

Accepted Manuscript

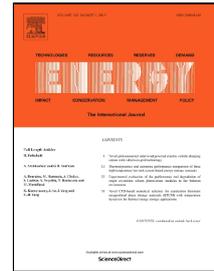
Smart Municipal Energy Grid within Electricity Market

Ilija Batas-Bjelic, Nikola Rajakovic, Neven Duic

PII: S0360-5442(17)31172-6
DOI: 10.1016/j.energy.2017.06.177
Reference: EGY 11185
To appear in: *Energy*
Received Date: 10 November 2016
Revised Date: 02 June 2017
Accepted Date: 30 June 2017

Please cite this article as: Ilija Batas-Bjelic, Nikola Rajakovic, Neven Duic, Smart Municipal Energy Grid within Electricity Market, *Energy* (2017), doi: 10.1016/j.energy.2017.06.177

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.



Smart Municipal Energy Grid within Electricity Market

Ilija Batas-Bjelic*, Nikola Rajakovic

Department of Power Systems, School of Electrical Engineering, University of Belgrade,
Serbia

e-mail: Batas@etf.rs, Rajakovic@etf.rs

Neven Duic

Faculty of Mechanical Engineering and Naval Architecture

University of Zagreb, Zagreb, Croatia

e-mail: Neven.Duic@fsb.hr

ABSTRACT

A smart municipal energy grid including electricity and heat production infrastructure and electricity demand response has been modeled in HOMER case study with the aim of decreasing total yearly community energy costs. The optimal configurations of used technologies (photovoltaic plants, combined heat and power plants, wind power plants) and sizing, with minimal costs, are presented and compared using three scenarios of average

* Corresponding author

21 electricity market price 3.5 c€/kWh, 5 c€/kWh and 10 c€/kWh. Smart municipal energy grids will
22 have an important role in future electricity markets, due to their flexibility to utilize excess
23 electricity production from CHP and variable renewable energy sources through heat storage.
24 This flexibility enables the levelized costs of energy within smart municipal energy grids to
25 decrease below electricity market prices even in case of fuel price disturbances. With initial
26 costs in the range 0- 3,931,882 €, it has been shown that economical and environmental
27 benefits of smart municipal energy grids are: the internal rate of return in the range 6.87-15.3%,
28 and CO2 emissions in the range from -4,885,203 to 5,165,780 kg/year. The resulting realistic
29 number of hours of operation of combined heat and power plants obtained by simulations is in
30 the range 2,410- 7,849 hours/year.

31 **KEYWORDS**

32 Smart grid, demand response, district heating, real time pricing.

33 **HIGHLIGHTS**

- 34 • A smart municipal energy grid has been modeled in HOMER.
- 35 • The national electricity grid has been modeled with real time prices.
- 36 • Smart municipal grids could utilize excess electricity as their heat source.
- 37 • The hours of operation should be obtained with respect to hourly simulations.
- 38 • Smart municipal energy grids reduce energy costs below the assumed market price.

39 **ABBREVIATIONS**

BGCHP	Biogas CHP
BMS	Biomass
CAPEX	Capital Investment Costs
CHP	Combined Heat and Power
HOMER	Hybrid Optimization of Multiple Energy Resources

IRR	Internal Rate of Return
LHV	Lower Heating Value
NGCHP	Natural Gas CHP
O&M	Operation and Maintenance
OPEX	Operation Costs
PV	Photovoltaic

40

41 **1. INTRODUCTION**

42 Future energy systems are in transition towards increased flexibility in operation which will
43 bring economic benefits [1]. One of these benefits might be the decrease in the levelized cost of
44 energy, which is a sound basis for final customer pricing. The demand response as a locally
45 available flexibility property, has been shown in [2]. It helps that these decentralized smart multi-
46 energy systems [3, 4] of future become more efficient, environmentally friendly, and reliable [5].
47 Reliability will be more and more important as the number of natural disasters such as floods
48 will increase in future [6], therefore increasing the need for more resilient smart municipal grids
49 [7, 8].

50 A possible smart isolated grid configuration with demand response and a biogas combined
51 heat and power plant has economic benefits thanks to its flexibility, which is proven using the
52 Hybrid Optimization of Multiple Energy Resources (HOMER) simulation tool [9]. HOMER
53 defines the levelized costs of energy as the average cost per kWh of useful electrical energy
54 produced by the system, excluding the costs for serving the thermal load. An intermittency
55 friendly system with heat/cold demand and storage, including trading electricity on the market,
56 has been demonstrated for different energy carrier prices in study [10]. A recent study which
57 provides a comparison of the least costly energy storage sizes and technologies [11] could be
58 useful for integration of higher amounts of locally produced energy into smart municipal energy

59 grids and achieving higher resilience standards. A smart municipal energy grid design and
60 economic response to governmental constraints has been shown using HOMER in [12].

61 In the article [13], the flexibility of heat and electricity provision from biomass plants is
62 assessed for Germany but not for Serbia, which is why this case study will be carried out in
63 Serbia for the City of Sabac. A technical feasibility study, including the techno-economic
64 analysis of a combined heat and power plant fuelled by biogas, has been carried out for plant
65 "Voganj" in Ruma, Serbia [14]. The problem of excess electricity and heat has been solved with
66 grid connection and food production nearby. Technical details regarding grid connection of a
67 small biogas plant are known from a similar pilot project in the region [15].

68 The economics of energy production depends significantly on yearly utilization. For heat
69 production only it is hard to run units for more than 2,500–3,000 hours per year [16]; therefore,
70 utilization should mean selling more energy to the national grid within a feed-in tariff scheme
71 [14, 17, 18] or participating in electricity markets. On the other hand feed-in tariff scheme might
72 be insufficient for electricity only utilization [19]. Specific investment costs for the combined heat
73 and power (CHP) plant based on a biogas engine depending on the plant size vary in the range
74 800-9,000 €/kW_{el} [20-22]. They can be estimated more precisely for each size using the formula
75 from [23]. Operation and maintenance (O&M) costs depend on gas quality 0.01-0.02 €/hour*kW
76 for a liquid gas engine [24] and can also be calculated using the formula in [23]. Resulting
77 levelized costs of heat production from waste/crops vary 3.4-6.6 c€/kWh, and for natural gas are
78 3.6 c€/kWh [25]. The levelized costs of electricity produced from a biogas CHP plant are 13
79 c€/kWh_{el}, as calculated in [14]. The price of input feedstock including transport varies from 0-
80 175 €/t feedstock [21], for poultry, 2.5 €/t for pig manure, energy maize 38-68 €/t [18], and food
81 waste 40 €/t [26]. Net costs can be calculated by subtracting the feed-in premium from this cost.

82 Therefore, for the community, the feedstock cost may also become negative [26], which could
83 enact a synergetic effect between agriculture and electricity from renewable energy [15]. It is
84 assumed that for the Republic of Serbia the natural gas price is 0.3-0.4 €/Nm³ for a small
85 consumer, while the fee for connection to the gas transport network is 0.1- 0.2 €/Nm³ . A study
86 for the CHP plant in Republic of Serbia [16] has found that the internal rate of return (IRR) is
87 6.92, with payback period of almost 11 years (discount rate 8%). In another study [14], also for
88 the Republic of Serbia, it has been calculated that the payback period for electricity only with the
89 feed-in tariff is 9.8-11 years, and that it is 4.6 years for electricity and heat sold, but with 15-20%
90 interest ratio.

91 The lower heating value (LHV) of biogas varies 12.6 - 22 MJ/kg [18, 27]. The gasification
92 ratio varies from 0.2 [t/t] for energetic crops [28] to 0.7 for manure, assuming the average of 0.5
93 [29]. The carbon content of biogas varies from 25%-45% [18, 22, 27]. Based on emission
94 factors for different energy sources [22] and equipment [29], emission-constrained dispatch
95 might be simulated in HOMER with respect to environmental constraints.

96 Currently, district heating in Serbia is predominantly based on fossil fuel only heat boilers:
97 natural gas (61%), lignite/coal (20%), and fuel oil (18%); there are no renewable district heating
98 grids in Serbia. There have been two energy licenses for biomass cogeneration issued in the
99 municipalities of Prijepolje and Cajetina. There is about 100 MW of biomass cogeneration with
100 640 GWh_{el}/a of electricity production envisaged by the National Renewable Energy Action Plan
101 [30]. According to this plan, the envisaged share of biomass cogeneration in district heating and
102 cooling amounts to 33% of heat energy produced from additionally commissioned facilities
103 (2009-2020), which is around 570 GWh_{th}/a. The electricity produced in Vojvodina, upper part of
104 Republic of Serbia in 2016 was 27.25 GWh, with insignificant heat production [19]. According to

105 the Law on the Privileged Producer, the feed-in tariffs (8.22-13.26 c€/KWh) are available for
106 electricity production from biomass but not either for heat energy or cogeneration. In the case of
107 biogas, feed-in tariffs are recently increased to 15 c€/KWh for the bigger plants (higher rates for
108 plants under 5 MW) and up to working 8,600 hours/year [19]. In addition, the law says that
109 municipalities are responsible for support schemes such as feed-in tariffs for renewable district
110 heating and cooling. On the other hand, a positive economic outlook should be expected from
111 rural communities – they should benefit economically from the localization of the heating and
112 cooling supply chain, but also from food industry, which has a considerable demand for heating
113 in the winter and cooling in the summer, all of which could be supplied by a smart municipal
114 energy grid. The community, the City of Sabac, has a district heating utility named "Toplana-
115 Sabac" with 72.3 MW capacity. Its heat production is mainly based on natural gas (93% of
116 capacity) and a small part on fuel oil (7%). The system supplies heat for about 6,700
117 households and 600 commercial users.

118 A case study should include the biomass district heating/cooling demand for a community of
119 around 450 households and 800 kW in other sectors – industry or services. Most economic
120 studies are based on the simplification of an assumed utilization ratio of biogas, natural gas
121 plants, and a feed-in contract to sell electricity at an agreed price [16, 25]. Utilization ratio is a bit
122 lower due to load management in a smart municipal grid [27]. In this article this has been tested
123 in an hourly simulation of distributed generators' economic dispatch under real time prices for
124 the Republic of Serbia, using a biogas plant as a load management unit, in the case of a smaller
125 community in the City of Sabac. The result is the decrease in operation of those generators with
126 similar payback times due to lowered interest rates.

127 **2. SMART MUNICIPAL GRID MODEL: SABAC COMMUNITY**

128 The HOMER simulation tool has been used for modeling and assessing smart municipal
129 energy grid configurations. It has been used a lot for simulations of integration of variable
130 renewable energy sources [31], it is well documented [32, 33], and contains a useful help file. The
131 tool has been used in a number of techno-economic studies for grid connected and islanded
132 operated systems e.g. [9, 12, 34-41].

133 In the study [36] HOMER was compared to the EnergyPLAN and another self-built tool for
134 assessment of demand response, but without consideration of variable renewable energy sources
135 and heat demand. The high profitability of a smart isolated energy grid based on renewable
136 generation, demand response and biogas CHP plant, has been presented in the case of Congo [9].
137 HOMER has been used as a planning tool for municipal smart energy grids in Serbia for the
138 purpose of the Covenant of Mayors optimal local energy plan [12, 42], but with fixed national
139 electricity grid tariff and not with real time electricity market prices. For more precision in physical
140 electricity grid modeling, HOMER may be soft-linked with the PowerWorld tool like in [34] or used
141 with DigSilent [43][44]. HOMER might be used to model smaller smart household energy systems
142 like in [45], where heat demand was not assessed but only electricity demand. HOMER has been
143 used to model a pumped hydro storage power plant [46] and therefore will be useful in the future to
144 assess demand response potential of water pumps for advanced agriculture in Macva, the state
145 district surrounding the City of Sabac. In a HOMER study [47] the use of a biogas CHP (BGCHP)
146 plant in combination of a photovoltaic (PV) and wind generator has been shown to be techno-
147 economically optimal in the case of a small energy system autonomous from the national grid.
148 Another HOMER study [48] finds an optimal autonomous microgrid design for Oujda city, Morocco.

149 HOMER with energyPRO or other tools should be further used for thermal process modeling in
150 distribution grids, especially in the systems with heat storage [11].

151 When it comes to distributed generation, optimal operation algorithm of weekly simulations,
152 with respect to detailed generator efficiency modeling and peak demand minimization of an
153 industrial grid can be found in [49]. Using EnergyPLAN and Matlab, it has been shown [18] that pit
154 storage has an economic advantage over a biomass power plant for peak shaving.

155 The City of Sabac was selected for the case study of a smart municipal energy grid because of
156 its significance for the research project "CoolHeating". However, any municipality or city in the
157 Republic of Serbia, or in the region, may be considered for future case studies. It has been
158 assumed that a small community consisting of 450 households with heat and electricity demand
159 and industry with a heating/cooling demand of 800 kW shall be supplied during one year.
160 Configuration of the smart municipal energy system has been shown in Fig. 1.

161 All houses and industry are connected to the national electricity grid and district heating grid
162 which is operated using natural gas boilers. Electricity load is divided into deferrable and non-
163 deferrable (primary) load. Possible investment options are a CHP plant based on biogas or natural
164 gas, photovoltaic (PV), and wind power plants. Also, the option of converting electricity to heat as
165 dump load has been considered [50].

166 **Demand.** It is assumed that in a community with the average household of 100m² and 150
167 kWh_{heat}/ m² * yearly demand, the total household demand is 18,480 kWh_{heat}/day. This is
168 comparable to yearly heat consumption in Austria [50], without hot water, but a sensitivity analysis
169 may be done since other values of yearly consumption are possible. The heat duration curve has
170 been obtained using the degree-day method and average yearly temperature. Additionally, besides

171 heat demand, hot water demand may be also considered in future work [26]. For industrial
172 heat/cold demand, it is assumed that there are 24 working hours 5 days a week during 53 weeks
173 with the constant demand of 800 kW and random day-to-day variability of 10% and hour-to-hour
174 variability of 10%. This is an optimistic assumption since such high utilization rates are not typical
175 for every industry. Besides heating, other or more specific industry heat use options with different
176 demand characteristics may be considered in future, e.g. drying in wood and agriculture industries,
177 or cooling in food industry [27].

178 Electricity demand is assumed to be 10.5 MWh/a per household, resulting in total community
179 demand of 13 MWh/d, of which 12 MWh/day are assumed as primary (nondeferrable) load, and 1
180 MWh/day as deferrable load. The electricity demand assumption is higher than average from
181 around 2.4 M households in the Republic in Serbia and residential consumption of around 13.8
182 TWh/a in the year 2014 [51]. The deferrable load is considered to be max 700 MW, with the ability
183 to "store" max 6,000 kWh.

184 **Generators.** For the PV array lifetime of 15 years, it is assumed that the derating factor is
185 80% and the slope is 32 degrees. The assumed costs are the capital costs of 740€/kW, the
186 replacement of 400€/kW, and operation and maintenance (O&M) of 15€/kW*year, which is low in
187 comparison to example investment costs of 1,231 – 1,403 €/kW, but similar to O&M costs of 12.5 –
188 15.1 €/kW*year [52]. Information on recent investment costs in Denmark and the United Arab
189 Emirates supports this cost assessment, because in these countries costs were even lower.

190 Solar resource inputs per month are given in Table 1 with the average of 3.47 kWh/m²*day. For
191 the wind turbine (S3.7), it is assumed that it has a lifetime of 20 years, hub height of 33.5m,
192 rated power of 1.8 kW, capital and replacement costs of 3,000€, and O&M costs of 30€/year per

193 turbine. The assumed capital costs are in the range of 1,451 – 1,836 €/kW, while the assumed
194 O&M cost are below 35.6 – 47.1 €/kW/year [52].

195 Table 1 shows the wind resource yearly average of 3.6 m/s, and the solar resource data
196 obtained from [53].

197 For the natural gas CHP (NGCHP) plant, it is assumed that it has a 60,000 working hour
198 lifetime, the minimal load ratio of 30%, and the heat recovery ratio of 70%. The costs of NGCHP
199 for different sizes are given in Table 2.

200 Assumed efficiency curves of the natural gas and biogas plant for different levels of load are
201 shown in Fig 2.

202 The assumed maximal overall efficiency of NGCHP plant at nominal output operation is
203 around 80%.

204 It is assumed that the biogas CHP (BGCHP) plant has a lifetime of 60,000 working hours,
205 minimal load ratio of 30%, and heat recovery ratio of 44%. Typical costs for different sizes of
206 biogas CHP plants (including engine and all facilities costs) are also given in Table 2. Those
207 costs for the BGCHP are within or above the values 1,935 – 6,723.5 €/kW, presented in [52].

208 Capital and replacement costs are the same for the purpose of simplicity. O&M specific
209 costs reduce with plant size.

210 The assumed efficiency curve for the BGCHP plant is lower assuming parasite heat (30%)
211 and power consumption (8%) of the digester [25], as shown in Fig. 2. The data from the biogas
212 plants in operation from [54] are used to calibrate feedstock consumption for biogas production
213 and realistic electricity and heat production. The heat demand of the digester can be modeled in

214 more detail as a separate heat demand with a seasonal effect [27]. Process related details for
215 biogas plants sized 75-500 kW_{el} may be found in [21].

216 The maximal overall energy efficiency of the BGCHP plant is around 65% at nominal output.
217 Besides the modeled CHP plant based on the engine, a gas turbine [55] may also be
218 considered in future techno-economic studies.

219 Optimization search space among different generators and different sizes is shown in Table
220 3.

221 The total number of possible system designs is $3*3*7*7 = 441$. Although it is possible to use
222 continuous variables in optimization, the discrete decision variables are an inherent feature of
223 the HOMER tool. In order to improve accuracy, one may decide to use more decision variables
224 around an optimal point or repeat the procedure, but this should be traded with computation
225 time.

226 ***Energy carriers and their prices.*** It is assumed that the national electricity grid real-
227 time price is on average 3 c€/kWh, 5 c€/kWh and 10 c€/kWh. Bearing in mind that wholesale
228 electricity prices in SEEPEX (Belgrade power exchange) auctions start with the daily average of
229 2.5 c€/kWh in March 2016 and up to 10 c€/kWh in January 2017, the price assumptions above
230 are realistic, although it has to be mentioned these are still low volume auctions in comparison
231 to overall load. The hourly price is dependable on wholesale electricity market prices. The
232 power density function for the average price of 5 c€/kWh is shown in Fig. 3. For other prices, the
233 power density function has been translated along the price axis (horizontal x-axis) assuming the
234 same distribution.

235 For natural gas it is assumed that the lower heating value is 45 MJ/kg [56], density 0.79
236 kg/m³, carbon content 67%, and sulphur content 0.33%. Regarding biogas, it is assumed that
237 there is a daily average of 1,000 t of manure and organic waste input. The assumed gasification
238 ratio is 0.5 kg of gas/kg feedstock, the assumed lower heating value of biogas is 18.5 MJ/kg,
239 and its carbon content is 38%. The assumed lower heating value of biogas and carbon content
240 are within the range of 21.5-23.5 MJ/kg and 15-45% [27]. Detailed methane production from
241 different feedstock types may be considered in the future [27]. Maximal manure feedstock costs
242 for a different feed-in support should not exceed 3-7€/t [17]. Farm distance from the BGCHP
243 plant and different ownership models (third party or farmers' ownership) result in different
244 economics of the smart municipal grid, which might be modeled as the increase in the price of
245 feedstock [57], even in more detail by using geographic information system tools [58].

246 The sensitivity analysis search space of the prices of natural gas and subvention feedstock
247 are given in Table 4.

248 The search space for sensitivity analysis consists of $5 \times 5 = 25$ options, which together with
249 441 possible system design options, creates 11,025 yearly simulations to run during
250 optimization.

251 The grid purchase/sale capacity of 1,000 kW is assumed.

252 When it comes to the economic situation, it is assumed that the annual real interest rate is
253 5%, and the project lifetime is 30 years.

254 The overall biogas production potential in the Republic of Serbia, and for Vojvodina have
255 been estimated [59, 60] but so far no exact details for the City of Sabac have been available.

256 Based on the first assessment, the availability of feedstock from animal manure for the City of
257 Sabac and the district of Macva is given in Table 5. This assessment has to be done with more
258 detail including other different feedstock and their biogas yield detail [21], as well as other
259 available sources of dry biomass [61].

260 When it comes to biomass resource input, the assumed constant annual availability of
261 feedstock is 1,000 t/d for the first case, but in the future some more realistic assessment needs
262 to be made, due to availability and possibility of seasonal scheduling.

263 **3. RESULTS**

264 The optimal system structure graph as a result of HOMER simulations of sensitivity
265 variables (natural gas price and biomass price) is shown in Fig. 4-6 for differently assumed
266 national grid electricity price, according to the wholesale market price. The additionally leveled
267 cost of energy for municipal grid customers (€/kWh) has been superimposed.

268 For the average national grid electricity price of 5c€/kWh, there are three (3) viable optimal
269 system structures (Fig. 4):

- 270 1. the combination of the national electricity grid with a natural gas generator
271 (Grid/NGCHP);
- 272 2. the combination of the national electricity grid with a biogas generator (Grid/BGCHP);
- 273 3. the combination of the national electricity grid with a natural gas generator and a biogas
274 generator (Grid/NGCHP/BGCHP).

275 A natural CHP in combination with the national electricity grid is the optimal system structure
276 for the natural gas price of 0.2 €/Nm³, and up to 0.4 €/Nm³, depending on the price of biomass
277 (lower area of the graph). The negative levelized cost of energy in the case of extremely low
278 natural gas prices of 0.1 €/Nm³, shows it is profitable to sell electricity from the NGCHP to the
279 national grid. In the case the low natural gas price of 0.2 €/Nm³, the levelized cost of energy
280 may decrease below the average national grid price. The upper triangle of the space defined
281 with moderate natural gas prices 0.2-0.4 €/Nm³ shows it is optimal to build a BGCHP besides a
282 NGCHP, while for the prices above 0.4 €/Nm³ NGCHP is not profitable. The levelized costs of
283 energy in all cases are below the national grid average price.

284 The calculated marginal cost of heat from the BGCHP is 0.5 c€/kWh, and from the NGCHP
285 it is 9 c€/kWh in the [0.3 €/Nm³, 5 €/t] scenario. These marginal costs are calculated based on
286 the capacity factors obtained through simulation: 72% for the BGCHP and 25% for the NGCHP.

287 For the average national grid electricity price of 3c€/kWh (Fig. 5), there are three viable (3)
288 optimal system structures:

- 289 1. the national electricity grid (Grid);
- 290 2. a combination of the national electricity grid with a natural gas generator (Grid/NGCHP);
- 291 3. a combination of the national electricity grid with a biogas generator (Grid/BGCHP).

292 The decreased national electricity grid average price of 0.3 c€/kWh resulted in the fact that the
293 national grid became one of the optimal system types. If the natural gas price is 0.25-0.5 €/Nm³,
294 the optimal system type depends on the biomass price (the middle triangle of the graph). The
295 construction of the BGCHP is advised for the natural gas price above 0.3 €/Nm³, in the case of the

296 subsidized biogas price or above the natural gas price of 0.4 €/Nm³ and 0.5 €/Nm³ for higher
297 biomass prices (the upper triangle). Below the natural gas price of 0.25 €/Nm³, the combination of
298 the national grid and the NGCHP is optimal (the lower rectangle). The levelized costs of energy
299 could be decreased based on the construction of the NGCHP or the BGCHP.

300 For the average national grid electricity price of 10c€/kWh, Fig. 6, there are eight (8) viable
301 optimal system structures:

- 302 1. a combination of the national electricity grid with a natural gas generator (Grid/NGCHP);
- 303 2. a combination of the national electricity grid with a natural gas and a biogas generator
304 (Grid/NGCHP/BGCHP);
- 305 3. a combination of the national electricity grid with a PV and natural generator
306 (Grid/PV/NGCHP);
- 307 4. a combination of the national electricity grid with a PV, natural, and biogas generator
308 (Grid/PV/NGCHP/BGCHP);
- 309 5. a combination of the national electricity grid with a wind and natural gas generator
310 (Grid/Wind/NGCHP);
- 311 6. a combination of the national electricity grid with a wind, natural gas and biogas generator
312 (Grid/Wind/NGCHP/BGCHP);
- 313 7. a combination of the national electricity grid with a PV, wind and natural gas generator
314 (Grid/PV/Wind/NGCHP);

315 8. a combination of the national electricity grid with a PV, wind, natural and biogas generator
316 (Grid/PV/Wind/NGCHP/BGCHP).

317 Starting from the natural gas price of 0.1 €/Nm³ for all biomass prices, the combination of
318 the national electricity grid with a natural gas generator (Grid/NGCHP) is the optimal system
319 structure, followed by the combination of the national electricity grid with a wind and natural gas
320 generator (Grid/Wind/NGCHP) first, and later, when the natural gas price reaches 0.2 €/m³, the
321 combination of the national electricity grid with a PV and biogas generator (Grid/PV/BGCHP).
322 The natural gas price of 0.35 €/Nm³ is still competitive in three system combinations: the
323 combination of the national electricity grid with a PV, wind and natural gas generator
324 (Grid/PV/Wind/NGCHP) shown at the right lower triangle, the combination of the national
325 electricity grid with a natural gas and biogas generator (Grid/NGCHP/BGCHP), and the
326 combination of the national electricity grid with a PV, natural and biogas generator
327 (Grid/PV/NGCHP/BGCHP). Above the price of 0.35 €/Nm³, natural gas generators and biogas
328 generators compete, differently sized for different price combinations.

329 All design cases are profitable for the national electricity grid with the average price of
330 10c€/kWh and higher because levelized costs of energy are negative.

331 **3.1. Rate of return**

332 The economics of different system configurations for the national electricity grid average
333 price of 5c€/kWh are shown in Table 6.

334 The first two rows show the assumed biomass and natural gas prices. The next three rows
335 show the resulting optimal system structures for the assumed prices. The base system, used for all

336 comparisons, consists only of the connection to the national electricity grid (Grid). Other scenarios
337 (S1-5) are:

- 338 • a combination of the national electricity grid with a natural gas generator (Grid/NGCHP);
- 339 • a combination of the national electricity grid with a natural gas and biogas generator
340 (Grid/NGCHP/BGCHP).

341 The selected sizes of biogas generators are 1,000 kW and 500 kW for natural gas generators.
342 The sixth row presents initial costs, which are capital investment costs (CAPEX) for equipment.
343 Assuming that the grid exists, the investment cost for the grid is zero. The total cost, the sum of
344 CAPEX and operation costs (OPEX) over project lifetime, are shown to be lower in scenarios S1-5
345 than in the base scenario. This results in the return of investment 7.56-10.4% for the
346 Grid/NGCHP/BGCHP system structure, and 13.9% for the Grid/NGCHP system structure. The
347 discounted payback is 6.13-8.9 years, showing that it is sensitive to economic subsidies for
348 biomass. Further calculations may show a desired level of subsidy for biomass.

349 **3.2. Hours of operation**

350 The realistic hours of operation for NGCHP and BGCHP plants, obtained from 8,760 hourly
351 simulations over one year, are shown in the last two rows of the Table 8. The capacity factor is
352 0.7-0.9 for the profitable BGCHP plant, and 0.25-0.5 for the profitable NGCHP plant. They are
353 not constant but rather dependable on many system design factors. At breakpoints, the hours of
354 operation of one generator structure may suddenly drop to zero, resulting in a jump of the hours
355 of operation of other generator types. Further analysis may show that the BGCHP plant is more
356 profitable than the NGCHP plant only in the higher hours of operation. Those realistic operation

357 conditions should be used for the development of detailed business plans for the future
358 expansion of small municipal distributed grids within the electricity market.

359 **3.3. Environmental benefits**

360 Fig. 7 shows that smart municipal energy grids entail significant environmental benefits,
361 which should not be neglected in the elaboration of their techno-economic optimality.

362 The yearly CO₂ emissions from the smart municipal grid obtained from the base scenario of
363 7,586,505 kg/year, decrease with investments in all 25 scenarios. This is due to equivalent
364 emission from the electricity grid in the Republic of Serbia, which is significant. The highest
365 emission savings are shown in the scenario with high natural gas costs and strong policy
366 support for biomass, resulting in negative total equivalent emissions of -4,855,203 kg/year,
367 including the exported renewable energy.

368 **4. CONCLUSION**

369 Many municipal grids of today operate connected to the national electricity grid without
370 investment in distributed generation. This article has shown that investment in a smart municipal
371 grid infrastructure could decrease the levelized cost of energy in the municipal grid below the
372 national electricity grid average market price, due to smart municipal grids' flexible operation
373 and optimal sales and purchases. Furthermore, the sensitivity analysis has shown that this
374 would not change even in case of disturbances of natural gas prices or biomass prices.

375 Although the levelized cost of energy in the municipal grid could decrease with optimal
376 investments decisions, the payback periods of the smart municipal infrastructure may

377 additionally decrease with a properly designed local economic support energy policy for the
378 biomass resource.

379 Moreover, the environmental benefits of smart municipal grids are substantial, due to high
380 equivalent emission from the national electricity grid.

381 More detailed results from this paper show that the hours of operation of the CHP plant
382 depend on various system design factors. Therefore, during the planning process it is advised
383 not to assume any constant values for hours of operation (obtained exogenously), but rather
384 obtain them as the result of the optimal investment decision and realistic operation. The hours of
385 operation should not be kept at a constant level in techno-economic feasibility studies when
386 making the investment decision.

387 **5. ACKNOWLEDGEMENTS**

388 The authors are acknowledging the support from the "CoolHeating" Horizon 2020 project
389 from European Commission grant nr. 691679. The first two authors are thankful to the Ministry
390 of Education, Science and Technological development on the grant nr. 42009/11 for the "Smart
391 grids".

392 **6. REFERENCES**

- 393 [1] Mitchell C. Momentum is increasing towards a flexible electricity system based on
394 renewables. *Nature Energy*. 2016;1:15030.
- 395 [2] Batas Bjelić I, Rajaković N, Ćosić B, Duić N. Increasing wind power penetration into the
396 existing Serbian energy system. *Energy*. 2013;57:30-7.

- 397 [3] Blaauwbroek N, Nguyen PH, Konsman MJ, Huaizhou S, Kamphuis RIG, Kling WL.
398 Decentralized Resource Allocation and Load Scheduling for Multicommodity Smart Energy
399 Systems. *Sustainable Energy, IEEE Transactions on*. 2015;6(4):1506-14.
- 400 [4] Capuder T, Mancarella P. Techno-economic and environmental modelling and optimization
401 of flexible distributed multi-generation options. *Energy*. 2014;71(0):516-33.
- 402 [5] Shariatzadeh F, Mandal P, Srivastava AK. Demand response for sustainable energy
403 systems: A review, application and implementation strategy. *Renewable and Sustainable
404 Energy Reviews*. 2015;45:343-50.
- 405 [6] Roudier P, Andersson JCM, Donnelly C, Feyen L, Greuell W, Ludwig F. Projections of future
406 floods and hydrological droughts in Europe under a +2°C global warming. *Climatic Change*.
407 2015:1-15.
- 408 [7] Chen C, Wang J, Qiu F, Zhao D. Resilient Distribution System by Microgrids Formation After
409 Natural Disasters. *IEEE Transactions on Smart Grid*. 2016;7(2):958-66.
- 410 [8] Batas-Bjelic I, Rajakovic N. More resilient smart municipal energy grids. *MEDPOWER*.
411 Belgrade2016.
- 412 [9] Montuori L, Alcázar-Ortega M, Álvarez-Bel C, Domijan A. Integration of renewable energy in
413 microgrids coordinated with demand response resources: Economic evaluation of a biomass
414 gasification plant by Homer Simulator. *Applied Energy*. 2014;132:15-22.
- 415 [10] Blarke MB. Towards an intermittency-friendly energy system: Comparing electric boilers
416 and heat pumps in distributed cogeneration. *Applied Energy*. 2012;91(1):349-65.
- 417 [11] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. *Energy
418 Storage and Smart Energy Systems*. 2016. 2016;11:12.

- 419 [12] Batas Bjelic I, Ciric RM. Optimal distributed generation planning at a local level – A review
420 of Serbian renewable energy development. *Renewable and Sustainable Energy Reviews*.
421 2014;39:79-86.
- 422 [13] Thrän D, Dotzauer M, Lenz V, Liebetrau J, Ortwein A. Flexible bioenergy supply for
423 balancing fluctuating renewables in the heat and power sector—a review of technologies and
424 concepts. *Energ Sustain Soc*. 2015;5(1):1-15.
- 425 [14] Ciric RM, Kuzmanovic Z. Techno-Economic Analysis of Biogas Powered Cogeneration.
426 *Journal of Automation and Control Engineering Vol*. 2014;2(1).
- 427 [15] Krkoleva A, Taseska V, Markovska N, Taleski R, Borozan V. Microgrids: The agraria test
428 location. *Thermal Science*. 2010;14(3):747-58.
- 429 [16] Stojiljković MM, Stojiljković MM, Blagojević BD, Vučković GD, Ignjatović MG. Effects of
430 implementation of co-generation in the district heating system of the Faculty of Mechanical
431 Engineering in Niš. *Thermal Science*. 2010;14(suppl.):41-51.
- 432 [17] Puksec T, Duic N. Economic viability and geographic distribution of centralized biogas
433 plants: case study Croatia. *Clean Technologies and Environmental Policy*. 2012;14(3):427-33.
- 434 [18] Dominković D, Ćosić B, Medić ZB, Duić N. A hybrid optimization model of biomass
435 trigeneration system combined with pit thermal energy storage. *Energy Conversion and*
436 *Management*. 2015.
- 437 [19] Zubić B, Prebiračević V. Korišćenje biogasa u Vojvodini. *Energetika*. Zlatibor 2017. p. 61-6.
- 438 [20] Mitschke T. Small Scale Slurry Biogas Plants for medium-sized farms in Serbia as an
439 additional income source. 2015.
- 440 [21] FNR. Guide to Biogas: From Production to Use: Fachagentur Nachwachsende Rohstoffe
441 2012.

- 442 [22] Cvetković SM, Kaluđerović-Radoičić TS, Kragić RB, Kijevčanin ML. Electricity production
443 from biogas in Serbia-assessment of emissions reduction. *Thermal Science*. 2015(00):189-
444 [23] Vukašinović V, Babić M, Gordić D, Jelić D, Končalović D. Pregled dostupnih modela gasnih
445 turbina i motora sa unutrašnjim sagorevanjem koji se mogu koristiti u kogeneracionim
446 sistemima. *Energija, ekonomija, ekologija*. 2013;15(3-4):265-78.
- 447 [24] Wellinger A, Murphy J, Baxter D. *The Biogas Handbook: Science, Production and*
448 *Applications*: Woodhead Pub Limited, 2013.
- 449 [25] Köttner M, Kayser K. Assessment of the framework conditions for biogas production in
450 Serbia. IBBK Fachgruppe Biogas GmbH 2014. p. 29.
- 451 [26] Gebrezgabher SA, Meuwissen MPM, Prins BAM, Lansink AGJMO. Economic analysis of
452 anaerobic digestion—A case of Green power biogas plant in The Netherlands. *NJAS -*
453 *Wageningen Journal of Life Sciences*. 2010;57(2):109-15.
- 454 [27] Rutz D, Mergner R, Janssen R. *Sustainable Heat Use of Biogas Plants. A Handbook,*
455 *Biogas Heat*, WIP Renewable Energies, Munich, Germany. 2012.
- 456 [28] Murphy J, Braun R, Weiland P, Wellinger A. Biogas from energy crop digestion. Conference
457 *Biogas from energy crop digestion*. IEA Bioenergy Task.
- 458 [29] DEA. *Technology Data for Energy Plants*. Danish Energy Agency; 2010.
- 459 [30] ***. Draft National Renewable Energy Action Plan. Belgrade: Ministry of Energy,
460 Development and Environmental Protection of Republic of Serbia; 2012.
- 461 [31] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the
462 integration of renewable energy into various energy systems. *Applied Energy*. 2010;87(4):1059-
463 82.
- 464 [32] Lambert T, Gilman P, Lilienthal P. *Micropower System Modeling with Homer*. Integration of
465 alternative sources of energy: John Wiley & Sons, Inc.; 2006. p. 379-418.

- 466 [33] Chowdhury O, Kim H-g, Cho Y, Shin C, Park J. Optimization of a Hybrid Renewable Energy
467 System with HOMER. In: Park D-S, Chao H-C, Jeong Y-S, Park JJ, editors. Advances in
468 Computer Science and Ubiquitous Computing: Springer Singapore; 2015. p. 93-9.
- 469 [34] Corrand M, Duncan SJ, Mavris DN. Incorporating Electrical Distribution Network Structure
470 into Energy Portfolio Optimization for an Isolated Grid. *Procedia Computer Science*.
471 2013;16:757-66.
- 472 [35] Weis TM, Ilinca A. The utility of energy storage to improve the economics of wind–diesel
473 power plants in Canada. *Renewable Energy*. 2008;33(7):1544-57.
- 474 [36] Neves D, Pina A, Silva CA. Demand response modeling: A comparison between tools.
475 *Applied Energy*. 2015;146(0):288-97.
- 476 [37] Basir Khan MR, Jidin R, Pasupuleti J, Shaaya SA. Optimal combination of solar, wind,
477 micro-hydro and diesel systems based on actual seasonal load profiles for a resort island in the
478 South China Sea. *Energy*. 2015;82(0):80-97.
- 479 [38] Hafez O, Bhattacharya K. Optimal planning and design of a renewable energy based
480 supply system for microgrids. *Renewable Energy*. 2012;45:7-15.
- 481 [39] Rui H, Low SH, Ufuk T, Chandy KM, Clarke CR. Optimal design of hybrid energy system
482 with PV/wind turbine/storage: A case study. *Conference Optimal design of hybrid energy system
483 with PV/wind turbine/storage: A case study*. p. 511-6.
- 484 [40] Giannoulis ED, Haralambopoulos DA. Distributed Generation in an isolated grid:
485 Methodology of case study for Lesbos – Greece. *Applied Energy*. 2011;88(7):2530-40.
- 486 [41] Al-Karaghoul A, Kazmerski LL. Optimization and life-cycle cost of health clinic PV system
487 for a rural area in southern Iraq using HOMER software. *Solar Energy*. 2010;84(4):710-4.
- 488 [42] Ilija BB. Subotica: energetska plan održive energetike. 2017. p. 1-17.

- 489 [43] Markova KK, Bijelic IB, Dobric G, Rajakovic N. Investment Decisions in the Photovoltaic
490 Power Plant in Terms of the Market Bearing in Mind the Physical Limitations of the
491 Transmission Network. INDEL 2016. Banja Luka 2016.
- 492 [44] Nikola R, Ilija BB. Planning of the optimal energy mix for smart cities. 2017. p. 1-6.
- 493 [45] Batas Bjelić IR, Škokljević IA, Pukšec T, Krajačić G, Duić N. Integrating the flexibility of the
494 average Serbian consumer as a virtual storage option into the planning of energy systems.
495 Thermal Science. 2014;18(3):743-54.
- 496 [46] Canales FA, Beluco A. Modeling pumped hydro storage with the micropower optimization
497 model (HOMER). Journal of Renewable and Sustainable Energy. 2014;6(4):043131.
- 498 [47] Ghaem Sigarchian S, Paleta R, Malmquist A, Pina A. Feasibility study of using a biogas
499 engine as backup in a decentralized hybrid (PV/wind/battery) power generation system – Case
500 study Kenya. Energy. 2015;90, Part 2:1830-41.
- 501 [48] Zahboune H, Zouggar S, Krajacic G, Varbanov PS, Elhafyani M, Ziani E. Optimal hybrid
502 renewable energy design in autonomous system using Modified Electric System Cascade
503 Analysis and Homer software. Energy Conversion and Management. 2016;126:909-22.
- 504 [49] Zeljković Č, Rajaković N. Cost-saving potential of customer-driven distributed generation.
505 Electric Power Systems Research. 2012;92(0):87-95.
- 506 [50] Rutz D, Doczekal C, Zweiler R, Hofmeister M, Jensen LL. Small Modular Renewable
507 Heating and Cooling Grids. Munich: WIP Renewable Energies, 2017.
- 508 [51] IEA–International Energy Agency.
- 509 [52] IRENA. Cost-competitive renewable power generation: Potential across South East Europe.
510 2017.
- 511 [53] Kempener R, Assoumou E, Chiodi A, Ciorba U, Gaeta M, Gielen D, et al. A Global
512 renewable energy roadmap: Comparing energy systems models with IRENA's remap 2030

- 513 project. Lecture Notes in Energy. International Renewable Energy Agency, IRENA Innovation
514 and Technology Centre, Bonn, Germany 2015. p. 43-67.
- 515 [54] Djatkov D, Effenberger M, Lehner A, Martinov M, Tesic M, Gronauer A. New method for
516 assessing the performance of agricultural biogas plants. *Renewable Energy*. 2012;40(1):104-12.
- 517 [55] Kang JY, Kang DW, Kim TS, Hur KB. Comparative economic analysis of gas turbine-based
518 power generation and combined heat and power systems using biogas fuel. *Energy*.
519 2014;67:309-18.
- 520 [56] Demirel Y. *Energy, green energy and technology*. Springer-Verlag London; 2012.
- 521 [57] Pukšec T, Duić N. Economic viability and geographic distribution of centralized biogas
522 plants: Case study Croatia. *Clean Technologies and Environmental Policy*. 2012;14:427-33.
- 523 [58] Konrad C, Strittmatter J, Grunert A, Brule M, Roth M, Herter M, et al. Regional energy
524 concepts-based on alternative biomass cultivation for rural areas and its efficient energy usage.
525 *International Journal of Sustainable Development and Planning*. 2013;8(1):59-74.
- 526 [59] Cvetković S, Kaluđerović Radoičić T, Vukadinović B, Kijevčanin M. Potentials and status of
527 biogas as energy source in the Republic of Serbia. *Renewable and Sustainable Energy*
528 *Reviews*. 2014;31:407-16.
- 529 [60] Martinov M, Đatkov Đ, Krstić J, Vujić G, Tešić M, Dragutinović G, et al. STUDY OF
530 POTENTIALS AND POSSIBILITIES FOR BIOGAS PRODUCTION AND UTILIZATION IN
531 AUTONOMOUS PROVINCE OF VOJVODINA. Novi Sad: Faculty of technical sciences
532 Department of environmental engineering; 2011.
- 533 [61] Eltrop L, Hertlajn M, Jensen T, Hensler M, Kruk K, Ezdemir ED, et al. Priručnik o čvrstim
534 biogorivima. In: Stručna agencija za obnovljive resurse ru, (FNR), Odeljenje za odnose sa
535 javnošću, editor. Beograd 2014. p. 205.

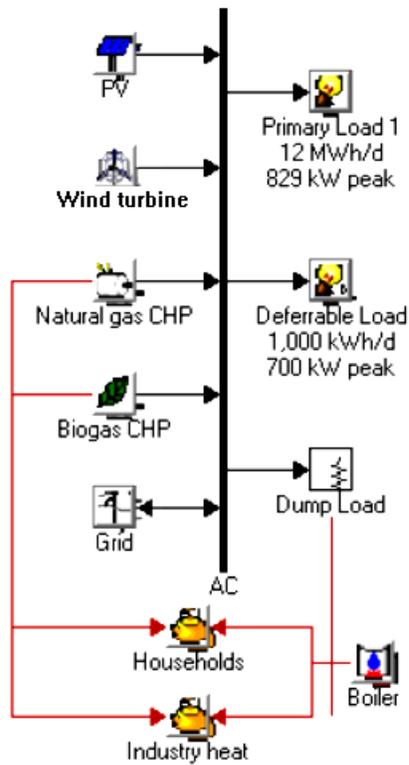


Figure 1 Smart municipal energy grid configuration: PV, Wind turbine, Natural gas CHP generator, Biogas CHP generator, Thermal load: Households, Industry, Primary and deferrable electricity load.

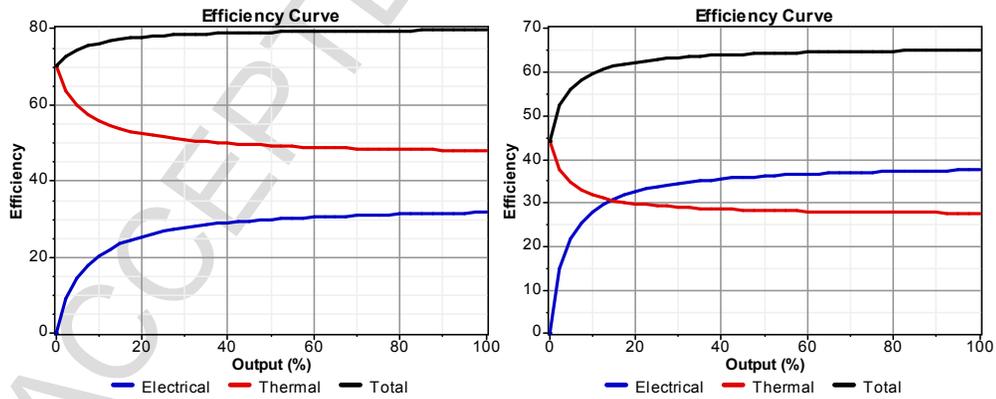


Figure 2 Natural gas (left) and biogas (right) CHP efficiency curve

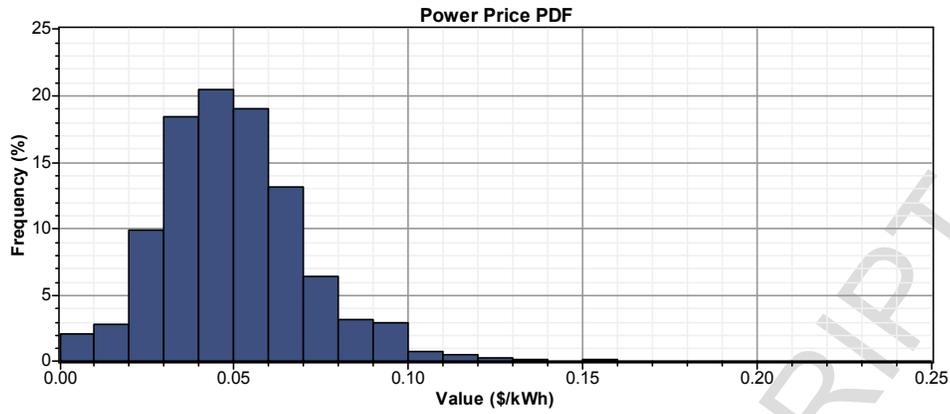


Figure 3 Power density function of the national electricity grid hourly price.

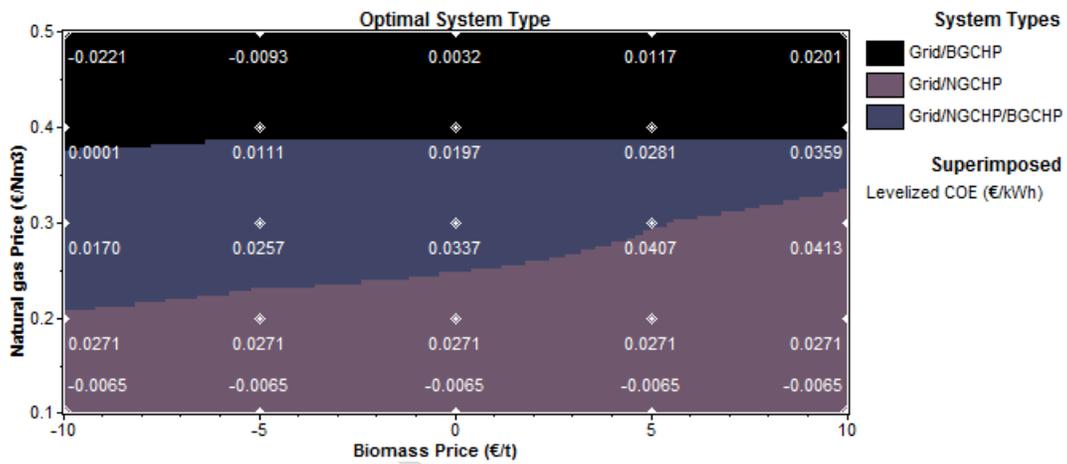


Figure 4 Optimal system structure for national electricity grid average price of 5c€/kWh.

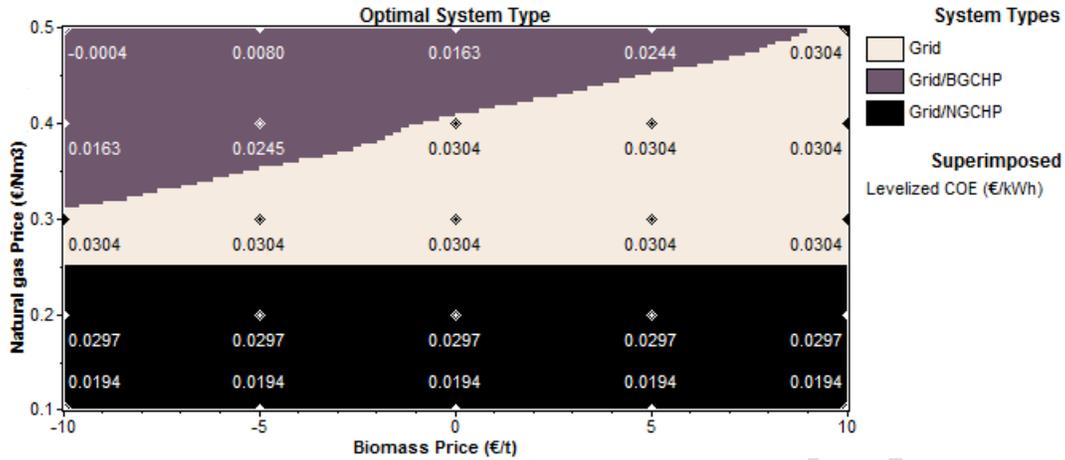


Figure 5 Optimal system structure for national electricity grid average price of 3c€/kWh.

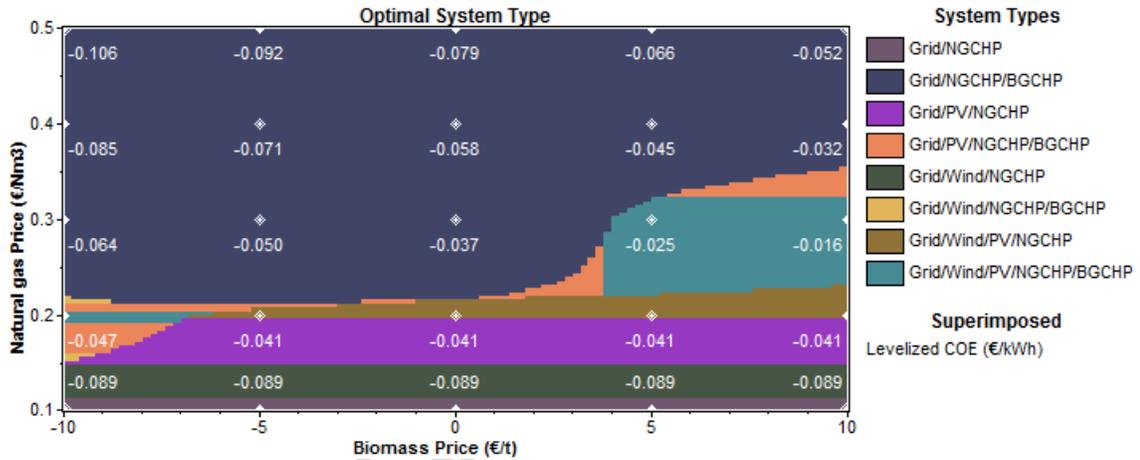


Figure 6 Optimal system structure for national electricity grid average price of 10c€/kWh.

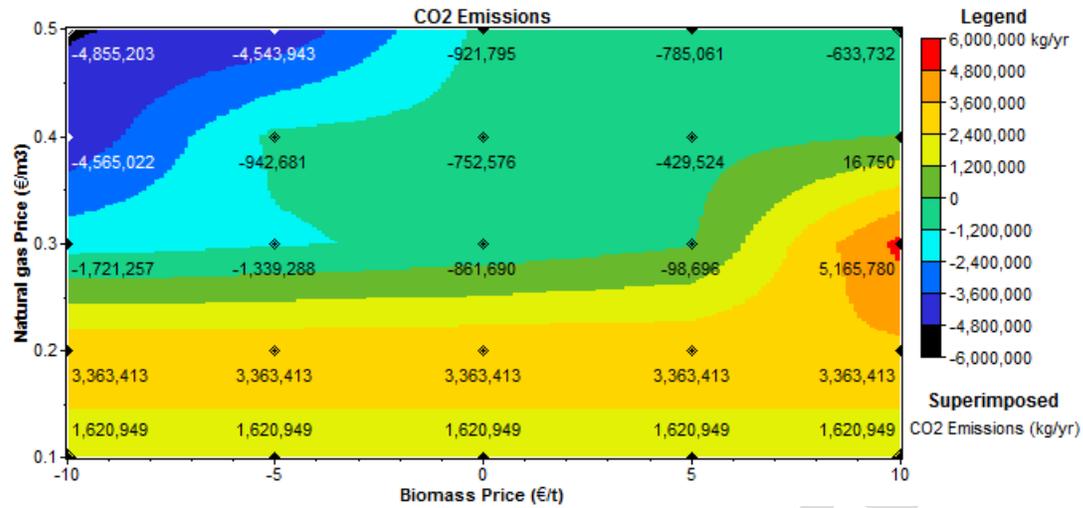


Figure 7 Surface plot of the smart municipal grid yearly CO₂ emissions for the 5c€/kWh average electricity market price and 25 different fuel price scenarios.

1 **Table 1 Solar and wind resource inputs**

Month	Clearness Index	Daily Radiation (kWh/m ² /d)	Wind Speed (m/s)
January	0.410	1.310	5.319
February	0.482	2.240	2.890
March	0.473	3.220	3.209
April	0.466	4.250	2.998
May	0.487	5.280	3.041
June	0.492	5.700	2.141
July	0.515	5.770	3.123
August	0.525	5.120	3.492
September	0.498	3.780	2.539
October	0.463	2.440	3.992
November	0.393	1.380	5.841
December	0.375	1.040	4.590

2

3

4 **Table 2 Natural gas and biogas CHP costs**

Size (kW)	Natural gas		Biogas	
	Capital / Replacement (€)	O&M (€/hr)	Capital / Replacement (€)	O&M (€/hr)
75	81,337	0.01	661,652	0.035
150	138,654	0.01	1,039,684	0.035
250	205,421	0.01	1,450,597	0.035
500	350,177	0.01	2,279,388	0.025
1,000	596,939	0.01	3,581,705	0.025
2,000	1,017,589	0.006	5,628,095	0.025
3,000	1,390,191	0.006	7,331,163	0.013
5,000	2,059,621	0.006	10,228,649	0.013

5

6

7 **Table 3 HOMER optimization search space (PV Array - photovoltaic array, S3.7 - wind turbine,**
 8 **NGCHP - natural gas CHP, BGCHP - biogas CHP, Grid - national electricity grid connection**

	PV Array (kW)	S3.7 (Quantity)	NGCHP (kW)	BGCHP (kW)	Grid (kW)
1	-	-	-	-	1,000
2	250	10	75	75	
3	500	25	150	150	
4			250	250	
5			500	500	
6			1,000	1,000	
7			1,500	1,500	

9

10

11 **Table 4 Sensitivity inputs space**

Biomass (€/t)	Natural gas (€/Nm ³)
-10	0.1
-5	0.2
0	0.3
5	0.4
10	0.5

12

13 **Table 5 Available feedstock for biogas production from manure in the Macva state district and City of**
 14 **Sabac.**

Area/Type	Cattle	Pigs	Sheep	Poultry	Σ Feedstock [t/d]
Macva state district	80,283	400,391	161,878	1,060,996	3,591
City of Sabac	26,837	116,881	36,233	289,520	1,117

15

16

17 **Table 6 Economics comparison of different system configurations with base configuration for the**
 18 **5c€/kWhel average price and four combinations of biomass and natural gas prices.**

System characteristics	Base	S1	S2	S3	S4	S5
Biomass [€/t]	-	-10	-5	0	5	10
Natural gas [€/Nm ³]	-	0.3				
NGCHP [kW]	-	500	500	500	500	1,000
BGCHP [kW]	-	1,000	1,000	1,000	1,000	-
Grid [kW]	1,000	1,000	1,000	1,000	1,000	1,000
Initial cost [€]	-	3,931,882	3,931,882	3,931,882	3,931,882	596,939
Total cost [€]	11,592,836	9,133,686	9,763,992	10,350,609	10,861,921	10,902,640
Present worth [€]	-	2,459,154	1,828,847	1,242,229	730,917	690,197
Annual worth [€/year]	-	159,971	118,969	80,809	47,547	44,898
Return on investment [%]	-	10.40%	9.41%	8.45%	7.56%	13.9%
Internal rate of return [%]	-	11.10%	9.58%	8.15%	6.87%	15.3%
Simple payback [years]	-	5.16	5.62	6.19	7.04	5.63
Discounted payback [years]	-	6.13	6.77	7.6	8.9	6.78
Hours NGCHP	-	2,410	2,410	2,410	2,410	4,327
Hours BGCHP	-	7,849	7,484	7,031	6,331	-

19

20