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# Energy Modelling and Techno-economic Analysis of a Biogas-fed CHP SOFC System Integrated with Microturbine: Case Study for a Wastewater Treatment Plant

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## Abstract

Wastewater Treatment Plants (WWTP) have a significant role in both processing wastewater to return to the water cycle, and in transforming between 40% and 60% of the dissolved organic matter into a non-fossil combustible gas (biogas) with a methane content of around 50–70 vol. %. Combined heat and power (CHP) concepts for small-scale distributed power generation offer a significant potential for saving energy and reducing CO<sub>2</sub> emissions. In this paper, an integrated configuration of an SOFC system and a Microturbine (MGT) in a reference WWTP is proposed. The concept is to utilize the available biogas in the plant to feed the SOFC and MGT to not only produce electrical power but also to provide the digester thermal demand. For the sake of comparison, the base case (SOFC is the only CHP unit) and the MGT case (integration of SOFC and microturbine systems) are proposed. Four additional scenarios using the performance of commercial micro turbines are developed varying both the size and the operating mode (constant vs. modulating power output). Results show that the use of the MGT along with the SOFC can increase the share of electricity covered by self-generation within the WWTP, while keeping stable the coverage of the thermal load. From an economic point of view, with short and long term cost scenarios for the SOFC system, the best configuration is the one related to an SOFC integrated with a small MGT installation working with partial load operation.

**Keywords:** *Solid Oxide Fuel Cell, microturbine, CHP, wastewater treatment plant, biogas, economic analysis.*

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## 35 **1. Introduction**

36  
37 The “Europe 2020” strategy promotes the shift towards a resource-efficient, low-carbon  
38 economy to achieve sustainable growth. The European policies on energy and sustainability  
39 are thus contributing to the diversification of the primary energy sources and to the introduction  
40 of distributed power technologies with high efficiency and low carbon emissions (European  
41 Strategic Energy Technology (SET) Plan for 2020 [1]).

42 One of the technologies playing a key role in achieving the goals of the mentioned strategy and  
43 has been paid much attention in recent years is the Fuel Cell technology. Solid oxide fuel cell  
44 (SOFC) is an interesting choice as like most fuel cell technologies have some advantages such  
45 as being modular, scalable, and efficient. Compared to other fuel cells, the SOFCs are fuel-  
46 flexible and can reform methane internally, use carbon monoxide as a fuel, and tolerate some  
47 degree of common fossil fuel impurities, such as ammonia and chlorides [2]. On the other hand,  
48 microturbine technology is an almost well-known and commercially developed for small scale  
49 power production. In his context, the integration of SOFC and microturbine systems has been  
50 of great interest for research to develop new hybrid systems which offer higher efficiency.

### 51 **1.1 Literature review**

52  
53 Williams et al. [3] proposed an indirect SOFC-GT hybrid system. They reported that the  
54 maximum achievable efficiency for their system is 45%. Also, it is shown that their system has  
55 lower efficiency value than that of the direct combination of the two systems. Cheddie et al.  
56 [4] proposed an indirect combination of an SOFC system into a 10 MW gas turbine plant.  
57 According to the developed thermo-economic model, it was predicted that under the optimized  
58 condition the system could produce 20.6 MW power with an efficiency of 49.9%. In another  
59 research [5], a semi-direct integration of an SOFC and a gas turbine was studied. Thermo-  
60 economic optimization results revealed that for the studied system, an output power of 21.6

61 MW could be obtained with an efficiency of 49.2%. Zhang et al. [6] proposed a new model for  
62 an SOFC- GT system. In their work, the waste heat from SOFC stack as well as the combustion  
63 chamber is utilized to heat up the gas turbine inlet. It is claimed that the hydrocarbons are  
64 feasible fuels for the SOFC. Bicer and Dincer [7] proposed a scheme consisting of a steam-  
65 assisted gravity drainage, underground coal gasification, solid oxide fuel cell, integrated  
66 gasification combined cycle and an electrolyzer. Energy and exergy efficiencies of 19.6% and  
67 17.3% are obtained for the combined system, respectively. Zhao et al. [8] studied a coal syngas  
68 fueled SOFC stack working in an atmospheric condition which is indirectly integrated into a  
69 Brayton cycle. is the authors concluded that the system efficiency increases with decreasing  
70 current density and the value could be in a range of 48-56%, depending on the operating  
71 temperature and current density. Inui et al. [9] introduced two types of carbon dioxide  
72 recovering SOFC-GT combined power generation systems in which a gas turbine either with  
73 carbon dioxide recycle or with water vapor injection is adopted as the bottoming cycle.  
74 Reportedly, with carbon dioxide recycle the overall efficiency of 63.87% (HHV) or 70.88%  
75 (LHV) is reached. These values for the system with water vapor injection are 65.00% (HHV)  
76 or 72.13% (LHV), respectively. Evely et al. [10] investigated an indirect combination of a gas  
77 turbine with an internal reforming SOFC system and an organic Rankine cycle (ORC)  
78 thermodynamically and economically. For toluene as the ORC working fluid, it is stated that  
79 the SOFC-GT-ORC system demonstrates an efficiency improvement of about 34% compared  
80 to the gas turbine as a stand-alone system, and of 6% compared to the hybrid SOFC-GT sub-  
81 system. It is predicted that the system would become profitable within three to six years. Inui  
82 et al. [11] proposed a combination of SOFC and closed cycle magneto hydrodynamic  
83 (MHD)/noble gas turbine with carbon dioxide recovery. It is reported that the overall thermal  
84 efficiency of the system using methane as the fuel could be 63.66% (HHV) or 70.64% (LHV).  
85 Sánchez et al. [12] compared the performance of conventional regenerative gas turbine with

86 the direct/indirect integration of the SOFC and GT systems at full and part loads. is the authors  
87 concluded that the indirect hybrid system is less efficient than the direct one since power and  
88 efficiency enhancement caused by the higher pressure in the SOFC is not present in the indirect  
89 system. It is also found that the total cost of a fuel-cell-based configuration is lower despite the  
90 greater initial investment/installation cost of an integrated system. Bin Basrawi et al. [13]  
91 investigated the performances of a biogas-fuelled micro gas turbine cogeneration system in  
92 different scales of sewage treatment plants for various output powers under various ambient  
93 temperature conditions.

## 94 **1.2 Present work**

95  
96 In the most of the previous researches regarding the integration of gas turbine and SOFC  
97 system, the process of the production of fuels to feed the SOFC has not been considered. In  
98 addition, integration of gas turbine and SOFC systems normally requires high-pressure system.  
99 In this article, a new combination of SOFC and micro gas turbine technologies in atmospheric  
100 pressure level for a wastewater treatment plant is proposed. A multi-scale simulation is  
101 performed involving both the detailed simulation of the SOFC and MGT system considering  
102 the biogas production process as well as the thermal integration of the whole wastewater  
103 treatment plant on a larger scale. The present research is a part of EU project called  
104 DEMOSOFC [14] which is a Fuel Cell & Hydrogen Joint Undertaking (FCH2-JU) funded  
105 project foreseeing the installation of the largest (in 2016) biogas fed Solid Oxide Fuel Cell  
106 (SOFC) in Europe.

## 107 **1.3 DEMOSOFC Project**

108

109 The SOFC will be the sole combined heat & power (CHP) generator within a medium-size  
110 wastewater treatment plant (WWTP) located in Torino (IT) (Figure 15). The mentioned

111 reference WWTP serves 270'000 equivalent inhabitants collecting an overall of 59'000 m<sup>3</sup> of  
112 wastewater on a daily basis that corresponds to ~220 liter/day/capita [15].

113 The objectives of this project can be summarized as follows:

- 114 1. Demonstration and detailed analysis of an innovative solution of distributed sub-MW  
115 CHP system based on SOFC, with high interest in the industrial/commercial  
116 application.
- 117 2. Demonstration of a distributed CHP system fed by biogas from anaerobic digestion
- 118 3. Demonstration of the high performance of such systems: electrical efficiency, thermal  
119 recovery, low emissions, plant integration, economic interest
- 120 4. Exploitation and business analysis of this type of innovative energy systems
- 121 5. Dissemination of the high interest (energy and economic) of such systems

122

123 Figure 1. SMAT wastewater treatment plant in Collegno (Turin) [16]. "DEMOSOFC Plant" shows the area  
124 where the three SOFC modules will be installed.

125 The main concept of the DEMOSOFC project is illustrated in **Errore. L'origine riferimento**  
126 **non è stata trovata..** The DEMOSOFC plant comprises the following sections [14]:

- 127 1. Biogas processing unit: The unit includes biogas dehumidification, contaminants  
128 removal and compression. Biogas from Collegno WWTP still contains hydrogen  
129 sulfide and siloxanes, both harmful for the fuel cell. These contaminants are removed  
130 via an adsorption-based system that uses activated carbons. Before the clean-up system,  
131 biogas is cooled and water is removed in a chiller, in order to guarantee the carbon  
132 optimal operation parameters. A gas analyzer, able to detect both H<sub>2</sub>S and siloxanes, is  
133 installed to online measure macro-composition and contaminants concentration both at  
134 the inlet and outlet of the clean-up system.

- 135 2. SOFC modules: The system is composed of 3 modules, able to produce about 58 kW  
136 AC each so the total amount of installed power is around 174 kWe.
- 137 3. Heat recovery system: Hot exhaust from the SOFC modules heats a water loop, able to  
138 provide partial heating to the sludge entering the digester. A new heat recovery loop is  
139 integrated with an existing one, where heat is provided by a boiler fed by extra biogas  
140 or natural gas from the grid.
- 141 4. A general control system is also implemented in order to control the system, both on  
142 site and remotely.

143 In the present research, the premise of the effort is to modify the current configuration of the  
144 DEMOSOFC project using the microturbine along with SOFC systems. In the following, a  
145 brief technology overview of two key components (SOFC and microturbine prime movers) of  
146 the plant is presented.

147  Figure 2. Concept diagram of the DEMOSOFC plant [14].

## 148 **2. Description of the technology**

### 149 **2.1 SOFC system configuration**

150 Figure 3a illustrates the proposed SOFC system layout in the plant. Air (state 1) is pre-heated  
151 in the air heat exchanger after being pressurized through the air blower (state 2). Then it is sent  
152 to the cathode side of the stack (state 3). Clean fuel (biogas/NG) is pressurized using the fuel  
153 blower before mixing with the anode gas recycle. The mixed gas is sent to the pre-reformer  
154 (state 6) where a fraction of methane is converted to hydrogen and carbon monoxide through  
155 reforming and shifting reactions. The reformer is modeled as an adiabatic reactor, where outlet  
156 temperature (state 7) and methane conversion are calculated depending on the inlet conditions.  
157 No external heat is thus required in this configuration. Then, the reformed gas is pre-heated  
158 through the fuel heat exchanger before feeding the anode side of the stack (state 8). The fuel  
159 gas experiences an internal reforming which brings a hydrogen-rich mixture participating in

160 the electrochemical reaction inside the fuel cell stack. Internal reforming has been considered  
161 as IIR (Indirect Internal Reforming), thus taking place not directly on the anode catalyst but on  
162 a physically separated catalyst thermally connected to the fuel cell in order to receive the  
163 required heat for the reaction. The electrochemical reaction generates thermal energy, a part of  
164 which is used to deliver the required heat for the internal reforming reaction, another part is  
165 employed to heat up the cell products and the residual reactants.

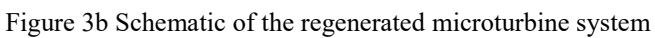
166 Anode and cathode exhaust gases (state 9 and state 4) with higher temperatures are obtained  
167 and electrical power is produced. An inverter is used to convert the DC power generated by the  
168 stack into AC grid-quality electricity. After accomplishing the electrochemical reactions in the  
169 SOFC, the excess air exiting the cathode (state 4) and the unreacted fuel exiting the anode (state  
170 12) are supposed to combust completely in the after-burner. However, a fraction of anode exit  
171 gas (state 11) is recirculated back to the mixer to be mixed with the fuel. A given amount of  
172 Steam-to-Carbon (SC) ratio, to avoid using external demineralized water, is defined for which  
173 the amount of recirculation fraction would be calculated. The exhaust stream of the SOFC units  
174 is sent to the exhaust heat recovery exchanger which will be explained in detail in the following  
175 sections.

176  Figure 3a. Proposed SOFC system layout.

## 177 **2.2 Micro gas turbine (MGT) technology**

178 MGTs can be defined as small, compact high-speed turbo-generators of between 30 and 300  
179 kW<sub>e</sub> that can deliver energy in the form of electricity and heat [17]. Basically, MGTs are based  
180 on a Brayton cycle and usually consist of a centrifugal compressor, a radial turbine and a  
181 permanent magnet alternator rotor. Their main features are that the high-speed generator is  
182 directly coupled to the turbine rotor and that they use power electronics instead of a gearbox  
183 and conventional generator to adapt the power produced to the grid power quality.

184 The microturbine efficiency can increase by taking advantage of regeneration and is meant to  
185 pre-heat the air at the burner inlet by exploiting the hot gases exhausted from the turbine as can  
186 be seen in Figure 3b.

187 

### 188 **3. Integrated cogeneration system**

189  
190 As discussed there is a potential of utilizing the available biogas in the SMAT Collegno to  
191 produce electrical power. Considering the use of SOFC to produce power as a base scenario  
192 which is supposed to be performed in DEMOSOFC project, base case layout is defined. In this  
193 case, the available biogas is just to be used in the SOFC units, meanwhile SOFC exhaust  
194 thermal energy as well as a boiler are used to supply the heat demand of the digester.

195 To give an upgraded layout, the MGT case which considers a novel integration of SOFC and  
196 micro gas turbine in the SMAT plant is proposed. In the latter case, the boiler is replaced with  
197 a micro gas turbine to provide a part of digester thermal energy demand.

#### 198 **3.1 Base Case**

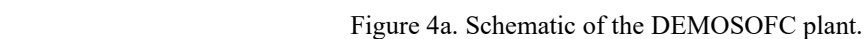
199 The exhaust gas exiting from three SOFC units (streams 14a, 14b and 14c) are used in three  
200 exhaust heat recovery exchangers (HXa, HXb and HXc) to heat up a hot water loop (stream 1).  
201 Then an intermediate closed loop (first loop) is embedded to deliver the recovered heat to a  
202 fraction of the sludge feeding the anaerobic digester (stream 7) flowing to the anaerobic  
203 digester using a heat exchanger (HX1). When the recovered heat from the SOFC plant is not  
204 sufficient to heat up the total amount of sludge and meet whole digester thermal load, an  
205 auxiliary boiler is also used. Thus, to provide the digester with the required heat for the  
206 digestion process, an amount of natural gas/biogas (streams 9a and 9b) is burned in an auxiliary  
207 burner with excess air (stream 10). The second water loop distributes by means of a heat  
208 exchanger (HX2) the heat from the boiler to the remainder of the sludge flow (stream 6) using.  
209 Finally, a mixer is used to mix two sludge streams in a single stream, which is then fed into the

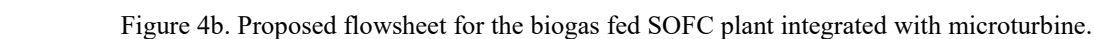
210 anaerobic digester [18]. Detailed schematic description of the base and MGT cases are  
211 presented in the following subsections.

### 212 **3.2 MGT Case**

213 The main difference between the MGT Case (Figure 4b) and the Base Case (Figure 4a) is that  
214 in the MGT Case the boiler is replaced with a microturbine operated in CHP mode to supply  
215 the heat that is required for preheating the sludge. An heat exchanger (HX4) is employed to  
216 transfer thermal energy from the third loop to the sludge. Then the partially heated sludge is  
217 heated up to the required temperature by means of the boiler and second loop. The excessive  
218 amount of as-produced biogas which is not fed into SOFC systems are sent to microturbine.  
219 When the available biogas is not enough for both SOFC and the microturbine systems, an  
220 external amount of natural gas (NG) is supplied from the grid.

221

222  Figure 4a. Schematic of the DEMOSOFC plant.

223  Figure 4b. Proposed flowsheet for the biogas fed SOFC plant integrated with microturbine.

## 224 **4. System analysis**

225 Thermodynamic and techno-economic modeling of the above cogeneration systems (Base Case  
226 and MGT Case) are presented in this section.

### 227 **4.1. Energy analysis**

#### 228 **4.1.1 Assumptions**

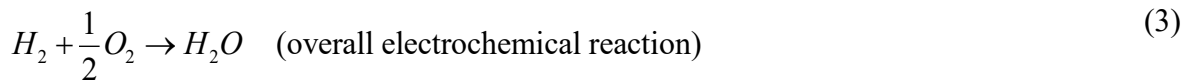
229 The following assumptions were used for simulation of the previously described plant  
230 configurations [18,19]:

- 231 • The atmospheric air is composed of 79% N<sub>2</sub> and 21% O<sub>2</sub>, on a volume basis.
- 232 • All gases are treated as ideal gases and gas leakage is negligible.

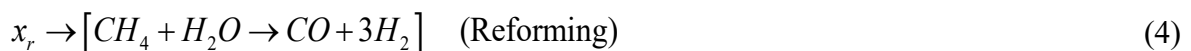
- 233 • Internal distribution of temperature, pressure, and gas compositions in each component is  
 234 uniform.
- 235 • Cathode and anode temperatures are assumed to be identical.
- 236 • The exhaust mass flow rates and temperatures of the three SOFC units are identical.
- 237 • Changes in the kinetic and potential energies of fluid streams are negligible.
- 238 • The biogas supplied to the SOFC contains 65% CH<sub>4</sub> and 35% CO<sub>2</sub> according to the reported  
 239 data by SMAT Collegno [15].
- 240 • For each of the compressors, pumps, blowers, and turbines, proper isentropic efficiencies are  
 241 considered.

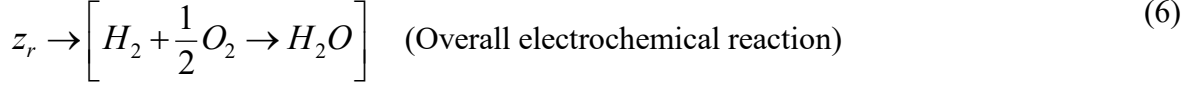
#### 242 ***4.1.2 Solid oxide fuel cell modeling***

243 DC power is produced in SOFC via electrochemical processes. The methane gas existing in  
 244 the biogas is reformed inside the anode side, producing mostly hydrogen which is oxidized in  
 245 the SOFC. The following reforming, shift and overall electrochemical reactions take place at  
 246 the cell anode electrode.



247 The molar conversion rates for reforming, shifting and electrochemical reactions are  
 248 considered to be  $x_r$ ,  $y_r$ , and  $z_r$ , respectively. Therefore, rates of consumption and production of  
 249 the components can be achieved by the following model:





250  $z_r$  could be found with the help of current density, Faraday constant, cell number, and active  
 251 surface area, as followed by equation (7)

$$z_r = \frac{j \cdot N_{FC} \cdot A_a}{2 \cdot F} \quad (7)$$

252 Applying mass balance equations along with considering equations for the mixing units and  
 253 the whole SOFC model, the flowing gas compositions may be achieved. In order to solve the  
 254 system of equations, 3 more equations are needed to complete the system.

255 Looking again in the equilibrium reactions of shifting and reforming, the equilibrium constants  
 256 can be written as follows respectively:

$$\ln K_s = -\frac{\Delta \bar{g}_s^o}{\bar{R} T_{FC,e}} = \ln \left[ \frac{(\dot{n}_{CO_2,8} + y_r) \times (\dot{n}_{H_2,8} + 3x_r + y_r - z_r)}{(\dot{n}_{CO,8} + x_r - y_r) \times (\dot{n}_{H_2O,8} - x_r - y_r + z_r)} \right] \quad (8)$$

$$\ln K_R = -\frac{\Delta \bar{g}_R^o}{\bar{R} T_{FC,e}} = \ln \left[ \frac{(\dot{n}_{CO,8} + x_r - y_r) \times (\dot{n}_{H_2,8} + 3x_r + y_r - z_r)^3}{(\dot{n}_{CH_4,8} + x_r) \times (\dot{n}_{H_2O,8} - x_r - y_r + z_r) \times \dot{n}_9^2} \left( \frac{P_9}{P_{ref}} \right)^2 \right] \quad (9)$$

257 Where,  $\bar{R}$  and  $T_{FC,e}$  are the universal gas constant (8.314 J.mole<sup>-1</sup>.K<sup>-1</sup>) and the temperature at the  
 258 exit of the SOFC, respectively. Also,  $\Delta \bar{g}^o$  is the change in the Gibbs free function of shifting  
 259 and reforming reactions.

$$\dot{W}_{FC,stack} = \sum_k \dot{n}_k \bar{h}_{k,9} + \sum_L \dot{n}_{L,4} \bar{h}_{L,4} - \sum_m \dot{n}_{m,8} \bar{h}_{m,8} - \sum_n \dot{n}_{n,3} \bar{h}_{n,3} \quad (10)$$

260 Where,  $k$ ,  $L$ ,  $m$  and  $n$  are the corresponding gas compositions in each states (e.g. gas  
 261 composition at state 9 ( $k$ ) is CO<sub>2</sub>, CO, H<sub>2</sub>O, CH<sub>4</sub>, N<sub>2</sub> and H<sub>2</sub>). On the other hand, the work rate  
 262 produced by the SOFC stack  $\dot{W}_{FC,stack}$  can be expressed as:

$$\dot{W}_{FC,stack} = N_{FC} \cdot j \cdot A_a \cdot V_c \quad (11)$$

263 Where cell voltage is defined as:

$$V_c = V_N - V_{loss} \quad (12)$$

264 Here,  $V_N$  is the Nernst voltage and  $V_{loss}$  the voltage loss, which is the sum of three separate

265 voltage losses; Ohmic, Activation and Concentration losses:

$$V_{loss} = V_{ohm} + V_{act} + V_{conc} \quad (13)$$

266 The Nernst voltage which is accounted as the ideal voltage can be expressed as;

$$V_N = -\frac{\Delta \bar{g}^o}{2F} + \frac{\bar{R}T_{FC,e}}{2F} \ln \left( \frac{a_{H_2}^{Anode,exit} \sqrt{a_{O_2}^{Cathode,exit}}}{a_{H_2O}^{Anode,exit}} \right) \quad (14)$$

267 In equation (14), the Gibbs energy difference is related to the overall electrochemical reaction. To determine the

268 actual cell voltage, the voltage losses should be calculated. To calculate the Ohmic loss the following formula is

269 used (See also

270 Table 1):

$$V_{ohm} = (R_{int} + \rho_{an}L_{an} + \rho_{cat}L_{cat} + \rho_{ely}L_{ely}) j \quad (15)$$

271

272 Table 1. Material Resistivity used for Ohmic voltage loss estimation [21]

273 The activation polarization is the sum of those defined for both the anode and cathode as

274 follows;

$$V_{act} = V_{act,a} + V_{act,c} \quad (16)$$

$$V_{act,a} = \frac{\bar{R}T_{FC,e}}{F} \left( \sinh^{-1} \left( \frac{j}{2j_{oa}} \right) \right) \quad (17)$$

$$V_{act,c} = \frac{\bar{R}T_{FC,e}}{F} \left( \sinh^{-1} \left( \frac{j}{2j_{oc}} \right) \right) \quad (18)$$

275 Where  $j_o$  is the exchange current density. Eqs. (19) and (20) are used to evaluate the values of  
 276 the exchange current density for the anode and the cathode, (see variables in Table 2),  
 277 respectively [21].

$$j_{0,a} = \gamma_{an} \left( \frac{RT}{2F} \right) e^{\left( \frac{E_{a,an}}{RT} \right)} \quad (19)$$

$$j_{0,c} = \gamma_{cat} \left( \frac{RT}{2F} \right) e^{\left( \frac{E_{a,cat}}{RT} \right)} \quad (20)$$

278

279 Table 2. Parameters correspond to the material anode and cathode sides [21]

280 Concentration loss is sum of the losses related to gas concentration occurring in the anode  
 281 and the cathode.

$$V_{conc} = V_{conc,a} + V_{conc,c} \quad (21)$$

282 where

$$V_{conc,an} = \frac{RT}{2F} \ln \left( \frac{P_{H_2} \times P_{H_2O,TPB}}{P_{H_2O} \times P_{H_2,TPB}} \right) \quad (22)$$

283 And

$$V_{conc,cat} = \frac{RT}{4F} \log \left( \frac{P_{O_2}}{P_{O_2,TPB}} \right) \quad (23)$$

284 where the subscript *TPB* denotes the three-phase boundary.

### 285 **4.1.3 Energy demand of the reference plant**

286 Explanation and values used for calculating the thermal terms are given in Table 3 and Figure  
 287 5a. Figure 5b shows the calculated total electrical demand of the wastewater treatment demand  
 288 (SMAT Collegno) and thermal energy demand of the digester for 2015. As the figure indicates,  
 289 during the summer months the required thermal and electrical demands are lower than those  
 290 for the other months. The energy requirements for wastewater treatments plant are

291 characterized by a fluctuating demand for electricity from the process plant equipment,  
292 illumination, etc. These significant variations are mainly due to a fluctuations on the  
293 wastewater inflow during the year. Heating is mainly required for boosting the anaerobic  
294 reaction in anaerobic digester. In this work, space heating for the buildings in the plant is not  
295 considered as energy demand. The average amount of electrical power and thermal load  
296 demands are 723.13 kW and 281.12 kW respectively.

297 The digester thermal load ( $Q_{dig}$ ), expressed in kW, is calculated as the sum of the following  
298 contributions:

- 299 • the thermal power required for the heating up sludge from a variable inlet temperature (14  
300 - 23°C) to the digester temperature (38 - 47°C),  $Q_{sl}$
- 301 • the extra heating of sludge that is required to compensate for heat losses through the  
302 digester walls,  $Q_{los}$
- 303 • the heat losses though piping,  $Q_{pipes}$

$$Q_{dig} = Q_{sl} + Q_{los} + Q_{pipes} \quad (24)$$

304 The first term in (Eq.25) is calculated based on:

- 305 • the sludge flow rate  $\dot{m}_{sl}$  (the average monthly value is used as calculated from the SMAT  
306 hourly measurements)
- 307 • the sludge inlet temperature  $T_{sl,in}$  (taken from the WWTP measurements)
- 308 • the digester process temperature  $T_{dig}$  (the average monthly value is taken, which is  
309 calculated from the SMAT daily measurements)
- 310 • being the solid content in sludge lower than 2% (weight), the specific heat capacity is  
311 calculated,  $c_p$ , is taken as equal to that of water.

312 The sludge pre-heating term is written as:

$$Q_{sl} = \dot{m}_{sl} \cdot c_p \cdot (T_{dig} - T_{sl,in}) \quad (25)$$

313 The digester thermal losses have been evaluated using (Eq. 27):

$$Q_{los} = Q_{ug} + Q_{ext} \quad (26)$$

314 Where:

$$Q_{los} = Q_{ug} + Q_{ext} \quad (27)$$

$$Q_{ug} = U_{ug} \cdot A_{ug} \cdot (T_{dig} - T_{gr}) \quad (28)$$

$$Q_{ext} = U_{ext} \cdot A_{ext} \cdot (T_{dig} - T_{ext}) \quad (29)$$

315  $Q_{ug}$  is the term for losses through the underground surface (heat exchange between walls and  
 316 ground).  $Q_{ext}$  accounts instead for losses through the external surface (heat exchange between  
 317 walls and external air).

318 Finally, the thermal through piping has been evaluated as a fixed share of the total sludge pre-  
 319 heating duty and digester thermal losses:

$$Q_{pipes} = \%_{pipes} \cdot (Q_{sl} + Q_{los}) \quad (30)$$

320 The values used for the thermal load calculation are listed in Table 3.

321 Table 3. Main parameters for digester thermal load calculations.

322

323 Figure 5a. Sludge inlet, air and ground temperature trend.

324 The digester thermal load will be covered partially by the SOFC heat recovery system and  
 325 partially by the boiler. The boiler will be fed first with extra-biogas and then with NG from the  
 326 grid.

327 Figure 5b. Trends of total electrical demand and required thermal energy for digester in SMAT Collegno  
 328 calculated for 2015.

329 In the current operational condition of the plant, no cogeneration is in service. Therefore biogas  
330 is used to supply heat to the digesters and natural gas is burnt in a boiler if required. The heating  
331 demand is calculated by a steady state energy balance in both digesters.

#### 332 **4.1.4 Energy efficiency**

333 The energy efficiency for the overall system has been defined as follows:

$$\eta_I = \frac{\dot{W}_{net} + \dot{Q}_{recovery}}{\dot{m}_{biogas} \cdot LHV_{biogas} + \dot{m}_{NG} \cdot LHV_{NG}} \quad (31)$$

334 Where  $\dot{W}_{net}$  is the net electrical power (stack AC power plus net MGT electrical power minus  
335 the blowers and pumps power consumptions) and  $\dot{Q}_{recovery}$  is the total heat recovered of the  
336 system. In the denominator, there is the sum of the biogas consumption and the NG  
337 consumption in the whole system.

#### 338 **4.1.5 SOFC model validation**

339 In order to validate the simulation results of SOFC, the available experimental data reported  
340 by Tao et al. [22] is used. Table 4 compares the cell voltage and power density obtained in the  
341 present model developed by the authors and those reported by Tao et al. [22]. The comparison  
342 shows a good agreement between them.

Table 4. Comparison of results obtained from the present work with the experimental values reported by Tao et al. [22]

343

#### 344 **4.2 Economic analysis**

345 Starting from the energy analysis on the four proposed scenarios, the economic analysis has  
346 been performed to identify the best layouts from the economic perspective. The analysis is  
347 based on the calculation of investment and operational costs. We calculate the cash flow trend  
348 over the system lifetime. Pay Back Time (PBT) and Levelized Cost of Electricity (LCOE) are  
349 used as economic indicators for the analyzed scenarios.

350 Capital costs have been calculated for the main plant sections.

- 351 • Biogas processing unit: this section is used to remove contaminants from the raw  
352 biogas. The clean-up unit is based on adsorption on activated carbon beds, as designed  
353 for the DEMOSOFC project. The cost has been taken from a recent workshop on  
354 cleaning systems for stationary fuel cell applications, promoted by the Argonne  
355 National Laboratory (US), where the most relevant fuel cell and cleaning system  
356 producers discussed on performance and price of the biogas processing system [23].  
357 Costs are available for three-time scenarios and are expressed as a function of the fuel  
358 cell electrical power: today (1,500 €/kWe), short term (1,000 €/kWe) and long term  
359 (500 €/kWe).
- 360 • SOFC modules: Each module includes both the stacks and BoP. Each module produces  
361 AC power and hot water from purified biogas and ambient air. The choice of using a  
362 unique cost for all the module is due to the current commercial availability of SOFC  
363 modules for producers. The costs have been taken from a 2015 report developed by the  
364 European Fuel Cell and Hydrogen Joint Undertaking (FCH-JU) on the status of  
365 stationary fuel cell systems [24]. Data are available based on manufactured units and  
366 are shown in Figure 6. Because of the slightly different SOFC module size of the present  
367 work (60 kWe each), the specific cost (€/kWe) has been derived from the report and  
368 used for the analysis. Three scenarios have been defined to account for technology  
369 learning of the SOFC: today, short term and long term (Figure 6).
- 370 • Heat recovery system: Most of the components shown in the heat recovery layout are  
371 already installed in the WWTP for the sludge heating line through the boiler (current  
372 scenario). Furthermore, the MGT heat recovery system has been considered as included  
373 in the MGT investment cost. The only new component, which has been considered in  
374 the analysis, is the sludge-water heat exchanger (named HX1 in Figure 4a and 4b),  
375 which should be installed to recover heat from the SOFC section. The cost for this

376 component (shell and tube) has been derived from a simulation on Aspen Heat  
377 Exchanger Design and Rating® software. The simulation is based on available data on  
378 the hot water stream (1 kg/s, cooled from 72 to 40 °C on nominal conditions) and the  
379 sludge stream (0.886 kg/s, heated from 16 to 52 °C on nominal conditions). Hot stream  
380 has been assumed to be on tube side. The final cost for the heat-exchanger is 10,760 €.

381 • Micro gas turbine: The cost for a complete MGT system, equipped with heat recovery  
382 system, has been taken from Capstone [25] and is 1,000 €/kWe by averaging the  
383 values available. No technology learning has been adopted since the technology is  
384 already mature.

385

386 Figure 6. Specific investment cost for a 50 kWe unit and share among the cost components (stack, added system  
387 and installation). Author own elaboration of [24].

388 The operating costs have been also calculated during the plant lifetime (which has been  
389 assumed equal to 15 years for all the scenarios):

390 • Biogas processing unit. The specific operational cost, due to the replacement of the  
391 sorbent materials, is given for the same three time scenarios as function of the electrical  
392 energy produced by the fuel cell system: today (1.00 c€/kWe), short term (1.00  
393 c€/kWe) and long term (0.50 c€/kWe), as derived from [23].

394 • SOFC module unit. The operating costs for the module are expressed as yearly general  
395 maintenance and stack substitution according to lifetime, for the three time scenarios  
396 [24]. Stack lifetime is considered improved in the future scenarios from 3/4 to 5 to 7/8  
397 years. Table 5 shows SOFC-related costs.

398 • Micro-gas turbine. The cost has been assumed as an average value from [25], and is  
399 equal to 1 c€/kWh.

- 400 • Natural gas. The cost of energy is related to the natural gas employed in the system for  
401 the boiler, the SOFC and the MGT. the cost of the natural gas is the one declared from  
402 the SMAT Collegno WWTP, equal to 0.6 €/m<sup>3</sup> (standard cubic meter) [15].
- 403 • Savings. No specific subsidy for electricity production from biogas has been  
404 considered. From the Italian legislation on feed-in-tariff for energy production from  
405 renewables [26], in the case of biogas from sewage sludge, the tariff is lower than the  
406 current price of electricity in the WWTP. For this reason, if the energy is required  
407 internally, the most convenient choice is to have self-consumption. The savings are thus  
408 accounted using the electricity price in the SMAT Collegno WWTP, equal to 16  
409 c€/kWh [15]. Savings are accounted as constant during the entire lifetime except for  
410 the first year, where 6 months of construction have been considered with a related 50%  
411 reduction in the yearly savings.

412 Table 5 summarize the investment and operating costs for the biogas processing unit, the SOFC  
413 module and the MGT.

414

415 Table 5. SOFC, biogas processing unit and MGT costs. [23] [24] [25]

416 Starting from the investment and the operational costs, the yearly cash flow can be evaluated.  
417 The methodology is explained in detail in the authors' previous work [27]. The discount rate  
418 has been assumed 2.5% (assumptions, the value used for discounting future costs and savings)  
419 and tax rate 24% (from the Italian previsions on industry for 2017. Taxes are applied to the net  
420 yearly cash flow, in case it is positive). The analysis has been done for a 15 years' period for  
421 all the analyzed scenarios.

422 The economic indicators are the standard Pay-back time (PBT: the first year in which the  
423 cumulated yearly cash flow is positive) and the Levelized cost of electricity (LCOE), defined

424 as the ratio between the total discounted lifetime costs (investment and operational) and the  
425 total discounted electrical energy production:

$$LCOE = \frac{\sum_{i=1}^N \frac{C_{inv,i} + C_{op,i}}{(1+r)^i}}{\sum_{i=1}^N \frac{E_i}{(1+r)^i}} \quad (32)$$

426

427 where:

428  $C_{inv,i}$  are the yearly investment costs

429  $C_{op,i}$  are the yearly operational costs

430  $E_i$  is the net yearly energy production

431  $r$  is the discount rate

432  $N$  is the system lifetime

433 The matrix of the analyzed case studies is shown in Table 6.

434 Table 6. Matrix of the analyzed case studies.

## 435 **5. Results and discussion**

436 To compare the performance of MGT case with that of the base case, required natural gas,  
437 covered thermal load of the digester, produced electrical power, system efficiency, as well as  
438 the results of economic analysis for both cases, are presented in this section. In addition, for  
439 the MGT case, four different scenarios using Capstone microturbine systems are developed to  
440 show which arrangement of the commercial products can be appropriate to cover the thermal  
441 demand of digester. To take the final decision, economic analysis results as well as those of the  
442 energy analysis will reveal the best choice among the scenarios.

### 443 **5.1. Energy simulation results**

444 For each SOFC module, 60 kW of electrical power is produced, so the amount of biogas  
445 required for feeding the SOFC modules is constant throughout the year.

446 NG and biogas consumptions (Figure 7a) in the boiler of the plant are calculated for the base  
447 case using the calculated data of digester thermal energy demand. The results are illustrated in  
448 Figure 7a, showing that the required NG in the boiler is lower than the available biogas (the  
449 portion of the produced biogas which is not fed into the SOFC system). As shown in the figure,  
450 during summer the available biogas is very low and thus NG consumption from the grid  
451 increases. The annual NG and biogas consumptions in the boiler are calculated to be 33,717  
452 Nm<sup>3</sup> and 165,411Nm<sup>3</sup>, respectively.

453 As shown in Figure 7b, the required amount of NG in the boiler increases when the system is  
454 equipped with MGT (instead of the simple boiler in the base case system). The increase in NG  
455 consumption is because by exploitation of the microturbine system in place of the boiler, the  
456 plant is supposed to produce electricity power along with meeting the thermal energy demand  
457 of digester simultaneously, so it is expected to burn more fuel in the combustion chamber of  
458 MGT system. The annual NG consumption for the MGT case is increased by up to 300%  
459 compared to the Base case.

Figure 7. Natural gas and biogas consumptions in the boiler for a) the Base Case b) the MGT Case

460  
461 In the Base Case configuration, the SOFC systems are the sole producers of the electrical  
462 power. However, in the MGT case, additional electrical power is produced using the  
463 microturbine as shown in Figure 8. Referring to the results shown in Figure 8, the produced  
464 electrical power by microturbine shows a decreasing trend from January to August and  
465 increasing trend for the next following months. Since the microturbine is governed in order to  
466 supply the heat demand of the digester and considering that the heat demand is low during  
467 summer season, the produced power follows the same trend of the heat demand.

468  
469 Figure 8. Electrical power demand and production in the proposed MGT integrated plant (MGT Case).

470 Figure 9 shows the total efficiency for both the base and the MGT cases. Referring to the figure,  
 471 it is found that although the NG consumption of the MGT case system is higher than that of  
 472 the base case system (Figure 7), the total efficiency for the MGT case is always higher due to  
 473 the extra electrical power production for this case. In addition, it should be noted that, when  
 474 the heat demand for the digester is higher, the difference in efficiency between the two cases  
 475 becomes more.

476 Figure 9. System efficiency for the Base Case and MGT Case.

477 It can be concluded that from the energy analysis results, using the MGT system instead of the  
 478 boiler would be effective as the system efficiency and also coverage of electrical demand of  
 479 the plant (SMAT Collegno) increase. In the following, using commercial MGT systems from  
 480 Capstone Company [13], four scenarios are proposed (Table 7). Two MGT systems, namely  
 481 C30 and C65 which are rated to produce net electrical power of 30 kW and 65 kW are chosen  
 482 [28]. The reason for choosing these two units is their thermal heat recovery potentials by which  
 483 the system could meet the required thermal demand of digester.

484 Operation under a partial load (PL) condition was also considered in this study. Outputs of  
 485 MGT-30 and MGT-65 at partial load condition can be obtained using the following equations  
 486 reported in Ref. [13]. Electrical power output  $P_e$ , recovered exhaust heat  $Q_{ehr}$ , and fuel flowrate  
 487  $Q_{fuel}$  for MGT-30 and MGT-65 models under partial load conditions (PL) can be estimated by  
 488 Eqs. (33-38) as function of the full load (FL) conditions.

$$\dot{W}_{MGT-30,PL} = \dot{W}_{MGT-30,FL} \times PL \quad (33)$$

$$\dot{Q}_{ehr,MGT-30,PL} = \dot{Q}_{ehr,MGT-30,FL} (0.1718 + 0.6529 \times PL + 0.1706 \times PL^2) \quad (34)$$

$$\dot{Q}_{fuel,MGT-30,PL} = \dot{Q}_{fuel,MGT-30,FL} (0.1513 + 0.7824 \times PL + 0.06004 \times PL^2) \quad (35)$$

$$\dot{W}_{MGT-65,PL} = \dot{W}_{MGT-65,FL} \times PL \quad (36)$$

$$\dot{Q}_{ehr,MGT-65,PL} = \dot{Q}_{ehr,MGT-65,FL} (0.1240 + 0.9707 \times PL - 0.1706 \times PL^2) \quad (37)$$

$$\dot{Q}_{fuel,MGT-65,PL} = \dot{Q}_{fuel,MGT-65,FL} (0.1228 + 0.9766 \times PL - 0.1131 \times PL^2) \quad (38)$$

489 In the first two scenarios (Scenario A and B) all the units are considered to be worked at full  
 490 load which means there is not any fluctuation in power production so that in scenario A and B,  
 491 the systems can produce 275kW and 310kW electrical power respectively. For the last two  
 492 scenarios (Scenario C and D) the MGT should be governed in such a way that the heat demand  
 493 of digester is supplied by means of exhaust thermal potential of MGT and consequently during  
 494 some months MGTs are supposed to work at partial load rather than full load. As mentioned  
 495 before, the SOFC units are operating under full load condition. Table 7 presents the  
 496 configuration of the different scenarios.

497 Table 7. Configurations and operating conditions of the investigated scenarios.

### 498 **5.1.1 Scenario A**

499 In full load conditions C65 and C30 can produce 105 kW and 56 kW thermal energy  
 500 respectively [13]. For Scenario A, the SOFC system, C65 and C30 are working at full load so  
 501 as can be seen in Figure 10a thermal load produced by MGT from March to December is quite  
 502 more than the required heat demand. However, as shown in Figure 10b, the produced electrical  
 503 power would be less than that of the MGT Case from January to May and more than it from  
 504 Jun to October. Meanwhile, results reveal that annual average electrical power production for  
 505 Scenario A would be 5.54% more compared to the MGT Case. The results show that using this  
 506 Scenario, the plant can cover almost 38% of total electrical power demand of SMAT Collegno.  
 507 However, looking at the total efficiency results shown in Figure 10c, it can be observed that  
 508 total efficiency is lower even compared to the base case due to higher consumption of NG and  
 509 consequently more waste heat is produced from May to November. The average system  
 510

511 efficiency for this scenario is 6.36% and 14.4% lower than that for the Base Case and MGT  
512 Case respectively.

Figure 10. a) Thermal load, b) Electrical power and c) Total efficiency for Scenario A.

513

### 514 **5.1.2 Scenario B**

515

516 The results calculated for Scenario B are illustrated in Figure 11. Referring to Figure 11a, for  
517 almost all along the year produced heat is exceeding the required heat for the digester.  
518 Consequently, the NG consumption should be higher than that for the Scenario A and also the  
519 electrical net power would be more than that of the scenario A. However, the results of total  
520 efficiency still unfold that the system efficiency for Scenario B is lower than that for Base Case  
521 and MGT Case by 7.4% and 15.4% respectively. This shows that despite having higher  
522 electrical power production. The negative effect of NG consumption overcomes the positive  
523 effect of produced electrical power. Nevertheless, using this scenario reveals that 42.8 % of  
524 total required electrical demand of the SMAT can be produced.

Figure 11. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario B

525

### 526 **5.1.3 Scenario C**

527

528 As discussed earlier, for Scenario C and D the MGT is governed in order to provide the needed  
529 heat demand of digester. For scenario C in which C30 unit and C65 unit are supposed to be  
530 implemented, for some months (from Jan to May and from October to December) C65 unit  
531 works at full load; however, for the rest the systems should work in partial load (Figure 12).  
532 On the other hand, C30 unit should be turned off from Jun to November as during these months  
533 C65 unit could produce enough thermal load to supply the required heat in the digester. The  
534 decision on when to have C65 at full load, when C30 is off, has been taken to better fit the  
535 thermal load. The produced electrical power and system efficiency curves found for this

536 scenario are close to those of the case MGT Case particularly from May to November. In  
537 January, the difference between the MGT Case and this scenario is because using both the C30  
538 and C65 even at full load could not meet the needed heat demand of digester. The annual  
539 average efficiency for scenario C. is found 62.74%. Also, using this Scenario the possibility to  
540 cover the electrical demand of the plant will be 35.01%.

Figure 12. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario C

541

#### 542 **5.1.4 Scenario D**

543

544 For the scenario D, the results are shown in Figure 13. Referring to Figure 13a, the thermal  
545 energy seems to be covered better than the other cases. By using two C65 it is found that almost  
546 98% of required heat demand could be produced. Figure 13b shows the obtained results for  
547 electrical power which indicates that the electrical power could be produced more than in  
548 scenario C so the trend is closer to the MGT Case rather than scenario C. The electrical  
549 efficiency values (Figure 13c) are almost similar to the scenario C (Figure 12c). The annual  
550 average efficiency for scenario D is 65.15%, which is higher than the value of Scenario C. In  
551 addition, 36.17% of total required electrical demand can be covered in the plant.

Figure 13. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario D

## 552 **5.2. Economic analysis results**

553 The first part of the techno-economic analysis has been devoted to the analysis of the energy  
554 inputs to the system, on a yearly basis. As can be seen in Table 8, the SOFC size is kept constant  
555 at 180 kW<sub>e</sub>, while the MGT size is varying depending on the scenarios, from 0 to 210 kW<sub>e</sub>.  
556 According to the system size and the regulation strategy, the yearly NG consumption can be  
557 evaluated as the sum of the MGT consumption, SOFC consumption (only required to keep  
558 stable the SOFC operating point in case of reduced biogas production, e.g. during summer

559 months) and boiler use (in case of not complete coverage of the digester thermal load through  
560 the system heat recovery). The highest natural gas consumption is related to the scenario B,  
561 where the turbines have the highest size and are working at full load. The same turbine size,  
562 with the partial load operation, has a reduction in natural gas consumption of 52.1%. A similar  
563 reduction (46.5 %) can be noticed among scenarios A and C, where the partial load is applied  
564 to the smallest turbine size.

565 Table 8. Electrical and natural gas yearly consumption for the different scenarios.

566 The power production from the system has been compared to the WWTP electrical and thermal  
567 loads. The electrical coverage, thanks to the MGT installation, increases from 24.9% to a  
568 maximum value of 42.9% in Scenario B (large ideal MGT at full load).

569 The digester thermal load coverage is also increased when the MGT integration is considered.  
570 As can be seen in Table 8, the NG consumption for boiler feeding is reduced by 100% in case  
571 of the ideal MGT Case, of 42% in scenarios A and C (C30+C65) and 84.6% in scenarios B and  
572 D (C65+C65). Thermal recovery from MGT thus helps, besides in increasing the electrical  
573 coverage, also in reducing the consumption of NG for thermal requirements.

574 From the analysis of the energy production in the different scenarios, the economic analysis  
575 has been performed with the calculation of the PBT and LCOE.

576 Figure 14 shows the LCOE for the different scenarios and cost trajectories during the time.  
577 Values should be compared with the current price of electricity in the WWTP, which  
578 corresponds to 0.16 €/kWh [15]. As can be seen, the ‘current’ scenario leads to high LCOEs,  
579 between 0.223 and 0.309 €/kWh for all the configurations: the cost of producing the electrical  
580 kWh, in none of the proposed case studies, can be considered cheaper than buying electricity  
581 from the grid, in a 15 years’ period. The MGT introduction always leads to a positive effect on  
582 the economic performance of the system: this is due to the relatively low investment costs  
583 (compared to the entire plant) compared to the increase in the electrical production of the

584 system. Among the different scenarios, the ideal MGT case is the one with the lowest LCOE,  
585 followed by scenario B and D with the 2xC65 gas turbines, working at full and partial load.  
586 The short-term scenario, related to a 500 units production (cumulative per company, see Figure  
587 6) brings to a strong reduction in the SOFC investment cost, and thus a better economic profile.  
588 All LCOEs are now lower than the current price of electricity in the SMAT site (0.16 c€/kWh),  
589 with values ranging from 0.116 to 0.134 €/kWh. Again, the lower costs is related to the ideal  
590 MGT case, followed by scenarios C and D, related to the partial load operations of the turbines.  
591 The analysis on the long term scenario confirms the trend discussed for the other case studies,  
592 with LCOE values in the range 0.088-0.102 c€/kWh.  
593 The introduction of a MGT, respect to the SOFC-only Base Case, brings to a 12% reduction in  
594 LCOE (from scenario MGT/C to A). Furthermore, in all the proposed configurations use of  
595 partial load brings to a reduction in the LCOE of around 6%.  
596 The second economic indicator, the payback time, varies from one scenario to another  
597 according to the same trends discussed for the LCOE. For this reason, the two indicators are  
598 compared only for the short term scenario (Table 9). The short term scenario, with a SOFC  
599 investment costs of 5'656 €/kWe, has been considered the most promising and achievable  
600 target, without any specific subsidy schemes, for SOFC systems. For this scenario, the  
601 breakdown of LCOE among CAPEX and OPEX costs is provided. Results are shown in Table  
602 9.

603 Figure 14. Levelized cost of electricity for the different scenarios and cost trajectories.

604 The highest LCOE of the SOFC-only case study (called 'Base case') is due to the high  
605 investment cost of the technology about the electrical energy produced. The introduction of an  
606 MGT leads to a higher increase in the energy produced respect to the increase in costs, and this  
607 results in a lower LCOE. On the other side, operating costs are indeed similar for the SOFC  
608 and ideal MGT cases, and slightly increasing for the real MGT scenarios (A, B, C, D) because

609 of the increase in the NG request. The payback time confirms this trends, with a value higher  
610 than 11 years for the SOFC-only case, reduced at 7.66 in the ideal MGT one. When analyzing  
611 real MGT scenarios, payback time are always between 7.9 and 8.5 years (reduction of 30%  
612 respect to the SOFC-only base case). Use of partial operation for MGT is again confirmed as a  
613 positive choice, which leads to a reduction in PBT of around 5%.

614 These values are strongly reduced in the long term economic analysis (SOFC cost equal to  
615 2'326 €/kWe). Here, the low cost of the SOFC technology, reduces the positive effect of the  
616 MGT, since they are able to provide similar electrical energy based on similar specific  
617 investment costs, but with a lower efficiency. In this case, the payback time is ranging from  
618 3.3 years (Scenario C) to 3.9 years (Base case).

619 From the complete economic analysis, it is pointed out that the MGT is able to increase the  
620 economic benefits of the SOFC system, especially in the current and short term scenario where  
621 the specific SOFC costs is still high (reduction in LCOE of 27.9 and 12.9% are found between  
622 MGT and Base Case for Current and Short Term scenario). The advantages of installing a MGT  
623 are reduced in the Long Term scenario (LCOE reduction of 1.3% between MGT and Base  
624 Case). Furthermore, when a MGT is installed, the option of the partial load operation shows a  
625 slightly better economic profile, while no essential differences are pointed out for the choice  
626 of a C65+C30 or C65+C65 layout.

627 Table 9. LCOE and PBT for the different technical scenario, with a short term economic scenario.

## 628 **6. Conclusion**

629 Biogas produced in wastewater treatment plants is versatile renewable energy source that can  
630 be efficiently transformed to heat or electricity and heat. Two plant configuraitons, namely  
631 Base case and MGT case, are developed and analyzed for a wastewater treatment plant located  
632 in Torino (IT). In both cases, the produced biogas from the digester of the plant is first sent to  
633 the SOFC having an electrical capacity of 180 kW. In the Base case, thermal power recovered

634 from the exhaust of the SOFC systems along with an biogas/NG external boiler are used to  
635 cover the digester thermal load. casein the MGT case, the boiler is replaced with the micro gas  
636 turbine operated in CHP mode. For the MGT case, after getting the first-hand results, four  
637 scenarios using the commercial micro gas turbines of Capstone are proposed. The following  
638 conclusions could be drawn from this work;

- 639 • Results show that although using the micro gas turbines in the plant requires the  
640 increase in NG from the grid, the the overall efficiency of the plant is increased by up  
641 to 7% due to an increase in the total electrical power of the plant.
- 642 • Comparing the obtained results for the base case with those of MGT case reveals that  
643 overall electrical power of the MGT case is averagely 110 kW more than that of the  
644 base case system.
- 645 • Comparing the effect of using different arrangements of the commercial micro gas  
646 turbines for the MGT case shows that by using C30 and C65 in the governing mode a  
647 reduction of the coverage occurs, equal to 3% in case of small size (C30+C65 MGT)  
648 and 6.2% in case of the larger installation (C65+C65 MGT).
- 649 • The shortest investment recovery is obtained with the MGT case, followed by the other  
650 MGT scenarios (cased A to D), which show a PBT between 7.66 and 8.46 years in a  
651 the shortterm economic scenario. The addition of a MGT to the base case scenario  
652 always leads to a benefit in terms of economic indicators.
- 653 • The choice of working in partial load with the MGT shows better economic  
654 performance.

655 Finally, it can be declared that suggested proposal for using the micro gas turbine along  
656 with SOFC system in the wastewater treatment plant is beneficial.

657

658

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746 **Figures' caption**

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- 748 Figure 1. SMAT wastewater treatment plant in Collegno (Turin) [16]. “DEMOSOFC Plant” shows the area  
 749 where the three SOFC modules will be installed.
- 750 Figure 2. Concept diagram of the DEMOSOFC plant [14].
- 751 Figure 3a. Proposed SOFC system layout.
- 752 Figure 4a. Schematic of the DEMOSOFC plant.
- 753 Figure 5a. Sludge inlet, air and ground temperature trend.
- 754 Figure 6. Specific investment cost for a 50 kWe unit and share among the cost components (stack, added system  
 755 and installation). Author own elaboration of [22].
- 756 Figure 7. Natural gas and biogas consumptions in the boiler for a) the Base Case b) the MGT Case
- 757 Figure 8. Electrical power demand and production in the proposed MGT integrated plant (MGT Case).

758 Figure 9. System efficiency for the Base Case and MGT Case.  
759 Figure 10. a) Thermal load, b) Electrical power and c) Total efficiency for Scenario A.  
760 Figure 11. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario B  
761 Figure 12. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario C  
762 Figure 13. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario D  
763 Figure 14. Levelized cost of electricity for the different scenarios and cost trajectories.  
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775 Figure 10. a) Thermal load, b) Electrical power and c) Total efficiency for Scenario A.  
776 Figure 11. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario B  
777 Figure 12. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario C  
778 Figure 13. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario D  
779 Figure 14. Levelized cost of electricity for the different scenarios and cost trajectories.

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790 **Figures**

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Figure 15. SMAT wastewater treatment plant in Collegno (Turin) [16]. “DEMOSOFC Plant” shows the area  
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Figure 16. Concept diagram of the DEMOSOFC plant [14].

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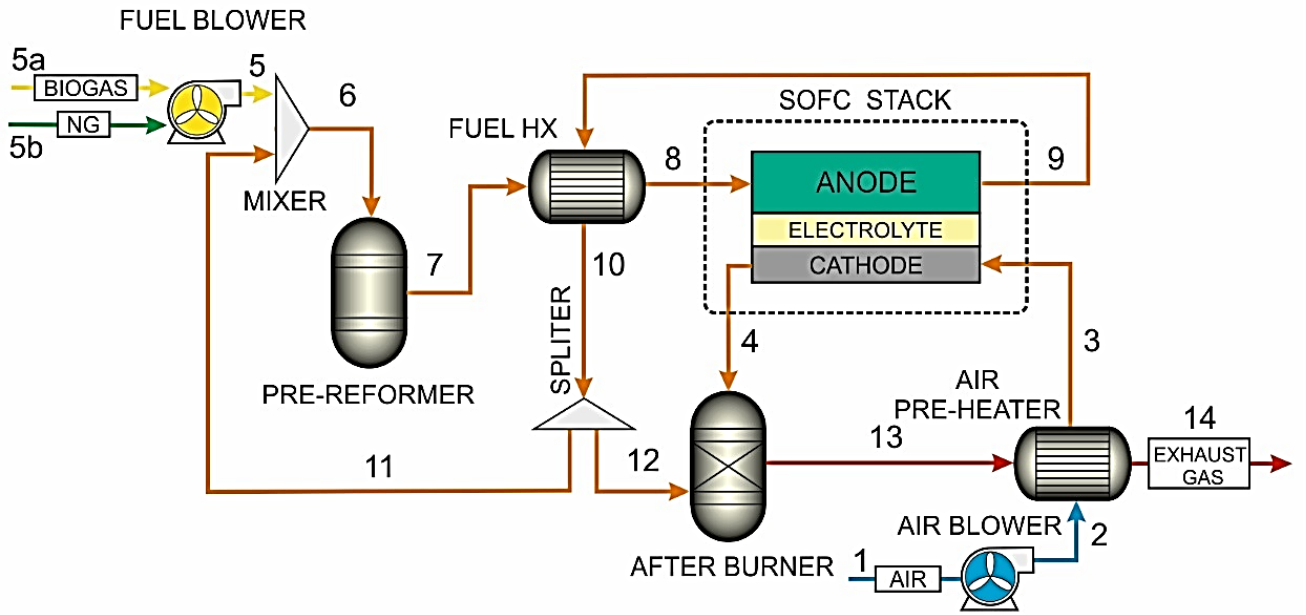
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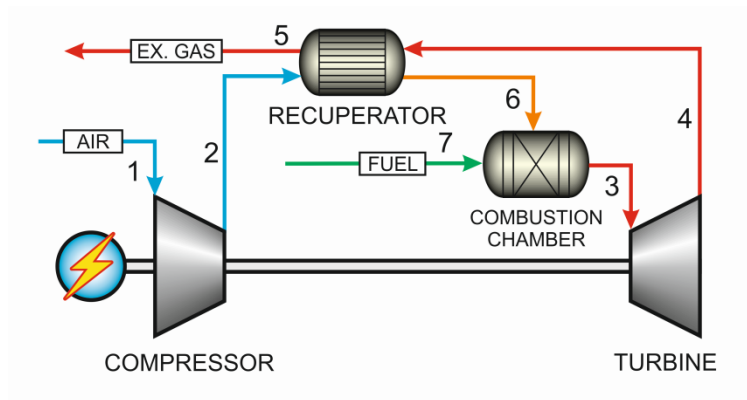
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Figure 17a. Proposed SOFC system layout.

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Figure 3b Schematic of the regenerated microturbine system

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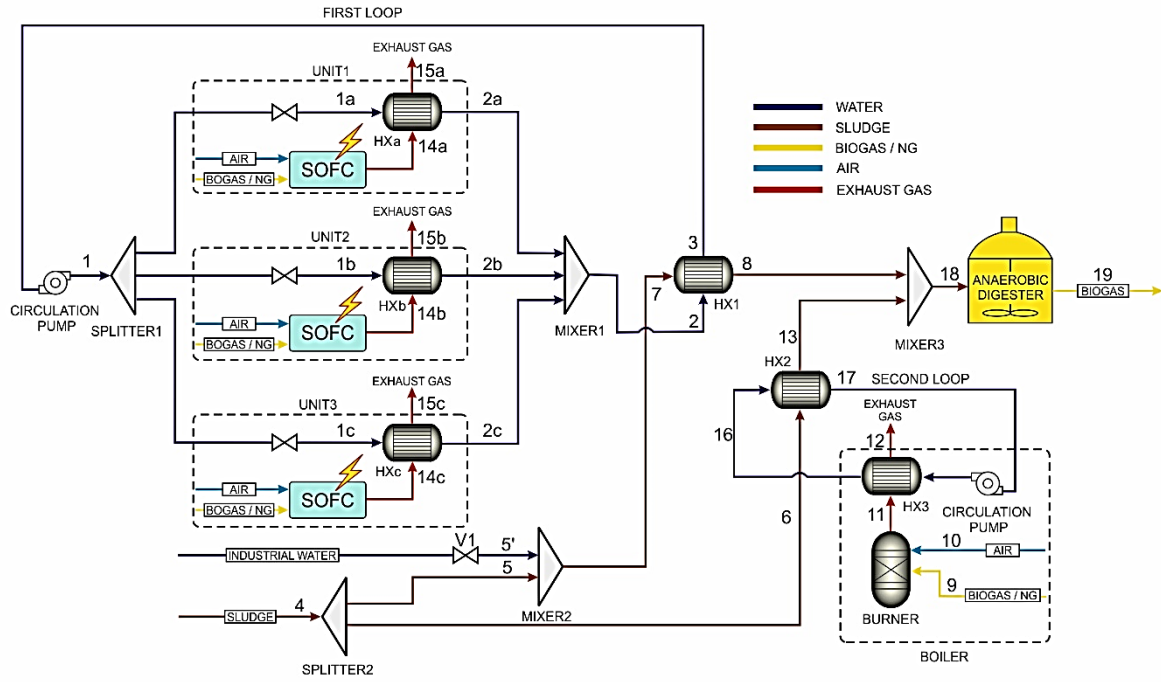
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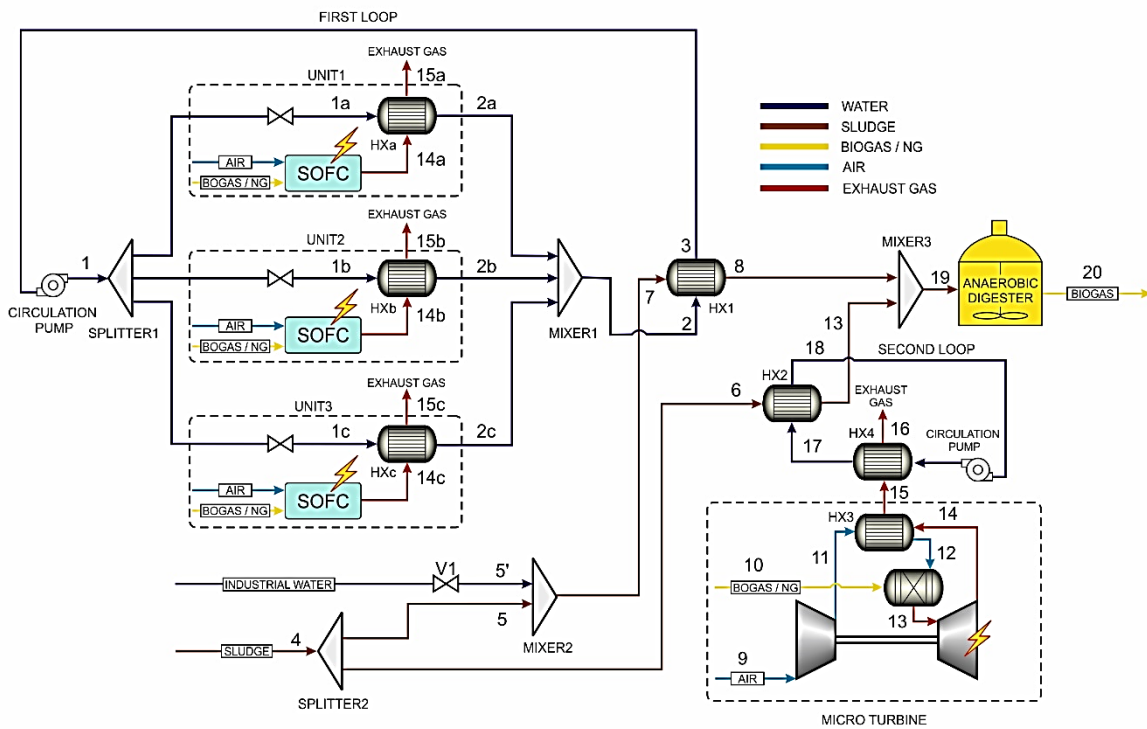
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Figure 18a. Schematic of the DEMOSOFC plant.



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Figure 4b. Proposed flowsheet for the biogas fed SOFC plant integrated with microturbine.

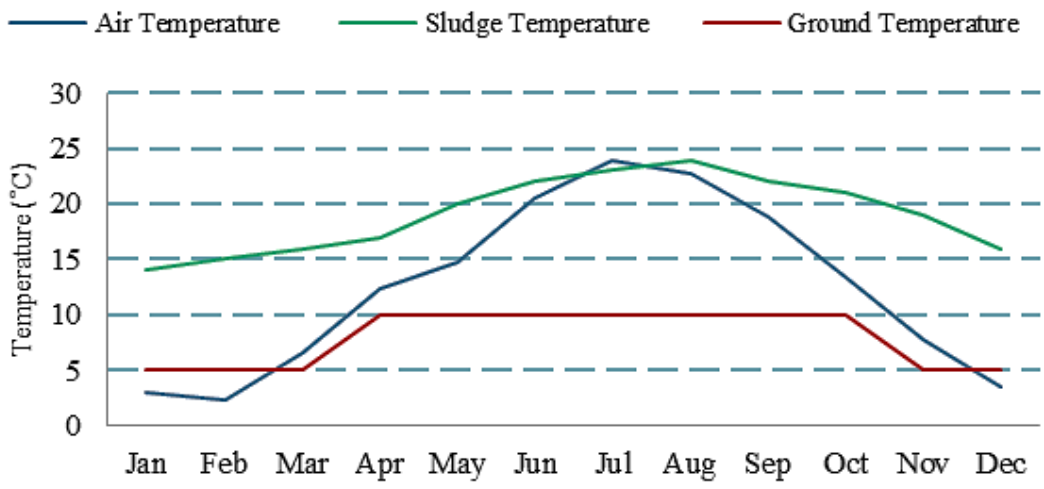
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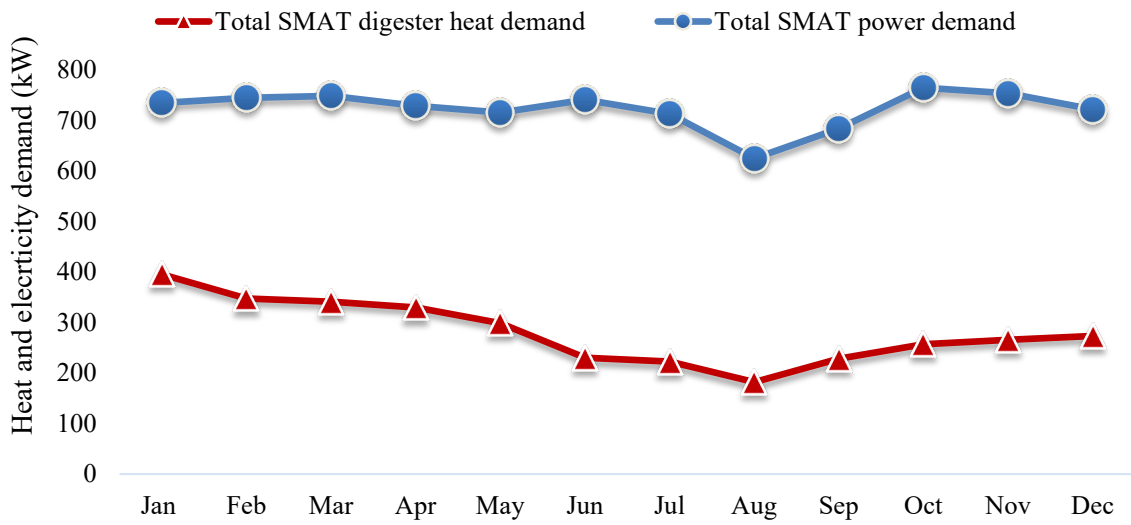
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Figure 19a. Sludge inlet, air and ground temperature trend.

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Figure 5b. Trends of total electrical demand and required thermal energy for digester in SMAT Collegno

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calculated for 2015.

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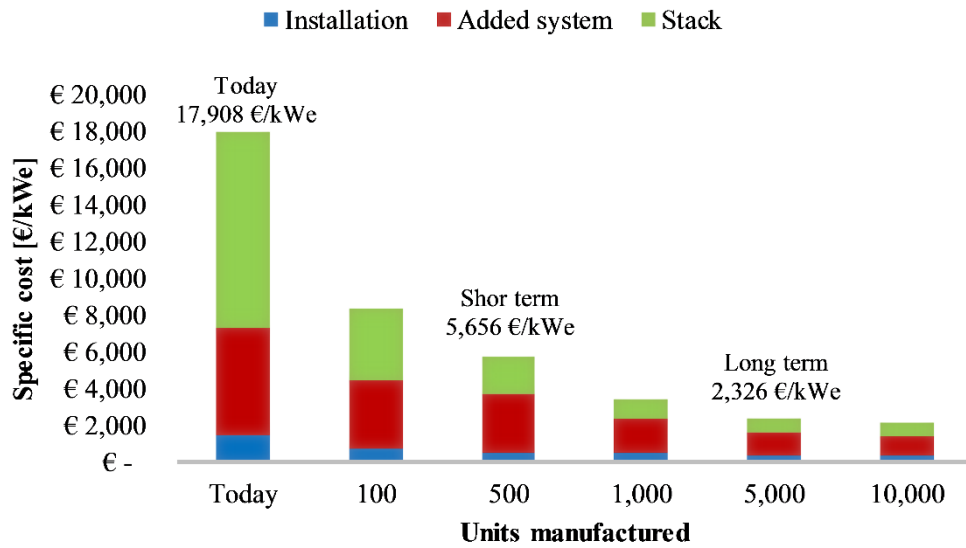
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Figure 20. Specific investment cost for a 50 kWe unit and share among the cost components (stack, added system and installation). Author own elaboration of [24].

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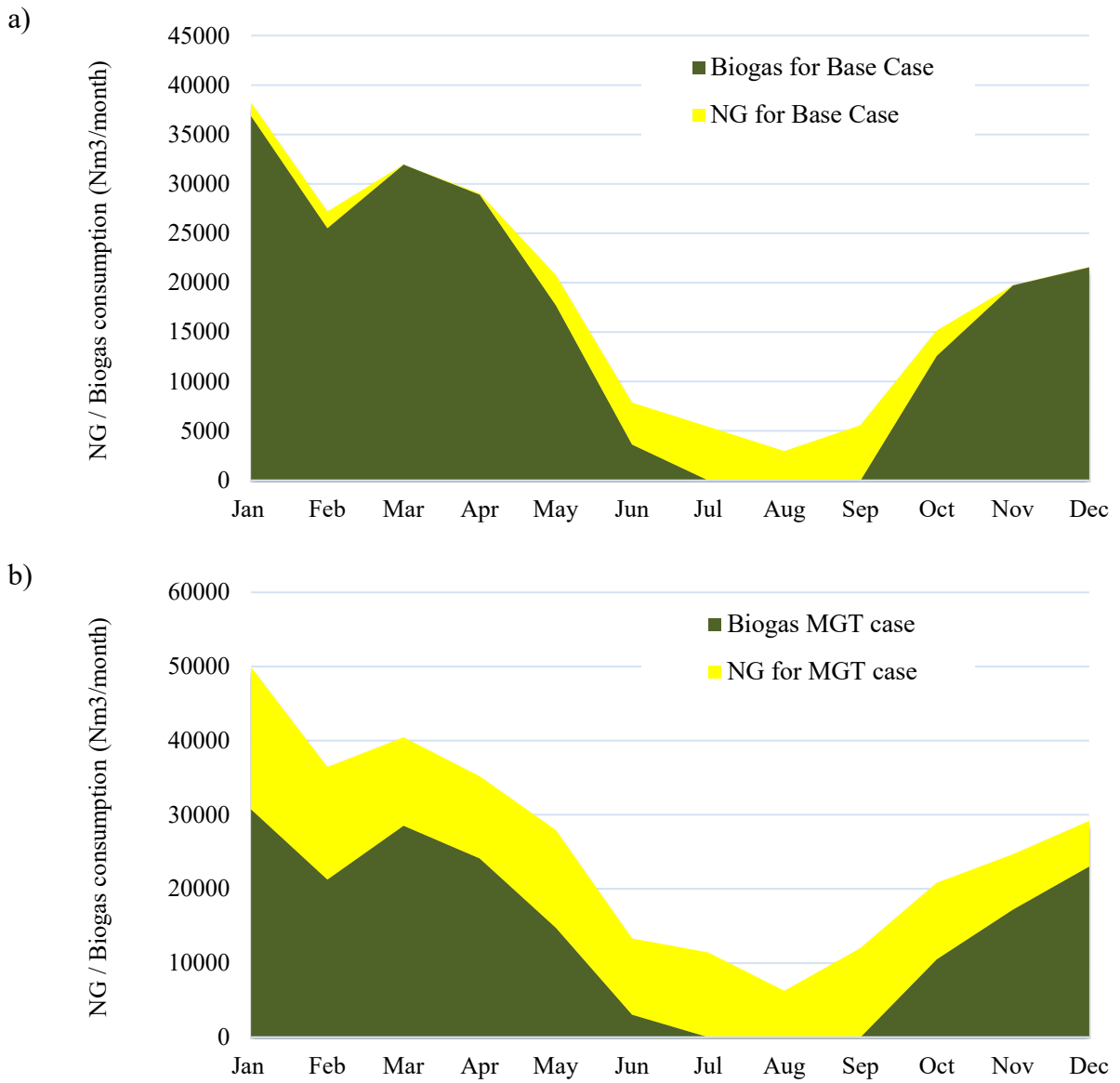


Figure 21. Natural gas and biogas consumptions in the boiler for a) the Base Case b) the MGT Case

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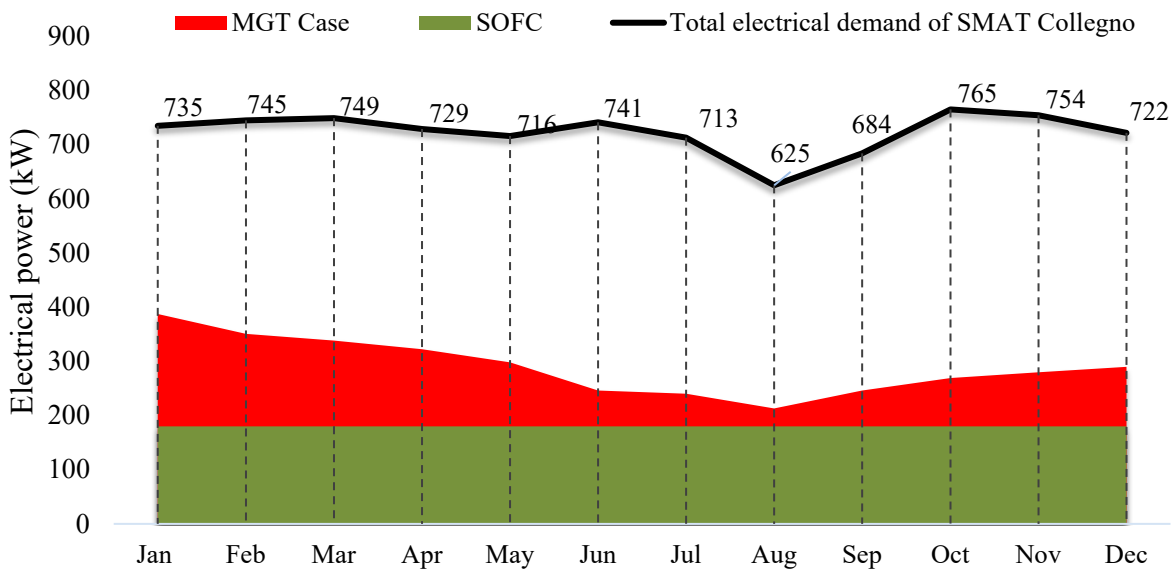
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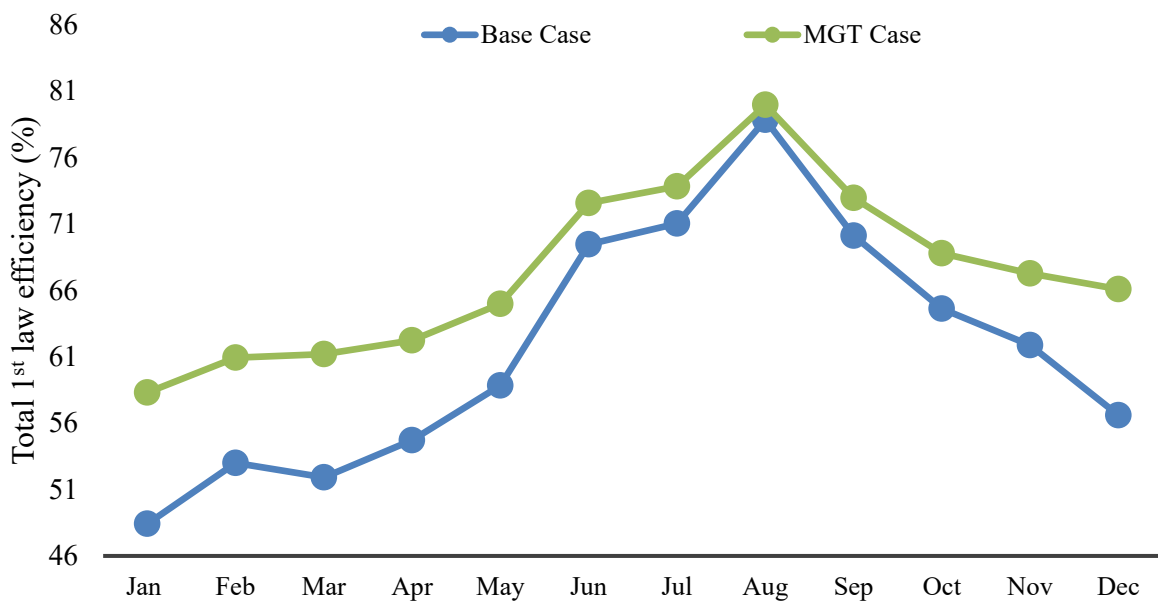
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Figure 22. Electrical power demand and production in the proposed MGT integrated plant (MGT Case).

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Figure 23. System efficiency for the Base Case and MGT Case.

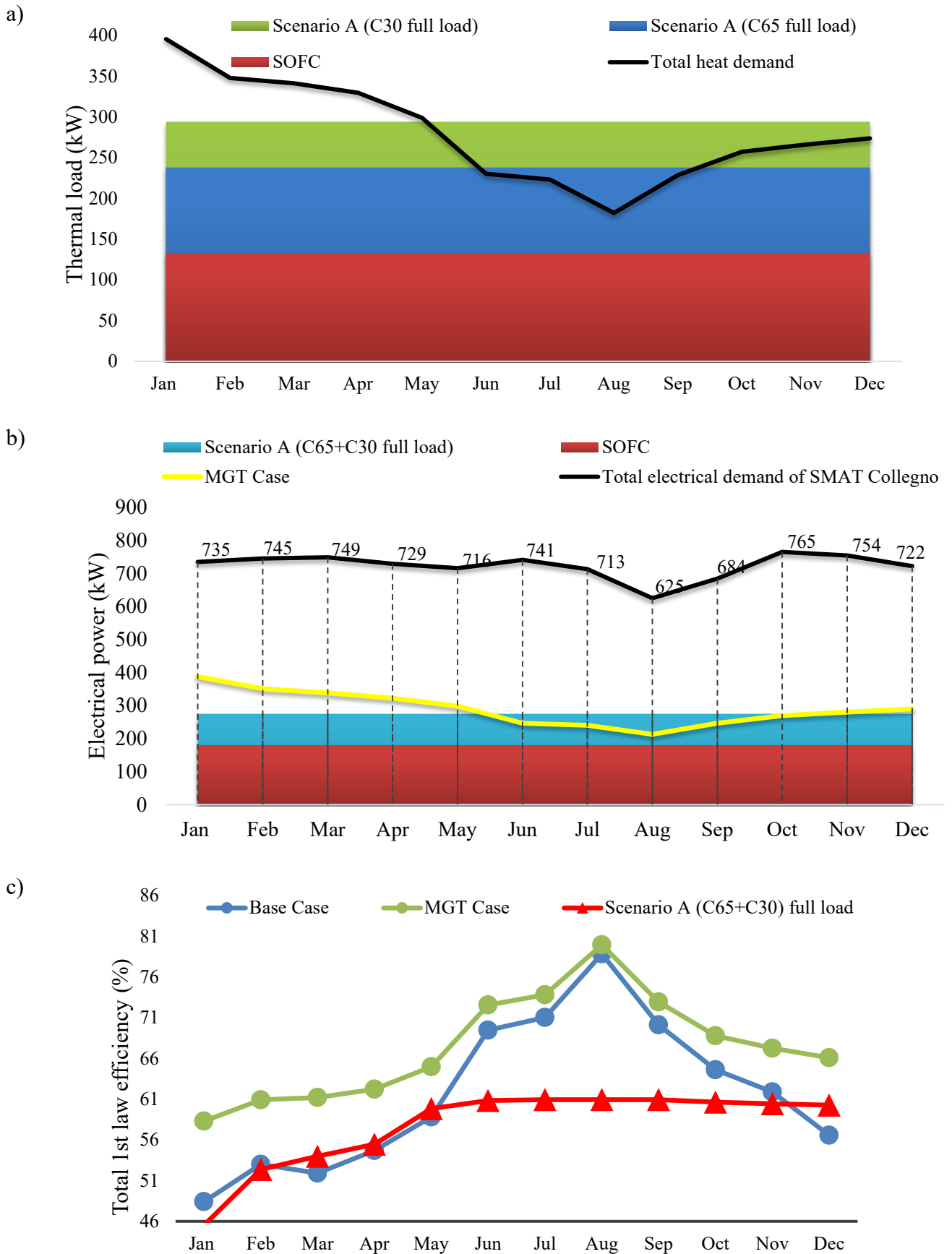


Figure 24. a) Thermal load, b) Electrical power and c) Total efficiency for Scenario A.

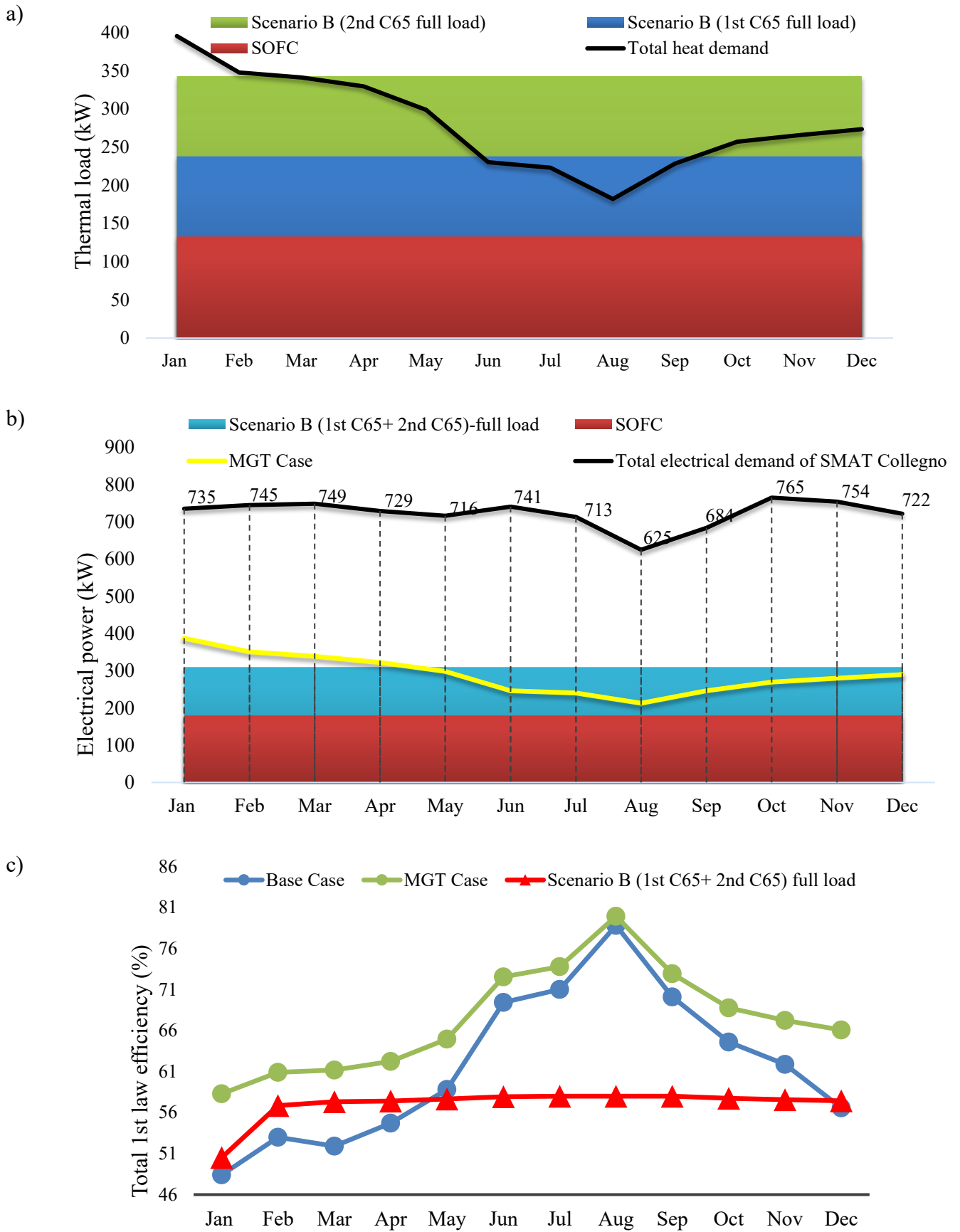


Figure 25. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario B

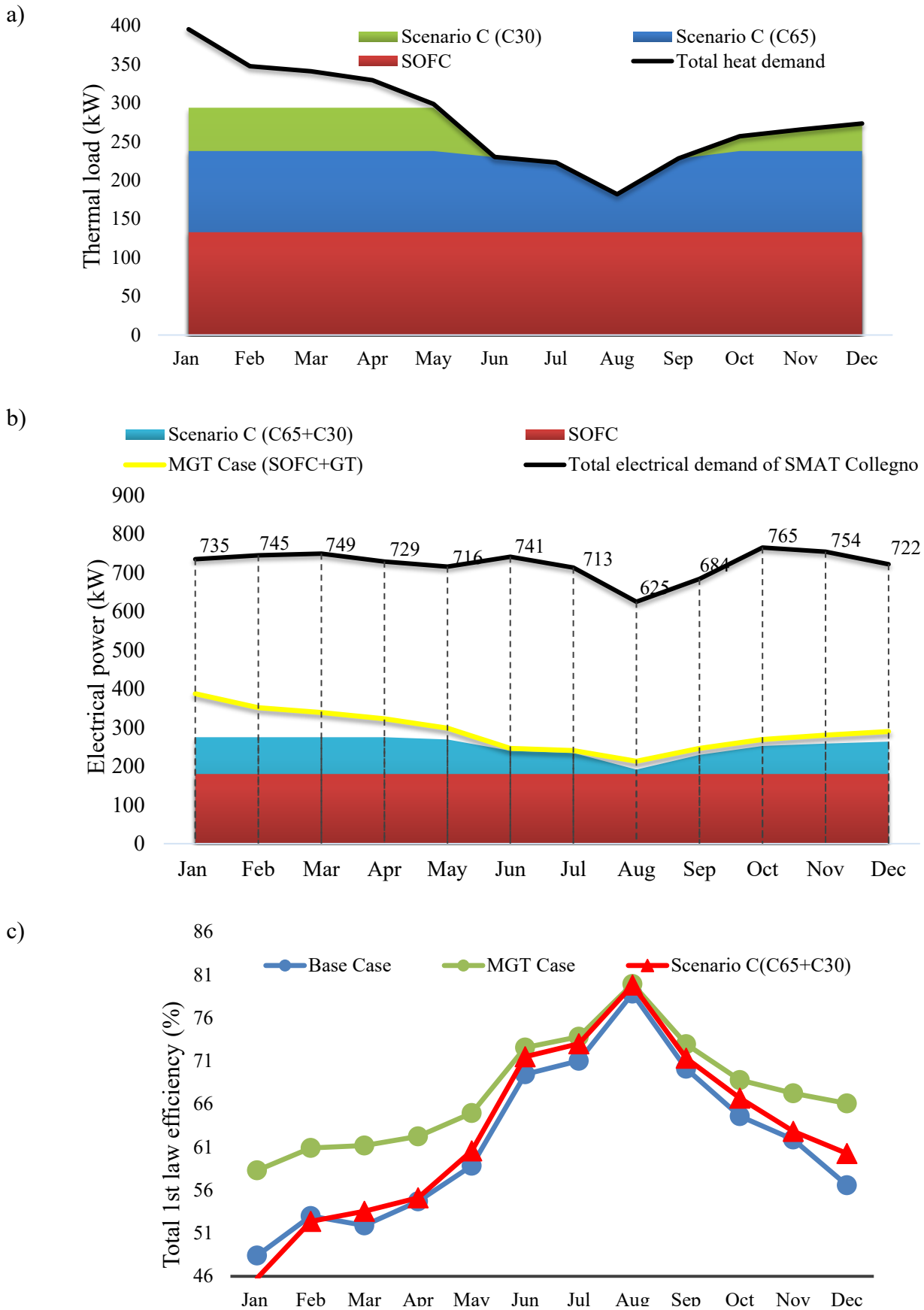


Figure 26. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario C

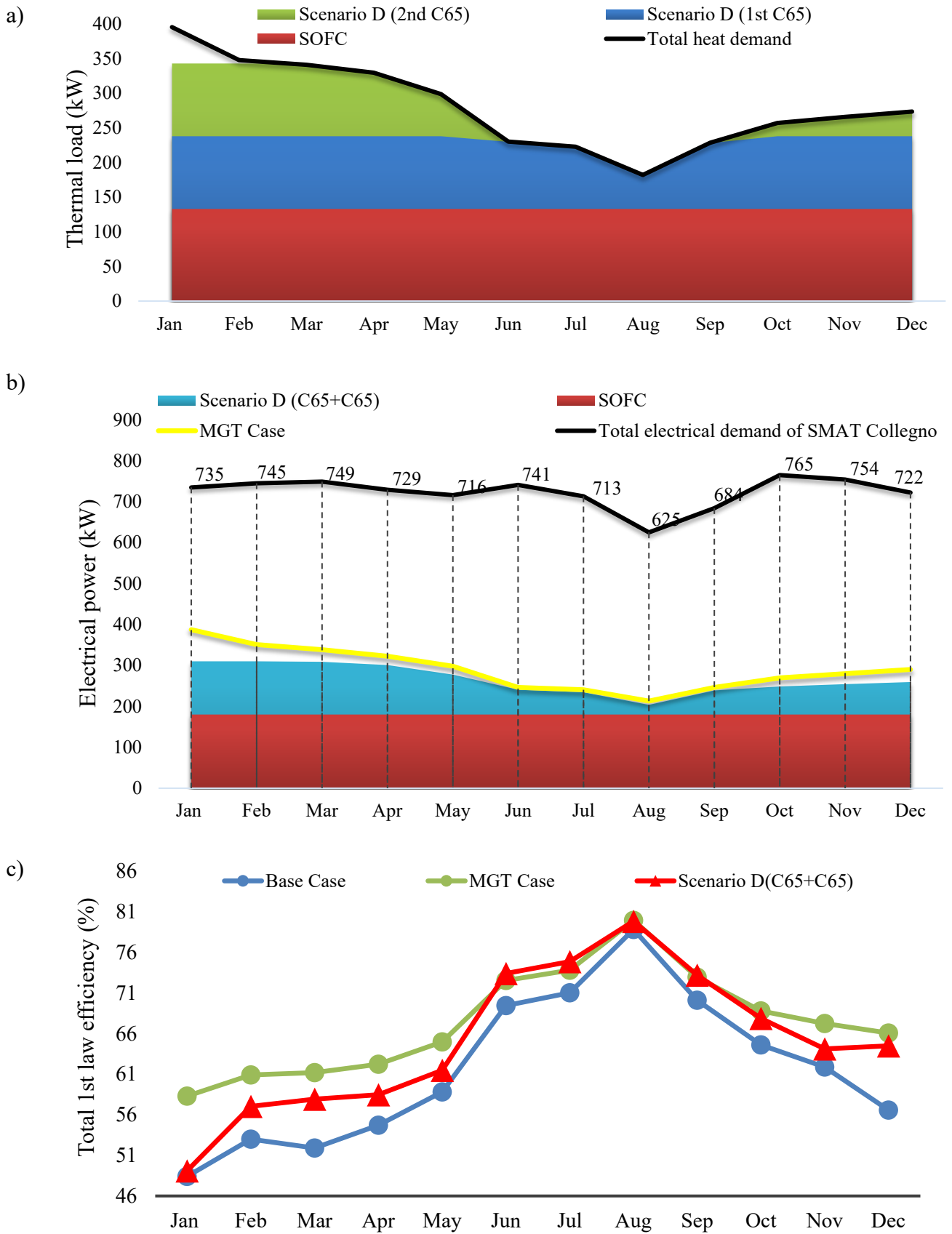
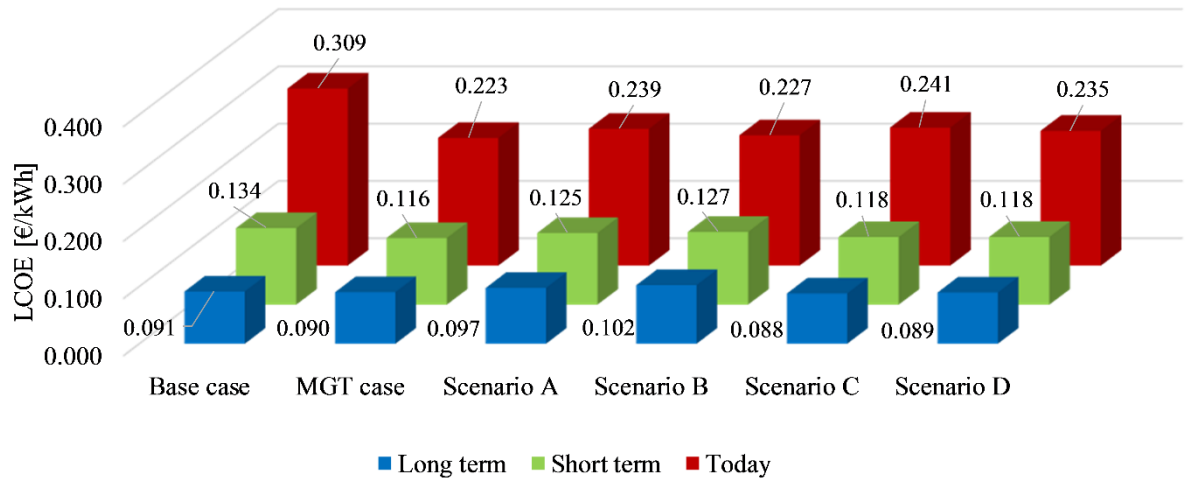


Figure 27. a) Thermal load, b) Electrical power and c) Total system efficiency for Scenario D

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Figure 28. Levelized cost of electricity for the different scenarios and cost trajectories.

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**Tables' caption**

- Table 1. Material Resistivity used for Ohmic voltage loss estimation [20]
- Table 2. Parameters correspond to the material anode and cathode sides [20]
- Table 3. Main parameters for digester thermal load calculations.
- Table 4. Comparison of results obtained from the present work with the experimental values reported by Tao et al. [27]
- Table 5. SOFC, biogas processing unit and MGT costs. [21] [22] [23]
- Table 6. Matrix of the analyzed case studies.
- Table 7. Configurations and operating conditions of the investigated scenarios.
- Table 8. Electrical and natural gas yearly consumption for the different scenarios.
- Table 9. LCOE and PBT for the different technical scenario, with a short term economic scenario.

971 **Tables**

972 Table 10. Material Resistivity used for Ohmic voltage loss estimation [21]

Component	Material	Resistivity	Thickness (mm)
Anode	Ni/YSZ cermet	$\rho_{an}=2.98 \times 10^{-5} \exp\left(\frac{-1392}{T_{FC,e}}\right)$	0.5
Cathode	LSM-YSZ	$\rho_{cat}=8.114 \exp\left(\frac{600}{T_{FC,e}}\right)$	0.05
Electrolyte	YSZ	$\rho_{ely}=2.94 \times 10^{-5} \exp\left(\frac{10350}{T_{FC,e}}\right)$	0.01
Interconnection	Doped LaCrO3	0.0003215	-

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975 Table 11. Parameters correspond to the material anode and cathode sides [21]

Component	Parameter	Value	Unit
Anode	Pre-exponential factor for anode, $\gamma_{an}$	$6.54 \times 10^{11}$	A m <sup>-2</sup>
	Activation energy for anode, $E_{a,an}$	140,000	J mol <sup>-1</sup>
Cathode	Pre-exponential factor for cathode, $\gamma_{ca}$	$2.35 \times 10^{11}$	A m <sup>-2</sup>
	Activation energy for cathode, $E_{a,cat}$	137,000	J mol <sup>-1</sup>

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977 Table 12. Main parameters for digester thermal load calculations.

Parameter	Symbol	Value	Unit	Ref.
Sludge inlet temperature	$T_{sl,in}$	14 (January) ÷ 23 (July)	°C	[29]
Sludge mass flow rate	$\dot{m}_{sl}$	1.82 (December) ÷ 3.09 (May)	kg/s	SMAT
Heat transfer coefficient for underground walls	$U_{ug}$	2.326	W/m <sup>2</sup> °C	SMAT
Heat transfer coefficient for non-underground walls	$U_{ext}$	0.930	W/m <sup>2</sup> °C	SMAT
Area of underground walls (floor and partial side walls)	$A_{ug}$	450.8	m <sup>2</sup>	SMAT
Area of non-underground walls ( partial side walls and roof)	$A_{ext}$	1132.1	m <sup>2</sup>	SMAT
Ground temperature	$T_{gr}$	5 (winter) ÷ 10 (summer)	°C	Assumption
External temperature	$T_{ext}$	2.3 (February) ÷ 23.9 (July)	°C	ilmeteo.it
Percentage of losses through pipes	% <sub>pipes</sub>	5	%	Assumption

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Table 13. Comparison of results obtained from the present work with the experimental values reported by Tao et al. [22]

Current density (A/m <sup>2</sup> )	Cell voltage (V) (Present work)	Cell voltage (V) (Tao et al.)	<i>Error (%)</i>	Power density (W/m <sup>2</sup> ) (Present work)	Power density (W/m <sup>2</sup> ) (Tao et al.)	<i>Error (%)</i>
<b>2000</b>	0.742	0.76	-1.368	0.148	0.15	-1.333
<b>3000</b>	0.684	0.68	0.272	0.205	0.21	-2.381
<b>4000</b>	0.634	0.62	0.868	0.253	0.26	-2.692
<b>5000</b>	0.582	0.57	0.684	0.294	0.295	-0.339
<b>6000</b>	0.547	0.52	1.404	0.328	0.315	4.127

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Table 14. SOFC, biogas processing unit and MGT costs. [23] [24] [25]

	<b>Today</b>	<b>Short Term</b>	<b>Long term</b>
<b>Units manufactured</b>	-	500	5,000
<b>Module CAPEX (€/kWe)</b>	17,908	5,656	2,326
<b>Maintenance (€/kWe/yr)</b>	120	60	47
<b>Stack replacement (€/kWe)</b>	2,710	712	482
<b>Stack lifetime during 15 years (y)</b>	3-3-4-4	5-5-5	7-8
<b>Clean-up system CAPEX (€/kWe)</b>	1,500	1,000	500
<b>Clean-up system OPEX (c€/kWe)</b>	1	1	0.5
<b>MGT CAPEX (€/kWe)</b>	1,000	1,000	1,000
<b>MGT OPEX (c€/kWe)</b>	1	1	1

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Table 15. Matrix of the analyzed case studies.

		SOFC and Clean-up costs		
		Present	Short term	Long Term
Plant layout	<i>Base Case</i>	<i>Base 1</i>	<i>Base 2</i>	<i>Base 3</i>
	MGT case	MGT1	MGT2	MGT3
	Scenario A	A1	A2	A3
	Scenario B	B1	B2	B3
	Scenario C	C1	C2	C3
	Scenario D	D1	D2	D3

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Table 16. Configurations and operating conditions of the investigated scenarios.

Scenario	Module	Load
Scenario A	SOFC	Full load
	C65	Full load
	C30	Full load
Scenario B	SOFC	Full load
	C65	Full load
	C65	Full load
Scenario C	SOFC	Full load
	C65	Full/Partial load
	C30	Full/Partial load
Scenario D	SOFC	Full load
	C65	Full/Partial load
	C65	Full/Partial load

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Table 17. LCOE and PBT for the different technical scenario, with a short term economic scenario.

Scenario	LCOE (€/kWh)	CAPEX share of LCOE (€/kWh)	OPEX share of LCOE (€/kWh)	PBT (y)
<b>Base Case</b>	0.134	0.057	0.076	11.57
<b>MGT Case</b>	0.116	0.042	0.075	7.66
<b>Scenario A</b>	0.125	0.040	0.085	8.46
<b>Scenario B</b>	0.127	0.037	0.090	8.30
<b>Scenario C</b>	0.118	0.044	0.074	8.01
<b>Scenario D</b>	0.118	0.043	0.075	7.95

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Table 18. Electrical and natural gas yearly consumption for the different scenarios.

	SOFC size [kW]	MGT size [kW]	Yearly NG to MGT (Nm <sup>3</sup> )	Yearly biogas to boiler (Nm <sup>3</sup> )	Yearly NG to SOFC (Nm <sup>3</sup> )	Yearly NG to boiler (Nm <sup>3</sup> )	Total yearly NG consumption (Nm <sup>3</sup> )	Total yearly electricity production (kWh)
<b>Base case</b>	180	0	0	165,411	11,630	33,718	45,348	1,576,800
<b>MGT Case</b>	180	210	134,405	173,153	11,630	0	146,036	2,539,854
<b>Scenario A</b>	180	95	162,740	173,153	11,630	19,528	193,898	2,409,000
<b>Scenario B</b>	180	130	242,928	173,153	11,630	4,584	259,141	2,715,600
<b>Scenario C</b>	180	95	87,028	173,153	11,630	19,528	118,186	2,217,000
<b>Scenario D</b>	180	130	116,243	173,153	11,630	4,584	132,458	2,324,141

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