction costs within the grid ($C^{D,grid}$) and within the heat production unit
 429 ($C^{D,HeatUnit}$), the fuel specific costs for the heat production unit ($c^{F,HeatUnit}$) and the product specific costs
 430 for the solar panels ($c^{P,panels}$). Based on the sizing rules used in this study, the sizing of the solar systems
 431 retained (see section 2.2) are: 1.78 kWp (11.84 m²) for solar PV to run the electric boiler; 0.76 kWp (5.05
 432 m²) for solar PV to run the air source heat pump; 0.53 kWp (3.51 m²) for solar PV to run the ground
 433 source heat pump; and 3.2 kWp (4.00 m²) for the ST collectors.

434

435 **Table 3.** Multicriteria performance of different systems for residential heat production.

Solution	η	ε	LCOE	CAPEX	OPEX	C^D	$C^{D,grid}$	$C^{D,HeatUnit}$	$c^{F,HeatUnit}$	$c^{P,panels}$	Δ^{CO2}
	[%]	[%]	[€/kWh]	[€/year]	[€/year]	[€/year]	[€/year]	[€/year]	[€/kWh _{ex}]	[€/kWh _{ex}]	[tCO ₂ /year]
Gas-fired boiler (GFB)	90.0	17.3	0.102	92	427	346	0	346	0.074	-	0.00
Biomass boiler (BB)	90.0	17.3	0.085	94	338	272	0	272	0.058	-	1.76
Grid + Elec boiler (Grid + EB)	38.8	7.4	0.143	50	678	942	406	536	0.130	-	1.34
PV panels + Elec boiler	20.0	4.0	0.144	367	443	813	264	549	0.133	0.139	1.55
Grid + ASHP	59.7	17.4	0.087	144	298	330	174	156	0.130	-	1.68
PV + ASHP	37.2	9.4	0.088	279	200	341	110	231	0.192	0.368	1.75
Grid + GSHP	68.1	23.1	0.071	150	212	213	121	92	0.130	-	1.76
PV + GSHP	45.9	12.8	0.081	285	147	257	77	180	0.209	0.551	1.81
ST collectors	39.0	7.6	0.140	335	381	526	227	299	0.130	0.129	1.61

436

437 In order to support the analysis, Figure 3 displays, for each solution, the energy and exergy efficiencies
 438 as well as CO₂ mitigation.

439

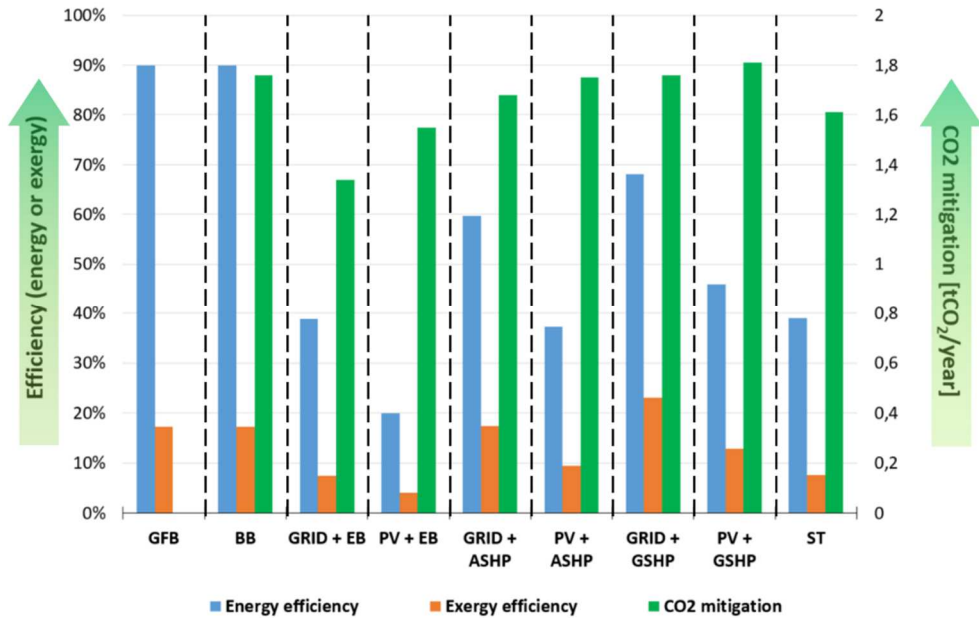


Figure 3. Energy, exergy and environmental performance of each solution.

440

441 Energy-wise, the biomass and gas-fired boilers are the best solutions thanks to their high efficiencies (90
 442 %), and because they do not need intermediate conversion units. The energy efficiencies of Grid + GSHP
 443 and Grid + ASHP are lower by 21.9% and 30.3%, respectively. These solutions cannot take full advantage
 444 of the heat pumps' good COPs because of the grid's comparatively low energy efficiency (i.e. 38.8%). PV
 445 + electric boiler is the worst solution energy-wise, with an energy efficiency of 20.0%, performing 48.1%
 446 worse than the Grid + GSHP and 39.7% worse than the Grid +ASHP. Moreover, replacing the Grid with
 447 the PV panels as the power source for the heat pumps reduces the energy efficiency by about 22%.
 448 Global efficiency of the ST solution is lower than expected. The collectors themselves have pretty good
 449 energy efficiency (80 %), and do not suffer from chained inefficiencies like other solutions. Thus, the
 450 only explanation is temporal mismatch: 1) A high share of the demands is covered by the backup (Grid +

451 Elec boiler), which has comparatively low efficiency; 2) A high share of heat produced by ST collectors is
452 dumped, thus penalizing performance (refer to Table 3).

453 Exergy-wise, the Grid + GSHP solution dominates clearly, which is understandable since these
454 subsystems have the two highest individual efficiencies (57.1% and 38.8%, respectively). The GSHP,
455 despite converting electricity to a lower-grade energy (i.e. heat), does so with a very high COP. The Grid
456 in France is rather efficient energetically, and it does not underperform exergy-wise because it converts
457 chemical energy to electric energy (which have the same exergy factors). The Grid + ASHP solution is
458 second-best, but from afar already (by 5.7%), because of the COP difference between GSHPs and ASHPs.
459 The Grid + ASHP solution is almost matched by the biomass and gas-fired boilers, which benefit from
460 high energy efficiencies in spite of converting chemical exergy to low-grade heat. Solutions based on
461 solar panels exhibit medium-to-low exergy efficiencies ranging from 4% (PV + electric boiler) to 12.8%
462 (PV + GSHP). Solar thermal collectors, despite their high energy efficiencies, transform solar irradiation
463 ($\theta \approx 0.93$) into low grade heat ($\theta \approx 0.20$). Moreover, they suffer from temporal mismatch as already
464 discussed. PV panels, despite transforming irradiation into electricity ($\theta = 1$), have low energy efficiency
465 themselves.

466 The environmental indicator prioritizes the PV + GSHP, closely followed by the Grid + GSHP, the Biomass
467 boiler, the PV + ASHP and the Grid + ASHP. The environmental attractiveness of the HPs is clear, even
468 when the grid is involved. This is certainly due to their high COPs and low carbon emissions from the
469 French national grid. It is important to note that the French national grid is quite environment friendly
470 with merely 56 g/kWh of CO₂ emissions (x_{CO_2}) when compared to a conventional coal-fired power plant
471 ($x_{CO_2} = 986$ g/kWh). This is because the French national grid primarily produces about 72% of its
472 electricity from nuclear energy, while relying on fossil sources for only 1.8% (coal), 7.7% (gas) and 0.7%
473 (fuel) [24]. The CO₂ mitigation (Δ^{CO_2}) of the French national grid + electric boiler is calculated to be 9.87
474 tCO₂/year (with reference to a coal-based power plant + electric boiler). Therefore, most grid-driven

475 solutions have good environmental performances anyway. The higher Δ^{CO_2} in case of biomass boiler is
476 as expected, since it does not run on fossil fuels and has very low carbon emissions. The ST collectors
477 perform decently, and both the solutions involving an electric boiler are clearly worse than their HP-
478 based counterparts. This results from the COP difference between the HPs and the electric boiler
479 leading to higher electricity requirements, and consequently higher CO₂ emissions, in the electric boiler-
480 based solutions. As expected, any solution involving solar panels performs quite well environmentally.
481 Also, as expected, the least attractive system is the gas-fired boiler.

482 It can also be seen on Fig. 3 that the energy, exergy and environmental criteria suggest different
483 solutions. This illustrates the interest of exergy as an independent criterion. Exergy analysis accounts for
484 both the quantity and quality of energy flows, while energy analysis only focuses on the quantity.
485 Besides, exergy optimality is sometimes associated to environmental optimality, but that is not
486 necessarily the case. While a CO₂ emissions analysis focuses on the energy source, an exergy analysis
487 covers the whole energy chain. In this study, that difference was relevant because intermediate
488 conversion units are involved.

489 Figure 4 presents the economic and exergoeconomic performances of every solution.

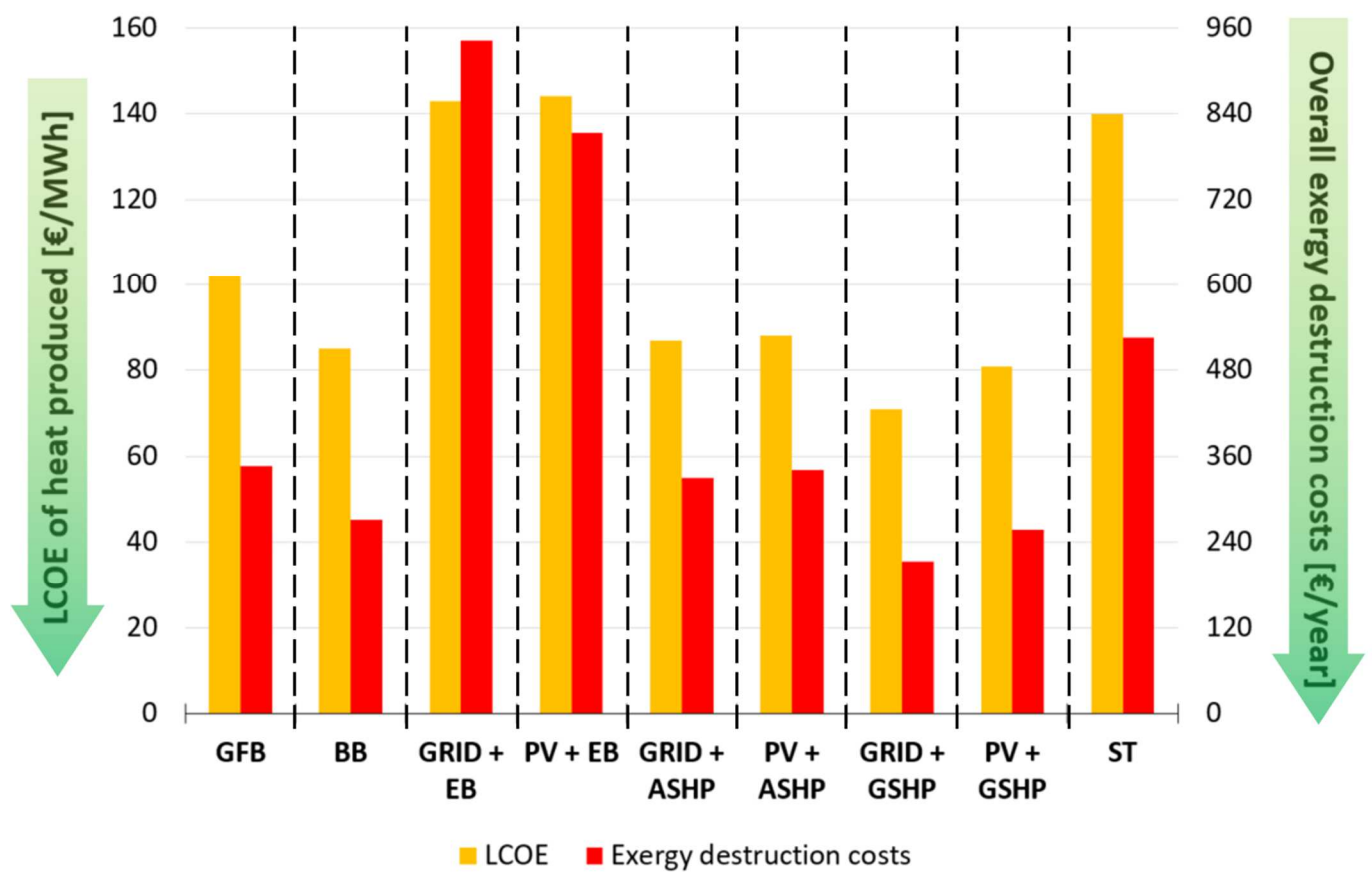


Figure 4. Economic and exergoeconomic performance of each solution.

490

491 From an economic standpoint, the grid-driven ground-source heat pump (GSHP) seems the best option
 492 ($LCOE = 0.071 \text{ €/kWh}$), thanks to its high COP. The PV-driven GSHP is second-best (0.081 €/kWh) for the
 493 same reason. It is followed by solutions involving either a biomass boiler (0.085 €/kWh) or an air-source
 494 heat pump (ASHP). In fact, the ASHP is almost as competitive when run by the grid (0.087 €/kWh) as by
 495 PV panels (0.088 €/kWh). This is remarkable, because the PV-driven ASHP needs investment on two
 496 units instead of one, and yet the $LCOE$ remains the same. The reason for this is that excess electricity
 497 produced by the panels can be sold to the grid, generating some additional revenues. The gas boiler is
 498 decent (0.102 €/kWh), but not quite at the top. While its CAPEX is among the lowest (92 €/year), its
 499 OPEX is among the highest (427 €/year). The ST collectors and both solutions involving an electric boiler
 500 are at the low end, by a large difference (around 4 c€/kWh higher than the gas-fired boiler). For the Grid
 501 + electric boiler system, the issue is a combination of the grid's high operating costs and the boiler's

502 poor COP. With PV + electric boiler the explanation is similar, because the boiler's poor COP forces the
503 system to back up with the grid more often. Due to temporal mismatch, the ST collectors can only utilize
504 some of the heat produced. This forces a frequent use of the grid backup. Besides, ST collectors have the
505 second highest investment costs. This is in agreement with the results in [16], where the solar thermal
506 system had a high initial cost compared to reference systems.

507 Exergoeconomics-wise, the grid-driven ground source heat pump is dominant again (213 €/year). Even
508 when PV-driven, it outperforms all other types of heat production systems (257 €/year). The main
509 reason is its high COP, as mentioned in the preceding paragraphs. In addition, the PV-driven GSHP
510 implies lower exergy destruction costs at the grid (77 €/year) than an entirely grid-driven GSHP (121
511 €/year), thanks to solar irradiation being a cost-free source. The solar thermal collectors (526 €/year) are
512 efficient and run on solar energy, too, but they cannot fully benefit from these advantages due to
513 temporal mismatch. Thus, their backup costs are simply too high. None of the other solutions benefits
514 from the two advantages at the same time (high efficiency and solar energy).

515 The PV-driven GSHP should outperform the Grid-driven GSHP thanks to the solar input, which is cost-
516 free. However, Figure 4 shows that it is not quite the case. This is due to the exergoeconomic balance
517 for the PV panels. Since the GSHP is efficient, it consumes little electricity. Little electricity consumed
518 means fewer opportunities to amortize investment on PV panels. This leads to a higher *LCOE* for
519 electricity produced by PV panels. As a result, average fuel costs for the GSHP ($c^{F,HeatUnit}$) are higher if
520 partially PV-driven (0.209 €/kWh_{ex}) than if entirely Grid-driven (0.130 €/kWh_{ex}). Consequently, exergy
521 destruction costs within the GSHP itself are also higher (180 €/year, in front of 92 €/year if entirely grid-
522 driven). In the end, global exergy destruction costs are higher for the PV-driven GSHP (257 €/year) than
523 for the grid-driven GSHP (213 €/year). Note how this difference is smaller if we compare the PV-driven
524 and Grid-driven ASHP instead: 341 €/year versus 330 €/year, because the ASHP consumes more
525 electricity. If the heating unit is as low-efficient as an electric boiler, the PV-driven solution finally
526 becomes preferable (813 €/year) to the Grid-driven solution (942 €/year). This leads to a counter-

527 intuitive conclusion: exergoeconomics-wise, a more efficient heat pumping unit is detrimental to the PV
528 panels in comparison to the grid.

529 The exergoeconomic criterion proved to diverge from the economic criterion. For instance, notice how
530 the LCOE of Grid + EB (143 €/MWh) is twice that of Grid + GSHP (71 €/MWh), but their exergy
531 destruction costs are more than a quadruple (942 €/y versus 213 €/y). Investment costs are not the
532 cause of this divergence: those of the electric boiler (50 €/y) are one third of those of the GSHP (150
533 €/y). Fuel costs are not the cause either, because both systems are grid-driven. The cause lies on the
534 poor exergy performance of the electric boiler. Notice how exergy destruction costs within the boiler
535 (536 €/y) are roughly 6 times those of the GSHP (92 €/y). Indirectly, grid exergy destruction costs are
536 also higher with the boiler (406 €/y) than with the GSHP (121 €/y), because more electricity is
537 consumed. This illustrates how exergoeconomics diverge from techno-economics. They can also diverge
538 from exergy. Although exergy and exergoeconomics recommend the same solution (Grid + GSHP) in this
539 study, this was purely coincidental.

540 After mono-criterion performances have been analyzed, a discussion is offered below on multicriteria
541 optimality. To facilitate a visual comparison, Figure 5 presents multicriteria relative optimality in the
542 form of a radar chart. In each criterion, the value of 1 represents the best solution(s). Thus, the
543 promising systems are those closest to the radar's outermost vertices. Polygons with the greatest areas
544 point out the solutions with the best multicriteria performances.

545

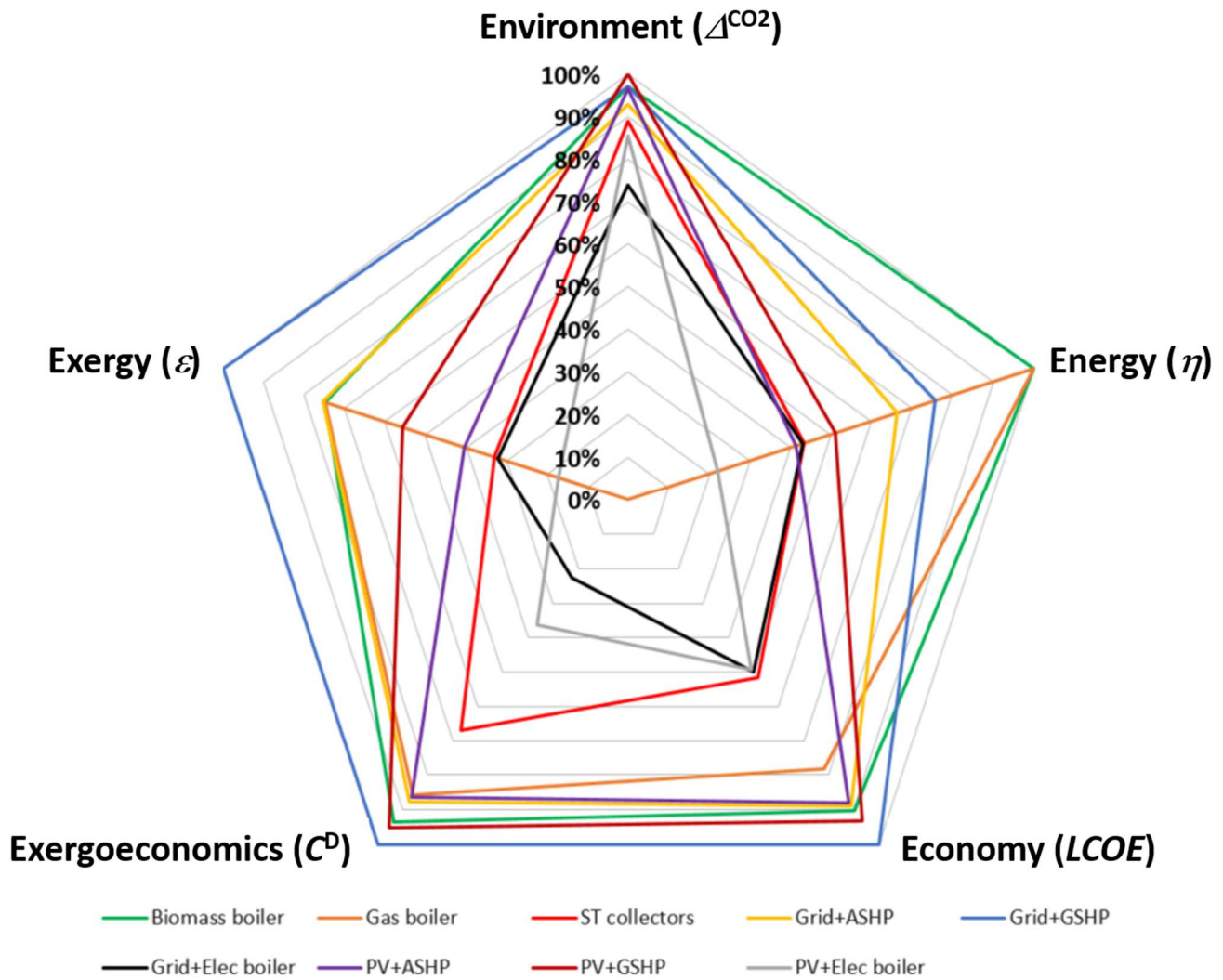


Figure 5. Multi-criteria comparison through relative optimality (nominal scenario).

546

547 If all criteria are given the same importance, the Grid-driven GSHP is the most promising solution. It
 548 outperforms all other solutions exergy-wise, economy-wise and exergoeconomics-wise. Only the PV-
 549 driven GSHP or the Biomass Boiler can compete in some aspects. The Grid + GSHP and PV + GSHP take
 550 advantage of the GSHP's high COP. In addition, the grid-driven GSHP takes full advantage of the grid's
 551 better efficiency compared to PV panels. In contrast, a PV-driven GSHP is more environmentally-
 552 friendly, but solar mismatch hinders it from being more promising in any of the other criteria. The
 553 biomass boiler is the most competitive energy-wise, and the second-most environmentally-friendly one.
 554 It outperforms the GSHP energy-wise because the GSHP requires a fair input of low-temperature heat.
 555 Exergy-wise, however, that low-temperature heat has very little value, allowing the Grid + GSHP solution

556 to outperform the biomass boiler. Since exergy and exergoeconomics have yet a limited presence in
 557 benchmarking, the biomass boiler may still be a commercially-appealing competitor.

558

559 3.2. Sensitivity analysis on economic parameters

560

561 The economic analysis has pointed out the most and least promising systems based on average costs for
 562 each unit. However, costs may vary depending on location and other techno-economic factors. This
 563 subsection analyzes potential competitiveness of each system based on variations of investment and
 564 fuel costs between the boundaries provided by the French ADEME (the French Agency for Environment
 565 and Energy Management) [12,27,32,37]. Those boundaries are shown in Table 4. Note that no variation
 566 is proposed for the grid's investment cost or the solar panels' fuel costs, because those costs are null.
 567 Complete amortization was assumed for the grid, and solar irradiation is cost-free.

568

Table 4. Variable economic parameters for the sensitivity analysis.

Unit	Parameter	Nominal value(s)	Boundaries	Units
National electric grid (Grid)	Specific fuel cost (c^F)	0.050	[0.045, 0.055]	€/kWh
Solar photovoltaic panels (PV)	Specific investment cost (z^{CI})	3110	[2840, 3380]	€/kWpeak
Solar thermal collectors (ST)	Specific investment cost (z^{CI})	1060	[940, 1180]	€/kWpeak
Electrically driven boiler (EDB)	Specific investment cost (z^{CI})	188	[169, 206]	€/kWpeak
	Specific fuel cost (c^F)	0.130 (Grid-driven)	[0.117, 0.143]	€/kWh
Gas-fired boiler (GFB)	Specific investment cost (z^{CI})	344	[309, 378]	€/kWpeak
	Specific fuel cost (c^F)	0.074	[0.066, 0.081]	€/kWh
Biomass boiler (BB)	Specific investment cost (z^{CI})	350	[200, 500]	€/kWpeak
	Specific fuel cost (c^F)	0.058	[0.041, 0.075]	€/kWh
Air source heat pump (ASHP)	Specific investment cost (z^{CI})	1250	[1100, 1400]	€/kWpeak
	Specific fuel cost (c^F)	0.130 (Grid-driven)	[0.117, 0.143]	€/kWh
Ground source heat pump (GSHP)	Specific investment cost (z^{CI})	1400	[1200, 1600]	€/kWpeak

569

570 Figure 6a shows sensitivity of the *LCOE* with respect to the abovementioned parameters. For each
 571 system, the high-end values correspond to maximum investment cost and fuel cost, and vice versa. The
 572 biomass boiler is clearly the most sensitive solution. Depending on the economic context, its *LCOE* may
 573 drop from 5.7 c€/kWh (giving the most promising solution) to 11.2 c€/kWh (setting this solution as the
 574 6th in the list). Meanwhile, the heat pumps (all types and all electricity sources) show the lowest
 575 sensitivities to economic uncertainties. These solutions stay in the range of 6.3-9.8 c€/kWh, with the
 576 Grid + GSHP solution being the most promising (as low as 6.3 c€/kWh). As explained in the analysis of
 577 Fig. 3, the cases with the grid and with a GSHP are more favorable than those with PV panels and an
 578 ASHP, respectively. Anyway, outside of the Grid + GSHP, the other heat pump solutions are almost
 579 equivalent economy-wise. The gas boiler (9.2 – 11.2 c€/kWh) may become competitive with the biomass
 580 boiler, but not with the heat pumps. The solar thermal collectors and both solutions involving an electric
 581 boiler are the least promising ones, all comprised in the tranche of 11.5 – 16 c€/kWh. These 3 systems
 582 are moderately sensitive to the parameters (wherein *LCOE* varies by approximately 2 c€/kWh), but not
 583 even in the best case can they look economically interesting. Overall, the heat pumps seem like the
 584 safest bet in the French residential sector, although higher economic sensitivities have been reported
 585 for electric boilers and heat pumps [48].

586 Figure 6b shows sensitiveness of the indicator C_D . In terms of this indicator, the Grid + GSHP system (192
 587 – 234 €/year) is the most promising and stable solution. The PV + GSHP is close (232 – 282 €/year), but
 588 suffers from the abovementioned drawbacks of running PV panels. The biomass boiler (192 – 352
 589 €/year) can actually become competitive with the Grid + GSHP, but again, this is subject to great
 590 uncertainty. The explanation to this is the high variations of both the investment and fuel costs for this
 591 type of boiler. As a result, its exergoeconomic indicator registers variations up to +/- 29% (80 €/year)
 592 with respect to the nominal scenario. In the most unfavorable of the cases, it can even be outperformed

593 by the gas-fired boiler (311 – 380 €/year). It is also noticeable that ASHP solutions (296 – 374 €/year) are
 594 inferior to GSHP solutions, because electricity prices are the same for both but the GSHP has better *COP*.
 595 This implies less electricity consumption, exergy destruction and fuel expenses. Since the *LCOE* of these
 596 solutions is more sensitive than the C_D , one might conclude that investment costs are currently the most
 597 influential economic parameter on heat pumps. The solar thermal collectors (473 – 578 €/year) perform
 598 decently in this criterion, but not quite enough to be promising. Again, the cause is a lack of a solid
 599 compensation method for temporal mismatch. Nevertheless, they manage to largely outperform all
 600 solutions involving electric boilers (which are in the range of 730 – 1040 €/year). This happens because
 601 both types of solar panels benefit from the costless solar source and similar *SPI* and *SCI* (refer to Table
 602 2), but solar thermal collectors are way more efficient than PV panels, individually. It can also be seen
 603 that PV-driven solutions perform worse than their grid-driven counterparts, except when they are
 604 connected to an electric boiler.

605

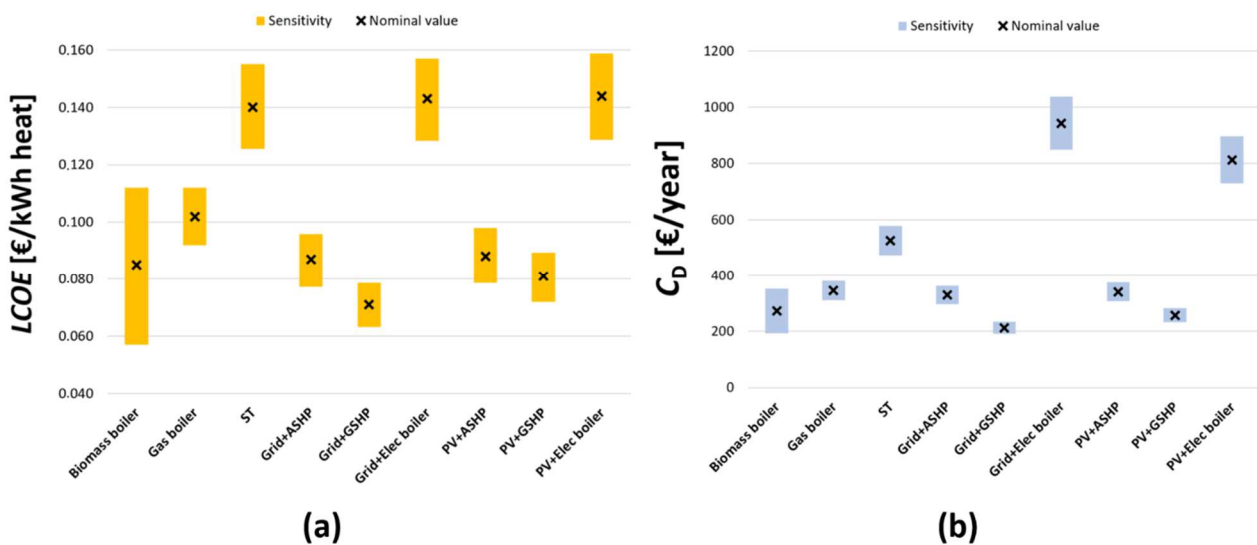


Figure 6. Sensitivity analysis of economy-related indicators: a) Levelized Cost Of Energy (*LCOE*); b) Cost of exergy destruction (C_D).

606

607

608 **4. DISCUSSION**

609
610 This section discusses qualitatively several key factors to increase competitiveness of renewables in a
611 wider context. The discussion includes operating parameters that were not considered in the
612 quantitative study.

613 614 **4.1. Discussion on the boilers depending on the fuel used**

615
616 The reference scenario for this study is using either a gas-fired boiler or an electrically grid-driven boiler
617 to satisfy the dwelling's heat demands. In our results, the biomass boiler outperforms those types of
618 boilers in several criteria. In addition, they avoid other technical issues, such as the risks of leakage or
619 even explosion of a gas-fired boiler. They are not susceptible to grid cut-offs like electric boilers, either.

620 However, a few operational drawbacks of biomass boilers have not been accounted for in this study.
621 First of all, moisture is an issue. As pointed out in the conclusions by Costa et al [49], the main potential
622 for improvement is on the decrease of the residual biomass moisture content. The conclusion from Las-
623 Heras-Casas et al [50] pointed out that climate is another factor. In their study, the savings were greater
624 with the increasing severity of winter weather, with a substantial reduction in energy costs.

625 Another drawback not considered in our study is the storage of biomass. If instantaneous availability of
626 the fuel (wood) is to be guaranteed, it must be stored. That storage can take up much space in the
627 dwelling.

628 Economics-wise and exergoeconomics-wise, fuel costs appear to be the key parameter according to
629 literature. For example, in [20] the boiler run by natural gas outperformed the other systems, which
630 were run by either fuel-oil or electricity. The main reason for this result were the costs of natural gas,
631 which were around 70% lower than those of the other fuels. The author of that study concluded that

632 fuel costs are highly significant parameter, especially when the compared systems have similar
633 performances [20]. In our study, performances are indeed very similar between the gas-fired boiler
634 (90%), the biomass boiler (90%) and the electric boiler (100%). This justifies the interest of running
635 sensitivity analyses on fuel costs. It also means that fuel costs differences must be taken into account
636 before generalizing the results of this study to other countries.

637

638

639 **4.2. Discussion on the heat pumps**

640

641 Electrically-driven heat pumps are direct competitors of electric boilers and have proven strictly better
642 in the multicriteria analysis. Nevertheless, electric boilers have two relative advantages. First, they do
643 not require an external heat source, so they are not susceptible to frosting , a typical limitation of heat
644 pumps [51]. Frosting is such a drawback that it can delimitate the areas in which heat pumps are
645 feasible [52]. Second, their output temperature can be adjusted by selecting the material, virtually
646 reaching pretty high temperatures. Heat pumps can only reach the same temperatures through a heat
647 source of accordingly high temperature.

648 The results from this study show that the LCOEs of the GSHP-based solutions (both GSHP+PV and
649 GSHP+grid) are higher than that of gas-fired boiler (GFB). Furthermore, the solutions based on electric
650 boiler (driven by PV/grid) have higher LCOEs when compared to the GSHP solutions (refer to Table 3 or
651 Fig. 4). This is in accordance with the results reported in [14], wherein the natural gas heating system is
652 found to be more economical, while electric resistance heating is reported to be economically inferior to
653 a GSHP system (grid-driven). However, it is worthwhile to note that the GSHP systems (PV/grid-driven)
654 outperform the gas-fired boiler from an exergoeconomic standpoint, exhibiting lower costs of exergy
655 destruction.

656 Ground source heat pumps (GSHP) outperformed air source heat pumps (ASHP) in this study. This
657 tendency is in agreement with those reported in other studies from the literature. For instance, in [18]
658 the GSHP showed at least 50% higher exergy efficiency than the ASHP. In our study, the GSHP has 36%
659 higher exergy efficiency than the ASHP if PV-driven, or 32% higher if Grid-driven (refer to the exergy
660 efficiencies in Table 3). The deviation with respect to [18] is explained by the diversity of applications in
661 our study, which leads to a diversity of temperature levels. In [18], condenser temperatures were 30-
662 40 °C because only space heating was considered. In our study we assumed a condenser temperature of
663 35 °C for space heating (which is essentially the same), but we considered domestic hot water
664 production too. DHW production requires condenser temperatures of at least 65 °C. Therefore, the heat
665 pumps are forced to operate with greater temperature lifts. And with greater temperature lifts, the
666 same increase in evaporator inlet temperature leads to smaller relative increases in COP. That explains
667 why in our study the GSHP outperforms the ASHP by a smaller margin exergy-wise. Note also that
668 exergy efficiencies reported in [18] are smaller than those in our study, because that other study
669 considered building and distribution losses, which were not in the scope of our study.

670 The heat source of ground source heat pump is at a higher temperature in winter, granting them a
671 better COP when most of the needs take place. Besides, that temperature remains quite stable
672 throughout the year, in contrast to air's. However, air temperature may surpass ground temperature
673 and grant air source heat pumps a better COP for DHW production in summer, or space heating in early
674 spring or late autumn. Furthermore, in summer the ground source heat pump is forced to operate in
675 reverse mode (cooling mode) to regenerate the ground source [53,54]. The CAPEX of ASHPs is lower
676 than that of GSHPs, however the OPEX is higher for ASHPs (Table 3). The GSHPs are economically more
677 favourable (lower LCOE) than ASHPs (in concurrence with the results given in [15]). Furthermore, the
678 costs of exergy destruction are also lower for GSHPs and thus, the GSHPs perform better than ASHPs
679 exergoeconomically as well. Besides, technical implementation of air source heat pumps is arguably
680 simpler. Furthermore, they take up less ground surface.

681

682 **4.3. Discussion on solar PV panels and concurrence with the grid**

683

684 Given the same electricity-to-heat conversion unit, the grid proved better energy-, exergy- and
685 economy-wise. On the other hand, PV panels were better environment-wise and exergoeconomics-wise.

686 It seems unthinkable that PV panels would surpass the grid energy- or exergy-wise in the future. Solar
687 PV panels are a developed technology, not likely to undergo an efficiency breakthrough in the next
688 years. Besides, this study did not account for some extrinsic operational issues that reduce their
689 effective production. According to literature, partial shading [55] can cause power output losses
690 between 10% and 70% [55,56]. Moreover, soiling [57,58] can reduce power output between 10% and
691 40% [59]. On the other hand, large areas are available for implementation of PV panels, perhaps
692 compensating for the low performance of this kind of energy harvesting.

693 The economic competitiveness of solar PV panels has several layers to discuss about. First of all, they
694 require an additional investment with respect to the grid. Moreover, if the dwelling does not run
695 electrically-driven heating, the investment cost increases. This may dissuade many residential users
696 from installing a PV array in their dwellings. On the other hand, solar irradiation is costless, and the low
697 maintenance costs of PV panels may compensate for the investment cost in the long run. In fact, this
698 study has found that PV-driven heat pumps are among the most interesting solutions, despite the
699 double investment. It has also been found that grid-driven solutions are more competitive, but from a
700 small margin. This margin varies depending on two factors: efficiency of the electricity-to-heat
701 conversion system, and temporal mismatch.

702 In the case of PV panels, there exists a trade-off between exergy efficiency and investment cost. As
703 Saloux et al [19] discussed in their study, solar energy cannot be recovered without an appropriate
704 investment on solar panels. With a substantial capital cost, irreversibilities can be reduced and system

705 performance increases. Therefore, real systems should be balanced between investment and exergy
706 losses [19]. These trade-offs exist for many units, and they can affect decision-making in these case
707 studies. Accounting for these kinds of trade-offs is a future work envisaged by the authors of the present
708 study.

709 The conversion system's efficiency affects indirectly the economic attractiveness of PV panels. As
710 observed in Fig. 3, the panels are almost as competitive as the grid if connected to an electric boiler
711 (COP = 1) or an air source heat pump (COP = 2-3). However, with a ground source heat pump (COP = 3-4)
712 they are clearly less attractive. A very efficient conversion system consumes less electricity; this gives
713 less opportunities of amortizing the PV panels investment cost. Thus, it seems that switching from the
714 grid to PV panels is more viable economically if the conversion system is not very efficient. A user who
715 has a ground source heat pump and ponders on installing PV panels may be discouraged by these
716 counter-intuitive findings. Nevertheless, excess PV electricity can still be utilized for the electric needs of
717 the dwelling (which were not considered in this study).

718 The economic impact of temporal mismatch on PV-driven solutions is less than expected. The main
719 reason is that excess electricity is sold to the grid. In some contexts, this or other forms of mismatch
720 compensation might be preferable to electric batteries. For instance, it has been suggested in literature
721 that collective load aggregation between different prosumers equipped with PV panels can reach 90%
722 self-consumption rates, without needing any storage at all [60]. On the other hand, the self-production
723 remains limited without storage. A detailed study comparing the economic performance of these two
724 strategies could be interesting.

725 Although the French energy market is economically very competitive, subsidies can further support
726 deployment of solar panels and other renewable sources. Such subsidies are typically state-led, but the
727 convenience of voluntary markets is discussed in literature too [61].

728 The environmental indicator shows an advantage for the PV panels, but by a lesser margin than
729 expected. This has two main causes: lower self-production in the absence of storage, and the French
730 grid's relatively low CO₂ emissions. Besides, the environmental advantage of solar panels may be less
731 attractive if their embodied energy was considered [62].

732

733 **4.4. Discussion on the Solar Thermal collectors**

734

735 Results for the ST solution are the most underwhelming in this study. Temporal mismatch (an extrinsic
736 issue) denies the ST collectors' intrinsic advantages, namely their high energy efficiency (up to 80%) and
737 the matching of energy type (they produce heat in adequacy to the demand). As a result, they are
738 outclassed by most of the other solutions in most of the criteria. Note how the biomass and gas-fired
739 boilers have similar energy efficiencies (90% each), but their situational efficiencies are 51% higher than
740 that of the ST solution with grid backup. Most of this difference comes from temporal mismatch.

741 ST collectors and PV panels suffer from just the same temporal mismatch, and that is visible if both are
742 given the same backup system. Note in Table 3 how the ST solution (with Grid + EB as backup) almost
743 doubles the energy and exergy performances of the PV + EB solution (with Grid + EB as backup).
744 However, note how their *LCOE* are almost the same (0.144 €/kWh for PV + EB and 0.140 €/kWh for ST).
745 This has one clear explanation: excess electricity is sellable to the national grid, contrary to excess heat.
746 In addition, note how the PV panels can outperform the ST collectors if they are given a more efficient
747 conversion unit, such as a Heat Pump. It may be concluded that PV panels can compensate temporal
748 mismatch better than ST collectors.

749 This uncovers another relative disadvantage of ST collectors: there exists no convincing thermal
750 equivalent for selling electricity to the grid. The closest equivalent would be selling excess heat to a
751 nearby district heating substation. However, district heating networks are not yet as generalized as
752 electric networks are. Other ways to compensate for solar thermal mismatch may include, but not

753 limited to: (i) storage, which can reduce mismatch at the expense of investment cost, reaching a
754 tradeoff; (ii) using the dwelling's thermal inertia, which is a typical problem in space cooling [63] but an
755 advantage in space heating, granting thermal flexibility [64]; (iii) at a district scale, collective self-
756 consumption may allow to cumulate the thermal profiles of residential and tertiary buildings, which are
757 complementary in time.

758 In the present study, the energy efficiency of ST collectors was evaluated as 39% (refer to Table 3 or Fig.
759 3). It should be noted that this value represents the annual energy efficiency in the absence of any
760 storage unit. The maximum collector efficiency in [65] was found to vary between 47-59% for a solar
761 water heating system consisting of solar collector, heat pipes (with different refrigerants) and storage
762 tank (condenser section). These values were obtained for the days with different weather conditions in
763 April and May (summer months) while considering a water storage tank. Hence, a lower energy
764 efficiency value than that reported in [65] seems quite reasonable.

765 Environment-wise, ST collectors and PV panels are almost equivalent (refer to the ST and PV + EB
766 solutions on Fig. 2). Like PV panels, ST collectors may look less environmentally friendly if their
767 embodied energy is considered. However, it has been stated in literature that solar thermal collectors'
768 embodied energy is less than that of PV panels [62].

769

770 **5. CONCLUSIONS AND PERSPECTIVES**

771

772 This study aimed to evaluate competitiveness of renewable sources for heat production in individual
773 housing. The novelty of this work is to compare several renewable-based solutions with their grid-based
774 counterparts, thanks to a multicriteria analysis (energy, exergy, economy, environment and
775 exergoeconomics - 5E). The quantitative analysis was followed by a qualitative discussion on additional
776 performance parameters, and the possibility to solve the drawbacks of each renewable-based system.

777 Since quantitative results may depend strongly on the context, only qualitative conclusions are
778 presented:

- 779 • For the specific context of an individual residence in France, a ground-source heat pump driven
780 by the electric grid is the most appealing solution exergy-wise, economy-wise and
781 exergoeconomics-wise.
- 782 • Nevertheless, a biomass boiler performs better energy-wise and is equivalent environment-wise,
783 and can therefore be a competitor. In addition, it does not depend on a low-temperature heat
784 input like heat pumps do. Economy-wise, it may become the most promising too, but this is
785 subject to great uncertainty.
- 786 • Given the same heat production unit, PV panels outperform the French electric grid from an
787 environmental standpoint, with a PV-driven ground-source heat pump being the best solution.
788 Nevertheless, the differences are rather small. Meanwhile, the grid usually outperforms the PV
789 panels in all other criteria.
- 790 • Economy-wise and exergoeconomics-wise, switching from the grid to PV panels may only be
791 interesting if the heat production unit is low-efficient, such as an electric boiler.
- 792 • Heat pumps outperform electric boilers in all criteria considered. This collides with the fact that
793 electric boilers are widespread.
- 794 • The biomass boiler is better than, or at least equal to, the gas-driven boiler with regards to all the
795 criteria considered. However, some parameters were not taken into account, such as the need
796 for storage space, or humidity issues.
- 797 • Adding storage batteries should improve PV panel's competitiveness from the environmental
798 and exergy standpoints strictly, and from the economic and exergoeconomic standpoints to
799 some extent.

- 800 • Solar thermal collectors are strongly hindered by production/consumption temporal mismatch.
801 Without a thermal storage, this solution is simply not promising.
- 802 • On the other hand, PV panels are submitted to just the same mismatch, but dispose of more
803 compensation mechanisms (aside of storage). Excess electricity can be sold to the grid, while
804 excess heat is complicated to manage. And while this study considered heat production only,
805 electricity produced by the PV panels can be consumed for the residence's appliances, too,
806 increasing matching indices. If properly investigated, this variety of solutions can seriously boost
807 competitiveness of PV-driven solutions with respect to their grid-driven counterparts, even in
808 the French energy market.

809 It is important to keep in mind that this study was applied on the specific context of France. The French
810 national electric grid is energy-efficient as well as cost-efficient, and has low CO₂ emissions thanks to the
811 high share of nuclear power. With such advantages, it is less of a counter-intuitive finding that some
812 grid-driven solutions are still competitive with renewable-driven solutions. Chances are that all grid-
813 driven solutions explored here would not be competitive enough in other energy markets, more reliant
814 on coal and other CO₂-heavy sources, or less efficient grids. Results from this study can be generalized to
815 other OECD countries in future conditions, i.e. when their shares of non-carbon electricity become very
816 high.

817 This study opened up two main perspectives. One of them is to perform a dynamic analysis considering
818 advanced strategies for improving efficiency of renewable-driven systems. Such strategies would include
819 thermal storage (sensible or latent) and electric storage. It would be worth investigating whether selling
820 excess electricity can be better than electric storage economy-wise. Such question depends on the
821 context, mainly on the prices of the energy market. Another advanced strategy would be to use the
822 dwelling's inertia, i.e. heating it before heating is actually needed. Such strategy can mitigate temporal
823 mismatch at the expense of the users' thermal comfort. Finally, accounting for the dwelling's cooling
824 and electric needs may yield a more comprehensive analysis.

825 The other perspective is to apply a similar study at district scale, where needs are much greater. This
826 allows to think of solutions that are not applicable to individual housing, such as concentrating solar
827 thermal plants or geothermal plants, for example. These kinds of plants can reach higher temperatures
828 than residential systems, allowing for cogeneration eventually. Even other types of renewable or
829 recovery sources could be considered: wind-powered electricity production, waste-to-energy power
830 plants, sewer heat recovery, wave energy if the district is close to the shore... Finally, a district has
831 complementary profiles of energy needs. One prime example is office and residential buildings, which
832 have essentially opposite profiles. This enables advanced management through collective self-
833 consumption, via district energy networks.

834

835

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837

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841

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