

1 Renewable energy can make small-scale mining in Europe 2 more feasible

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20 Abstract

21 As one of the largest energy consumers and greenhouse gas (GHG) emitters, the mining industry is
22 switching to renewable energy to help reduce its energy and environmental impacts. There are already
23 renewable energy systems (RES) in operation at large scale mines. However, for off-grid small-scale
24 mining operations, conventional diesel generators are still preferred given their mobility and
25 modularity. The aim of this paper is to assess the techno-economic feasibility of RES for switch-on,
26 switch-off mining, an emerging concept for mobile small-scale mining, in Europe. Simulations were
27 performed using the HOMER Pro software to evaluate whether mobile and modular containerised RES
28 available on the market are economically viable compared with diesel generators for potential mine
29 sites across Europe. The results suggests that mobile and modular containerised RES are technically
30 and financially feasible for powering switch-on, switch-off mining at different geographical locations
31 in Europe, with varying system designs depending on the renewable resources available and providing
32 significant reductions in GHG and air pollutant emissions. However, the use of RES in SSM could
33 potentially have both positive and negative environmental and social impacts from a life cycle
34 perspective, which extend beyond the mine site due to a diverse supply chain and deserve further
35 research.

36

37 **Keywords:** *renewable energy system, mobile and modular, small-scale mining, feasibility*

38

39 1 Introduction

40 The mining industry is responsible for up to 11% of the global energy consumption and its energy is
41 almost entirely sourced from fossil fuels, with only a fraction generated by on-site renewable energy
42 [1]. In a partly self-supplying cycle, the main output of the extractive industry is fossil fuels, with 86%
43 of the 17.4 billion tonnes of raw material extracted in 2014 being oil, gas and coal [2]. The reliance on
44 fossil energy creates economic instability in the mining sector. For example, fluctuations in the oil price
45 affects the economic feasibility of mining operations and, thereby, metal/mineral commodity prices.
46 Furthermore, the extractive industries, particularly fossil fuel extraction companies, is a significant
47 contributor to greenhouse gas (GHG) emissions [3] and one of the most challenging industries for
48 emission reduction. To limit anthropogenic climate change, the mining industry needs to decarbonise,
49 e.g., through new technologies, improved efficiency and renewable energy supply. Ultimately, there is
50 a need to decouple metal and mineral mining from the fossil fuel extraction industries, as an action
51 towards the United Nations ambitions of reducing future consumption, and decoupling economic
52 activity from negative environmental impacts [4].

53 Understanding the energy usage of the mining industry is crucial for its decarbonisation. Currently,
54 electricity is used in stationary processes and liquid fuels are used by diesel engine powered mobile
55 equipment. However, almost all processes in mining, including transport, can be electrified. Given the
56 volatilities in fossil fuel prices and significantly reduced cost of renewable energy systems (RES),
57 electrification combined with on-site renewables has become an increasingly attractive and effective
58 approach to sustainable mining. For example, an all-electric gold mine in Canada can save 2 million
59 litres of diesel, 1 million litres of propane and 7,000 tonnes of CO₂ emissions annually [5]. Globally, 1
60 GW of RES has already been installed at existing mines, with another 1 GW in the pipeline [2].

61 The global mineral-energy nexus [6] summarises the interplay of energy-intensive mining for the raw
62 materials of the energy-generating infrastructure. The total materials requirement of the renewable
63 energy transition demonstrates that a diverse array of commodities are used [7,8], either in bulk for
64 large structures or in small quantities where metals/semi-metals have the specialist properties required
65 for the advanced technologies of energy-capture. Recycling can contribute most effectively to the
66 supply of raw materials that were previously used by society, but increasing global consumption
67 requires that the mining industry provide more. Large-scale mining is the de-facto response of the
68 industry to its foundation role in the manufacturing chain: the economies of scale support a consistent,
69 reliable supply of raw materials at consistently low commodity prices. Mining for the diverse array of
70 technology metals is not always facilitated by available economic, technological, environmental and
71 societal solutions [9]. Thus, the mining industry is challenged to develop more diverse solutions to
72 underpin the green energy transition.

73 Small-scale mining (SSM) [10], as a modern technological endeavour, is potentially amenable to
74 extraction of ore from the small, high-grade and complex mineral deposits that are abundant in Europe
75 [9], for early return on investment if capital expenditure is low. This includes where the economic status
76 of an ore body fluctuates with commodity price and short duration (switch-on, switch-off, SOSO)
77 mining is accomplished using mobile technologies. SSM can additionally operate to reduce economic
78 risk by project staging on large ore deposits [11]. Where SSM employs selective mining techniques,
79 transportation of ore is reduced, and ore sorting further reduces the amount of rock comminuted in the
80 most energy-intensive steps of raw materials production. Emerging innovative business models for
81 switch on-switch off (SOSO) mobile mining require access to multiple different small and complex
82 deposits, to accommodate a changing emphasis on commodity and economic viability of individual
83 deposits. The technological innovations in equipment and planning [12] for SOSO mining could
84 potentially facilitate integration of RES into mining operations, accelerating the adoption of low-carbon
85 mining practice.

86 Transportation costs and logistics planning are important considerations for the application of
87 renewable energy at a mine site in a supply chain context [13]. Tailored to a SOSO mining model, with

88 operations moving between multiple small complex ore deposits, the RES have to be mobile and
89 modular, providing flexibility in terms of movement and generation capacity. Mobile and modular
90 containerised RES (MMCREs) is a relatively new concept where RES are designed and prefabricated
91 to fit into standard shipping containers. Prefabrication allows MMCREs to be commissioned,
92 decommissioned and redeployed on another site relatively quickly. Scalability is another key feature of
93 MMCREs to provide the desired generation capacity by adding up containers. The balance of system
94 (BoS) for MMCREs is designed to incorporate batteries, diesel generator or different types of
95 renewables to provide continuous power output. MMCREs has been on the market for no more than a
96 decade, and an increasing interest in this type of RES is notable in recent years. The MMCREs could
97 be a potential solution to make mining more sustainable by providing clean energy to the mines.

98 The mines located in remote areas are entirely off-grid due to unreliable grids or absence of distribution
99 networks. These mines tend to rely on the most readily available form of electricity generation, i.e.
100 diesel generators. The levelised cost of energy for solar and wind is lower in comparison to diesel
101 generation, showing significant cost-savings with renewable energy [2]. A study performed by Votteler,
102 2016 for South African mines reveals that hybrid solar and wind power generation can reduce CO₂
103 emissions, levelised cost of electricity and fuel consumption. Over 20 years, € 44 million can be saved
104 with diesel-solar PV hybrid and € 55 million with a diesel-wind hybrid in comparison to diesel
105 generation [14]. However, the diesel generation has lower installation costs, space requirements and
106 can be implemented in short duration in comparison to renewable-based generation [1,14]. MMCREs
107 can play a crucial role in overcoming these disadvantages when compared to diesel generation. For
108 example, Shanta Gold's New Luika mine in Tanzania installed eight containerised solar PV systems as
109 of 2017 with a total generation capacity of 674 kW, saving approximately 219,000 litres of fuel and
110 reducing CO₂ emissions by 660 tonnes annually [15].

111 To determine if RES is viable for meeting energy demand at a given site, a feasibility study is essential.
112 There are few feasibility studies in the academic literature on the use of RES in the mining industry.
113 These feasibility studies mostly focus on technical and economic aspects of RES for the given locations
114 [16–19]. According to Sinha and Chandel [20] techno-economic analysis of hybrid RES is essential for
115 the efficient utilization of available renewable energy resources. They presented a review on 19 different
116 software tools for the design and optimization of RES and assessing their economic viability [20].
117 Fattahi et al [13] considered the application of renewable energy at a mine site with a project duration
118 of 20 years and demonstrate cost-saving for mining in longer planning horizons. However, there are
119 many reports that advocate hybrid power generation for mining industries based on information from
120 existing mines with installed renewables [1,5,21–23]. The Australian Renewable Energy Agency has
121 published a handbook on hybrid power generation for off-grid mines, which helps develop the business
122 case for RES in mining. According to this handbook, hybrid power generation is not economically
123 viable for life of mine shorter than three years considering the technologies and prices at the end of
124 2017. They also report that re-deployable solar PV can be integrated with diesel generators for life of
125 mine more than three years. For wind turbines they suggest life of mine to be more than seven years
126 while for concentrated solar power it should be more than 15 years [21].

127 The application of RES as a function of life of mine was also investigated by Guilbaud [23] who
128 concluded that hybrid RES can provide significant economic and environmental benefits for long-life
129 mines, with reductions of up to 57% in lifecycle cost and up to 82% in carbon emissions. However,
130 fuel-based power generation systems are preferred for mines with a lifetime shorter than 5 years because
131 of high risk involved in investments [23]. However, their simulation did not include a salvage value for
132 the power generation systems because the life of mine was similar to the lifetime of the power systems.
133 Choi and Song presented a review of PV and wind power systems installed in ten operating large-scale
134 mines industry [24]. Similarly Paraszczak and Fytas presented an overview of existing and planned
135 RES for mines [25], and Zharan and Bongaerts performed a cost analysis of the case studies for RES
136 integration in mining operations [26], both concluding that use of RES is more attractive for mines with
137 a long life.

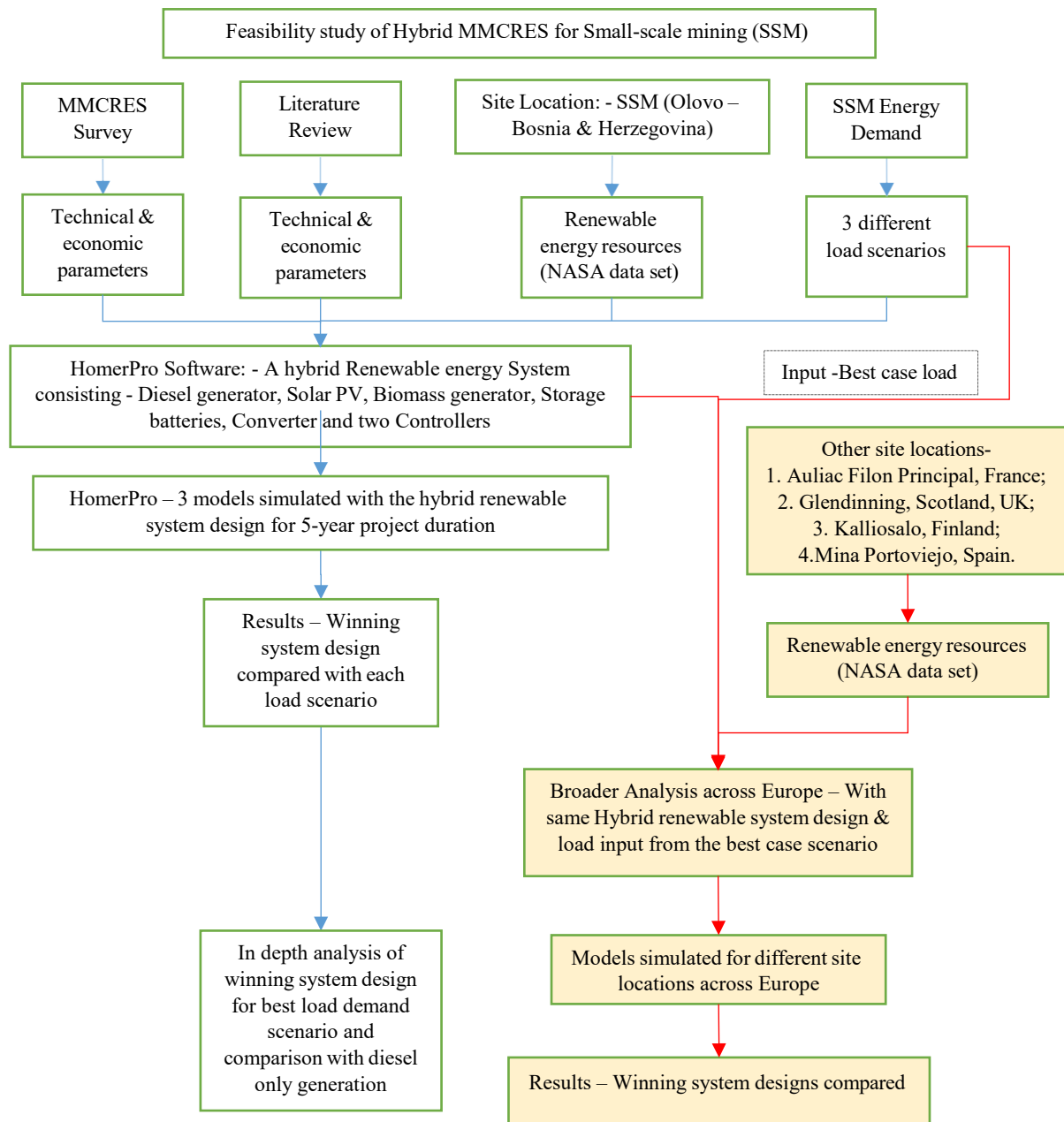
138 Uniquely, Ledwaba [27] carried out a feasibility study on the use of RES for SSM with mine-life of 5
139 years in South Africa using the HOMER Pro software. The results showed that hybrid RES with solar
140 PV and diesel generators are more technically and economically feasible than standalone PV or diesel
141 generators for SSM [27]. Moreover, there are mines like Degruusa in Western Australia and Cannington
142 in Queensland Australia (under planning) where RES are integrated despite a short life of mine [1].
143 Thus, re-deployable and modular RES are becoming an attractive option in the mining sector where
144 power purchasing agreement can be made flexible for short life of mine and there is a big gap in the
145 knowledge for integration of RES into SSM and its impact. The urgency with which the mining industry
146 needs to adapt and diversify to meet the requirements of modern society, including the green energy
147 transition, requires critical appraisal of energy demand and supply. We aim to model the techno-
148 economic feasibility of using MMCRES at short-life mines. We constrain the energy demand for a SSM
149 and use scenarios for mine sites across the Balkans and Europe where different MMCRES systems may
150 be appropriate for SOSO mining. The results are expected to inform the testing and adoption of RES in
151 SSM in Europe and more widely in order to help sustainably meet the increasing demand for raw
152 materials.

153 **2 Method and data**

154

155 A comprehensive approach for assessing the techno-economic feasibility of the use of MMCRES in
156 off-grid SSM in Europe is developed in this study, based on energy demand scenarios for the mining
157 and mineral processing activities involved, characteristics of diesel generator systems and MMCERS
158 currently available and renewable energy resources at different locations. The software used to simulate
159 different MMCRES configurations is HOMER Pro, one of the most widely used tools for optimising
160 energy systems under off-grid conditions with the largest coverage of different energy technologies
161 [20]. The input data needed for HOMER Pro was collected through several different methods. A survey
162 was performed to identify and characterise different types of MMCRES available on the market and
163 create product profiles with technical, economic and physical parameters, with any missing data
164 obtained from the literature. Average hourly energy demand over a typical day for SSM were estimated
165 based on an innovative containerised Mobile Modular Plant (MMP) designed for SOSO mining as part
166 of an EU H2020 research project IMP@CT [12]. Simulations were performed for potential mine sites
167 across Europe to evaluate whether MMCRES available on the market were economically viable
168 compared with diesel generators. An overview of our approach is illustrated in Figure 1 and more details
169 are explained in subsequent sections.

170



171

172 Figure 1 Overall approach for feasibility study of MMCRES for SSM in Europe

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174

175 2.1 Technical and cost data on MMCRES

176 A survey was performed through email to collect technical data and cost information from developers
 177 and manufacturers on MMCRES that are readily available on the market. An internet search was first
 178 conducted to identify existing MMCRES suppliers using keywords that can capture the mobile and
 179 modular properties of the target systems. Although containerisation of most types of renewable energy
 180 technologies is possible, the ease of commissioning, decommissioning, redeployment and scaling up
 181 varies significantly for different renewable technologies. For example, containerised solar photovoltaic
 182 (PV) systems often have a racking system or ballast to provide structural stability when installed and
 183 can be easily stored in containers when decommissioned and redeployed at another site. They can be
 184 scaled up easily as only more PV panels (i.e., more containers) and larger land areas are required.

185 However, containerised micro-hydro turbines require water resources near the generation sites that can
186 meet certain flow characteristics and some onsite groundwork and/or construction [28,29]. Our survey
187 therefore focuses on MMCRES and covers solar PV, bioenergy systems and wind turbines as they can
188 be made mobile and modular by containerisation and have widespread resource availability. Other
189 renewable technologies like micro-hydro are available in the containerised form but are not considered
190 to be sufficiently mobile and therefore excluded in our study and the survey.

191 A total of 43 MMCRES manufacturers were identified as of January 2019. Then a questionnaire with
192 22 questions was sent to all of the 43 manufacturers identified, 17 out of which responded to the
193 questionnaire. The information collected through the survey and additional information such as
194 technical data sheets, company and product history, which were freely accessible from the websites of
195 some manufacturers were used to characterise the MMCRES products. In addition to the questionnaire
196 responses, some manufacturers provided case studies and/or additional data on their MMCRES
197 products. More details on the survey method and findings are presented in the supplementary
198 information.

199 **2.2 Energy demand in SSM**

200 Integration of RES in mining requires a good understanding of the total energy requirements, covering
201 all aspects of the mining operations. The energy demand for the SSM case study was estimated based
202 on technical specifications of a novel MMP for SOSO mining developed within the IMP@CT project
203 and characteristics of a small mine at Olovo in Bosnia & Herzegovina - Jelik (44°7.6'N, 18°35.0'E)
204 featuring selective underground mining in a high-grade lead (cerussite) ore deposit with above-ground
205 sorting and processing.

206 The IMP@CT MMP [12,30] has power requirements rather different from those of a conventional
207 mining and processing plant. The containerised MMP system covers the mining operations and
208 downstream processes up to the production of the concentrate at the mining site. The total power rating
209 of the equipment in the MMP is 159 kW [12,30]. In addition to the mining and mineral processing
210 activities, there are also ancillary processes such as mine ventilation and workshops at the mining site
211 for a smooth and safe workflow. The ancillary processes necessary for a SSM have a total power rating
212 of 381.5 kW, based on the Olovo mine - Mineco Ltd [31].

213 Although the maximum theoretical power required by the MMP and ancillary processes is 540.5 kW,
214 not all power-consuming equipment are used simultaneously. The mining of raw materials is based on
215 a fixed process chain which consists of shared processes as resources with limited capacity (e.g.
216 extraction, loading, transportation, processing), which is run through one after the other. The mining
217 and mineral processing activities can be staged, such that a uniform load over a day and week can be
218 maintained for continuous mine operation. In order to achieve a uniform load and to avoid load peaks
219 different consumer groups were defined which served as input factors for load profiles. With the help
220 of targeted planning of operation and processes a set of 11 scheduling scenarios were designed, resulting
221 in different temporal power demand profiles over a typical day. The scheduling scenario with the lowest
222 peak power demand and overall power consumption will be identified and used to assess the feasibility
223 of MMCRES at other sites in Europe.

224 A database for small complex deposits in Europe was used to select four other possible sites where a
225 SOSO mining model can be implemented [12,30] and varying renewable energy resources availability
226 across Europe can be tested. These sites include: Auliac Filon Principal, France - Talizat (45°8.8'N,
227 3°3.1'E); Glendinning, Scotland, UK - Langholm DG13 0NN (55°15.8'N, 3°5.0'W); Kalliosalo, Finland
228 - Seinajoki (62°43.8'N, 22°56.9'E); and Mina Portoviejo, Spain - Valencia de Alcantara, Caceres
229 (39°31.6'N, 7°20.7'W).

230 2.3 Energy system simulations

231 Simulation of the MMCRES were performed using HOMER Pro, an optimisation model that simplifies
 232 evaluation of various power system designs for a variety of applications. HOMER Pro provides an
 233 excellent platform to design RES for different locations with algorithms to optimise the choice and
 234 sizing of energy systems from a large number of technology options to meet the required energy supply
 235 with least cost, considering variations in technology costs and energy resource availability [32].

236 A general energy system model in HOMER Pro is created by defining different input parameters such
 237 as temporally explicit energy demand, technical and cost details and resources available (e.g., wind
 238 speed and solar irradiation) for the energy components and control technologies considered, project
 239 economics (e.g., project lifetime and discount rate), and any technical, economic and environmental
 240 constraints. The input parameters can also be defined as sensitivity variables to evaluate the impacts of
 241 changes in these variables on system performance. HOMER Pro then simulates the operation of the
 242 energy systems considered, identifies system configurations optimised by cost and provides sensitivity
 243 analyses on any sensitivity variables defined. More details of creating a system model and the inputs
 244 and outputs in HOMER Pro is explained in the supplementary information.

245 The rest of this section presents the key input data for HOMER Pro. The energy demand profiles were
 246 created based on 3 scheduling scenarios mentioned earlier. As all of the processes involved were
 247 electrified, electricity is the only form of energy required. Three hourly electrical load profiles over a
 248 typical day were used as inputs over the entire project duration. Once the load profiles are specified in
 249 HOMER Pro, the software calculates the average and peak loads in a day and the annual average
 250 electricity demand. The main characteristics of these energy demand scenarios are shown in Table 1.
 251 Scenario 1, 2 and 3 have the lowest load as these scenarios only cover the demand for the MMP but not
 252 the ancillary processes. Scenarios 4 and 11 have the highest and lowest loads and electricity demands,
 253 respectively, thus these load profiles were chosen for simulation inputs as worst case and best-case
 254 scenarios. Whereas scenario 8 was used to create average load profile between best- and worst-case
 255 load profiles

256 Table 1 Annual average daily electricity demand and peak electric load calculated in HOMER Pro for
 257 the 11 energy demand scenarios

Energy demand scenario	Processes covered	Annual average electricity demand (kWh/day)	Peak load (kW)	Average load (kW)	Simulation carried out
Scenario 1	MMP	1,100.99	104.0	45.87	
Scenario 2	MMP	1,100.99	81.3	45.87	
Scenario 3	MMP	1,107.75	81.3	46.16	
Scenario 4	MMP + Ancillary processes	4,774.11	461.0	198.9	Yes
Scenario 5	MMP + Ancillary processes	2,529.94	206.0	105.4	
Scenario 6	MMP + Ancillary processes	2,573.31	183.3	107.22	
Scenario 7	MMP + Ancillary processes	4,536.64	302.0	189.03	
Scenario 8	MMP + Ancillary processes	3,938.51	212.0	164.10	Yes
Scenario 9	MMP + Ancillary processes	2,749.13	219.5	114.55	
Scenario 10	MMP + Ancillary processes	2,414.98	179.7	100.62	
Scenario 11	MMP + Ancillary processes	2,184.03	157.0	91	Yes

258 Selection of the component technologies for the RES was made based on the MMCRES survey, which
 259 suggested that there were mobile and modular solar PV, wind turbine, biomass gasification and hybrid
 260 systems already available on the market (see details in section 3.1). Many of these systems also included
 261 balance of systems and energy storage technologies such as batteries. Therefore, the RES model created
 262 in our study for SSM in Europe included solar PV, wind turbine, biomass generator, battery, converter
 263 and diesel generator. Diesel generator was included for comparison, in order to determine if MMCRES
 264 solutions can achieve the required energy demand at lower system costs. In addition, this reflects reality
 265 as some of the MMCRES manufacturers offer hybrid systems that include or can include diesel
 266 generators. Figure 3 in the supplementary information illustrates this system model with the different
 267 components included.

268 A detailed analysis for the Olovo mine site was carried out as the energy demand was estimated based
269 on characteristics of this mine. Three energy demand scenarios were simulated for Olovo. A 5-year
270 project duration was used as this short project life reflected a SOSO mining operation. Finally, the
271 energy demand scenario with the lowest peak load and annual electricity consumption (Scenario 11)
272 was used in the simulations for the other 4 potential mining sites in Europe.

273 Details of the data used for the key input parameters for all the components of our hybrid RES model
274 are shown in Table 2. The complete data is presented in Tables A5-A10 in the supplementary
275 information. The data sources include the MMCRES survey, academic and grey literature and HOMER
276 Pro default data. In terms of renewable energy resources, solar and wind data were taken from the
277 NASA database. The biomass resource was assumed to be sufficient to cover the demand, given that
278 there are abundant local forestry biomass residues in both Bosnia and Herzegovina and Europe. All
279 prices were converted into Euros using exchange rates on 19th July 2019 (1 USD = 0.889 Euro and 1
280 GBP = 1.110 Euro [33]).

281 For the diesel generator, the capital and replacement costs were taken from [34]. The operation &
282 maintenance (O&M) cost was calculated following [35] using the capital investment, average of
283 variable non-fuel OPEX and average of variable fuel OPEX. Thus, the O&M cost includes diesel fuel
284 prices averaged from higher and lower variable fuel OPEX - 0.27 & 0.46 €/kWh [35]. The emission
285 factors and lifetime of the generator were HOMER Pro default values for a 1 kW auto-size gen-set. The
286 remaining prices are estimate values to provide variability to evaluate the impact on the total cost of the
287 system.

288 The capital and replacement cost for the biomass generator considered in the simulation are taken from
289 MMCRES survey manufacturer [36]. Whereas the O&M was calculated from the capital cost following
290 [37,38]. The operation lifetime of the generator was the HOMER Pro default. The biomass fuel resource
291 technical specifications were collected from our MMCRES survey and [39,40] and similar to the
292 HOMER Pro default values. The O&M cost calculated was based on biomass fuel transportation from
293 all over Europe. Therefore, the transportation cost and O&M cost would be lower if the biomass fuel
294 was sourced locally, than the O&M calculated here. The emission factors used were from a study on
295 life cycle assessment of electricity generated from gasification of woody biomass residues [41]. The
296 capacity of biomass generator was sized in a broad range (0-500 kW) for the optimisation calculation,
297 reflecting the wide range found in our survey (9-1000 kW). Finally, the biomass fuel price was also set
298 as a sensitivity variable, with the price ranges for two different types of biomass fuels taken from reports
299 [37,42].

300 Data for the solar PV panel were from the MMCRES manufacturer [43] that provided the costs for their
301 complete containerised system. The panel type and make used by this MMCRES manufacturer was
302 available in the HOMER Pro database and shown in Table A7 in the supplementary information.

303 Data for the wind turbine were from the HOMER Pro database as the MMCRES survey failed to obtain
304 costs of the mobile and modular turbines available on the market. Given this lack of economic data and
305 the low wind speeds at the Olovo site, the default generic 1 kW wind turbine available in HOMER Pro
306 was used.

307 Storage technology considered for the RES model was Tesla powerwall 2.0 lithium-ion batteries. A
308 three-phase bidirectional converter designed for hybrid power systems was used in the system model.
309 Data used for the batteries and converter were default values in the HOMER Pro database.

310 The controller component was used to specify a dispatch strategy, i.e., a set of rules, on how the RES
311 system will operate during the HOMER Pro simulation. The controller dispatches generators and
312 storage banks to overcome the intermittency of renewable power generation and provide continuous
313 power supply according to the load. In our RES system design, two controllers with different dispatch
314 strategies were used. The Cycle Charging strategy operates generators at full capacity when power is
315 required with surplus power generation used to charge batteries while the Load Following strategy

316 operates the generators at capacities required to produce just enough power to meet demand [32].
 317 HOMER Pro simulates and optimises the choice between the two dispatch strategies to lower overall
 318 system costs.

319 In the economic parameters, the nominal discount rate input was adjusted to bring the real discount rate
 320 to 4%. The inflation rate is a default value from the software which was used for the IMP@CT project
 321 feasibility study.

322 Table 2 Data for the key input parameters for the hybrid RES model

Hybrid RES Component	Parameter	Value
Diesel Generator	Capacity (kW)	1
	Initial Capital (Euro)	€ 924.2 [34]
	O&M (Euro/kW op.hour) fuel inclusive	€ 0.389 (Calculated based on [35])
	Operation lifetime (hours)	15000 (a)
	Minimum load ratio (%)	25 (a)
Biomass Generator	Capacity (kW)	1
	Capital (Euro)	€ 3,771.4 (MMCREs survey and [36])
	O&M (Euro/op. hour)	€ 0.092 (Calculated based on [37,38])
	Operation lifetime (hours)	20000 (a)
	Minimum load ratio (%)	50 (a)
	Variable Biomass Prices (Euro/tonne)	Woodchips from local energy crops - € 53 [37]
		Woodchips from local energy crops - € 84 [37]
		Woodchips from Scandinavian forestry residues to continental Europe - € 102 [37]
		Pellet cost Low - € 105 [42]
		Pellet cost Medium - € 133 [42]
	Pellet cost High - € 161 [42]	
Solar PV with ballast [43]	1 array Capacity (kW)	11.2 [43]
	Capital (Euro)	€ 9,956.8 [43]
	O&M (Euro/year)	€ 124.32 [43]
Wind Turbine - HOMER Pro generic 1 kW	Capital	€ 7,000 (a)
	O&M	€ 70 (a)
	Lifetime (years)	20 (a)
	Hub Height (m)	17 (a)
Batteries - Tesla Powerwall 2.0	Capacity (kWh) – 1 String	13.2 (a)
	Capital (Euro)	€ 5,125 (a)
	O&M (Euro/year)	€ 0 (a)
Converter - Leonics MTP-413F 25kW	Capacity (kW)	1 (a)
	Capital (Euro)	€ 471 (a)
	O&M (Euro/year)	€ 0 (a)
Controller - HOMER Pro default	Capital (Euro)	€ 111 [19]
	O&M (Euro/year)	€ 0 (b)
Project economics	Nominal Discount rate (%)	6.08 (b)
	Real Discount rate (%)	4
	Expected inflation rate (%)	2 (a)
	Project Lifetime (years)	5
	Currency	Euro

Notes: (a) HOMER Pro default values;
 (b) Assumed

323

324 3 Results and discussions

325 3.1 Characteristics of MMCREs on the market

326 The types of renewable technologies used in MMCREs available on the market were found to include
 327 solar PV (with or without batteries), wind turbines, biomass generators using gasification or anaerobic
 328 digestion (AD) and hybrid systems that can include any combinations of solar PV, wind turbines and
 329 biomass generators. Containerised AD systems require a supply of agricultural or residential bio-waste
 330 to generate biogas and then electricity is generated from the biogas [44]. This is a significant challenge
 331 in terms of reliability in off-grid or remote locations, where the required feedstock can be difficult to
 332 source. Therefore, containerised AD systems were excluded from the survey. In the supplementary
 333 information presents the MMCREs manufacturers identified in our study and their products, covering
 334 solar PV, wind turbines, biomass gasification generators and hybrid systems.

Existing MMCRES on the market varied in terms of power ratings and physical dimensions, available in various numbers (1-10) of 10-foot, 20-foot and 40-foot ISO certified containers (see Table A3 in the supplementary information). Rated power is the key technical parameter that determines the theoretical maximum power output from the MMCRES. The installed horizontal dimension, is the key physical parameter that can limit the applicability of MMCRES depending on suitable land area available (e.g., in locations that are mountainous and/or forested). Figure 2 illustrates the rated power and installed horizontal dimensions for the MMCRES products on which information is available. For solar PV with batteries and hybrid systems, only the renewable power capacities are included (i.e., batteries and diesel capacities are excluded) while for the biomass gasification systems, only the electrical generating capacity is included. The numbers of the containers in the systems are illustrated using different colours. Most of the systems comprise of one container (blue). One biomass gasification system and one solar PV system use two containers (red). One biomass gasification system is incorporated in 3-4 containers (orange). The 1 MW biomass gasification system is comprised of 10 containers (yellow), which can be stacked when in use.

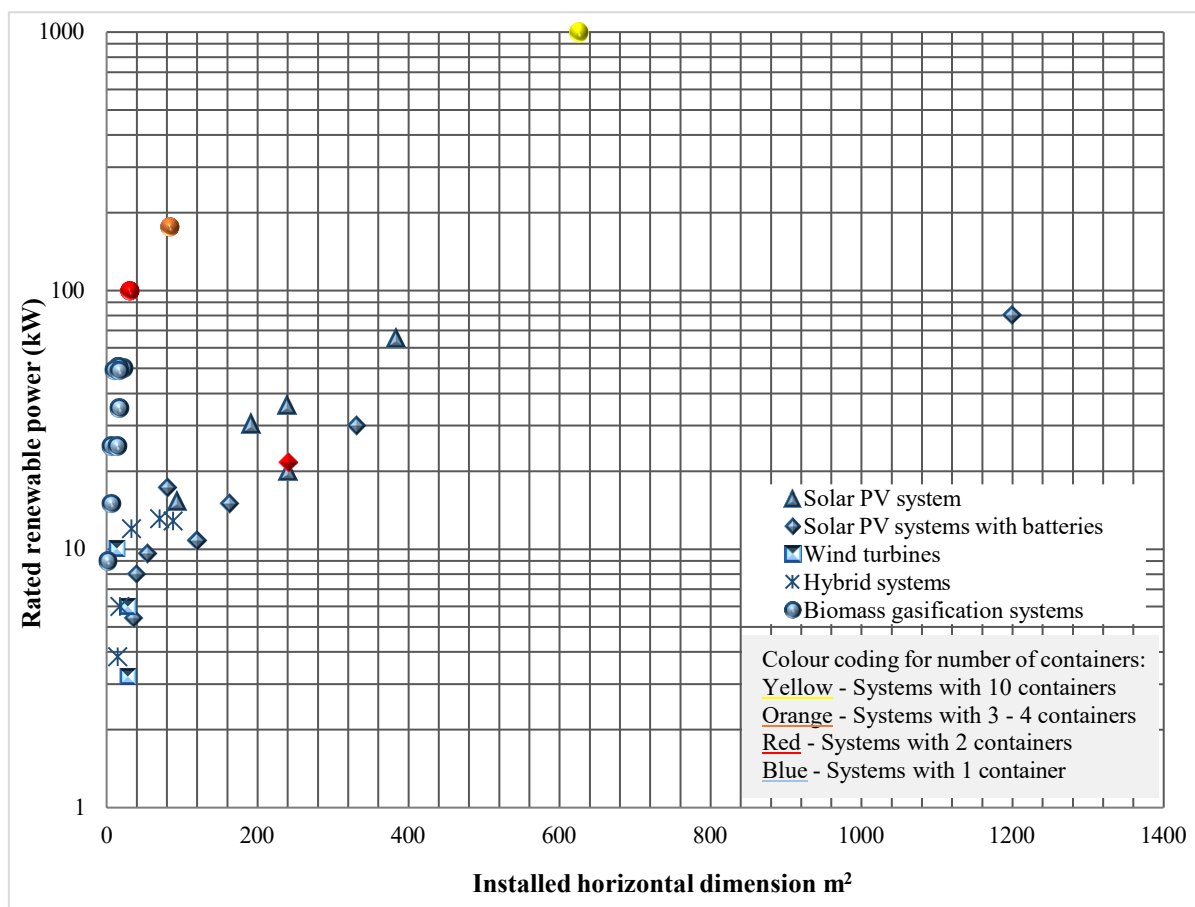


Figure 2. Rated renewable power and installed horizontal dimensions of MMCRES in this survey

It is evident that the biomass gasification systems have the lowest land footprints at the same level of power outputs whereas solar PV systems have the highest land footprint. However, these dimensions include only the MMCRES: the fuel storage for the biomass gasification systems is not included. All biomass gasification systems come with a hopper to provide 1-4 hours of fuel, but sizes of biomass storage can vary significantly based on consumption rates, availability of biomass and space available on the site. The rated renewable power, numbers and sizes of containers and installed horizontal dimensions used in Figure 2 as well as calculated electrical densities (measured as the ratio of rated

359 power and installed horizontal dimensions) are shown in Table A3 in the Appendix of supplementary
360 information.

361 The survey results suggest that containerised biomass gasification products have the highest electrical
362 power density (higher than 1500 W/m² for most systems excluding fuel storage). The smallest system
363 can generate a rated power of 9 kW with a land footprint of 2.94 m². The product with the highest
364 electrical power density can generate a rated power of 49 kW with 11.16 m². Furthermore, these systems
365 can generate electricity continuously with a regular supply of fuel. Therefore, containerised biomass
366 gasification systems have a high potential to replace diesel generators, especially when high electrical
367 power density and continuous power output are required.

368 Solar PV systems and solar PV-battery systems are most suitable for off-grid generation in areas where
369 solar radiation is high and land availability is not an issue. Based on the survey, it is evident that PV
370 systems and PV-battery systems have the lowest electrical power density among the MMCRES. The
371 PV system product with the highest electrical power density (169.3 W/m²) can generate a rated power
372 of 65 kW with a 384 m² land footprint. Whereas the solar PV-battery system with the highest electrical
373 power density (213.1 W/m²) can generate 17.3 kW with a land footprint of 81.2 m². With advances in
374 technology, PV-battery systems can generate electricity more cheaply than diesel generators at a
375 community scale [1]. However, batteries are still one of the most expensive components in these
376 systems so that an economic feasibility study of batteries might be needed before their integration in
377 off-grid solar PV applications.

378 The three containerised wind turbine products available on the market have relatively small land
379 footprints though they can have substantial heights. One of the wind turbine products has the second
380 highest electrical power density (683.1 W/m²) after the biomass gasification systems. When installed in
381 regions with high wind speeds, these systems can be cheaper than diesel power generation [45].

382 Hybrid systems also have a high market potential because of their ability to utilise different renewable
383 resources and hence generate more reliably in locations and under different environmental conditions.
384 Furthermore, with the addition of diesel generators to provide additional or backup power they can have
385 higher electrical power density than biomass gasification systems. In Figure 2, the capacities of hybrid
386 systems do not include the diesel generator capacities as they are often not specified. Therefore these
387 systems have lower renewable electrical power density than biomass gasification systems. The hybrid
388 containerised system with the highest renewable electrical power density of 364 W/m² can generate a
389 rated power of 12 kW from solar and wind resources with a land footprint of 33 m² and there are options
390 to increase the power capacity by adding diesel generators. The addition of diesel generators enables
391 hybrid systems to provide even more consistent power in different environmental contexts, making it
392 easier to design economically feasible off-grid generation systems.

393 The survey questionnaire also included the cost of the systems but only 9 companies replied to the
394 question. This is mainly because the cost of MMCRES is often determined on a case-by-case basis
395 depending on customer requirements.

396 **3.2 In-depth analysis for the Olovo mine site**

397 In this section, results for the Olovo mine site were presented. First, results for one of the 3 selected
398 energy demand scenarios are explained in detail. Then the results for all the three selected energy
399 demand scenarios are summarised and discussed.

400 HOMER Pro simulates all possible combinations of the available technologies and identifies the system
401 architecture with the lowest net present cost (NPC) – the winning system architecture. Table 3 describes
402 the characteristics of the winning system architecture for the energy demand scenario 11, in comparison
403 with a diesel generator only system as the base case system. This winning system architecture consists
404 of a biomass generator, solar PV, storage batteries and a converter with a load-following dispatch
405 strategy when the biomass fuel price is lowest, i.e. 53 €/tonne.

406 The software has simulated for all possible combinations from the equipment selected while optimising
 407 the system for the lowest NPC. Here only the winning system design is discussed and compared with
 408 the diesel power generation as a base case system.

409 **Scenario 11 winning system**

410 The winning architecture in Table 3 is the lowest cost system for all sensitivity used in the modelling
 411 for scenario 11. For each sensitivity case, there are several optimisation results. The results in Table 3
 412 are for sensitivity variables with lowest fuel prices.

413 In the diesel-only system, a 180 kW generator will be used for the project duration with an initial capital
 414 investment of €166,467. Whereas in winning hybrid renewable system a CAPEX of €1.87 million is
 415 required for 892 kW of solar PV, a biomass generator of 150 kW, 82 Tesla battery strings and a 189
 416 kW system converter. Although the CAPEX for a diesel-only system is lower, Table 3 shows that over
 417 the 5-year project duration, a diesel-only system is more expensive than a hybrid RES.

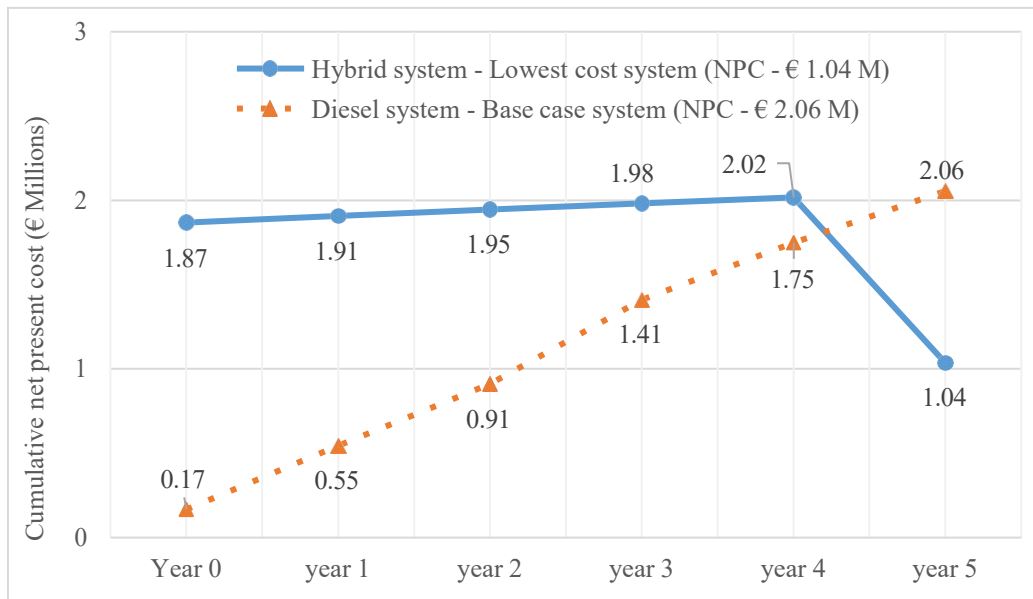
418 The emission data in Table 3 shows that switching to hybrid RES has a positive impact on reducing
 419 emissions of CO₂ and air pollutants. The hybrid RES emits 323 tonne/year of CO₂, negligible amount
 420 of carbon monoxide, nitrogen oxide, particulate matter and no sulphur dioxide. The CO₂ emissions are
 421 direct emissions from biomass combustion and the net CO₂ emissions could be even lower as the carbon
 422 in the biomass is from the atmosphere. Whereas the diesel-only system emits 569 tonne/year of CO₂,
 423 air pollutant emissions an order of magnitude higher than those of the hybrid RES.

424 Table 3 Comparison of winning hybrid system with a base case diesel only system

System components	Winning System (Hybrid system)	Base case system (Diesel system)
Controller	Homer Load following	Homer Cycle charging
Generator	Biomass 150 kW	Diesel -180 kW
Solar PV - Jin350	892 kW	
Batteries - Tesla PW2.	82 strings	
Converter – Leon 25	189 kW	
Project Duration	5 years	5 years
Cost summary		
Initial capital	€ 1.87 Million	€ 166,467
Operation & Maintenance	€ 139,361	€ 1.76 Million (Fuel cost included for diesel system)
Fuel cost	€ 44,513	-
Cost of Energy/kWh	€ 0.29	€ 0.58
Salvage value	€ 1.01 Million	€ 16,681
Total NPC	€ 1.04 Million	€ 2.06 Million
Emissions		
Carbon Dioxide (tonne/yr)	323	569
Carbon Monoxide (tonne/yr)	0.15	3.6
Unburned Hydrocarbons (tonne/yr)	0.01	0.157
Particulate Matter (tonne/yr)	0.01	0.022
Sulphur Dioxide (tonne/yr)	0	1.4
Nitrogen Oxides (tonne/yr)	0.18	3.4
Electricity		
Total production (kWh/yr)	1,233,087	803,275
Total consumption (kWh/yr)	797,156	797,172
Excess (kWh/yr)	383,377	6,103
Electricity production % from total		
Diesel (%)	-	100
Solar PV (%)	85.1	-
Biomass (%)	14.9	-
Renewable fraction (%)	100	-
Excess production (%)	31.1	0.76
Sensitivity variables		
Fuel price	Biomass price – €53/tonne	

425 The cumulative cash flow for the winning system versus the base case is plotted in Figure 3. It is clear
 426 that the renewable only hybrid system has high CAPEX in the first year while the base case diesel-only

427 system has high OPEX. After the 5-year project duration, the equipment in both cases are salvaged
428 according to their lifetime and the NPC is calculated. The overall NPC is €1.04 million for the winning
429 system and €2.06 million for the diesel-only system.

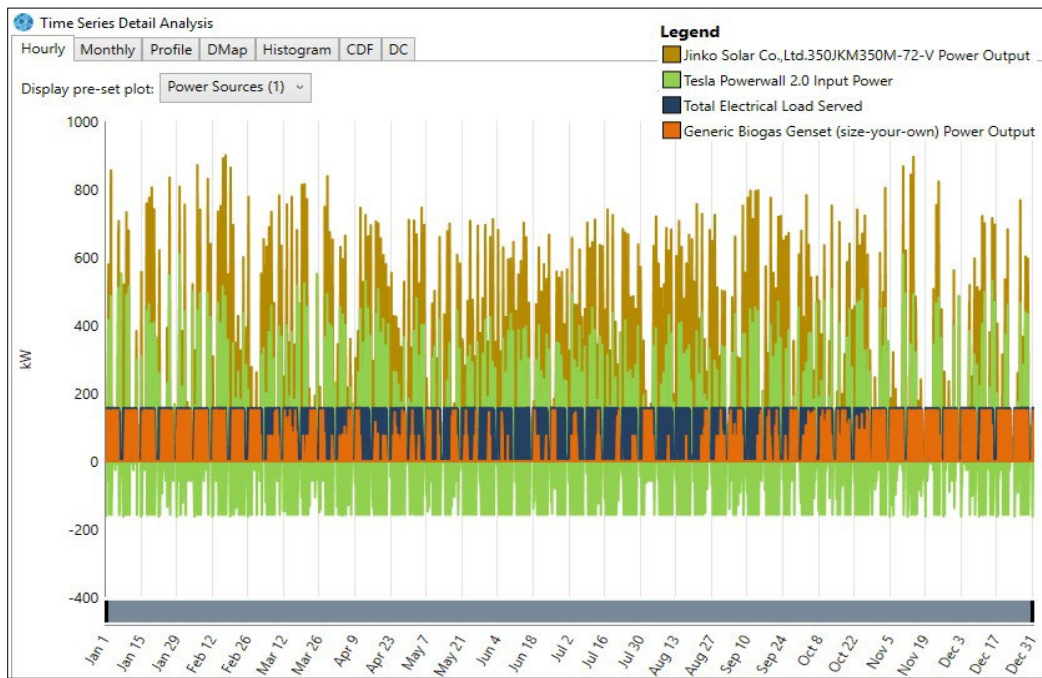


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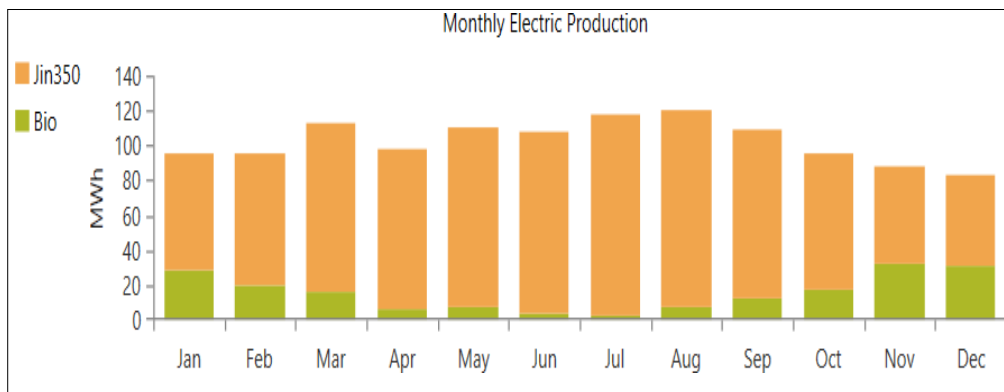
431 Figure 3: Winning hybrid system vs Diesel only system for load scenario 11

432 Figure 4 presents all power generating sources in the winning architecture for scenario 11, along with
433 the total electric load served. In this model, solar PV is the primary source for power generation,
434 accounting for 85.1% of the total electricity production. The remaining 14.9% is produced by the
435 biomass generator, which is used when power from the solar PV is insufficient to meet the demand.
436 This can be further explained when electrical production results are analysed, as shown in Figure 5 and
437 Table 3. The system design generates 31.1% excess electricity which can be reduced by increasing the
438 battery storage, but that will increase the NPC substantially. In the optimisation table for this sensitivity
439 variable, there are different equipment combinations which do have a lower percentage of excess
440 electricity but with high NPC of the system, and emissions are higher if a diesel generator is operating.

441



442
443 Figure 4 Scenario 11- Power generation source and load served



444
445 Figure 5 Scenario 11 - Electricity production, solar PV + biomass

446

447 **Comparison of load scenarios**

448 The 3 models simulated for 3 different load scenarios were analysed. As it is not possible to present all
449 the results together in the paper, only the winning systems for the 3 load scenarios are described in
450 Table A11 in supplementary information.

451 Scenario 4 has the highest average energy demand per day, which requires higher electricity production
452 and thus a bigger system than other scenarios. The winning architecture for Scenario 4 has the largest
453 solar PV and biomass generation capacities, with high CAPEX and high NPC. However, lower OPEX
454 and high salvage return at the end of the project duration has benefited the cost of energy (COE) in
455 Scenario 4. The COE is lowest in Scenario 4, but similar to that in Scenario 11. Solar PV accounts for
456 81.2% of total power generated in Scenario 4 with the remaining 18.8% from biomass generation, which
457 results in high direct CO₂ emissions.

458 Scenario 11 has the lowest average energy demand per day, requiring the smallest systems. Solar PV
459 accounts for 85.1% of the total power generation in Scenario 11 and the remaining 14.9% is provided

460 by the biomass generator. Lower contribution from biomass generation has reduced direct CO₂
461 emissions and costs, resulting in the lowest NPC and emissions in Scenario 11.

462 In Scenario 8 where average energy demand per day is higher than Scenario 11 but lower than Scenario
463 4, the winning architecture features a relatively large solar PV capacity providing 83.3% of the total
464 power generated, the largest battery storage capacity, an extensive use of biomass generator providing
465 15.8% of the total power generated and a backup diesel generator providing 0.9% of the total power
466 generated. The biomass generator in Scenario 8 has lower mean electrical efficiency (86.7%) than
467 Scenario 4 (91.4%), resulting in higher biomass fuel consumption. The direct CO₂ emissions are high
468 in Scenario 8 because of the extensive use of a biomass generator and the incorporation of a diesel
469 generator in the system design as a backup. From the results for all three scenarios, it is evident that
470 Scenario 11 is the best case to adopt in order to reduce the cost and impacts of the mining operation.

471

472 **3.3 Broader analysis across Europe**

473 The general system model was further used to simulate the performance of MMCRES at the selected
474 complex ore deposit sites across Europe. The temporal load profile used was scenario 11, as shown in
475 Table 1. Similar input parameters were used as presented in Section 2.3 and the project duration was
476 kept as 5 years. The winning architectures for all geographical locations are presented in Table 4, with
477 the complete system configurations. In all site locations across Europe, the optimum system designs do
478 not include diesel generators. Wind turbines are also not included in the winning systems even for high
479 wind speed sites such as Scotland because of the small capacity and high cost of the small-scale turbines
480 needed to meet the mobility and modularity requirements for SSM.

481 The winning architectures for all sites considered are 100% renewable energy based, comprising of
482 solar PV, biomass generator, batteries for storage and a system converter. Depending on the site
483 location, the solar PV size varies across Europe. For example, in southern European countries such as
484 Spain and France with good solar radiations the winning RES architectures have higher capacities of
485 solar PV than those in northern European countries such as Scotland and Finland. The solar PV capacity
486 in the system design is directly linked with the batteries for storage, resulting in higher numbers of
487 batteries in southern European than in northern European sites. The biomass generator incorporated in
488 the winning design is of the same size (150 kW) for all sites but its operational hours are dependent on
489 solar radiation availability and PV and battery capacities incorporated in the designs. In southern Europe
490 with high solar PV capacity and higher battery storage, the biomass generator is used on standby to
491 provide power when required. For example, at the Spanish site solar PV produces 91.7% of the total
492 power whereas biomass generates only 8.3%. In northern European sites, the biomass generators are
493 used more extensively and generate an almost equal amount of power as solar PVs.

494 The direct CO₂ emissions of the hybrid RES are lower at southern European sites than the baseline
495 diesel-only system. With extensive use of the biomass generator, direct CO₂ emissions of the hybrid
496 RES at northern European sites are higher than at southern European sites and that of the baseline diesel-
497 only system. The amount of excess electricity produced is related to high solar PV production. The RES
498 produce more excess electricity at southern European mining sites (31-35% higher than demand) than
499 at northern European sites (17-19% higher than demand).

500 The NPC of the RES is higher at northern European sites because of higher O&M cost from more
501 extensive use of biomass generators. The RES requires higher capital investment at southern European
502 sites but has lower O&M cost as the biomass generator is used only when solar PV is not able to generate
503 enough power. This results in lower COE at southern European sites. Finally, when the winning RES
504 systems for all sites are compared with the diesel-only system (Table 3), it is evident that switching to
505 RES is cost effective with reduced emissions.

506 Table 4 Simulation results for the winning RES at different European sites using load Scenario 11

Parameters	Auliac Filon Principal France - Talizat (45°8.8'N, 3°3.1'E)	Glendinning , Scotland - Langholm DG13 0NN, UK (55°15.8'N, 3°5.0'W)	Kalliosalo, Finland - Seinajoki (62°43.8'N, 22°56.9'E)	Mina Portoviejo SPAIN - Valencia de Alcantara, Caceres (39°31.6'N,7°20.7' W)	Olovo, Bosnia - Jelik (44°7.6'N, 18°35.0'E)
Load - Scaled Annual Average (kWh/day)	2,184.03	2,184.03	2,184.03	2,184.03	2,184.03
Peak load (kW)	157.00	157.00	157.00	157.00	157.00
Sensitivity/Biomass Price (€/tonne)	€ 53	€ 53	€ 53	€ 53	€ 53
Architecture/Jin350 (kW)	864	552	507	790	892
Architecture/G1					
Architecture/Bio (kW)	150	150	150	150	150
Architecture/Gen (kW)					
Architecture/TeslaPW2	83	26	25	84	82
Architecture/Leon25 (kW)	177	177	181	199	189
Architecture/Dispatch	CC	CC	CC	LF	LF
Cost/NPC (€)	€ 1.05 Million	€ 1.14 Million	€ 1.12 Million	€ 0.88 Million	€ 1.04 Million
Cost/COE (€)	€ 0.297	€ 0.322	€ 0.315	€ 0.248	€ 0.292
Cost/total Operation & Maintenance (€)	€ 144,173	€ 236,583	€ 232,695	€ 96,284	€ 139,361
Cost/Initial capital (€)	€ 1.84 Million	€ 1.27 Million	€ 1.23 Million	€ 1.79 Million	€ 1.87 Million
System/Ren Frac (%)	100	100	100	100	100
System/Elec Prod (kWh/yr)	1269471	996405	1008708	1309164	1233087
System/Elec Cons (kWh/yr)	797172	797172	797172	797120	797156
System/Excess Elec (%)	32	17	19	35	31
System/CO ₂ (tonne/yr)	402	825	815	192	323
Bio/Hours	1652	3407	3380	932	1551
Bio/Production (kWh)	245706	503204	496222	108657	183279
Bio/Fuel (tonnes/yr)	235	481	476	112	189
Bio/O&M Cost (€/yr)	€ 22,798	€ 47,017	€ 46,644	€ 12,862	€ 21,404
Bio/Fuel Cost (€/yr)	€ 12,434	€ 25,519	€ 25,211	€ 5,956	€ 9,999
Jin350/Capital Cost (€)	€ 7,67,871	€ 4,90,665	€ 4,50,556	€ 7,02,110	€ 7,92,928
Jin350/Production (kWh/yr)	1023766	493201	512487	1200507	1049808
TeslaPW2/Autonomy (hr)	12.03938	4	4	12	12
TeslaPW2/Annual Throughput (kWh/yr)	291146	106339	67147	269905	239009
TeslaPW2/Nominal Capacity (kWh)	1096	343	330	1109	1082
TeslaPW2/Usable Nominal Capacity (kWh)	1096	343	330	1109	1082
Leon25/Rectifier Mean Output (kW)	6	5	2	0.09	0.3
Leon25/Inverter Mean Output (kW)	69	39	37	79	70
Power production % from total					
Solar PV (%)/Year	80.6	49.5	50.8	91.7	85.1
Biomass generator (%)/Year	19.4	50.5	49.2	8.3	14.9
Total renewable power production (%)	100	100	100	100	100

508 **3.4 Wider implications**

509 This study focuses on the techno-economic feasibility of the RES for SSM, however, in order to have
510 a triple bottom line perspective, the environmental and social viability of the RES should also be
511 assessed. To that end, Beylot et al. [46] assess the environmental performance of the SOSO approach
512 while Muller et al. assess its social performances [47], both using a RES for the Olovo SSM from a life
513 cycle perspective. The environmental life cycle assessment (LCA) and the social LCA are conducted
514 based on the RES as defined in Table 3 in comparison with a diesel generator system. Potential impacts
515 are calculated for 13 environmental impact categories using the EF 2.0 impact assessment method and
516 39 social indicators relevant to the mining sector using the PSILCA v2.0 social LCA database.

517 The implementation of the RES leads to significantly lower impacts for most environmental impact
518 categories such as climate change and air pollution related impacts. However, trade-offs are also
519 observed in particular for three impact categories, freshwater eutrophication and ecotoxicity and non-
520 cancer human health effects, for which the RES has higher impacts [46]. In terms of the social impacts,
521 the RES results in higher impacts for 27 of the 39 social indicators than the diesel generator system.
522 Although the main social hotspots are the same for both systems, a majority of the hotspots of the RES
523 occur outside Bosnia, likely due to the fact that the supply chain of the electric system is more
524 diversified leading to more globalised impacts [47]. Overall, these results suggest that running the SSM
525 on RES has both advantages and disadvantages compared to diesel generator (see [46] and [47] for the
526 complete assessment). It should be noted that these environmental and social LCAs were performed
527 based on one mine site and for one energy scenario only. Even through general conclusions cannot be
528 drawn, such results can provide insights for the deployment of RES for SSM on a broader scale.

529

530 **4 Conclusions**

531 A modelling-based feasibility study on RES for SSM in Europe under off-grid conditions has been
532 carried out using the HOMER Pro software and technical data collected through a survey on MMCRES
533 products on the market. The results suggest that it is technically feasible and financially viable to use
534 existing MMCRES products that combine technologies such as solar PV, biomass gasification
535 generators and lithium ion batteries to power SSM across Europe, with significant reductions in GHG
536 and air pollutant emissions compared with conventional diesel generator systems. At all site locations
537 across Europe that were simulated in our study, the optimum system designs do not include diesel
538 generators. Nevertheless, the geographical location in Europe influences GHG emissions at a mine site
539 due to the relative contribution of biomass and PV power production. We suggest that our approach can
540 inform mining and minerals process scheduling for small-mine operation with optimal average and peak
541 energy demand that minimizes GHG emissions. We acknowledge that the use of RES in SSM could
542 potentially have both positive and negative environmental and social impacts from a life cycle
543 perspective, which extend beyond the mine site due to a diverse supply chain and deserve further
544 research.

545

546 **5 Acknowledgement**

547 This project has received funding from the EU Horizon 2020 research and innovation programme
548 (Grant no 730411). The authors would like to thank all the manufacturers listed in Table A1 of
549 supplementary information for taking part in the survey and particularly those who provided
550 information about their products.

551

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