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

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Abstract

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

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

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1 Introduction

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

Understanding the energy usage of the mining industry is crucial for its decarbonisation. Currently, electricity is used in stationary processes and liquid fuels are used by diesel engine powered mobile equipment. However, almost all processes in mining, including transport, can be electrified. Given the volatilities in fossil fuel prices and significantly reduced cost of renewable energy systems (RES), electrification combined with on-site renewables has become an increasingly attractive and effective approach to sustainable mining. For example, an all-electric gold mine in Canada can save 2 million litres of diesel, 1 million litres of propane and 7,000 tonnes of CO_2 emissions annually [5]. Globally, 1 GW of RES has already been installed at existing mines, with another 1 GW in the pipeline [2].

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

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

Transportation costs and logistics planning are important considerations for the application of renewable energy at a mine site in a supply chain context [13]. Tailored to a SOSO mining model, with operations moving between multiple small complex ore deposits, the RES have to be mobile and modular, providing flexibility in terms of movement and generation capacity. Mobile and modular containerised RES (MMCRES) is a relatively new concept where RES are designed and prefabricated to fit into standard shipping containers. Prefabrication allows MMCRES to be commissioned, decommissioned and redeployed on another site relatively quickly. Scalability is another key feature of MMCRES to provide the desired generation capacity by adding up containers. The balance of system (BoS) for MMCRES is designed to incorporate batteries, diesel generator or different types of renewables to provide continuous power output. MMCRES has been on the market for no more than a decade, and an increasing interest in this type of RES is notable in recent years. The MMCRES could be a potential solution to make mining more sustainable by providing clean energy to the mines.

The mines located in remote areas are entirely off-grid due to unreliable grids or absence of distribution networks. These mines tend to rely on the most readily available form of electricity generation, i.e. diesel generators. The levelised cost of energy for solar and wind is lower in comparison to diesel generation, showing significant cost-savings with renewable energy [2]. A study performed by Votteler, 2016 for South African mines reveals that hybrid solar and wind power generation can reduce CO_2 emissions, levelised cost of electricity and fuel consumption. Over 20 years, € 44 million can be saved with diesel-solar PV hybrid and € 55 million with a diesel-wind hybrid in comparison to diesel generation [14]. However, the diesel generation has lower installation costs, space requirements and can be implemented in short duration in comparison to renewable-based generation [1,14]. MMCRES can play a crucial role in overcoming these disadvantages when compared to diesel generation. For example, Shanta Gold's New Luika mine in Tanzania installed eight containerised solar PV systems as of 2017 with a total generation capacity of 674 kW, saving approximately 219,000 litres of fuel and reducing CO_2 emissions by 660 tonnes annually [15].

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

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

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

2 Method and data

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

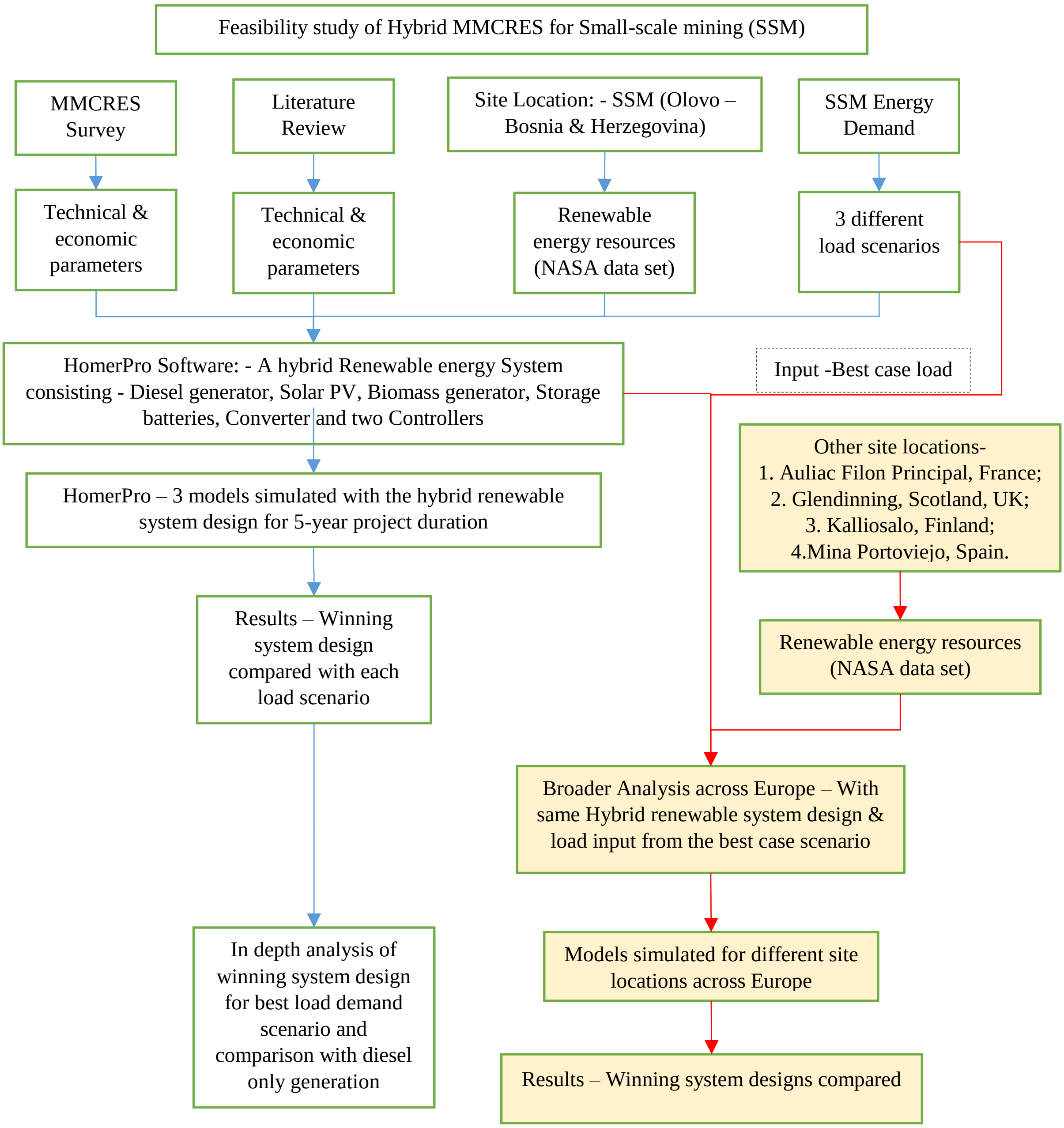

Figure 1 Overall approach for feasibility study of MMCRES for SSM in Europe

2.1 Technical and cost data on MMCRES

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

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

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

2.2 Energy demand in SSM

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

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

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

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

2.3 Energy system simulations

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

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

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

Table 1 Annual average daily electricity demand and peak electric load calculated in HOMER Pro for 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

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

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

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

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

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

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

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

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

The controller component was used to specify a dispatch strategy, i.e., a set of rules, on how the RES system will operate during the HOMER Pro simulation. The controller dispatches generators and storage banks to overcome the intermittency of renewable power generation and provide continuous power supply according to the load. In our RES system design, two controllers with different dispatch strategies were used. The Cycle Charging strategy operates generators at full capacity when power is required with surplus power generation used to charge batteries while the Load Following strategy operates the generators at capacities required to produce just enough power to meet demand [32]. HOMER Pro simulates and optimises the choice between the two dispatch strategies to lower overall system costs.

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

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

3 Results and discussions

3.1 Characteristics of MMCRES on the market

The types of renewable technologies used in MMCRES available on the market were found to include solar PV (with or without batteries), wind turbines, biomass generators using gasification or anaerobic digestion (AD) and hybrid systems that can include any combinations of solar PV, wind turbines and biomass generators. Containerised AD systems require a supply of agricultural or residential bio-waste to generate biogas and then electricity is generated from the biogas [44]. This is a significant challenge in terms of reliability in off-grid or remote locations, where the required feedstock can be difficult to source. Therefore, containerised AD systems were excluded from the survey. In the supplementary information presents the MMCRES manufacturers identified in our study and their products, covering 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-feet, 20-feet and 40-feet 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.

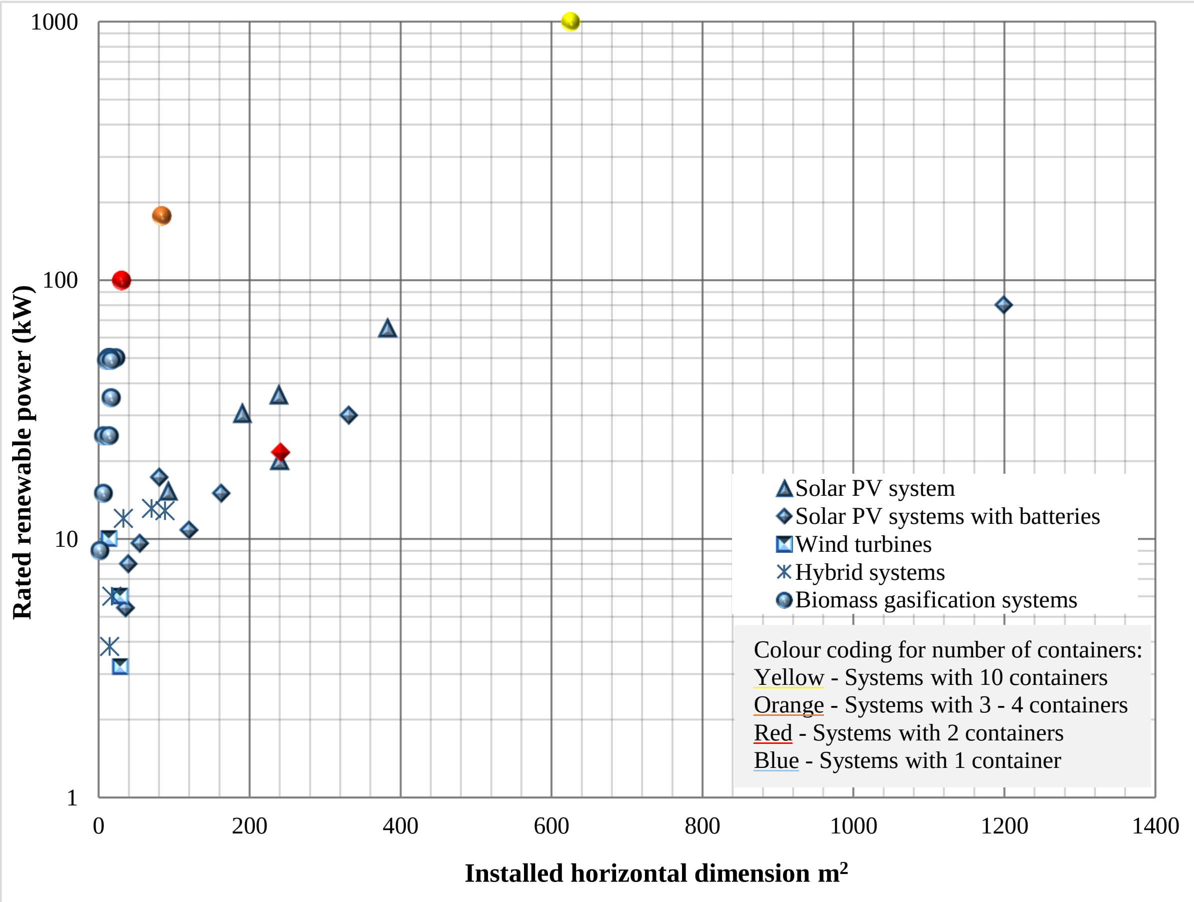

Figure 2. Rated renewable power and installed horizontal dimensions of MMCRES in this survey

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

The survey results suggest that containerised biomass gasification products have the highest electrical power density (higher than 1500 W/m^2 for most systems excluding fuel storage). The smallest system can generate a rated power of 9 kW with a land footprint of 2.94 m^2. The product with the highest electrical power density can generate a rated power of 49 kW with 11.16 m^2. Furthermore, these systems can generate electricity continuously with a regular supply of fuel. Therefore, containerised biomass gasification systems have a high potential to replace diesel generators, especially when high electrical power density and continuous power output are required.

Solar PV systems and solar PV-battery systems are most suitable for off-grid generation in areas where solar radiation is high and land availability is not an issue. Based on the survey, it is evident that PV systems and PV-battery systems have the lowest electrical power density among the MMCRES. The PV system product with the highest electrical power density (169.3 W/m^2) can generate a rated power of 65 kW with a 384 m^2 land footprint. Whereas the solar PV-battery system with the highest electrical power density (213.1 W/m^2) can generate 17.3 kW with a land footprint of 81.2 m^2. With advances in technology, PV-battery systems can generate electricity more cheaply than diesel generators at a community scale [1]. However, batteries are still one of the most expensive components in these systems so that an economic feasibility study of batteries might be needed before their integration in off-grid solar PV applications.

The three containerised wind turbine products available on the market have relatively small land footprints though they can have substantial heights. One of the wind turbine products has the second highest electrical power density (683.1 w/m^2) after the biomass gasification systems. When installed in regions with high wind speeds, these systems can be cheaper than diesel power generation [45].

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

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

3.2 In-depth analysis for the Olovo mine site

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

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

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

Scenario 11 winning system

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

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

The emission data in Table 3 shows that switching to hybrid RES has a positive impact on reducing emissions of CO_2 and air pollutants. The hybrid RES emits 323 tonne/year of CO_2, negligible amount of carbon monoxide, nitrogen oxide, particulate matter and no sulphur dioxide. The CO_2 emissions are direct emissions from biomass combustion and the net CO_2 emissions could be even lower as the carbon in the biomass is from the atmosphere. Whereas the diesel-only system emits 569 tonne/year of CO_2, air pollutant emissions an order of magnitude higher than those of the hybrid RES.

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	

The cumulative cash flow for the winning system versus the base case is plotted in Figure 3. It is clear that the renewable only hybrid system has high CAPEX in the first year while the base case diesel-only system has high OPEX. After the 5-year project duration, the equipment in both cases are salvaged according to their lifetime and the NPC is calculated. The overall NPC is €1.04 million for the winning system and €2.06 million for the diesel-only system.

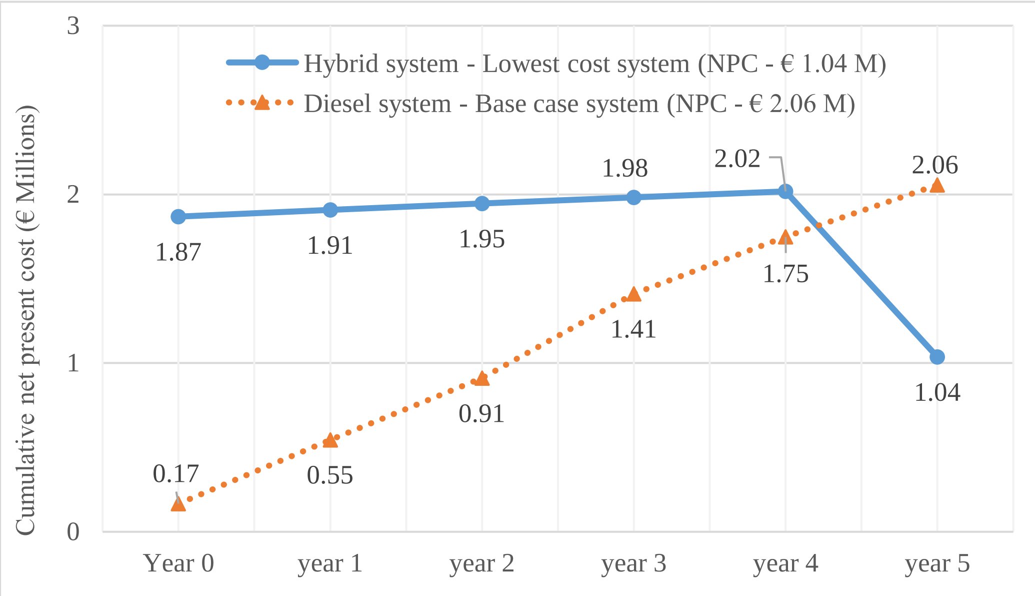

Figure 3: Winning hybrid system vs Diesel only system for load scenario 11

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

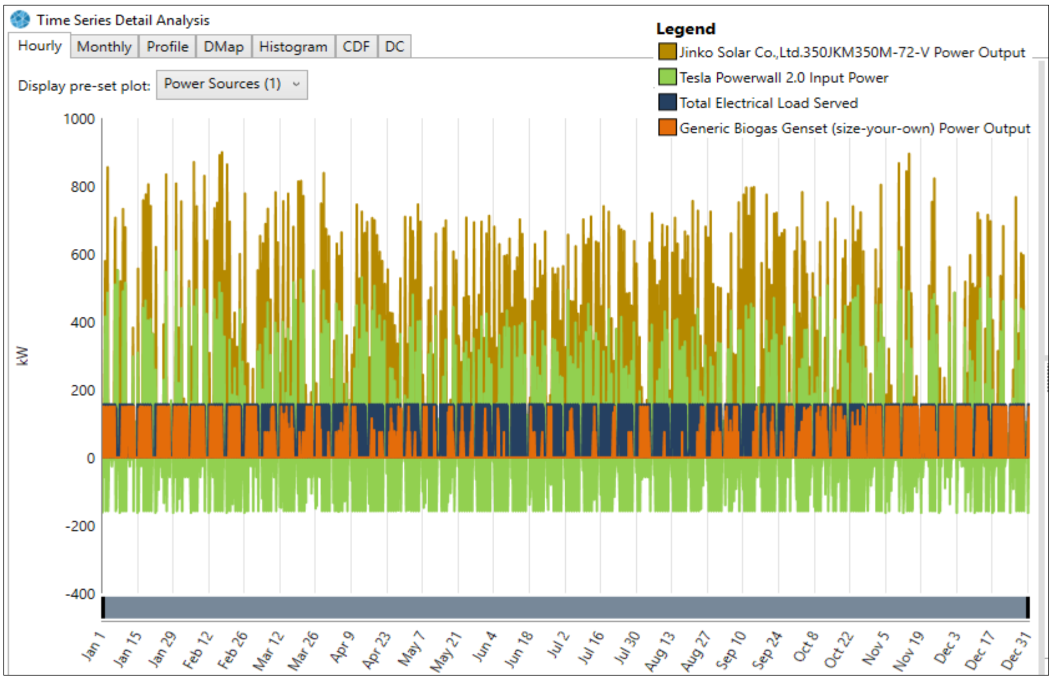

Figure 4 Scenario 11- Power generation source and load served

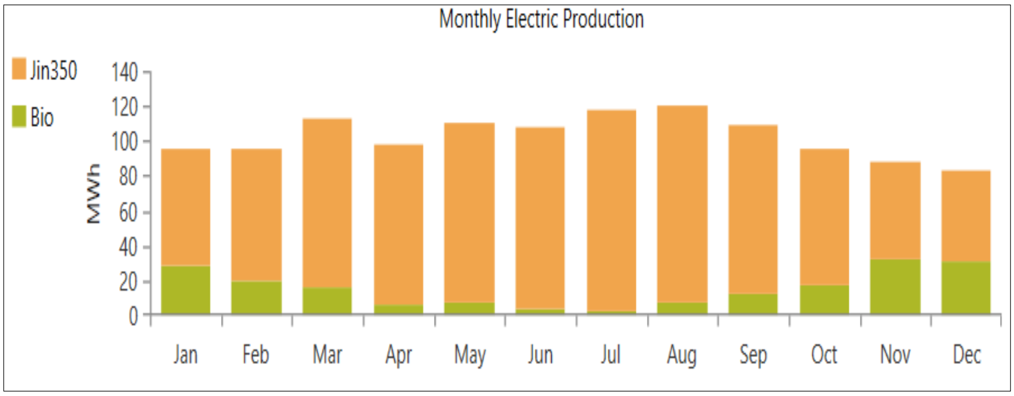

Figure 5 Scenario 11 - Electricity production, solar PV + biomass

Comparison of load scenarios

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

Scenario 4 has the highest average energy demand per day, which requires higher electricity production and thus a bigger system than other scenarios. The winning architecture for Scenario 4 has the largest solar PV and biomass generation capacities, with high CAPEX and high NPC. However, lower OPEX and high salvage return at the end of the project duration has benefited the cost of energy (COE) in Scenario 4. The COE is lowest in Scenario 4, but similar to that in Scenario 11. Solar PV accounts for 81.2% of total power generated in Scenario 4 with the remaining 18.8% from biomass generation, which results in high direct CO_2 emissions.

Scenario 11 has the lowest average energy demand per day, requiring the smallest systems. Solar PV accounts for 85.1% of the total power generation in Scenario 11 and the remaining 14.9% is provided by the biomass generator. Lower contribution from biomass generation has reduced direct CO_2 emissions and costs, resulting in the lowest NPC and emissions in Scenario 11.

In Scenario 8 where average energy demand per day is higher than Scenario 11 but lower than Scenario 4, the winning architecture features a relatively large solar PV capacity providing 83.3% of the total power generated, the largest battery storage capacity, an extensive use of biomass generator providing 15.8% of the total power generated and a backup diesel generator providing 0.9% of the total power generated. The biomass generator in Scenario 8 has lower mean electrical efficiency (86.7%) than Scenario 4 (91.4%), resulting in higher biomass fuel consumption. The direct CO_2 emissions are high in Scenario 8 because of the extensive use of a biomass generator and the incorporation of a diesel generator in the system design as a backup. From the results for all three scenarios, it is evident that Scenario 11 is the best case to adopt in order to reduce the cost and impacts of the mining operation.

3.3 Broader analysis across Europe

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

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

The direct CO_2 emissions of the hybrid RES are lower at southern European sites than the baseline diesel-only system. With extensive use of the biomass generator, direct CO_2 emissions of the hybrid RES at northern European sites are higher than at southern European sites and that of the baseline diesel-only system. The amount of excess electricity produced is related to high solar PV production. The RES produce more excess electricity at southern European mining sites (31-35% higher than demand) than at northern European sites (17-19% higher than demand).

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

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

3.4 Wider implications

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

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

4 Conclusions

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

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