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1 **Thermoeconomic optimization and performance analysis of solar combined heating and**
2 **power systems: A comparative study**

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6

7 **Abstract**

8 Although solar energy is one of the most abundantly available and inexhaustible forms of
9 clean renewable energy, its use suffers from economic barriers mainly linked to its
10 intermittence. This article aims at comparing to a conventional reference system (national
11 grid and gas boiler) four different solar combined heating and power systems, namely
12 photovoltaic panels with solar-assisted heat pump, national grid and solar thermal panels,
13 photovoltaic and solar thermal panels together and photovoltaic thermal hybrid solar
14 collector. The study is carried out for an individual house of 120 m² located in Chambéry,
15 France. The optimal designs (number of solar panels and electrical and thermal storage
16 capacities) are determined for each case using genetic algorithm based on a thermoeconomic
17 indicator, i.e. the total unit product cost. Furthermore, the solutions are compared against one
18 another and with the reference case, using the following additional indicators: solar self-
19 production, solar self-consumption, energy produced by solar panels, energy requirement
20 from grid and fuel savings. Implementation of unit solar panel-driven systems without
21 storage shows the lowest unit product costs, with a positive solar contribution, especially for
22 solar-assisted heat pump with photovoltaic panels (-41% than the reference). Further, a wise
23 increase of the solar system sizes allows to improve the solar self-production (by up to 30%)
24 and fuel saving indexes (by up to 3230.3 kWh/y), at the expense of the solar self-
25 consumption, while maintaining unit production costs lower than the reference system
26 (0.1836€/kWh). Despite of their intermittence, solar thermal collectors, with grid-driven
27 electric boiler as backup, are proving to be an economical competitor to the reference gas
28 boilers (with 11% lower unit product costs). However, photovoltaic systems suffer from low
29 economic competitiveness compared to the high efficiency and low cost French national grid
30 (by -36%), which could be compensated when coupled with heat pump to satisfy heating
31 demand.

32 **Keywords:** *solar energy; solar combined heat and power; thermoeconomic optimization;*
33 *genetic algorithm; self-production; self-consumption*

Nomenclature

A_{PV}	Area of photovoltaic panel (m ²)
A_{PVT}	Area of photovoltaic thermal hybrid panel (m ²)
A_{ST}	Area of solar thermal panel (m ²)
$c_{el,grid}$	Cost of electricity from the French national grid (€/kWh)

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$c_{el,sold}$	Selling price of excess electricity to the grid (€/kWh)
c_{ng}	Cost of natural gas (€/kWh)
$c_{p,el}$	Unit cost of electricity produced by the system (€/kWh)
$c_{p,dhw}$	Unit cost of domestic hot water produced by the system (€/kWh)
$c_{p,sh}$	Unit cost of space heating provided by the system (€/kWh)
$c_{p,th}$	Unit cost of thermal energy produced by the system (€/kWh)
$c_{p,total}$	Total unit cost of products of the system (€/kWh)
$COP_{SAHP}^{65^{\circ}C}$	Coefficient of performance of solar-assisted heat pump for domestic hot water production at 65 °C
$COP_{SAHP}^{35^{\circ}C}$	Coefficient of performance of solar-assisted heat pump for space heating at 35 °C
CRF	Capital recovery factor
$E_d(t)$	Hourly electrical energy demand of an individual house (kWh)
$E_{grid}(t)$	Hourly electrical energy required from the auxiliary system i.e. national grid (kWh)
$E_s(t)$	Hourly electrical energy produced by solar (PV/PVT) panels (kWh)
$E_{sold}(t)$	Hourly excess electrical energy from PV panels sold to the grid (kWh)
$E_u(t)$	Hourly useful electrical energy produced by the solar (PV/PVT) panels (kWh)
$\Delta E_{store}(t)$	Hourly electrical energy used from the battery storage (kWh)
F_{sav}	Fuel savings of the system (kWh/y)
i	Economic rate of return (%)
$I_G(t)$	Hourly global solar radiation (W/m ²)
l	Operational lifetime of a component of the system (y)
L_{tank}	Losses from the storage tank (%/h)
M	Maintenance cost of the system (€/y)
n	Lifetime of the system (y)
N	Number of solar (PV/ST/PVT) panels
N_{opt}	Optimal number of solar panels in the system
O	Operation cost of the system (€/y)
$O\&M$	Total operation and maintenance cost of the system (€/y)
P	Principal investment cost of the system (€)
P_{eff}	Effective present cost of the system including the replacement costs of components (€)
P_{net}	Net present cost of the system (€)
$P_{net,el}$	Net present cost of the subsystem producing electrical energy (€)
$P_{net,th}$	Net present cost of the subsystem producing thermal energy (€)
$P_{net,th,DHW}$	Net present cost of the subsystem for domestic hot water production (€)
$P_{net,th,SH}$	Net present cost of the subsystem for space heating (€)
$Q_{d,DHW}(t)$	Hourly domestic hot water demand of an individual house (kWh)
$Q_{d,SH}(t)$	Hourly space heating demand of an individual house (kWh)
$Q_{grid}(t)$	Hourly thermal energy required from the auxiliary system i.e. grid-driven

	electrical boiler (kWh)
$Q_s(t)$	Hourly thermal energy produced by the solar (ST/PVT) panels (kWh)
$Q_{s,DHW}(t)$	Hourly thermal energy produced by solar panels for domestic hot water production (kWh)
$Q_{s,SH}(t)$	Hourly thermal energy produced by solar panels for space heating (kWh)
$Q_{store,DHW}(t)$	Hourly thermal energy available in the DHW tank (kWh)
Q_{SAHP}^{DHW}	Thermal energy produced by solar-assisted heat pump for domestic hot water production by utilizing electricity from PV panels and battery (kWh)
Q_{SAHP}^{SH}	Thermal energy produced by solar-assisted heat pump for space heating by utilizing electricity from PV panels and battery (kWh)
$Q_{u,DHW}(t)$	Hourly useful thermal energy produced by the solar (ST/PVT) panels for domestic hot water needs (kWh)
$Q_{u,SH}(t)$	Hourly useful thermal energy produced by the solar (ST/PVT) panels for space heating needs (kWh)
$r_{d,DHW}$	Ratio of annual domestic hot water demand to the total thermal demand
R	Replacement cost of the component of the system (€)
s_{batt}	Self-discharge rate of the battery (%/day)
S	Salvage value of the system at the end of lifetime (€)
SOC_{batt}	Minimum state of charge of the battery (%)
T_{DHW}	Temperature of DHW production (°C)
T_{SH}	Temperature of space heating (°C)
$\eta_{batt,c}$	Charging efficiency of the battery
$\eta_{batt,d}$	Discharging efficiency of the battery
$\eta_{batt,r}$	Round-trip efficiency of the battery
η_{CB}	Efficiency of the conventional gas boiler
η_{PV}	Electrical efficiency of photovoltaic panel
$\eta_{PVT,el}$	Electrical efficiency of photovoltaic thermal hybrid panel
$\eta_{PVT,th}$	Thermal efficiency of photovoltaic thermal hybrid panel
η_{ST}	Thermal efficiency of solar thermal panel
ϕ_{sp}	Solar self-production
ϕ_{sc}	Solar self-consumption
Subscripts	
$batt$	Battery
el	Electrical
th	Thermal
DHW	Domestic hot water
PV	Photovoltaic panel
PVT	Photovoltaic thermal hybrid panel
SAHP	Solar-assisted heat pump
SH	Space heating
ST	Solar thermal panel

35 1 Introduction

36 As a result of the rising environmental concerns, the technologies based on solar energy are
37 gaining an increased recognition as a substitute to the conventional fossil fuel-driven
38 alternatives [1]. Photovoltaic (PV) panels convert solar energy directly into electricity which
39 could be used to serve the specific electricity demands of a housing or even at an industrial
40 scale through a PV power plant. As a matter of fact, the annual energy potential from the sun
41 is approximately 1.78×10^9 MW, which is 800 times and 50 times greater than the potentials
42 from oil and coal reserves, respectively [2]. However, solar energy-based systems suffer from
43 fluctuating outputs resulting from intermittent weather conditions. Thus, an auxiliary system
44 is required to provide for the mismatched demands. The high initial investments of PV
45 panels, availability of global solar radiation and favourable incentives from the government
46 significantly impact the economic viability of grid-connected PV systems [3]. Additionally,
47 solar energy can also be harnessed to meet the heating requirements, such as domestic hot
48 water (DHW) production and/or space heating (SH), using solar thermal (ST) panels. ST
49 panels absorb the incident solar radiation and convert it into heat, which is then transferred to
50 a working fluid (water/air) flowing either under or over the absorber plate [4]. Over the years,
51 several techniques and methodologies to improve the thermal efficiency, and thus, the overall
52 performance of the solar thermal (ST) panels have been explored [5]. In fact, when
53 implemented on a large-scale for industrial applications, a solar thermal system was reported
54 to obtain rather significant energy savings (9722–20833 kWh) and carbon savings (2–5
55 tonnes of CO₂/kWh) [6]. A building-integrated solar thermal system with seasonal storage
56 was found to attain quite reasonable solar contributions (37–68%) for space heating and
57 DHW production [7]. It was observed that the implementation of seasonal storage with solar
58 thermal systems could achieve solar fractions as high as 90% for building-scale heating
59 applications [8]. Xu et al. investigated a flat-plate solar thermal system with borehole
60 seasonal energy storage for district heating applications and recommended the use of optimal
61 control schemes to achieve better thermal comfort and energy savings [9]. However, the
62 improvements in solar fraction may not effectively counterbalance the relatively higher costs
63 of a seasonal thermal energy storage for small-scale applications, as an individual house, in
64 case of inexpensive and highly de-carbonized grid systems (such as the French national grid).
65 A combination of PV and ST technologies, wherein a working fluid (air/water) is made to
66 flow either under or over the PV panels allowing the withdrawal of heat from the PV panels,
67 was first reported by Wolf [10] and is known as a photovoltaic thermal (PVT) hybrid panel.
68 Solar cells absorb about 90% of the incident solar radiation, out of which only around 15% is
69 converted into electricity [11]. The remaining energy (~75%) exists in the form of thermal
70 energy, which increases the temperature of the solar cells. Hence, the potential for heat
71 removal from solar cells is quite high. The removal of heat from the PV panels, reduces the
72 operating temperature and consequently, enhances the electrical efficiency of the solar cells
73 [12]. Moreover, the heated working fluid could be used for thermal applications [13]. Several
74 researches stress the significance of PVT systems [14] and some debate that such systems
75 will be adequate to serve the energy requirements in the near future [15]. Furthermore, a heat
76 pump driven by solar panels, i.e. a solar-assisted heat pump (SAHP), serves as an interesting
77 hybrid technology to cover the heating requirements. A combination of PV coupled with an

78 air-source heat pump was reported to be the best economically feasible space heating solution
79 for grid electricity costs up to 0.23 €/kWh (compared to water-source heat pump driven by (i)
80 flat plate ST collector, (ii) PVT collector, and (iii) PV and ST together [16]. SAHP driven by
81 PVT collectors was concluded to be profitable to meet the domestic hot water (DHW) and
82 space heating/cooling needs with the inclusion of subsidies for PVT implementation [17].
83 The primary energy savings, carbon emissions and annual cost of a ground-source heat pump
84 system were found to improve (by about 4%, 46% and 14%, respectively) when coupled with
85 solar energy (concentrated PVT collectors) [18]. Gunasekar et al. [19] proposed and
86 recommended an artificial neural network model for predicting the energy performance of a
87 PVT evaporator of a SAHP. Huide et al. [20] compared the energy performances of PV, ST
88 and PVT systems for residential applications at different locations in China. PVT systems
89 were recommended in case of urban residential buildings with limited installation space;
90 while, a combination of PV and PVT may have the highest prospective for rural buildings
91 with lower energy demands and higher space availability.

92 Due to the intermittent and random nature of solar radiation and the demand profiles,
93 designing a solar-energy based system becomes a complex task. The system size and design
94 parameters have a considerable influence on the performance of such systems. Several
95 authors have investigated and discussed different solar-driven systems to evaluate the
96 thermodynamic performance feasibility of such systems at various locations. However, it is
97 imperative to recognize the economic implications of the system as well, and therefore, a
98 performance study should be supplemented with an economic analysis. Consequently,
99 accounting for both thermodynamic as well as economic performances of the system
100 becomes more important when finding an optimal design/sizing for a solar-driven system.
101 The term thermoeconomics denotes a combination of thermodynamics with the principles of
102 economics, i.e. thermodynamic-assisted cost estimation [21]. Thermoeconomics provides a
103 mechanism to include the principal investment cost, operating costs and other costs (such as
104 maintenance and replacement costs) incurred during the lifetime of the system with respect to
105 the useful energy produced by the system [22]. Therefore, over the last decade, some studies
106 also focus on the thermoeconomic performances of different solar combined heating and
107 power systems. Sokhansefat et al. [23] investigated the thermoeconomic performance of ST
108 collectors in terms of net present value and payback period, along with an environmental
109 analysis. Wang et al. [24] concluded that a solar combined heating and power system
110 (consisting of PVT panels) aligns with the wider goal of energy decarbonisation; despite the
111 fact that it is at present economically less favourable to an equivalent gas-fired internal
112 combustion engine system. Behzadi et al. [25] optimized the design of a PVT system based
113 on the exergy efficiency and total product cost, using the TRNOPT tool in TRNSYS
114 software. The system was studied and optimized to meet the domestic hot water and
115 electricity requirements of a building. The system employed a storage tank to allow smart
116 interactions between the building, and the grid and district heating networks. The optimized
117 PVT system was found to considerably reduce the electricity and heating costs (by 16.7
118 €/MWh and 7.7 €/MWh, respectively) compared to the combination of the grid and district
119 heating network.

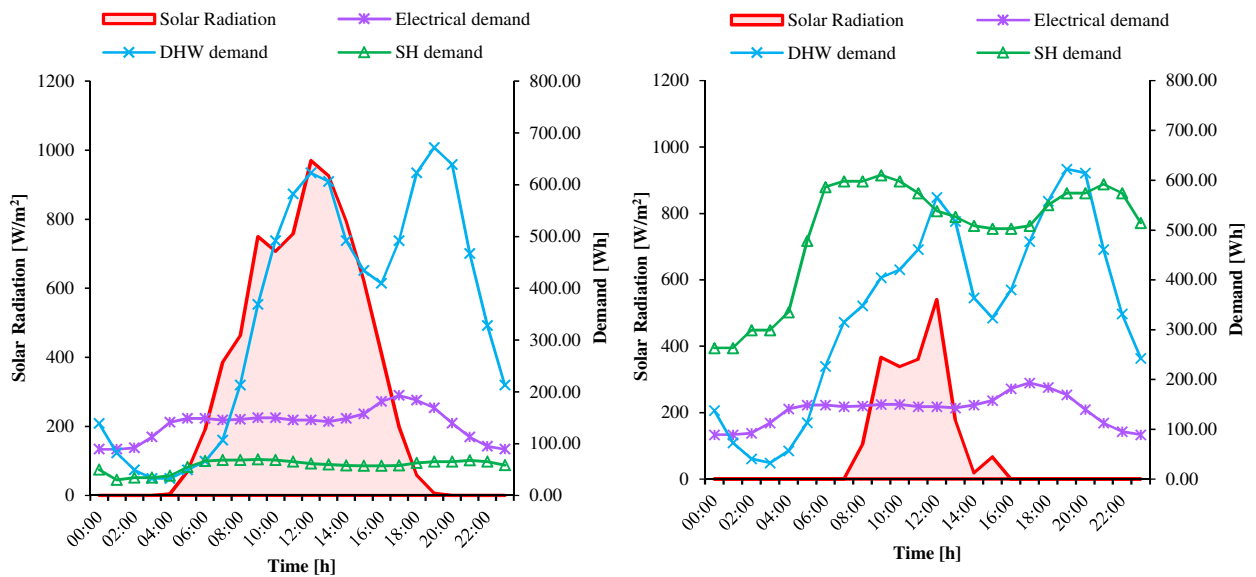
120 Starke et al. [26] optimized a SAHP for swimming pool heating using genetic algorithm in
121 terms of annualized lifecycle cost and comfort level. The optimized SAHP was reported to
122 achieve lower annualized lifecycle cost with the same level of comfort when compared to a
123 standard air-source heat pump. Herrando et al. [27] performed thermoeconomic modelling
124 and optimization of a solar combined heating and power system based on PVT panels. The
125 optimal sizing of the system (i.e. number of PVT panels and volume of storage tank) was
126 determined by varying the number of panels from 1 to 33 (i.e. an iterative approach).
127 Levelized production cost (cost per kWh) of total energy generated, percentage of energy
128 demand covered and payback time were selected as the thermoeconomic optimization
129 indicators. Keshavarzzadeh and Ahmadi [28] applied different evolutionary algorithms to
130 optimize a solar-based combined cooling, heating and power system. The objective of
131 optimization was to maximize the exergy efficiency while minimizing the total cost rate of
132 the system. Genetic algorithms can be considered as one of the most popular optimization
133 techniques applied to energy systems, while other commonly used optimization techniques
134 include direct search, simulated annealing, particle swarm optimization [29]. Genetic
135 algorithm, a meta-heuristic evolutionary algorithm, provides satisfactory results with
136 reasonable convergence accuracies [30].

137 The objective of this paper is to optimize and compare alternative solar-driven systems for
138 combined heating (including domestic hot water production and space heating) and power
139 generation, based on total unit costs and solar indexes. As per the author's knowledge, there
140 is no existing work in the literature optimizing and comparing different solar-driven solutions
141 amongst each other and with a conventional reference system, both based on energy and
142 thermoeconomics. In the present study, [Case I] PV panels + solar-assisted heat pump
143 (SAHP), [Case II] grid + ST panels, [Case III] PV + ST panels and [Case IV] PVT panels
144 have been examined, with grid + gas boiler as the reference system. In order to allow a fair
145 comparison, each solar-driven system [Cases I–IV] is optimized to find the most appropriate
146 system size and storage capacities specific to the demand profiles and location considered: an
147 individual house of 120 m² located in Chambéry, France built after 2012 (as per the French
148 RT2012 standards [31]). Genetic algorithm has been used to obtain the optimal design
149 configurations of each system based on a single objective of minimization of the total unit
150 product cost. Opportunities to improve the solar contributions from each system by
151 increasing the solar system size, while keeping its total unit product cost lower than that of
152 the reference system are then suggested. Thereafter, an in-depth comparison based on
153 additional indicators, as the solar indices (self-production and self-consumption), energy
154 performances, fuel savings and total and dissociated unit product costs, has been presented.
155 Finally, to complete the discussion, alternate components such as PV panels are fared against
156 the grid for power generation, while ST panels are compared with the conventional gas boiler
157 and SAHP for heating demands.

158 **2 Methods**

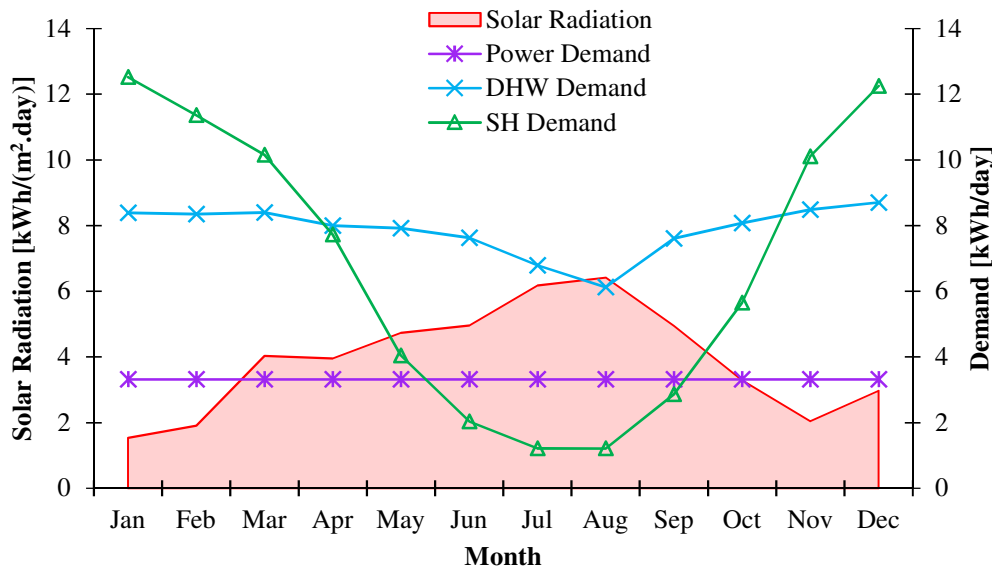
159 The present study focuses on the performance of different solar combined heating and power
160 systems to meet the electrical and thermal demands of an individual housing of 120 m² floor
161 area, located in Chambéry, France (H1 climatic zone) and built after 2012, thus adhering to

162 the French RT2012 regulations. The electrical hourly profile of the individual house is
 163 obtained from XPair website [32] and while, the thermal demands, i.e. domestic hot water
 164 (DHW) and space heating (SH), are calculated from the enquête performance de l'habitat,
 165 équipements, besoins et usages de l'énergie (PHEBUS) investigation [33] and Agence de
 166 l'environnement et de la maîtrise de l'énergie (ADEME) report [34]. The hourly space heating
 167 demands are evaluated from the percentage of heating needs for different months, days of
 168 week and hours of day for a house [35]. Both the domestic hot water requirement at 65 °C
 169 and space heating requirement at 35 °C have been considered in this study. Further, the data
 170 for the meteorological parameter, i.e. global solar radiation, is obtained using photovoltaic
 171 geographical information system (PVGIS) application [36] for the location Chambéry, France
 172 (latitude 45.567°, longitude 5.922° and elevation 282 m), optimal slope (35°) and optimal
 173 azimuth (1°) [37]. The data is obtained from PVGIS SARAH database [38]. Figs. 1a-c show
 174 the variation of climatic and demand profiles for the considered scenario of an individual
 175 house. As illustrated, there is a mismatch between the availability of solar radiation and
 176 demands over the day during off-sunshine hours (before sunrise and after sunset). Also, a
 177 higher magnitude of solar radiation is available in summer months, with lower heating
 178 requirements, than in winter months, with higher heating requirements. This results in an
 179 additional mismatch between available solar energy and demands over the year. Moreover, as
 180 shown in Figs. 1a and 1c, the space heating demands are considerably low but still exist, i.e.
 181 non-zero, in the summer months. This is because, the estimation of hourly space heating
 182 demands are based on the average values for a typical hour in a typical day of a typical month
 183 of the year [35].



a. Hourly solar irradiation and demands for a typical summer day (1st July 2016)

b. Hourly solar irradiation and demands for a typical winter day (1st January 2016)



184

185 c. Average daily solar radiation and demands from 1st January to 31st December 2016

186 Fig 1: Meteorological and demand profiles for an individual house adhering to the French
 187 RT2012 regulations (H1 zone)

188

189 **2.1 Examined cases and theory**

190 In this study, four different solar combined heating and power systems utilizing solar energy
 191 to meet the electrical and thermal (for domestic hot water and space heating) demands of an
 192 individual house have been studied. Further, the solar-energy based systems are compared
 193 against a reference case involving conventional systems to meet the energy requirements. The
 194 following cases have been considered in this study:

- 195 ○ **[Reference case] National grid + Conventional gas boiler:**
 196 In this case, the French national grid supports the electrical demands of the house, while
 197 the domestic hot water (DHW) and space heating (SH) demands are met using a
 198 conventional gas boiler.
 199
- 200 ○ **[Case I] Photovoltaic (PV) panels + Solar-assisted heat pump (SAHP):**
 201 PV panels convert solar radiation into electrical energy, in order to cover the electrical
 202 demands of the house. Further, an air-source heat pump is employed to meet the thermal
 203 demands. The surplus electricity produced by PV panels (if any) is used to drive the
 204 SAHP. The excess electricity is first used for SH and then for DHW, as the coefficient of
 205 performance (COP) of heat pump is higher for SH than for DHW (resulting from the
 206 lower temperature for SH). In the absence of surplus electricity from PV, the heat pump
 207 utilizes the electricity from the grid.
 208
- 209 ○ **[Case II] National Grid + Solar thermal (ST) panels:**

210 The French national grid is used to meet the electrical demands, in this case. ST panels,
 211 i.e. flat plate solar thermal collectors with water as working fluid, are used to suffice the
 212 domestic hot water (DHW) and space heating (SH) demands.

213

214 ○ **[Case III] PV panels + ST panels:**

215 PV panels are employed to meet the electrical demands, while ST panels are used to
 216 supply the thermal requirements of the house. In this case, there is a requirement of a
 217 higher surface area on the roof of the house to accommodate both types of panels.

218

219 ○ **[Case IV] Photovoltaic thermal (PVT) panels:**

220 A PVT panel is combination of PV and ST panels, wherein a working fluid (water or air)
 221 is flown under the PV panel which reduces the solar cell temperature and improves the
 222 electrical efficiency of PV panel. Moreover, the heated fluid is used for thermal
 223 applications. Therefore, PVT panels may meet both the electrical and thermal demands of
 224 the house. The solar cells meet the electrical demands and the heated water from the
 225 outlet of the PVT panels is used for DHW and SH requirements.

226 In order to deal with the intermittence associated with solar energy, the French national grid
 227 and a grid-driven electric boiler are chosen as the auxiliary systems for power generation and
 228 thermal needs (DHW and SH), respectively. Further, a lead-acid battery has been considered
 229 for the storage of electrical energy generated by solar cells in Cases I, III & IV and a water
 230 tank has been used in Cases II-IV for thermal storage. It is important to note that the excess
 231 electricity produced by PV/PVT panels in Cases I, III & IV, is first used to charge the battery
 232 up to its capacity. Then, after the battery capacity is reached, the remaining excess electricity
 233 from PV/PVT panels is sold to the grid. Additionally, the hot water produced by the ST/PVT
 234 panels, is stored in the tank and then the required hot water is utilized as per the demand
 235 profile. It should be noted that the present study does not take into account any seasonal
 236 thermal energy storage. Implementation of a seasonal storage may lead to further
 237 improvements in the solar contribution [8], although the higher investment and maintenance
 238 costs make it economically uncompetitive for small-scale applications.

239 The design parameters of the different components considered in the study have been listed in
 240 Table 1.

241

Table 1: Design and economic parameters considered in the study

Temperature of DHW production	T_{DHW}	65 °C	[39]
Temperature of space heating	T_{SH}	35 °C	[39]
Efficiency of conventional boiler	η_{CB}	0.9	[40]
Electrical efficiency of PV panel	η_{PV}	0.15	[14,41,42]
Area of PV panel	A_{PV}	1.64 m ²	[43,44]
Thermal efficiency of ST panel	η_{ST}	0.80	[45–47]
Area of ST panel	A_{ST}	2 m ²	[48]
Electrical efficiency of PVT panel	$\eta_{PVT,el}$	0.20	[49]
Thermal efficiency of PVT panel	$\eta_{PVT,th}$	0.50	[49]

Area of PVT panel	A_{PVT}	1.64 m ²	[43,44]
COP of SAHP for DHW at 65 °C	$COP_{SAHP}^{65^{\circ}C}$	2	[50]
COP of SAHP for SH at 35 °C	$COP_{SAHP}^{35^{\circ}C}$	3	[50]
Charging efficiency of battery	$\eta_{batt,c}$	0.9	[51,52]
Discharging efficiency of battery	$\eta_{batt,d}$	0.9	[51,52]
Round-trip efficiency of battery	$\eta_{batt,r}$	0.8	[51,52]
Minimum state of charge of battery	SOC_{batt}	30%	[51,52]
Self-discharge rate of battery	s_{batt}	0.5 %/day	[51]
Losses from tank	L_{tank}	20%	[53]
Economic rate of return	i	5%	[21]
Lifetime of the system	n	25 y	[21]
Cost of electricity from the grid	$c_{el,grid}$	0.13 €/kW	[45,54]
Selling price of excess electricity to the grid	$c_{el,sold}$	0.10 €/kW	[55]
Cost of natural gas	c_{ng}	0.0839 €/kW	[56,57]

242

243 2.2 Performance indicators

244 In order to evaluate the different solar combined heating and power systems [Cases I-IV], the
245 following performance indicators based on energy and thermoeconomics have been used.

246 The hourly electrical energy generated by the PV panels [Cases I & III] is calculated as:

$$E_s(t) = N \cdot \eta_{PV} I_G(t) A_{PV} \quad (1)$$

247 where, N is the number of panels (PV, in these cases) and $I_G(t)$ is the hourly global solar
248 radiation. η_{PV} and A_{PV} are the electrical efficiency and area, respectively, of a PV panel.

249 The hourly thermal energy produced by ST panels [Cases II & III] can be computed as:

$$Q_s(t) = N \cdot \eta_{ST} I_G(t) A_{ST} \quad (2)$$

250 where, N is the number of panels (ST, in these cases), η_{ST} and A_{ST} are the thermal efficiency
251 and area, respectively, of an ST panel.

252 The hourly thermal energy produced by ST panels for DHW production ($Q_{s,DHW}$) is
253 evaluated as follows:

$$Q_{s,DHW}(t) = Q_s(t) \cdot r_{d,DHW} \quad (3)$$

254 where, $r_{d,DHW}$ denotes the ratio of the annual domestic hot water (DHW) demand to the
255 annual thermal demand (including domestic hot water and space heating). The value of
256 $r_{d,DHW}$ has been computed as 53.88%.

257 Similarly, $Q_{s,SH}(t)$ can be obtained by multiplying $Q_s(t)$ with the factor $(1 - r_{d,DHW})$. It
258 should be noted that if the hourly DHW and SH demands are lower than $Q_{s,DHW}(t)$ and
259 $Q_{s,SH}(t)$, respectively, the remaining energy is stored in the tank. The stored energy can be

260 then used either in the same hour to meet the other heating demand (if required) or stored for
261 use in the following hours.

262 The hourly electrical energy ($E_s(t)$) and hourly thermal energy ($Q_s(t)$) produced by PVT
263 panels [Case IV] can be obtained by substituting η_{PV} with $\eta_{PVT,el}$ and $\eta_{PVT,th}$, respectively,
264 and A_{PV} with A_{PVT} in Eqs. (1) and (2).

265 The hourly thermal energy produced by solar-assisted heat pump (SAHP) employed in Case
266 I, for domestic hot water (DHW) production and space heating (SH) can be evaluated by
267 multiplying the respective COPs (Table 1) with the input electrical energy. The input
268 electrical energy to drive the SAHP comes from the excess electricity produced by PV
269 panels, battery storage or from the grid. First and foremost, the excess electricity from PV
270 panels, i.e. $E_s(t) - E_d(t)$, is used to run the SAHP in order to meet the thermal demands.
271 The remaining electrical energy required to satisfy the thermal demands is supplied from the
272 battery storage and then from the grid (if required). Q_{SAHP}^{DHW} and Q_{SAHP}^{SH} denote the component
273 of thermal energy produced by SAHP by utilizing the electricity from PV panels and battery
274 to meet the corresponding thermal demand. If the excess electricity from PV panels is not
275 sufficient to meet both the thermal demands, then the electricity from PV is first used to meet
276 the space heating demand ($Q_{d,SH}(t)$) and then the domestic hot water demand ($Q_{d,DHW}(t)$)
277 due to the higher coefficient of performance for space heating ($COP_{SAHP}^{35^\circ C}$, Table 1).

278 The hourly electrical energy ($E_s(t)$) produced by the solar panels [Case I, III & IV] is first
279 used to meet the hourly electrical demand ($E_d(t)$), wherein two cases arise. If $E_s(t) \leq E_d(t)$,
280 the total hourly electrical energy ($E_s(t)$) produced by PV/PVT panels is utilized to meet the
281 demand. The remaining demand is either met from the battery or the grid (if battery cannot
282 meet the demand). In the second case, if $E_s(t) > E_d(t)$, the extra electricity from solar panels
283 will first be used to charge the battery up to the limit of its maximum capacity. After charging
284 the battery, the remaining electricity from solar panels, if any, is sold to the grid ($E_{sold}(t)$). If
285 at any step the battery charge falls below the minimum state of charge, SOC_{batt} (Table 2),
286 then it is charged from the grid to maintain the SOC_{batt} . Also, a self-discharge rate (s_{batt} ,
287 Table 2) of 0.5% per day has been considered for the battery.

288 The hourly thermal energy for DHW production ($Q_{s,DHW}(t)$) generated by ST/PVT panels
289 [Case II–IV] is stored in the water tank and then used to satisfy the hourly demand
290 ($Q_{d,DHW}(t)$). At the $t + 1^{th}$ hour, $Q_{s,DHW}(t + 1)$ is added to the remaining thermal energy
291 available in the tank from the previous hour ($Q_{store,DHW}(t)$), i.e. $Q_{store,DHW}(t + 1) =$
292 $Q_{s,DHW}(t + 1) + Q_{store,DHW}(t)$. During each hour, the thermal energy available in the tank
293 ($Q_{store,DHW}(t)$) will be used to meet the demand ($Q_{d,DHW}(t)$). If $Q_{d,DHW}(t) > Q_{store,DHW}(t)$,
294 the auxiliary system, i.e. grid + electric boiler, is used to provide the remaining thermal
295 energy. Further, the tank loses 20% (L_{tank} , Table 2) of the thermal energy stored within the
296 tank every hour.

297 The hourly useful electrical energy ($E_u(t)$), hourly useful thermal energy for DHW
298 production ($Q_{u,DHW}(t)$) and for space heating ($Q_{u,SH}(t)$) produced by solar panels

299 (PV/ST/PVT) correspond to the hourly energy produced by the panels which is used to meet
 300 the electrical demand, DHW demand and SH demand, respectively.

$$E_u(t) = \begin{cases} E_s(t) + \Delta E_{store}(t) & \text{if } E_s(t) \leq E_d(t) \\ E_d(t) & \text{if } E_s(t) > E_d(t) \end{cases} \quad (4)$$

301 where $\Delta E_{store}(t)$ is the electrical energy utilized from battery storage (which has been
 302 charged through solar panels) in order to meet the remaining demand ($E_d(t) - E_s(t)$).

303 Similarly, $Q_{u,DHW}(t)$ and $Q_{u,SH}(t)$ can be evaluated, as follows:

$$Q_{u,DHW}(t) = \begin{cases} Q_{store,DHW}(t) & \text{if } Q_{store,DHW}(t) \leq Q_{d,DHW}(t) \\ Q_{d,DHW}(t) & \text{if } Q_{store,DHW}(t) > Q_{d,DHW}(t) \end{cases} \quad (5)$$

304 where, $Q_{store,DHW}(t)$ denotes the hourly thermal energy available in the DHW tank, after
 305 adding the hourly thermal energy produced by solar panels ($Q_{s,DHW}(t)$) and the remaining
 306 thermal energy in the tank from the previous hour ($Q_{store,DHW}(t-1)$).

$$Q_{u,SH}(t) = \begin{cases} Q_{s,SH}(t) & \text{if } Q_{s,SH}(t) \leq Q_{d,SH}(t) \\ Q_{d,SH}(t) & \text{if } Q_{s,SH}(t) > Q_{d,SH}(t) \end{cases} \quad (6)$$

307 where, $Q_{d,SH}(t)$ represents the hourly space heating demand.

308 It should be noted that a storage for space heating has not been implemented in the present
 309 study. Also, if $Q_{s,SH}(t) \leq Q_{d,SH}(t)$, the remaining space heating demand is met using the
 310 auxiliary system, i.e. grid + electric boiler.

311 Solar self-production (ϕ_{sp}) and self-consumption (ϕ_{sc}) are two significant indicators when
 312 dealing with solar-driven systems. Solar self-production can be defined as the ratio of total
 313 useful energy produced by solar panels to the total demand, and is given by:

$$\phi_{sp} = \frac{\sum E_u(t) + \sum Q_{u,DHW}(t) + \sum Q_{u,SH}(t)}{\sum E_d(t) + \sum Q_{d,DHW}(t) + \sum Q_{d,SH}(t)} \quad (7)$$

314 where, $\sum E_d(t)$, $\sum Q_{d,DHW}(t)$ and $\sum Q_{d,SH}(t)$ represent the total annual electrical, DHW and
 315 SH demands, respectively.

316 Solar self-consumption is the ratio of total useful energy produced by solar panels to the total
 317 energy produced by the solar panels, defined as:

$$\phi_{sc} = \frac{\sum E_u(t) + \sum Q_{u,DHW}(t) + \sum Q_{u,SH}(t)}{\sum E_s(t) + \sum Q_{s,DHW}(t) + \sum Q_{s,SH}(t)} \quad (8)$$

318 The effective present cost (P_{eff}) is the total investment cost, taking into consideration the
 319 costs of replacing certain components (R) of the system, if any, in present value, and is
 320 obtained using:

$$P_{eff} = P + R \left[\frac{1}{(1+i)^l} + \frac{1}{(1+i)^{2l}} + \dots + \frac{1}{(1+i)^{j \cdot l}} \right] \quad (9)$$

321 where, P is the principal investment cost of the system, i is the rate of return and l is the
 322 operational lifetime of the component. The term $j \cdot l$ denotes the highest multiple of l less
 323 than n (system lifetime). Thus, $j \cdot l$ signifies that the component is replaced j times before the
 324 system lifetime is over.

325 The net present cost (P_{net}) of the system is the total present value of all the costs associated
 326 with the system, including the effective present cost, operation and maintenance cost and
 327 salvage value at the end of the system lifetime (n years). P_{net} is calculated as:

$$P_{net} = P_{eff} + O\&M \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] - S(1+i)^{-n} - c_{el,sold} \cdot \sum E_{sold}(t) \quad (10)$$

328 where, $O\&M$ is the total operation and maintenance cost of the system, S is the salvage value
 329 at the end of the system lifetime and $\sum E_{sold}(t)$ is the total excess electricity produced by
 330 PV/PVT panels which is sold to the grid.

331 The total unit cost of products ($c_{p,total}$) represents the total cost incurred (including the
 332 principal investment, operation, maintenance and replacement costs) per kWh of energy
 333 produced by the system. $c_{p,total}$ is computed as per the following relation:

$$c_{p,total} = \frac{P_{net} \cdot CRF}{\sum E_d(t) + \sum Q_{d,DHW}(t) + \sum Q_{d,SH}(t)} \quad (11)$$

334 where, CRF denotes the capital recovery factor, given by:

$$335 \quad CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

336 Further, the total unit cost of products ($c_{p,total}$) can be dissociated based on the type of
 337 product into unit cost of electricity ($c_{p,el}$) and unit cost of thermal energy ($c_{p,th}$). In order to
 338 calculate the dissociated unit cost of products ($c_{p,el}, c_{p,th}$), P_{net} for the complete system in
 339 Eq. (11) is replaced by net present cost for just the respective sub-system ($P_{net,el}$ or $P_{net,th}$).
 340 Similarly, the denominator in Eq. (11), i.e. $\sum E_d(t) + \sum Q_{d,DHW}(t) + \sum Q_{d,SH}(t)$, is replaced
 341 with the respective demand ($\sum E_d(t)$ or $\sum Q_{d,DHW}(t) + \sum Q_{d,SH}(t)$). Additionally, the unit
 342 cost of domestic hot water ($c_{p,dhw}$) and unit cost of space heating ($c_{p,sh}$) can be evaluated by
 343 segregating the unit cost of thermal energy ($c_{p,th}$). $P_{net,th}$ is dissociated into the DHW and
 344 SH components by multiplying with the fraction of the respective annual demands with
 345 respect to the total thermal demand.

$$\begin{aligned} P_{net,th,DHW} &= P_{net,th} \frac{\sum Q_{d,DHW}(t)}{\sum Q_{d,DHW}(t) + \sum Q_{d,SH}(t)} \\ &= P_{net,th} \cdot r_{d,DHW} \end{aligned} \quad (12)$$

$$P_{net,th,SH} = P_{net,th} \frac{\sum Q_{d,SH}(t)}{\sum Q_{d,DHW}(t) + \sum Q_{d,SH}(t)}$$

$$= P_{net,th} \cdot (1 - r_{d,DHW}) \quad (13)$$

346 Fuel savings (F_{sav}) corresponds to the total savings in kWh/y due to the incorporation of
 347 renewable solar technologies. It is equal to the portion of demands (electric + domestic hot
 348 water + space heating) met through renewable solar energy.

$$F_{sav} = \sum E_u(t) + \sum Q_{u,DHW}(t) + \sum Q_{u,SH}(t) \quad (14)$$

349 The principal investment cost (P), maintenance cost (M) and operational lifetime (l) of
 350 different components considered in this study are given in Table 2. Operation cost (O)
 351 includes the fuel cost required to operate the system over its lifetime. The operation cost (O)
 352 for different systems is evaluated based on the specific fuel costs of electricity from the grid
 353 ($c_{el,grid}$) and natural gas (c_{ng}) given in Table 1. Since, solar energy is freely available, the
 354 fuel cost for the portion of the demands met using solar-driven components, namely PV, ST,
 355 PVT and SAHP (when the heat pump is powered by solar energy), is considered to be zero.
 356 Therefore, in the cases with solar-driven components, O represents the cost of fuel required to
 357 meet the demands when solar radiation is not sufficient or not available (i.e. through the
 358 auxiliary system).

359 Table 2: Economic data used in the numerical study

Component	P	M	l	Ref.
Conventional gas boiler	4500 €	105 €/y	15 y	[21,45,58]
Electric boiler (auxiliary system)	600 €	10% of P	15 y	[21,47]
PV panel	3110 €/kW _{el}	68.1 €/kW _{el} /y	25 y	[21,47]
SAHP (air-source)	1250 €/kW _{th}	40 €/kW _{th} /y	17 y	[21,47]
ST panel	1060 €/m ²	15 €/m ² /y	20 y	[21,47]
PVT panel	60% of PV + ST	60% of PV + ST	25 y	[21,47]
Battery storage	140 €/kW	11.5 €/kW/y	6 y	[51]
DHW tank	51 c€/L	2% of P	25 y	[59]

360

361 2.3 Thermo-economic optimization

362 As the number N of solar panels (PV/ST/PVT) is increased, the energy production from clean
 363 renewable resources increases (Eqs. (1) and (2)) implying a lower reliance on the backup
 364 grid. However, the principal investment cost, and also, the operation and maintenance costs
 365 (Table 2) increase for a higher number of solar panels, N . Hence, there is a need to determine
 366 an optimal value of N in order to strike a balance between the costs and energy produced
 367 from solar panels. Further, the storage capacity would directly impact the energy output from
 368 solar-driven components, but as the storage capacity increases, the principal investment and
 369 operation and maintenance costs also increase (Table 2). Thus, both the battery storage
 370 capacity and DHW tank capacity need to be optimized.

371 In this study, a thermo-economic optimization of each system [Cases I-IV] has been
 372 performed using genetic algorithm, thanks to its reliability. No significant deviations are

373 observed in the literature compared to other meta-heuristic optimization algorithms such as
374 particle swarm optimization [60], cuckoo search [61], differential evolution [61], water cycle
375 [62] and moth-flame [62] algorithms. Genetic algorithm is a bio-inspired randomized search
376 algorithm which mimics the natural evolution process according to the rule of survival of the
377 fittest [63]. The algorithm begins by generating a random initial population. A population
378 consists of individual solutions in the search space, wherein the fitness of each solution in the
379 search space is evaluated. The algorithm then generates the subsequent population of the next
380 generation by considering the current population as parents following the processes of
381 selection, mutation and crossover. MATLAB 2019b software has been used to implement the
382 genetic algorithm optimization for Cases I-IV. The parameters to be optimized are the
383 number of solar panels (PV/ST/PVT for Cases I/II/IV, respectively, or both PV and ST for
384 Case III), battery size (in kWh) [Cases I, III & IV] and DHW tank capacity (in L) [Cases II-
385 IV]. The total unit cost of products, $c_{p,total}$ (Eq. (11)) has been used as the fitness function to
386 be minimized during optimization. Integer constraints have been put on the number of panels
387 (N) and the DHW tank capacity. The initial population size and the maximum number of
388 generations have been set to 50 and 200, respectively. The scattered crossover function,
389 ‘crossoverscattered’, and gaussian mutation function, ‘mutationgaussian’, have been used for
390 crossover and mutation, respectively. The scattered crossover function combines two
391 individual solutions, or parents, to form a crossover child for the next generation by creating
392 a random binary vector. The crossover child includes the elements from the first parent where
393 the vector value is 1, while the elements from the second parent are selected where vector
394 value is 0. The gaussian mutation function makes small random changes in individual
395 solutions to produce mutation children by adding a random number from a gaussian
396 distribution to each element of the parent vector. The mean of the gaussian distribution is
397 zero and standard deviation is set by the parameters scale, shrink and the population range.
398 The scale and shrink parameters govern the standard deviation at the first generation and the
399 decline in standard deviation between generations, respectively. Both the scale and shrink
400 parameters are set to the default value of 1 in the gaussian mutation function
401 ‘mutationgaussian’.

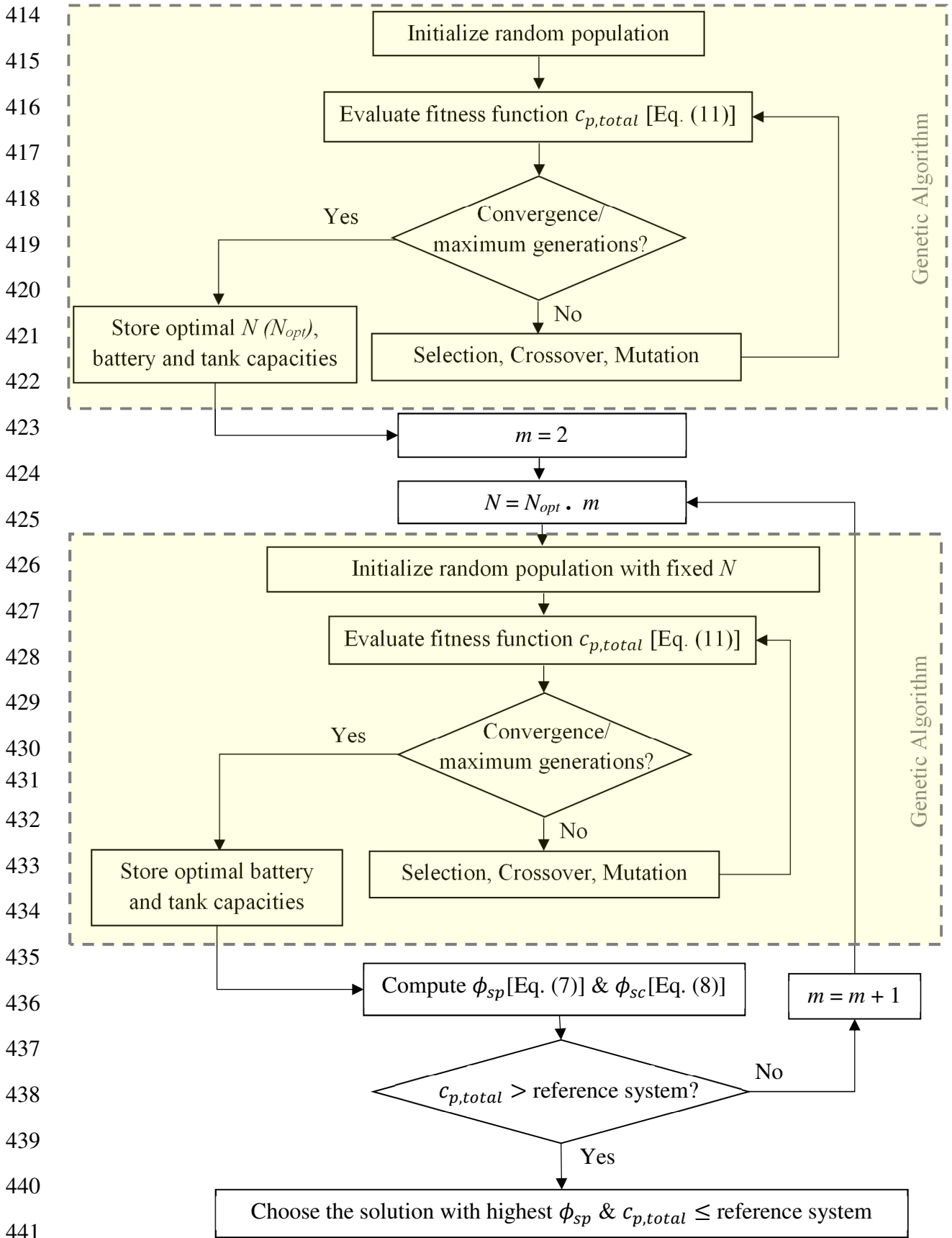
402 The methodology followed for thermoeconomic optimization has been presented in Fig. 2.
403 The stopping criteria may be convergence of the algorithm to an optimal solution or if the
404 maximum number of generations have been reached. The optimization based on $c_{p,total}$ alone
405 focuses on minimizing the costs, as expected. However, a marginal increase in $c_{p,total}$ may
406 be acceptable if it means less reliance on the auxiliary system (i.e. based on the grid) or
407 alternatively, a higher solar self-production (Eq. (7)). Therefore, a variation of solar self-
408 production (ϕ_{sp}) and self-consumption (ϕ_{sc}) with $c_{p,total}$ needs to be studied for an in-depth
409 analysis and selection of the best solution for each system [Cases I-IV].

410

411

412

413



442 Fig. 2: Thermoeconomic optimization based on genetic algorithm applied to the solar
443 combined heating and power systems

444 **3 Results**

445 The methodology shown in Fig. 2 has been used for each solar combined heating and power
 446 system [Cases I-IV] in order to determine the best solution (i.e. optimal design) minimizing
 447 the unit product cost, for each case. Thereafter, the best solutions for Cases I-IV are
 448 compared against each other in terms of the energy provided from solar-driven components
 449 and energy requirement from grid. Furthermore, the Cases I-IV and the reference case are
 450 also compared by evaluating the fuel savings, F_{sav} (Eq. (14)), and the dissociated unit product
 451 costs ($c_{p,el}$, $c_{p,dhw}$ and $c_{p,sh}$).

452 **3.1 Optimization of system size and storage capacity [Cases I-IV]**

453 Table 3 presents the optimal values of N (number of solar panels) and storage capacities for
 454 Cases I-IV. As the number of solar panels and the storage capacities are varied, the principal
 455 investment cost (P), operation & maintenance cost ($O\&M$) and salvage value (S) (Table 2)
 456 and the total excess electricity from solar panels sold to the grid ($\sum E_{sold}(t)$) also change.
 457 Consequently, the net present cost (P_{net}) varies as well. The results from genetic algorithm
 458 are based on the minimization of the total unit product cost, $c_{p,total}$ (Eq. (11)). Furthermore,
 459 $c_{p,total}$ for the reference case is calculated from Eq. (11). The design and economic
 460 parameters given in Table 1 have been used to evaluate the results.

461 Table 3: Optimal number of solar panels (N_{opt}), battery size, water tank capacity for Cases I-
 462 IV and the corresponding $c_{p,total}$ and solar indices

	PV panels	ST panels	Battery capacity (kWh)	DHW tank capacity (L)	$c_{p,total}$ (€/kWh)	ϕ_{sp}	ϕ_{sc}
Ref Case	-	-	-	-	0.1836	-	-
Case I	1	-	0	-	0.1080	10%	100%
	0	-	0	-	0.1044	-	-
Case II	-	1	-	100	0.1483	24%	70%
	-	0	-	0	0.1482	-	-
Case III	1	1	0	100	0.1521	29%	72%
	0	0	0	0	0.1482	-	-
Case IV		1	0	100	0.1419	21%	82%
		0	0	0	0.1482	-	-

463

464 It can be seen from Table 3 that incorporating PV or ST or PVT panel allows to reduce the
 465 total unit product cost ($c_{p,total}$) compared to the reference case (up to -41%, for Case I).
 466 Therefore, an introduction of solar panels not only improves the solar indices, and
 467 subsequently the environmental impact, but also lowers the total unit product cost of the
 468 reference system. The reference system, in the present study, is a combination of the French
 469 national grid and conventional gas boiler as it remains one of the most commonly used
 470 systems in typical French households.

471 Further, as shown in Table 3, the total unit product cost ($c_{p,total}$) in Case I increases when a
 472 PV panel is employed. It is worthwhile to note here that in the absence of solar panels

473 (PV/ST/PVT), the values of $c_{p,total}$ denote the costs associated with the auxiliary systems
474 (grey values in Table 3). Thus, heat pump when coupled to the grid (i.e. auxiliary system for
475 Case I) turns out to be the best solution economically, however without any solar production.
476 Therefore, the minimum number of PV panels in Case I was set to one to facilitate a
477 comparison between different solar technologies. This in turn also allows for better solar
478 production indices and lower environmental impact of the system. A similar result is
479 observed for Case III, wherein the $c_{p,total}$ from the auxiliary system (i.e. without PV/ST
480 panels) is lower than the $c_{p,total}$ with single PV and ST panels. Another important point to
481 observe for Case III is that the solution with a unit ST panel and no PV panel is in fact the
482 same as Case II (grid + ST). Thus, the minimum number of solar panels (both PV and ST)
483 were set to unity to obtain unique cases for a comprehensive comparison. Moreover, the
484 implementation of ST panels [Case II] is economically competitive, to the auxiliary system
485 grid + electrical boiler), with higher renewable production rates (ϕ_{sp} and ϕ_{sc}). Furthermore,
486 introduction of a PVT panel [Case IV] is found to be more beneficial in terms of both
487 economics and solar performance indices.

488 A preliminary comparison amongst the cases listed in Table 3 shows that a heat pump (driven
489 by grid or PV) significantly decreases the total unit product cost (with the economically best
490 solution when coupled to the grid, though without any solar contribution). PV panel remains
491 more expensive than the grid (in the absence of any subsidies). However, the solar self-
492 production index (ϕ_{sp}) slightly increases when a PV panel is employed. Moreover, a 100%
493 solar self-consumption (ϕ_{sc}) in Case I with unit PV panel contributes to an increase in the
494 profitability of the system. Case III is economically inferior to Case II owing to the
495 implementation of PV; however, it improves the solar indices (ϕ_{sp} and ϕ_{sc}). PVT [Case IV]
496 appears to be the best alternative with lower total unit product cost (excluding the heat pump-
497 based solutions in Case I) and reasonable solar indices.

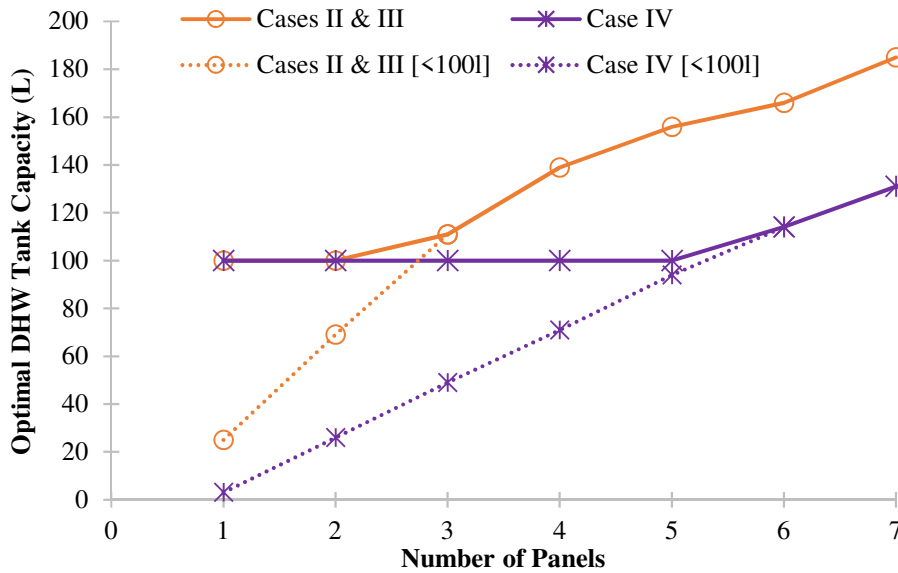
498 Furthermore, the optimal battery capacity in each case where battery is considered [Cases I,
499 III & IV] is 0 kWh, i.e. no battery. This observation is in accordance with the results reported
500 by Behzadi et al. [25], wherein the removal of battery was found to significantly reduce the
501 investment costs. The additional investment cost plus the extra operational costs, related to
502 the self-discharge rate and the need to maintain a minimum state of charge (SOC_{batt}) of 30%
503 in the battery justify not to implement electric storage, as the national grid can handle
504 electricity production in excess and in deficit at low cost.

505 In order to satisfy the DHW demand, a minimum value of 100 L has been assigned to the
506 DHW tank capacity, adequate for an average 2-person household with a consumption of
507 roughly 50 L/person per day. Similarly, the operational benefits of implementing thermal
508 storage [Cases II to IV] for further valorisation of the heat produced is counterbalanced by
509 the corresponding additional investment cost. Thus, unit production cost overpasses the
510 reference case for higher capacities, mainly due to the heat losses considered.

511 As stated earlier, an optimization based on $c_{p,total}$ alone minimizes the costs, but does not
512 take into account the solar self-production (ϕ_{sp}). Hence, the solar self-production of the
513 optimal solutions for Cases I–IV given in Table 3 is quite low, i.e. 10%–29%. An increase in

514 $c_{p,total}$ may be considered acceptable if it leads to a higher solar self-production. Therefore,
 515 the effect of increasing the number of solar panels in each case (in order to achieve higher
 516 solar self-production) has been studied. In order to conduct this study, the optimal storage
 517 capacities are determined using genetic algorithm as the number of solar panels (N) are
 518 increased, for Cases I-IV.

519 The optimal battery capacity remains 0 kWh as the number of solar panels (PV/PVT) are
 520 increased [Cases I, III & IV]. Thus, from an economic standpoint, the systems without battery
 521 perform better than with a battery. Fig. 3 shows the variation of the optimal DHW tank
 522 capacities with the number of panels (ST/PVT) for Cases II-IV. The optimal DHW tank
 523 capacities in the absence of the 100 L minimum capacity constraint are shown with dashed
 524 lines. The optimal DHW tank capacity increases almost linearly (~ 19 L/kW_{peak}) with the
 525 number of solar panels for all the cases, highlighting the needs for thermal storage capacity to
 526 valorise locally large heat production, as the excess heat requirement cannot be supported by
 527 an external network, as for electricity.

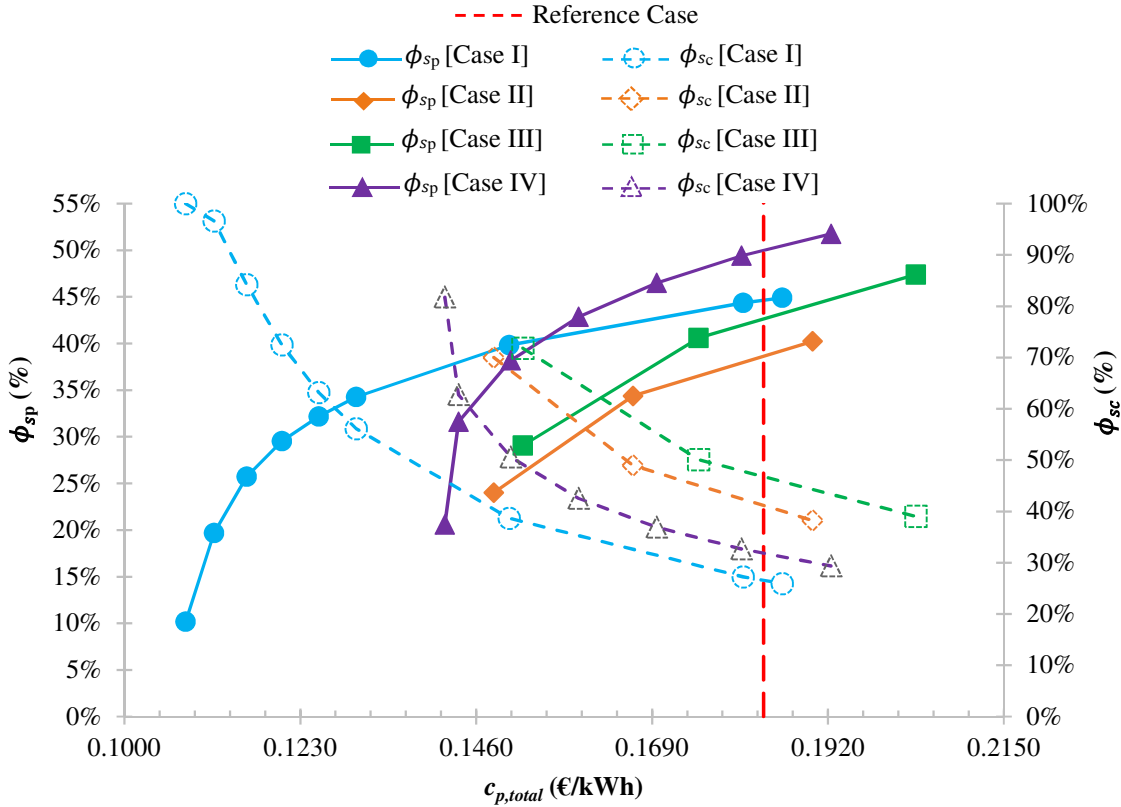


528

529 Fig. 3: Variation of optimal DHW tank capacity with number of solar panels for Cases II-IV

530 Fig. 4 portrays the influence of increasing the number of solar panels on $c_{p,total}$ and the solar
 531 indices for Cases I-IV. At each point, the respective optimal DHW tank capacity (from Fig.
 532 3) has been used in order to study the variation of solar indices with $c_{p,total}$. As expected,
 533 $c_{p,total}$ increases with the number of solar panels, and therefore, the leftmost point on each
 534 line represents the lowest number of panels and vice versa. This result is in agreement with
 535 those observed in [64], stating that the associated costs increase in case of a higher solar
 536 output (or efficiency). As justified by Table 3, the absolute optimal design for each solution
 537 [Cases I-IV] from an economic standpoint, considering a non-zero solar contribution, is to
 538 have a unit solar panel. However, these designs for Cases I-IV have fairly low solar self-
 539 production (ϕ_{sp}) ranging from 10% to 29%, leading to a substantial reliance on the auxiliary
 540 system based on the grid. If the number of solar panels or consequently, the surface area of
 541 solar panels is increased, the solar self-production (ϕ_{sp}) improves, but the total unit product

542 cost ($c_{p,total}$) also rises. It has been illustrated in Fig. 4 that as the value of $c_{p,total}$ increases,
 543 owing to an increase in number of solar panels, the solar self-production (ϕ_{sp}) increases,
 544 while solar self-consumption (ϕ_{sc}) decreases for all the cases. Thus, a compromise between
 545 the economic gains (low $c_{p,total}$) and the environmental impact (high ϕ_{sp}) needs to be
 546 reached. In the present study, the environmental impact is favoured up until positive
 547 economic gains are achieved with respect to the reference system. In other words, the highest
 548 value of ϕ_{sp} is preferred while keeping $c_{p,total}$ lower than the $c_{p,total}$ of the reference system
 549 (depicted by a red dashed line in Fig. 4).



550
 551 Fig. 4: Variation of solar self-production (ϕ_{sp}) and self-consumption (ϕ_{sc}) with total unit
 552 product cost for Cases I-IV

553 Therefore, the design with the highest self-production (ϕ_{sp}) and $c_{p,total}$ limited up to the
 554 $c_{p,total}$ of the reference case (0.1836 €/kWh), is chosen as the optimal design for each
 555 system. The chosen optimal design for each system [Cases I-IV], from Fig. 4, is given in
 556 Table 4.

557 Table 4: Optimal designs for solar combined heating and power systems [Cases I-IV]

	PV panels	ST panels	Battery capacity (kWh)	DHW tank capacity (L)	$c_{p,total}$ (€/kWh)	ϕ_{sp}	ϕ_{sc}
Case I	16	-	0	-	0.1809	44%	27%
Case II	-	2	-	100	0.1665	34%	49%
Case III	2	2	0	100	0.1751	41%	50%

Case IV	6	0	114	0.1807	49%	33%
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558

559 Thanks to the energy management flexibility offered by the national electric grid, the number
560 of PV panels could be increased up to 16 (3.9 kW_{peak}, 26 m²) without overpassing the
561 reference unit production cost, leading to a self-production index close to 50%, with SAHP
562 [Case I]. Inversely, solar thermal-based solutions lead to a smaller installation as a larger
563 solar self-consumption index has to be targeted to limit excess heat production that cannot be
564 valorised, as for electricity [Cases II and III]. Hybrid PVT solution [Case IV] sizing results
565 from a compromise between the flexible use of electricity thanks to the grid and the
566 constrained use of heat.

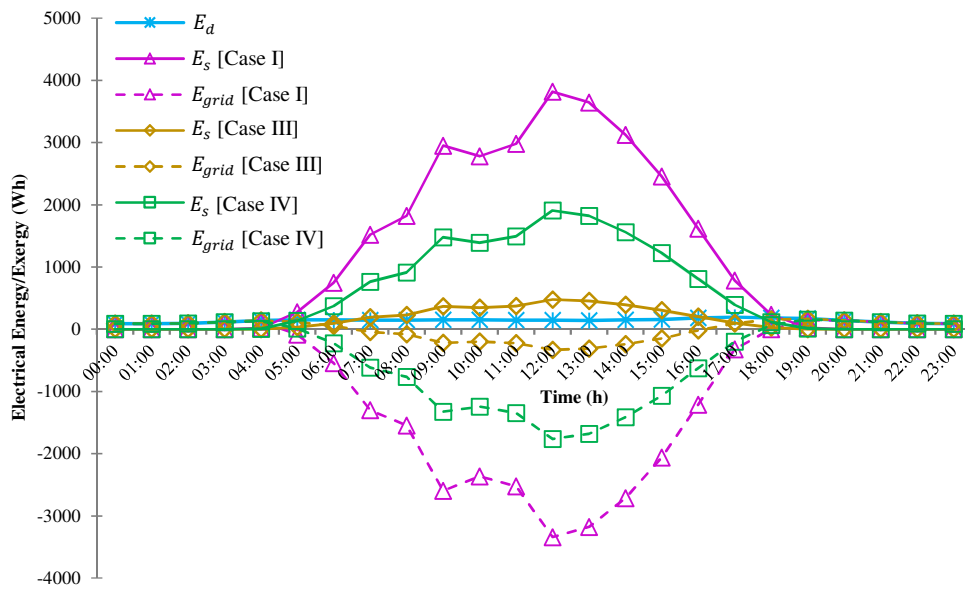
567 3.2 Comparison of different energy systems with optimal design

568 Figs. 5a and 5b show the hourly variations of electrical demand (E_d), electricity generated by
569 solar panels (E_s) and electricity requirement from the grid (E_{grid}) for the optimal designs of
570 Cases I, III & IV (Table 4) for the two typical days depicted in Figs. 1a and 1b, respectively.
571 As illustrated in the figures, the electrical energy generated from PV is the highest in Case I,
572 followed by Cases IV and III, since the number of PV/PVT panels is the highest in Case I,
573 then Case IV and Case III (Table 4). Consequently, the electricity requirement from the grid
574 is also the lowest in Case I. It is worthwhile to note that a negative value of E_{grid} signifies
575 that the excess electricity from PV/PVT panels is sold to the grid. Also, the grid is used to
576 meet the electrical demand (i.e. $E_{grid} = E_d$) during off sunshine hours ($I_G = 0$ W/m²) for
577 both typical summer and winter days. Furthermore, since the grid is used to meet the
578 electrical demands in the Reference case and in Case II, E_{grid} is equal to the electrical
579 demand (E_d) in these cases.

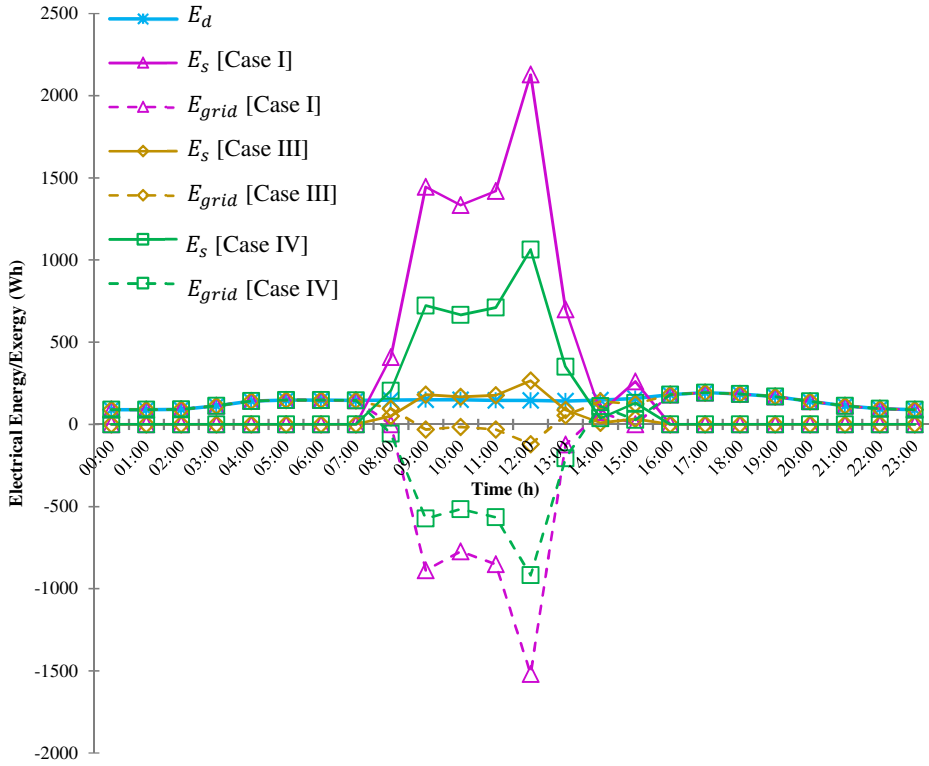
580 The hourly variations of DHW demand ($Q_{d,DHW}$), useful thermal energy produced by solar-
581 driven solutions for DHW ($Q_{u,DHW}$) and thermal energy required from the grid + electric
582 boiler for DHW (Q_{grid}) for the optimal designs of Cases II–IV (Table 4) for a typical
583 summer day (Fig. 1a) and a typical winter day (Fig 1b) are portrayed in Figs. 6a and 6b,
584 respectively. During peak sunshine hours, in both summers and winters, the DHW demand is
585 completely met using solar energy ($Q_{u,DHW}$) for all the Cases I–IV. Case I requires support of
586 the auxiliary system (Q_{grid}) the earliest, i.e. at 18:00h in Fig. 6a and at 14:00 h in Fig. 6b.
587 This is because there is no storage tank in this case to store DHW for use during low sunshine
588 hours. Following Case I, Cases II & III are the next systems to require Q_{grid} , at 20:00 h in
589 Fig. 6a and at 14:00 h in Fig. 6b. Cases II & III have the same number of ST panels and
590 DHW tank capacity (Table 4), therefore they show the same results. Finally, Case IV requires
591 the auxiliary system (Q_{grid}) at 22:00 h in Fig. 6a and at 17:00 h in Fig. 6b. This is due to the
592 higher number of solar panels and DHW tank capacity in Case IV, than Cases II & III.

593 Figs. 7a and 7b depict the hourly variations of space heating demand ($Q_{d,SH}$), useful thermal
594 energy generated by solar-driven solutions ($Q_{u,SH}$) and thermal energy required from the grid
595 + electric boiler (Q_{grid}) for space heating for Cases I–IV for a typical summer day (1st July)

596 and a typical winter day (1st January), respectively. The optimal designs for Cases I–IV given
 597 in Table 4 have been used to obtain the results. As shown in Fig. 7a, there is no requirement
 598 from the grid in any system [Case I–IV] on a typical summer day during sunshine hours from
 599 05:00 h to 18:00 h. After 18:00 h, the solar radiation becomes very low at 19:00 h and from
 600 20:00 h onwards there is no solar radiation. After 19:00 h, all the systems rely on the
 601 auxiliary system to meet the space heating demand. This is observed since there is no storage
 602 implemented for space heating in the present study. However, during the typical winter day
 603 (Fig. 7b) since the solar radiation is much lower in magnitude, the auxiliary system is
 604 required even during the sunshine hours. The absence of storage for space heating may have
 605 contributed to this result.



a. for Cases I, III & IV on a typical summer day (1st July 2016)



610

611

b. for Cases I, III & IV on a typical winter day (1st January 2016)

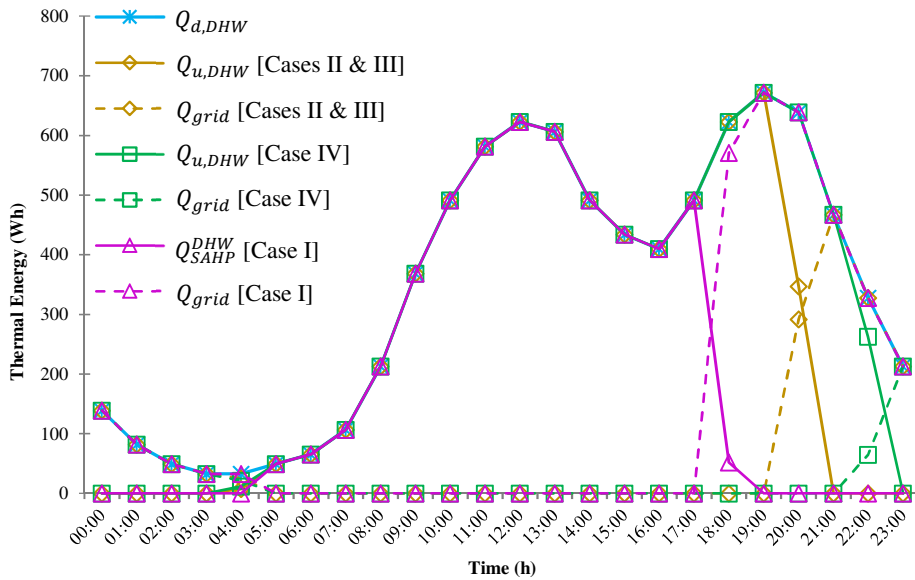
612

Fig. 5: Hourly variation of solar radiation, electrical demand, E_s and E_{grid} for two typical

613

representative days

614

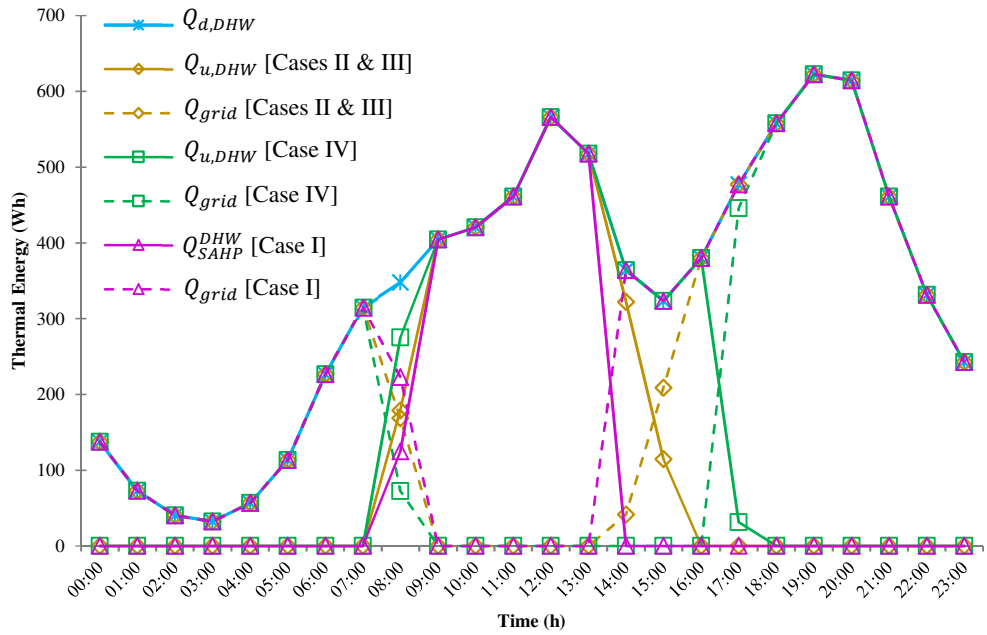


615

616

a. for Cases I-IV on a typical summer day (1st July 2016)

617



618

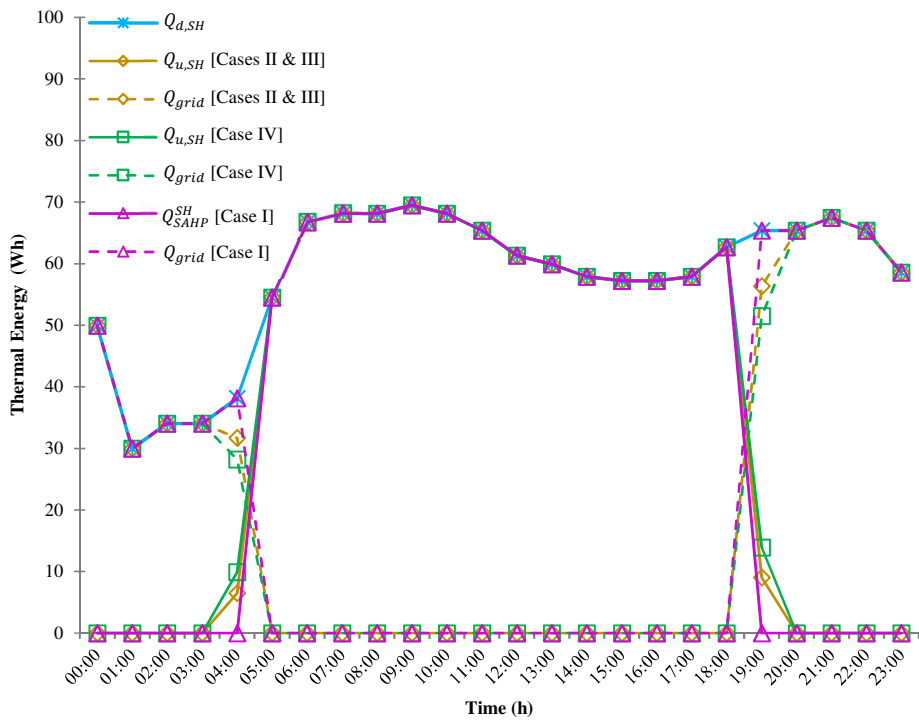
619

b. for Cases I–IV on a typical winter day (1st January 2016)

620

Fig. 6: Hourly variation of solar radiation, DHW demand, useful thermal energy for DHW
621 from solar-based solutions and Q_{grid} for two typical representative days

622



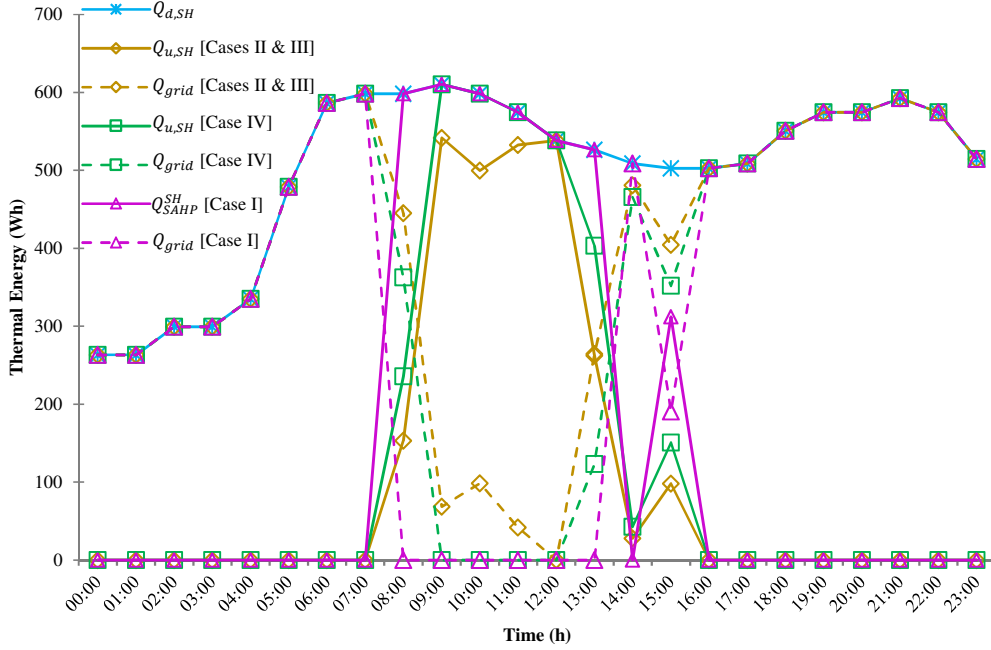
623

624

a. for Cases I–IV on a typical summer day (1st July 2016)

625

626



627

628

b. for Cases I–IV on a typical winter day (1st January 2016)

629

Fig. 7: Hourly variation of solar radiation, SH demand, useful thermal energy for SH from solar-based solutions and Q_{grid} for two typical representative days

630

631

Moreover, it can be seen from Fig. 7b that for a typical winter day, $Q_{u,SH}$ is the highest for Case I, followed by Case IV, while Cases II & III have the lowest value of $Q_{u,SH}$. This is due to the highest number of PV panels in Case I, which are used to drive the SAHP for space heating. Case IV has six PVT panels, which is greater than two ST panels in Cases II & III, thus, Case IV produces more thermal energy than Cases II & III. Subsequently, the requirement from the auxiliary system (Q_{grid}) is the highest in Cases II & III, followed by Case IV and Case I. It should be noted that the entire thermal demand ($Q_{d,SH} + Q_{d,DHW}$) is met using the conventional gas boiler in the Reference case. Thus, a fuel cost corresponding to the cost of natural gas (c_{ng}) given in Table 1, contributes to the operation cost (O) of the reference system.

640

641

The fuel savings (F_{sav}), total and dissociated unit product costs ($c_{p,total}$, $c_{p,el}$, $c_{p,dhw}$ and $c_{p,sh}$) for the reference system and the different solar combined heating and power systems [Cases I–IV] are given in Table 5. The fuel savings (F_{sav}) are the highest in Case IV, followed by Case I, Case III and Case II. This means that the total annual useful energy, i.e. $\sum E_u(t) + \sum Q_{u,DHW}(t) + \sum Q_{u,SH}(t)$, produced by Case IV is the highest as per Eq. (14). This is also in accordance with the results presented in Table 4, wherein Case IV has the highest solar self-production (ϕ_{sp}). The fuel savings (F_{sav}) in the Reference case is zero since the reference system consists of the grid and conventional gas boiler, and does not have any contribution from solar energy. Moreover, the unit product cost of electrical energy ($c_{p,el}$) is the highest for Case I, followed by Case III and Case IV. The $c_{p,el}$ of Case I is the highest as the design of Case I incorporates the highest number of PV panels. In Case I, the PV panels

651

652 not only provide for the electrical demand, but also for the additional electrical consumption
653 by SAHP for heating needs. This in turn increases the total electricity requirement and
654 consequently, $c_{p,el}$ of Case I in comparison to the other cases. The lowest value of $c_{p,el}$ i.e.
655 0.1300 €/kWh is obtained for the reference system and Case II where the grid supplies the
656 electrical demand. Hence, $c_{p,el}$ of the solar solutions [Cases I, III & IV] is always higher than
657 the $c_{p,el}$ of the grid [Ref. case & Case II]. It should be noted that the $c_{p,el}$ of the grid denotes
658 the cost of electricity from the grid ($c_{el,grid}$, Table 1) and neglects the investment cost
659 pertaining to the national grid. Although, a higher $c_{p,el}$ of the solar solutions is compensated
660 by the lower $c_{p,dhw}$ and $c_{p,sh}$, as shown in Table 5.

661 Further, Case I achieves the lowest unit product cost of domestic hot water ($c_{p,dhw}$). The
662 lower $c_{p,dhw}$ results from comparatively lower investment, operation and maintenance costs
663 of SAHP. Also, the electricity requirement to drive the SAHP is partially covered by the
664 excess electrical production from the PV panels in Case I, thereby reducing the need to buy
665 electricity from the grid. The value of $c_{p,dhw}$ calculated for Cases II & III is equal, since two
666 ST panels and a 100 L tank are employed in the optimal design for both the cases. Case IV
667 has the third lowest value and the Reference case has the highest value of $c_{p,dhw}$. Similarly,
668 the unit product cost of space heating ($c_{p,sh}$) is the lowest for Case I, followed by Cases II &
669 III (equal values), Case IV and the Reference case. Therefore, Case IV, i.e. PVT panels, has
670 the highest fuel savings (F_{sav}) and solar self-production (ϕ_{sp}) with a satisfactory value of
671 $c_{p,total}$ (i.e. $c_{p,total}$ lower than that of the reference system). Whereas, based on the
672 thermoeconomic indicator ($c_{p,total}$) alone, Grid + ST panels [Case II] is superior to the other
673 systems. However, it should be noted that Case II has relatively lower fuel savings (2248.1
674 kWh/y) and solar self-production (34%).

675 Table 5: Annual fuel savings and thermoeconomic comparison of different systems

System	F_{sav} [kWh/y]	$c_{p,total}$ [€/kWh]	$c_{p,el}$ [€/kWh]	$c_{p,dhw}$ [€/kWh]	$c_{p,sh}$ [€/kWh]
Ref. Case: Grid + Boiler	0	0.1836	0.1300	0.1055	0.0903
Case I: PV + SAHP	2897.1	0.1809	0.6429	0.0409	0.0350
Case II: Grid + ST	2248.1	0.1665	0.1300	0.0942	0.0806
Case III: PV + ST	2653.8	0.1751	0.1764	0.0942	0.0806
Case IV: PVT	3230.3	0.1807	0.1580	0.1001	0.0857

676

677 4 Discussion

678 The results obtained from thermoeconomic optimization using genetic algorithm and
679 comparison of the different solar combined heating and power systems have been presented
680 in Section 3. In this section, an in-depth inspection and analysis of different system
681 components used in Cases I–IV and the reference case has been performed. Such an analysis
682 facilitates a detailed comparison of different alternative system components used for the same
683 objective (power generation, domestic hot water production or space heating).

684 The use of solar thermal (ST) panels instead of a conventional gas boiler in order to serve the
685 thermal demands (DHW and SH) can be justified by comparing Case II with the Reference
686 case. The fuel savings (F_{sav}) and solar self-production (ϕ_{sp}) of 2248.1 kWh/y and 34%,
687 respectively, are achieved by replacing a conventional gas boiler with 2 ST panels (4 m²)
688 with a 100 L water tank (Tables 4 and 5). This increase in F_{sav} and ϕ_{sp} is due to the partial
689 coverage of domestic hot water and space heating needs by thermal energy from ST panels.
690 ST panels are favoured over a conventional gas boiler economically as well, depicting a
691 decrease of $c_{p,dhw}$ and $c_{p,sh}$ by 1.13 c€/kWh and 0.97 c€/kWh, respectively (Table 5).

692 When comparing the grid and photovoltaic (PV) panels to meet the electrical demands of an
693 individual house, a comparison could be made by inspecting Case II, i.e. Grid + ST, and Case
694 III, i.e. PV + ST. The fuel savings (F_{sav}) and solar self-production (ϕ_{sp}) improve by 405.7
695 kWh/y and 7%, respectively, when the grid is replaced by PV panels (Tables 4 and 5).
696 Although this increase may seem minor, it should be noted that the increase is primarily due
697 to electrical energy, i.e. a high-grade energy. Further, the magnitude of low-grade thermal
698 energy overpowers the magnitude of electrical energy when calculating the solar self-
699 production. While, on the other hand, the unit product cost of electricity ($c_{p,el}$) is lower for
700 the grid, i.e. 0.13 €/kWh, compared to PV panels, i.e. 0.1764 €/kWh (Table 5). As a
701 conclusion, PV panels could only be economically competitive to the grid if the costs of
702 electricity bought from the grid and/or sold to the grid is raised. Otherwise, subsidies are
703 needed to compensate for the cheap electricity from the grid.

704 Solar-assisted heat pump (SAHP) can be compared against ST panels for domestic hot water
705 and space heating demands by studying Cases I & III. SAHP achieves higher fuel savings
706 (F_{sav}), by 243.3 kWh/y, and consequently, solar self-production (ϕ_{sp}), by 3%, when
707 compared to ST panels (Tables 4 and 5). This increase justifies by the COP of SAHP for
708 space heating and domestic hot water production being set to 3 and 2, respectively (Table 1).
709 Thus, 1 Wh of electrical energy produces 3 Wh of thermal energy for space heating (2 Wh for
710 DHW production). Moreover, the unit product cost of domestic hot water ($c_{p,dhw}$) of SAHP
711 is lower than that of ST panels by 5.33 c€/kWh. Additionally, SAHP has a lower unit product
712 cost of space heating ($c_{p,sh}$) than ST panels by 4.56 c€/kWh. However, it is important to note
713 that the $c_{p,el}$ of Case I (PV + SAHP) is significantly higher than Case III (PV + ST), i.e. by
714 46.65 c€/kWh. This is due to the higher number of PV panels in Case I compared to Case III
715 (Table 4), contributing towards the extra electricity generated by PV panels which is used by
716 SAHP to meet the thermal demands. Thus, the increase in $c_{p,el}$ cannot be neglected when
717 comparing SAHP and ST panels to cover the thermal demands. The total unit product cost
718 ($c_{p,total}$) of PV + SAHP [Case I] is higher than for PV + ST [Case III] by 0.58 c€/kWh.

719 To complete the discussion on the comparison of SAHP and ST panels certain drawbacks of
720 a heat pump need to be mentioned. Heat pumps produce noise during operation which may
721 not be suitable for some locations. Also, there is a requirement of outdoor space for the
722 installation of heat pump, which may not always be available. Furthermore, retrofit
723 installation of a heat pump is fairly challenging. These drawbacks of heat pumps may lead to
724 the ST panels being chosen as the better alternative depending on the location and

725 requirements of the installation site. A major advantage of ST panels is that the installation is
726 not too disruptive, while heat pumps can be tough to install.

727 An additional point to be discussed is related to the subsidies and other benefits provided by
728 the government to promote the use of renewable energy technologies. In France, the
729 generation of electricity from renewable technologies is encouraged through a feed-in tariff
730 and tax aids, while heat production from renewable sources is promoted by means of
731 subsidies, tax regulation mechanisms and zero-interest loans [65]. If these factors are also
732 accounted for in the thermoeconomic analysis, the effective investment cost of a renewable
733 energy-based system would be lower (after subtracting the subsidies and other monetary
734 benefits). Subsequently, the unit product cost ($c_{p,total}$, Eq. (11)) of the system would reduce,
735 indicating higher economic gains from the renewable energy-based systems.

736

737 **5 Conclusions and perspectives**

738 This study presents thermoeconomic optimization and comparison of four different solar
739 combined heating and power systems: photovoltaic (PV) panels and solar-assisted heat pump
740 (SAHP), national grid and solar thermal (ST) panels, PV and ST panels, and hybrid
741 photovoltaic thermal (PVT) panels. These combined heating and power solutions are
742 evaluated and compared, also against the reference national grid and gas boiler, to cover the
743 electrical and thermal (space heating and domestic hot water) needs of an individual
744 household (120 m²) in Chambéry (France). The system design parameters namely, number of
745 solar panels, electrical and thermal storage capacities are first optimized for each system
746 using genetic algorithm to minimize the total unit product cost (i.e. thermoeconomic
747 objective). An increase in the system size at the expense of cost, however, may be justified in
748 terms of higher solar contribution until the unit product cost remains lower than the reference;
749 the optimal designs for the different systems are thereby chosen. Further, the performances of
750 the considered systems are assessed in terms of solar self-production, solar self-consumption,
751 energy from solar panels, energy required from the grid, fuel savings and unit cost of each
752 product.

753 The following conclusions can be drawn from this study:

- 754 (i) Introduction of ST panel [Case II] is economically competitive to the case without
755 panels (i.e. just the auxiliary system of grid + electrical boiler running) with a higher
756 contribution from renewable sources. Moreover, ST panels have higher fuel savings
757 (F_{sav}) and solar self-production (ϕ_{sp}), and lower $c_{p,dhw}$ and $c_{p,sh}$ compared to a
758 conventional gas boiler. Thus, ST panels perform better than a natural gas boiler to
759 meet the thermal demands of an individual house. Further, this system is superior to
760 the other systems in terms of $c_{p,total}$. However, Case II has the lowest fuel savings
761 (2248.1 kWh/y) and solar self-production (34%) amongst Cases I–IV.
- 762 (ii) The fuel savings and solar self-production improves when the grid is replaced by PV
763 panels to meet the electrical demands, however, $c_{p,el}$ of the grid is lower than that of

764 PV panels by 4.64 c€/kWh (without considering any subsidies). The high investment
765 and maintenance costs of PV panels overpower the operating costs from the French
766 national grid (relatively inexpensive). Though, the inclusion of subsidies could
767 enhance the profitability of the PV panels. Hence, PV panels are better in terms of
768 fuel savings but worse economically than the grid for the electrical requirements of an
769 individual house. However, it is worthwhile to mention here that these results
770 correspond to the specific case of the French national grid, having high efficiency and
771 low cost. Nevertheless, similar trends would be observed in a perspective of future
772 decarbonized and efficient national grids.

773 (iii) From an economic standpoint, Case III (PV + ST panels) performs worse than Case II
774 (grid + ST panels) due to the implementation of PV panels. However, it achieves
775 higher solar indices: + 7% in ϕ_{sp} and +1% in ϕ_{sc} , thanks to additional solar
776 production.

777 (iv) Heat pump, whether driven by the grid or PV panels, leads to a significant reduction
778 in the total unit product cost ($c_{p,total}$). The best solution economically remains a grid-
779 driven heat pump, though without any solar gains. SAHP attains more fuel savings by
780 243.3 kWh/y and a higher solar-self production by 3% compared to ST panels,
781 whereas $c_{p,total}$ is higher for PV + SAHP system than PV + ST system by 0.58
782 c€/kWh.

783 (v) Single PVT panel [Case IV] seems to be the cheapest solution (economically alone)
784 excluding heat pump-based solution [Case I], which attains considerably lower
785 $c_{p,total}$. Moreover, increasing the number PVT panels (up to 6 panels) leads to the
786 highest fuel savings (3230.3 kWh/y) and solar self-production (49%), while keeping
787 the total unit product cost ($c_{p,total}$) lower than that of the reference system.

788 The present study opens up several perspectives for future research. To begin with, a storage
789 for space heating, in addition to domestic hot water production, may be employed for a more
790 thorough analysis. To achieve this, a storage tank could be implemented for both domestic
791 hot water and space heating applications. Seasonal storage could also be investigated. An
792 alternative approach could be to introduce the building's thermal inertia as a storage strategy
793 for space heating. However, this approach stores thermal energy at the cost of the thermal
794 comfort inside the building. Another perspective would be to identify strategies for orienting
795 public policies in cities based on the results of this study. The public policies may be
796 designed by investigating different ways to achieve a compromise between the economic
797 savings and the environmental implications of a combined heating and power system.
798 Further, the combined heating and power systems based on other renewable and clean
799 energies, such as wind, hydro and biomass energy, could be studied and optimized from a
800 thermoeconomic standpoint. Moreover, subsidies provided by the government to promote the
801 renewable energy-based systems may be included in the thermoeconomic analysis, thereby
802 making the renewable energy-based systems more profitable.

803

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806

807 **References**

- 808 [1] Hermelink A, Schimschar S, Boermans T, Pagliano L, Zangheri P, Armani R, et al.
809 Towards nearly zero-energy buildings Definition of common principles under the
810 EPBD—Final Report. Proceedings of the 2013 European Council for an Energy Efficient
811 Economy, Brussels, Belgium 2013;17:469.
- 812 [2] Elibol E, Özmen ÖT, Tutkun N, Köysal O. Outdoor performance analysis of different PV
813 panel types. *Renewable and Sustainable Energy Reviews* 2017;67:651–61.
814 <https://doi.org/10.1016/j.rser.2016.09.051>.
- 815 [3] Adaramola MS. Viability of grid-connected solar PV energy system in Jos, Nigeria.
816 *International Journal of Electrical Power & Energy Systems* 2014;61:64–9.
817 <https://doi.org/10.1016/j.ijepes.2014.03.015>.
- 818 [4] Tiwari GN. *Solar Energy: fundamentals, design, modelling and applications*.
819 Pangbourne: Alpha Science Int.; 2008.
- 820 [5] Pandey KM, Chaurasiya R. A review on analysis and development of solar flat plate
821 collector. *Renewable and Sustainable Energy Reviews* 2017;67:641–50.
822 <https://doi.org/10.1016/j.rser.2016.09.078>.
- 823 [6] Kylili A, Fokaides PA, Ioannides A, Kalogirou S. Environmental assessment of solar
824 thermal systems for the industrial sector. *Journal of Cleaner Production* 2018;176:99–
825 109. <https://doi.org/10.1016/j.jclepro.2017.12.150>.
- 826 [7] Antoniadis CN, Martinopoulos G. Optimization of a building integrated solar thermal
827 system with seasonal storage using TRNSYS. *Renewable Energy* 2019;137:56–66.
828 <https://doi.org/10.1016/j.renene.2018.03.074>.
- 829 [8] Beausoleil-Morrison I, Kemery B, Wills AD, Meister C. Design and simulated
830 performance of a solar-thermal system employing seasonal storage for providing the
831 majority of space heating and domestic hot water heating needs to a single-family house
832 in a cold climate. *Solar Energy* 2019;191:57–69.
833 <https://doi.org/10.1016/j.solener.2019.08.034>.
- 834 [9] Xu Q, Dubljevic S. Modelling and control of solar thermal system with borehole seasonal
835 storage. *Renewable Energy* 2017;100:114–28.
836 <https://doi.org/10.1016/j.renene.2016.05.091>.
- 837 [10] Wolf M. Performance analyses of combined heating and photovoltaic power systems for
838 residences. *Energy Conversion* 1976;16:79–90. [https://doi.org/10.1016/0013-](https://doi.org/10.1016/0013-7480(76)90018-8)
839 [7480\(76\)90018-8](https://doi.org/10.1016/0013-7480(76)90018-8).
- 840 [11] Dupeyrat P, Ménézo C, Fortuin S. Study of the thermal and electrical performances of
841 PVT solar hot water system. *Energy and Buildings* 2014;68:751–5.
842 <https://doi.org/10.1016/j.enbuild.2012.09.032>.
- 843 [12] Braunstein A, Kornfeld A. On the Development of the Solar Photovoltaic and Thermal
844 (PVT) Collector. *IEEE Transactions on Energy Conversion* 1986;EC-1:31–3.
845 <https://doi.org/10.1109/TEC.1986.4765770>.
- 846 [13] Chow TT. A review on photovoltaic/thermal hybrid solar technology. *Applied Energy*
847 2010;87:365–79. <https://doi.org/10.1016/j.apenergy.2009.06.037>.
- 848 [14] Zondag H. Flat-plate PV-Thermal collectors and systems: A review. *Renewable and*
849 *Sustainable Energy Reviews* 2008;12:891–959.
850 <https://doi.org/10.1016/j.rser.2005.12.012>.

- 851 [15] Herez A, El Hage H, Lemenand T, Ramadan M, Khaled M. Review on
852 photovoltaic/thermal hybrid solar collectors: Classifications, applications and new
853 systems. *Solar Energy* 2020;207:1321–47. <https://doi.org/10.1016/j.solener.2020.07.062>.
- 854 [16] Bellos E, Tzivanidis C, Moschos K, Antonopoulos KA. Energetic and financial
855 evaluation of solar assisted heat pump space heating systems. *Energy Conversion and*
856 *Management* 2016;120:306–19. <https://doi.org/10.1016/j.enconman.2016.05.004>.
- 857 [17] Calise F, Dentice d'Accadia M, Figaj RD, Vanoli L. A novel solar-assisted heat pump
858 driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic
859 optimization. *Energy* 2016;95:346–66. <https://doi.org/10.1016/j.energy.2015.11.071>.
- 860 [18] Chen Y, Wang J, Ma C, Shi G. Multicriteria performance investigations of a hybrid
861 ground source heat pump system integrated with concentrated photovoltaic thermal solar
862 collectors. *Energy Conversion and Management* 2019;197:111862.
863 <https://doi.org/10.1016/j.enconman.2019.111862>.
- 864 [19] Gunasekar N, Mohanraj M, Velmurugan V. Artificial neural network modeling of a
865 photovoltaic-thermal evaporator of solar assisted heat pumps. *Energy* 2015;93:908–22.
866 <https://doi.org/10.1016/j.energy.2015.09.078>.
- 867 [20] Huide F, Xuxin Z, Lei M, Tao Z, Qixing W, Hongyuan S. A comparative study on three
868 types of solar utilization technologies for buildings: Photovoltaic, solar thermal and
869 hybrid photovoltaic/thermal systems. *Energy Conversion and Management* 2017;140:1–
870 13. <https://doi.org/10.1016/j.enconman.2017.02.059>.
- 871 [21] Bejan A, Tsatsaronis G, Moran MJ. Thermal design and optimization. New York: Wiley;
872 1996.
- 873 [22] Cetina-Quñones AJ, Xamán J, Bassam A, Soberanis MAE, Perez-Quintana I. Thermo-
874 economic analysis of a flat solar collector with a phase changing material under tropical
875 climate conditions: Residential and industrial case. *Applied Thermal Engineering*
876 2021;182:116082. <https://doi.org/10.1016/j.applthermaleng.2020.116082>.
- 877 [23] Sokhansefat T, Kasaeian A, Rahmani K, Heidari AH, Aghakhani F, Mahian O.
878 Thermoeconomic and environmental analysis of solar flat plate and evacuated tube
879 collectors in cold climatic conditions. *Renewable Energy* 2018;115:501–8.
880 <https://doi.org/10.1016/j.renene.2017.08.057>.
- 881 [24] Wang K, Herrando M, Pantaleo AM, Markides CN. Thermoeconomic assessment of a
882 PV/T combined heating and power system for University Sport Centre of Bari. *Energy*
883 *Procedia* 2019;158:1229–34. <https://doi.org/10.1016/j.egypro.2019.01.312>.
- 884 [25] Behzadi A, Arabkoohsar A, Yang Y. Optimization and dynamic techno-economic
885 analysis of a novel PVT-based smart building energy system. *Applied Thermal*
886 *Engineering* 2020;181:115926. <https://doi.org/10.1016/j.applthermaleng.2020.115926>.
- 887 [26] Starke AR, Cardemil JM, Colle S. Multi-objective optimization of a solar-assisted heat
888 pump for swimming pool heating using genetic algorithm. *Applied Thermal Engineering*
889 2018;142:118–26. <https://doi.org/10.1016/j.applthermaleng.2018.06.067>.
- 890 [27] Herrando M, Ramos A, Freeman J, Zabalza I, Markides CN. Technoeconomic modelling
891 and optimisation of solar combined heat and power systems based on flat-box PVT
892 collectors for domestic applications. *Energy Conversion and Management* 2018;175:67–
893 85. <https://doi.org/10.1016/j.enconman.2018.07.045>.
- 894 [28] Keshavarzzadeh AH, Ahmadi P. Multi-objective techno-economic optimization of a
895 solar based integrated energy system using various optimization methods. *Energy*
896 *Conversion and Management* 2019;196:196–210.
897 <https://doi.org/10.1016/j.enconman.2019.05.061>.
- 898 [29] Evins R. A review of computational optimisation methods applied to sustainable
899 building design. *Renewable and Sustainable Energy Reviews* 2013;22:230–45.
900 <https://doi.org/10.1016/j.rser.2013.02.004>.

- 901 [30] Yang B, Wang J, Zhang X, Yu T, Yao W, Shu H, et al. Comprehensive overview of
902 meta-heuristic algorithm applications on PV cell parameter identification. *Energy*
903 *Conversion and Management* 2020;208:112595.
904 <https://doi.org/10.1016/j.enconman.2020.112595>.
- 905 [31] Norme AFNOR NF EN 12831-1 - July 2017 n.d.
906 [https://www.boutique.afnor.org/standard/nf-en-12831-1/energy-performance-of-](https://www.boutique.afnor.org/standard/nf-en-12831-1/energy-performance-of-buildings-method-for-calculation-of-the-design-heat-load-part-1-space-heating-load-module-m3-3/article/822089/fa184817)
907 [buildings-method-for-calculation-of-the-design-heat-load-part-1-space-heating-load-](https://www.boutique.afnor.org/standard/nf-en-12831-1/energy-performance-of-buildings-method-for-calculation-of-the-design-heat-load-part-1-space-heating-load-module-m3-3/article/822089/fa184817)
908 [module-m3-3/article/822089/fa184817](https://www.boutique.afnor.org/standard/nf-en-12831-1/energy-performance-of-buildings-method-for-calculation-of-the-design-heat-load-part-1-space-heating-load-module-m3-3/article/822089/fa184817) (accessed February 17, 2021).
- 909 [32] Aubert E, Ravat F. Etude CRIGEN - Profil journalier de consommation d'électricité
910 spécifique pour une MI de 120 m² 2014.
911 [https://conseils.xpair.com/actualite_experts/chaudiere-condensation-kit-photovoltaique-](https://conseils.xpair.com/actualite_experts/chaudiere-condensation-kit-photovoltaique-couplage-maisons-rt2012.htm)
912 [couplage-maisons-rt2012.htm](https://conseils.xpair.com/actualite_experts/chaudiere-condensation-kit-photovoltaique-couplage-maisons-rt2012.htm).
- 913 [33] Enquête Performance de l'Habitat, Équipements, Besoins et Usages de l'énergie
914 (Phébus). Ministère de l'Environnement (SDES), France; 2013.
- 915 [34] Les besoin d'eau chaude sanitaire en habitat individuel et collectif. France: ADEME,
916 COSTIC; 2016.
- 917 [35] Profils types de demande de chaleur et monotone. *Energie Plus Le Site* 2016.
918 [https://energieplus-lesite.be/donnees/cogeneration4/profils-types-de-demande-de-chaleur-](https://energieplus-lesite.be/donnees/cogeneration4/profils-types-de-demande-de-chaleur-et-monotone/)
919 [et-monotone/](https://energieplus-lesite.be/donnees/cogeneration4/profils-types-de-demande-de-chaleur-et-monotone/) (accessed February 18, 2021).
- 920 [36] Photovoltaic Geographical Information System (PVGIS), EU Science Hub, European
921 Commission, 2001-2020 n.d. <https://ec.europa.eu/jrc/en/pvgis>.
- 922 [37] Huld T, Müller R, Gambardella A. A new solar radiation database for estimating PV
923 performance in Europe and Africa. *Solar Energy* 2012;86:1803–15.
924 <https://doi.org/10.1016/j.solener.2012.03.006>.
- 925 [38] SARA Solar Radiation Data, EU Science Hub, European Commission, 2005-2016 n.d.
926 <https://ec.europa.eu/jrc/en/PVGIS/downloads/SARA>.
- 927 [39] Centre Scientifique et Technique du Bâtiment (CSTB, Scientific and Technical Center
928 for Building): ANNEXE - Méthode de calcul Th-BCE 2012 [Annex to the calculation
929 method Th-BCE2012], *J Off* 2011, n°0106: 77:1377 n.d.
- 930 [40] Brenn J, Soltic P, Bach Ch. Comparison of natural gas driven heat pumps and
931 electrically driven heat pumps with conventional systems for building heating purposes.
932 *Energy and Buildings* 2010;42:904–8. <https://doi.org/10.1016/j.enbuild.2009.12.012>.
- 933 [41] Benemann J, Chehab O, Schaar-Gabriel E. Building-integrated PV modules. *Solar*
934 *Energy Materials and Solar Cells* 2001;67:345–54. [https://doi.org/10.1016/S0927-](https://doi.org/10.1016/S0927-0248(00)00302-0)
935 [0248\(00\)00302-0](https://doi.org/10.1016/S0927-0248(00)00302-0).
- 936 [42] Agrawal B, Tiwari GN. Life cycle cost assessment of building integrated photovoltaic
937 thermal (BIPVT) systems. *Energy and Buildings* 2010;42:1472–81.
938 <https://doi.org/10.1016/j.enbuild.2010.03.017>.
- 939 [43] Wang Z, Zhu Y, Wang F, Wang P, Shen C, Liu J. Proceedings of the 11th International
940 Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019): Volume III:
941 Buildings and Energy. Springer Nature; 2020.
- 942 [44] Solar Panel Size Guide: How Big Is A Solar Panel? Unbound Solar 2019.
943 <https://unboundsolar.com/blog/solar-panel-size-guide> (accessed February 18, 2021).
- 944 [45] Modes de chauffage dans l'habitat individuel (Heating methods in individual homes).
945 ADEME (French Agency for ecology transition); 2014.
- 946 [46] AMORCE/ADEME. Comparatif des modes de chauffage & prix de vente de la chaleur
947 en 2011 (Comparison of heating methods & heat sales price in 2011). Agence de
948 l'Environnement et de la Maîtrise de l'Énergie (ADEME, French Agency for ecology
949 transition); 2013.

- 950 [47] Coûts des énergies renouvelables en France . Agence de l'Environnement et de la
951 Maîtrise de l'Énergie (ADEME, French Agency for ecology transition); 2016.
- 952 [48] Abuşka M, Şevik S. Energy, exergy, economic and environmental (4E) analyses of flat-
953 plate and V-groove solar air collectors based on aluminium and copper. *Solar Energy*
954 2017;158:259–77. <https://doi.org/10.1016/j.solener.2017.09.045>.
- 955 [49] Guarracino I, Mellor A, Ekins-Daukes NJ, Markides CN. Dynamic coupled thermal-and-
956 electrical modelling of sheet-and-tube hybrid photovoltaic/thermal (PVT) collectors.
957 *Applied Thermal Engineering* 2016;101:778–95.
958 <https://doi.org/10.1016/j.applthermaleng.2016.02.056>.
- 959 [50] Yang Y, Li R, Zhu Y, Sun Z, Zhang Z. Experimental and simulation study of air source
960 heat pump for residential applications in northern China. *Energy and Buildings*
961 2020;224:110278. <https://doi.org/10.1016/j.enbuild.2020.110278>.
- 962 [51] Zhang Y, Lundblad A, Campana PE, Yan J. Employing Battery Storage to Increase
963 Photovoltaic Self-sufficiency in a Residential Building of Sweden. *Energy Procedia*
964 2016;88:455–61. <https://doi.org/10.1016/j.egypro.2016.06.025>.
- 965 [52] Muselli M, Notton G, Poggi P, Louche A. PV-hybrid power systems sizing
966 incorporating battery storage: an analysis via simulation calculations. *Renewable Energy*
967 2000;20:1–7. [https://doi.org/10.1016/S0960-1481\(99\)00094-4](https://doi.org/10.1016/S0960-1481(99)00094-4).
- 968 [53] BRE Garston, Watford (on behalf of Department of Energy and Climate Change, UK
969 Government). SAP 2012: The Government's Standard Assessment Procedure for Energy
970 Rating of Dwellings. 2012.
- 971 [54] Rénovation : Se chauffer mieux et moins cher. Agence de l'Environnement et de la
972 Maîtrise de l'Énergie (ADEME, French Agency for ecology transition); 2019.
- 973 [55] Photovoltaïque.info - Arrêté tarifaire en vigueur n.d.
974 [https://www.photovoltaïque.info/fr/tarifs-dachat-et-autoconsommation/tarifs-](https://www.photovoltaïque.info/fr/tarifs-dachat-et-autoconsommation/tarifs-dachat/arrete-tarifaire-en-vigueur/)
975 [dachat/arrete-tarifaire-en-vigueur/](https://www.photovoltaïque.info/fr/tarifs-dachat-et-autoconsommation/tarifs-dachat/arrete-tarifaire-en-vigueur/) (accessed February 18, 2021).
- 976 [56] Eurostat, European Commission. Natural gas price statistics - Statistics Explained 2020.
977 https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics
978 (accessed February 19, 2021).
- 979 [57] Eurostat, European Commission. Gas prices for household consumers - bi-annual data
980 (from 2007 onwards). 2020.
- 981 [58] Boilers in France: Regulations, Maintenance, Repair & Replacement in 2021 2020.
982 <https://en.selectra.info/energy-france/guides/electricity/boiler>.
- 983 [59] Comparison of the cost per litre of water storage in poly tanks 2016.
984 [https://rainwatertanksdirect.com.au/blogs/comparison-of-the-cost-per-litre-of-water-](https://rainwatertanksdirect.com.au/blogs/comparison-of-the-cost-per-litre-of-water-storage-in-poly-tanks/)
985 [storage-in-poly-tanks/](https://rainwatertanksdirect.com.au/blogs/comparison-of-the-cost-per-litre-of-water-storage-in-poly-tanks/).
- 986 [60] Maleki A, Hafeznia H, Rosen MA, Pourfayaz F. Optimization of a grid-connected
987 hybrid solar-wind-hydrogen CHP system for residential applications by efficient
988 metaheuristic approaches. *Applied Thermal Engineering* 2017;123:1263–77.
989 <https://doi.org/10.1016/j.applthermaleng.2017.05.100>.
- 990 [61] Ikeda S, Ooka R. Metaheuristic optimization methods for a comprehensive operating
991 schedule of battery, thermal energy storage, and heat source in a building energy system.
992 *Applied Energy* 2015;151:192–205. <https://doi.org/10.1016/j.apenergy.2015.04.029>.
- 993 [62] Das M, Singh MAK, Biswas A. Techno-economic optimization of an off-grid hybrid
994 renewable energy system using metaheuristic optimization approaches – Case of a radio
995 transmitter station in India. *Energy Conversion and Management* 2019;185:339–52.
996 <https://doi.org/10.1016/j.enconman.2019.01.107>.
- 997 [63] Holland JH, Holland P of P and of EE and CSJH, Holland SL in HRM. *Adaptation in
998 Natural and Artificial Systems: An Introductory Analysis with Applications to Biology,
999 Control, and Artificial Intelligence*. MIT Press; 1992.

- 1000 [64] Hajabdollahi Z, Hajabdollahi H. Thermo-economic modeling and multi-objective
1001 optimization of solar water heater using flat plate collectors. Solar Energy 2017;155:191–
1002 202. <https://doi.org/10.1016/j.solener.2017.06.023>.
- 1003 [65] RES Legal Europe, European Commission. Renewable energy policy database and
1004 support: France. 2012.
- 1005