The potential role of solid biomass for rural electrification: A techno economic analysis for a hybrid microgrid in India

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ABSTRACT

This paper focuses on the design optimization of a stand-alone hybrid microgrid serving a 2000 inhabitants community located in a rural area of Bihar (India) and it investigates the potential of the use of wood biomass for electricity generation.

The economic performance of the different power generation configurations is evaluated simulating the microgrid operation over four periods of five days representative of a whole year with a time step of 10 min. The system operation is defined by an Energy Management System (EMS) which ensures that the demand of different goods by the community (AC and DC power, heating, domestic hot water, cooling and water for irrigation and domestic use) is satisfied with the minimum operational cost thanks to a proper optimization of the programmable units scheduling. For each time step, the most cost effective schedule is obtained using Mixed Integer Linear Programming (MILP) embedded in a rolling horizon approach considering start-up penalties, battery wear cost, ramp limits of each component and other operational constraints.

Three different system configurations are investigated. The first one considers the combination of pho-tovoltaic panels and a diesel internal combustion engine (ICE). The other two investigate the possibility to substitute the fossil fuel generator with a renewable energy dispatchable generator powered by wood biomass: (i) a down-draft gasifier coupled with an ICE and (ii) a boiler coupled with an Organic Rankine Cycle (ORC).

The obtained results show that the integration of renewable energy sources technologies has a bene-ficial effect on the LCOE of isolated microgrids. The introduction of PV panels allows, in the optimal case, a LCOE reduction of 19% in comparison with system based only on Diesel engine. A further, twice as much, decrease (up to 38%) is attainable using biomass as main energy source: both Gasifier-based and ORC-based systems show similar economic performances and ensure a share of electricity generated by renewables of about 95%.

Keywords:
Rural energy access
Stand-alone microgrid
Optimal microgrid management
Renewable energy sources
penetration Biomass

Nomenclature

C c	cost/consumption
CF	cash flow
CHP	combined heat and power
CM	Cooling Medium
D-ICE	diesel internal combustion engine
EL	electric mode
EMS	energy management system
FC	fuel cell
GA	genetic algorithm
GC	grid connected
GWP	global warming potential
HP	heat pump
HS	heat source
ICE	internal combustion engine
IEA	International Energy Agency
k	scale factor
LCOE	Levelized Cost Of Electricity
LT	lifetime
MILP	mixed integer linear programming
MG	microgrid
ng	natural gas
NPV	net present value
OF	objective function
O&M	operation and maintenance
ORC	organic rankine cycle
P p	production
PV	photovoltaic
SA	stand-alone
SOC	state of charge
RES	renewable energy source
T	set of time steps, temperature
U	set of programmable units
WT	wind turbine

Subscripts/superscripts

c	cooling
el	electrical
i	generic unit
j	generic year
t	time step
th	thermal

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Published Journal Article available at: http://dx.doi.org/10.1016/j.apenergy.2016.02.051

1. Introduction

The limited access to electricity is one of the first reasons of poor life quality in rural contexts in developing countries. The availability of affordable and clean energy is a crucial task with the aim of achieving the Millennium Developing Goals [1]. In 2012 the International Energy Agency (IEA) [2] estimated that more than 1 billion people were living in villages without grid con-nection and so without the possibility to stock perishables, medici-nes and vaccines, to install a pump to draw water from a well or to purify water. The availability of electricity can dramatically increase the quality of life, allowing the reduction of the infant mortality and the transmission of diseases. Furthermore the lack of clean energy limits the opportunity for women and children who spend several hours daily harvesting wood or water for domestic purposes subtracting time to education or social and eco-nomic activities [3]. India is the country with the highest number of people without electricity access (288.8 million according to IEA [2]) and, although the Government has pursued important rural electrification policies in the past, there are regions where the electrification rate is still very low. This is the case of Bihar, a state of north east India where rural electrification rate does not exceed 35% [4]. In some cases the electrification can be easily obtained by an extension of the national grid, but in many rural contexts, characterized by sparse small villages, this solution results economically unfeasible because of the low reliability of the main grid and the very high investment cost related to grid extension, leading in conclusion to an extremely high Levelized Cost Of Electricity (LCOE) [5]. A solution commonly proposed in these contexts is the installation of a standalone microgrid (MG), not connected to the national grid and able to self-produce the required energy through the use of small size generators.

Diesel generators are the most common solution to power iso-lated MGs [5]. They are relatively inexpensive and capable to follow the variable grid demand. However, they take along several significant disadvantages: (i) diesel oil is expensive, especially in isolated locations, thus the cost of generated electricity is high,(ii) their emissions (NOx, CO, UHC, particulate matter) are harmful for inhabitants and, as all fossil fuels driven engines, they emit greenhouse gases. The addition of generators fed by renewable energy sources (RES) could support or either replace the electricity generation based on fossil fuels, thus alleviating or even removing the above mentioned disadvantages [6–8]. In sunny locations, a significant improvement to all these drawbacks can be achieved by adding a PV array to diesel generators [1,6,9]. Similar considerations are appropriate also for wind energy [10]. The non-programmability of these energy sources requires the adoption of an electric energy storage to properly dispatch energy but it entails charge/discharge losses and higher capital costs. On the other hand, the production of electricity (and heat when appropriate) is efficiently dispatchable when the primary energy source can be easily and economically stored as for biomass. Although wood biomass is abundant in vast regions of the world where there is a strong need of electricity and irrigation, in literature there are few studies analysing its application in MG for rural electrification. Buragohain et al. [11] performed a feasibility study regarding biomass gasification for decentralized power generation in India. The potential cost saving related to biomass integration in a standalone MG, evaluated using an approach not based on the simulation of real operation, is relevant and higher than that one related to intermittent RES. Similar results have been obtained by Montuori et al. [12], who evaluated the economic performance simulating the MG operation with a heuristic dispatch strategy. Final results show that biomass gasification is far more convenient than traditional supply by diesel generators. Ho et al. [13] proposed a design approach for a biomass-based MG. The optimal generator size is obtained using a mixed integer linear programming (MILP) model which takes into account weather variation and biomass availabil-ity. The biomass-based generators are present in the optimal solu-tion obtained for a specific test case, proving the competitiveness of these technologies.

Even if economic feasibility seems to be proven by the above-mentioned publications, the impact of a biomass-based generator in the real operation of a MG has not been investigated yet. In fact, biomass based generators are generally treated as perfectly dispatchable generators, omitting start-up and ramp constraints and/or part-load efficiency during the simulation. Considering that these constraints would deeply affect the operation using a heuristic strategy, in this work the operation of the MG is defined by an energy management system (EMS) which is the result of an optimization process based on forecasts. The optimal schedule is obtained using a MILP model which adopts a time-step of 10 min: in addition to fast fluctuations of power and loads, the reduced time-step allows to properly consider ramp constraints and units start-ups obtaining a more realistic behaviour of "slow" components as gasifiers and boilers. The increase in computation time related to a smaller time-step has been softened resorting to a rolling horizon approach with variable time-steps in the MILP problem [14] and simulating the MG operation for 15 days representative of the whole year. The methodology is then applied to a rural community in Bihar: in the case study, the EMS fulfils the demand of different goods (electricity, heating, cooling, potable water, irrigation) scheduling properly the available programmable units (water pumps, osmosis plant, heat pump, chiller and power generators).

The definition of the optimal MG design is faced exploring a predefined grid with the aim of understanding the effect of the size of each component on the final result. The value of the dispatchability is finally evaluated considering the impact of both biomass-based generators and PV panels on MG overall cost.

2. Biomass as electricity source

Biomass energy could play a relevant role in rural electrification in the next future. Considering only wood biomass and agricultural wastes, the worldwide potential is estimated to be 1.6×10^4 TW h/year [15]. The wood biomass source is rather uniformly spread over the world and it is abundant in main developing areas, as Sub-Saharan Africa, Latin America and Asia. Nowadays biomass covers ca. 15% of worldwide primary energy consumption; how-ever, a relevant part is still used inefficiently in developing coun-tries for cooking and heating. In most cases, an efficient usage of the biomass source could ensure clean energy access without increasing further exploitation. Furthermore, if compared with other RES technologies (i.e. PV, WT), biomass energy has a crucial property to offer in an off-grid system: the dispatchability. In fact, unlike solar and wind based power generators, the fuel can be stored and the generator produces electricity only when it is required. Due to the limited electricity demand in rural areas, it is not possible to install big size plants. Regards small-scale application, two are the most suitable power generation technologies: gasification with internal combustion engine and solid biomass combustion with ORC [16].

The first technology is nowadays the most common for rural electrification, in particular in India [11]. According to an IRENA report [17], 60 plants with downdraft gasifier (the most suitable configuration below 1 MW) have been installed around the country to power more than 250 rural communities. The working principle consists in two steps: (i) first in the gasifier a gaseous product (syngas) is formed by partial combustion of the biomass in a low oxygen environment, then (ii) the syngas feeds an ICE, which produces electricity and eventually low temperature heat. Usually a syngas cleaning system, composed by a cyclone, scrubbers and/or fabric filters, is placed between the gasifier and the engine to keep under control the pollutants emission and the quality of the syngas [18]. The overall energy conversion performance (considering only electricity) is about 20% [16], assuming typical values of efficiency for each component (65% for gasifier, 32% for a Otto based ICE). On the other hand, some drawbacks are related to the gasifier operations. In fact, the quality of the syngas produced can considerably change due to the feedstock composition and the operating condition, leading to frequent plant shutdowns, significant maintenance requirements and high wear of the ICE. For this reason, the generator will be affected by a reduced lifetime and higher O&M costs in comparison with fossil-fuel fed ones [19].

The ORC technology is the second option to exploit the bio-mass potential for the sustainable generation of electricity. The ORCs are based on a Rankine thermodynamic cycle where a suit-able organic fluid (refrigerant fluids, hydrocarbons or siloxanes) is used instead of water. The possibility to select the best working fluid depending on the heat source characteristics is the key factor of the success of ORC since it allows exploiting low temperatures and/or small available energy sources with high efficiency cycles and to design efficient expanders. Nowadays, ORCs are the best technical solution to exploit a large variety of energy sources like geothermal hot brines, waste heat recovery from industrial processes and biomass combustion. The interest in this latter application has been noticeably grown in last decades in north Europe where the abundance of cheap biomass and feed-in tariff mechanism (promoted to reduce carbon dioxide emis-sion) have favoured the installation of these kind of plants. Today, Turboden is overtly the market leader with more than 260 plants installed in Europe while other companies like GMK, Exergy and Adoratech are gaining a large share in recent years. The total installed power worldwide overpasses 350 MW with plant sizes ranging from 200 kW_{el} to 6500 kW_{el} [20]. Medium size (above 1 MW_{el}) biomass ORC is a proven technology with less technical issues than a Gasifier+ICE system: ORCs have a long operative life (20 years), low maintenance costs and high off-design performances making them a promising solution for remote applica-tions like rural electrification; in addition the biomass boiler is a component less critical than a gasifier without plugging issues and a more stable operation varying the biomass composition. Three main components are present in a biomass ORC power plant: (i) the burner where the biomass combustion takes place,(ii) the heat transfer fluid loop which transfers heat from the furnace to the thermodynamic cycle and (iii) ORC engine.

In spite of the increasing interest in biomass field, only few commercial ORC packages are available on the market for a power between of 25–100 kW_{el} mainly because of the difficulties in designing and producing small expanders while reaching high working temperatures. The list of the five main manufacturers of ORCs in a range between 30 kW and 300 kW suitable for biomass application is reported in Table 1 with the main information obtainable from public datasheets. Besides these companies many others are present on the market (Weiss gmbh, GMK, Adoratec, etc.) but they are not considered for this study because of the lack of thorough public datasheet or referenced operative installations. Most of these cycles work at low temperature with hot or pressurized water as heat transfer fluid and they consequently show poor electrical efficiency; a substantial increase of performance can be obtained using saturated steam or hot thermal oil. The expander is the key component of an ORC and for small power application different solutions are explored: Electratherm bases its cycle on a twin screw expander which is a robust, low cost and slow volumetric machine with the drawback of a limited built in volume ratio, while the other competitors are oriented on 50 Hz axial turbines (Turboden), or high rotational speed single stage radial inflow turbines with magnetic bearing, fast generator and power electronic system for frequency control. Despite of the differences in the heat source characteristics, the expander type and the operation mode all the commercial packages show a similar second law efficiency (values range between 39% and 56%) when compared with the so-called "Lorentz efficiency". This parameter represents the maximum efficiency attainable with a chain of reversible processes for a cycle working with a variable temperature heat source and a constant temperature heat sink: an average value equal to 44.6% is assumed as representative of this technology and it is used to evaluate the performance of the generic ORC for this study. As reported in last row of Table 1, the ORC is fed by a thermal oil loop at high temperature and condenses at low temperature releasing heat to the cooling water; the resulting efficiency is 20% in pure electric generation mode while a decrement of 4 percentage points is considered when the cycle is operated in CHP mode because of higher condensing temperature and the lower expander efficiency in off-design conditions. The detailed design of the ORC, the choice of the working fluid and the project of the expander is beyond the scope of this study but in authors' experience it is reasonable to consider a medium high complexity fluid (HFC or light siloxane) as working fluid and a single or two stages radial inflow turbine at high rotational speed as expander.

Table 1
Summary of main characteristics of commercial small-scale ORCs (50–250 kW_{el}) obtained from public datasheets. Where data are not available Lorentz efficiency coincides with Carnot efficiency.

	Model	Operation mode	Installed biomass plants power (number)	Q_{in} (kW)	W_{net} (kW)	T_{in} HS (°C)	T_{out} HS (°C)	T_{in} CM (°C)	η_{net}	η_L	η_{II}	Heat source	Expander type	RPM
Electra therm	4200	CHP	46 kW (1)	650	35	116	n/a	65	5.4%	13.1%	41.0%	Pressurized water	Twin screw	3000
	4400	CHP		880	65	116	n/a		7.4%	13.1%	56.2%			
	6500	CHP		1600	110	122	n/a		6.9%	14.5%	47.5%			
Turboden	Turb 2	EL	200 kW (6)	1234	188	200	181	35	15.2%	33.6%	45.4%	SS 16 bar	Axial turbine	3000
	Turb 2	CHP		1624	178	226	209	75	11.0%	29.1%	37.7%	SS 26 bar		
	Turb 3	EL		1708	282	220	201	35	16.5%	36.3%	45.5%	SS 23 bar		
	Turb 3	CHP		1971	274	234	216	55	13.9%	34.1%	40.7%	SS 30 bar		
	Turb 3	CHP		1817	280	310	221	60	15.4%	38.0%	40.5%	Thermal oil		
	Turb 3	CHP		1835	277	310	227	75	15.1%	35.6%	42.4%			
Zuccato	30 UHT	EL	50 kW (1)	350	30	94	86	26	8.6%	17.7%	48.5%	Hot water	Radial turbine	15,000
	40 UHT	EL		450	40				8.9%	17.7%	50.3%			
	50 UHT	EL		550	50				9.1%	17.7%	51.5%			
	100 LT	EL	100 kW (1)	850	100	160	140	26	11.8%	29.3%	40.1%	Pressurized water		
	150 LT	EL		1100	150	155	135		13.6%	28.5%	47.9%			
TriOgen		EL/CHP	124 kW (1) 130 kW (2) 160 kW (1)	900	165	350	250	35	18.3%	39.08%	39.7%	Any hot source	Radial turbine (high Vr)	18,000–28,000
Progeco	Clean cycle	EL	125 kW (5)	1000	125	150	n/a	15	12.5%	31.9%	39.1%	Any hot source	Radial turbine	54,000
Assumptions for this study		EL CHP	–	–		320	200	20 30	20% 16%	44.7% –	44.6% –	Thermal oil	Radial turbine	High speed

Table 2
Climatic data of Patna district, India.

		Winter			Pre-monsoon			Monsoon				Post-monsoon	
		December	January	February	March	April	May	June	July	August	September	October	November
Minimum temperature average	°C	10	9	12	17	22	25	27	26	26	26	22	15
Maximum temperature average	°C	24	22	26	32	37	38	36	33	33	33	32	29
Rainfall	mm/day	7.4	11.5	16.4	7.5	15.8	41.9	185.5	339.3	259.3	241.6	39.2	17.1
Global radiation on tilted surface (25°)	kW h/m^2/day	5.3	5.06	6.24	7.12	6.87	6.37	5.15	4.5	4.86	5.07	5.79	6.17

3. Case study

The case study analysed in this work is a rural village of 2000 inhabitants located in Patna district in the state of Bihar, India. Despite of being one the fastest growing district of India, the rural area still suffers the lack of a reliable electricity access since 33.5%of villages are not electrified [4]. A summary of the environmental and weather conditions of the village location, a description of the needs of the community and the proposed MG architectures are reported in following sections.

3.1. Climatic condition

Bihar is characterized by a humid subtropical climate and average meteorological data are reported in Table 2. Three main periods can be detected during the year: (i) the monsoon season, with high temperature, abundant rainfall and lowest solar potential (from June to September); (ii) the winter, with low temperature, dry climate and medium solar potential (from December to February); (iii) the pre-monsoon and the post-monsoon seasons, with high temperature, low rainfalls and the highest solar potential (from March to May and from October to November).

The feasibility of generators based on intermittent RES, as sun and wind, is strictly related to the potential of the source. The wind potential in this region is very low [21] and consequently wind turbine technology will not be taken into account in this work. On the other hand, the solar potential in the region is noticeable. According to NASA database, the yearly average potential is around 5.7 kW h/m^2/day with high average daily radiation during the whole year and the lowest values during the monsoon season because of the frequent presence of clouds.

3.2. Needs of the community

The community taken into account is formed by 400 private households, one healthcare centre, one school and some little business activities. Differently from the majority of the studies conducted for rural electrification, we do not consider only electrical loads but we face the problem taking into account all the needs of the community. One of the most important advantages of this approach is the possibility to decouple the production and the consumption of different goods with storage systems more economic than electrical batteries. In addition, the capability to shift in time the usage of different units may allow a further reduction of operating cost [22,23].

The daily demand of the different goods consumed by the final users is reported in Table 3 for each period. The demand of each good is considered as non-deferrable and it is always satisfied by

Table 3
Average daily consumption of different goods by the case study community.

Good		End-user	Monsoon	Winter	Pre/post monsoon
Electricity	kW h_{el}	Households		487.6	
		Public lighting		298.8	
		Business act		301.3	
		Hospital		367.0	
		School		192.8	
		Total		1647.4	
Ground water	m^3	Irrigation	3805.5	2609.2	2171.4
Cold potable water	m^3	Households		170.0	
		Business act		10.0	
		Hospital		12.0	
		School		9.6	
		Total		201.6	
Hot potable water	m^3	Hospital		7.8	
		School		1.4	
		Total		9.2	
Heating	kW h_{th}	Hospital	0.0	889.8	0.0
		School	0.0	275.1	0.0
		Total	0.0	1164.9	0.0
Cooling	kW h_c	Hospital	1392.2	0.0	910.2
		School	481.2	0.0	314.5
		Total	1873.5	0.0	1224.7

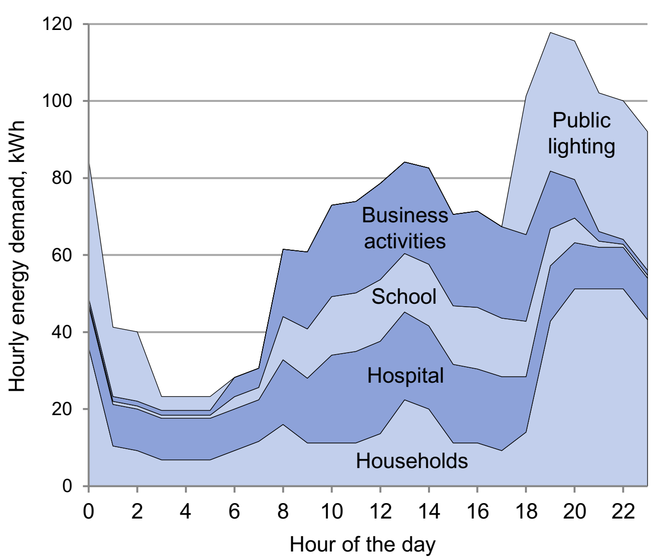

Fig. 1. AC consumption daily pattern (week day).

means of the contextual production and/or the discharge of the relative storage. In addition, some of these goods can be consumed by dedicated units to produce other goods: an example is an osmosis plant which consumes ground water and electricity to produce cold potable water.

The average daily pattern of the AC directly consumed by final users is reported in Fig. 2 and it is assumed constant during the whole year. In average each household is equipped with 4 low power lamps (cfl), 1 radio and 1 television. The school consumption is limited to diurnal hours, as well as the business activities load, while public lights are switched on during nocturnal hours. The hospital, which operates the whole day has a peak of electricity consumption during diurnal hours. During weekend the school and the business activities consumption is set equal to zero.

The main activity of the community is agriculture which requires a large amount of water to ensure the highest field productivity [24]. The water demand for agriculture (60 hectares in this case) in the different periods of the year has been evaluated with Blaney–Criddle equation [25], assuming a yearly rotation of three different crops (rice, wheat, vegetables): a part of this water need is obtained by rainfall (see Table 2), while the rest is extracted by pumps from a 10 m depth groundwater basin.

In addition to ground water and electricity consumption, the public and private users consume potable water while the two public buildings (i.e. the school and the hospital) demand for air-conditioning (fan coil units are used for both heating and cooling depending on the season) and hot water.

3.3. Microgrid architectures

The base layout of the MG is shown in the right side of Fig. 2: it consists of different subsystems (one for each good) connected by multi-input/multi-output units. The AC bus is connected to the diesel ICE and it provides electricity to the domestic and the public users appliances (i.e. household, hospital, school and business activities), to the public lighting and to all the other electrical devices required for the operation of the MG units. The AC bus exchange electricity through an inverter with the DC bus which is connected with the electric storage (a lead acid battery) and polycrystalline PV panels. Ground water is pumped from the well in a non-potable water tank and used mainly for irrigation and for potable water production which is obtained with an osmosis process, consuming AC electricity. The potable cold water (20 °C) is then stored in vessels and it is consumed by domestic and public users. In addition it can be heated up to produce sanitized hot water at 60 °C: the heat required is obtained from the high temperature stream of the cogenerative ICE or it is released by a Heat Pump (HP). The low-medium temperature storage consists of two water vessels at 45 °C and 35 °C respectively and it is used in the fan coil units for the heating of the school and the hospital. The ICE low temperature cogenerative heat can be used to store energy at medium temperature as well. Except for the winter season the two public buildings needs for air cooling and a chiller is used releasing heat to the ground water storage.

Finally the possibility to add a biomass dispatchable power generator to the genset is investigated. The two solutions here proposed are represented in the left side of Fig. 2: the first one (A) is a boiler coupled with an Organic Rankine cycle (ORC), the second one (B) is a down-draft gasifier coupled with a cogenerative ICE. In both cases a chipper, powered by the AC bus, is used to chop the wood down to the size required by the gasifier unit and the biomass furnace. The gasifier and the ICE operate like a single unit because it is assumed that syngas cannot be stored. On the other hand, oil storage is considered and thus the operation of the bio-mass boiler is decoupled from the ORC one. The ORC can operate in two modes: in pure electric production mode, it condenses at low pressure releasing heat to the ground water tank; in cogener-ation mode it condenses at higher temperature storing heat in the medium temperature water tank.

All the assumptions related to the programmable loads are reported in Table 4 while the nominal and off-design performance of the programmable generators and the battery are represented in Fig. 3. Nominal biomass boiler efficiency is equal to 88% based on LHV value [26] while a fixed efficiency equal to 94% is assumed for the inverter. Finally, the properties of the different goods are reported in Table 5. The Oil-Heat and the woodchips storage sizes are expressed with the time span of nominal utilization while the cooling storage represents the building inertia.

4. Problem resolution

The definition of the optimal set of generators to be installed in a standalone MG is a challenging mathematical problem which can

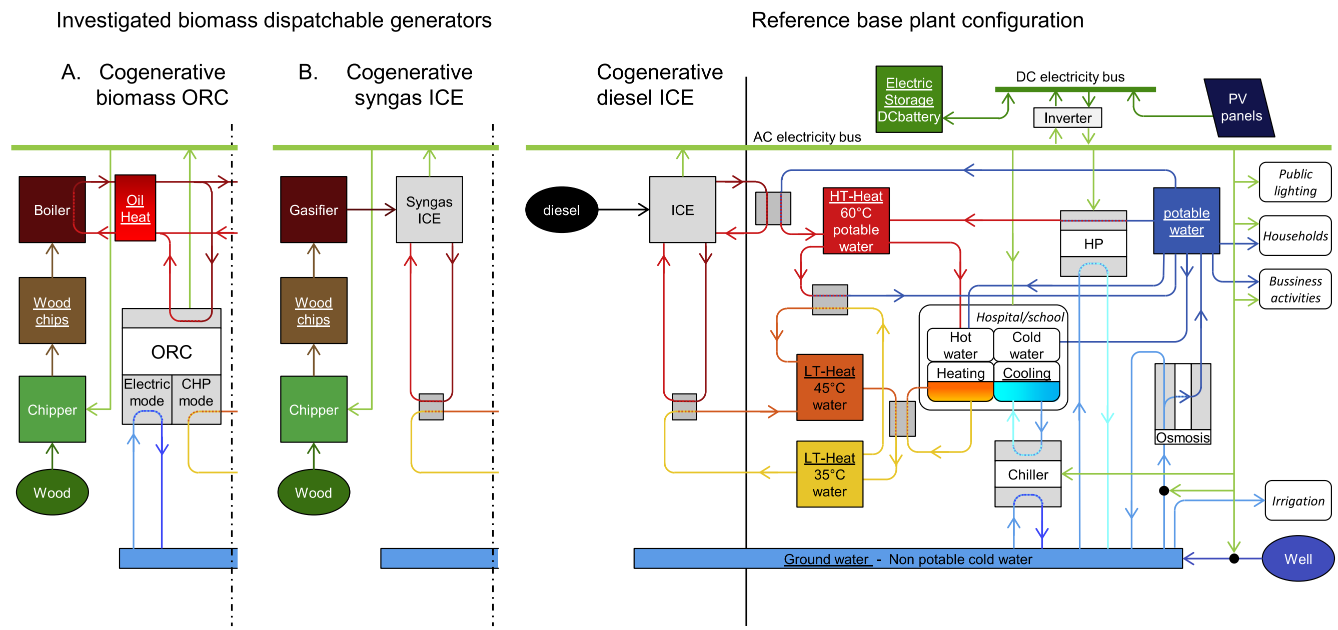

Fig. 2. Schematic representation of the three MG architectures considered in the simulations.

Table 4
Main properties of the schedulable loads.

UNIT	Produced good	Nominal output		Off-design limit (% nominal output)	Consumed good	Consumption		
						@pmin	@pmax	
Water pump	Ground water	259	m^3/h	0.0%	AC	0	30	kW
Osmosis plant	Potable water	14	m^3/h	25.0%	AC	3.75	15	kW
					Ground water	3.85	15.4	m^3/h
Chipper	Woodchips	500	kg/h	No off-design	AC	6.25		kW
Heat pump	HT-Heat	14	kW	21.4%	AC	0.68	3.42	kW
Chiller	Cold	178	kW	10.1%	AC	4.95	24.80	kW

be generally divided in two hierarchical steps as reported in Fig. 4: at the outer level different MG solutions are investigated selecting the best one on the basis of a certain figure of merit. At the inner level the figure of merit for each configuration is calculated simulating the MG operation over a period of time and defining the management of all the schedulable units, generators as well as loads. Both sub-problems can be faced with a heuristic/enumerative approach or using an effective optimization algorithm. The solving procedure for the inner problem is the most difficult and a dedicated tool is required to consider all the multiple information about the climate data and weather forecast, the community needs and the operational constraints of the schedulable units. A lack in accuracy in the solution of the inner problem or the use of simplified assumptions directly affects the outer optimization problem leading to a selection of MG design far from the best one.

This topic has been receiving an increasing attention as proven by the relevant number of scientific studies published in recent years: a summary of the features and the contents of a selected list of recent papers is reported in Table 6. The publications consider both grid connected (GC) and standalone (SA) microgrids and the goal is generally to minimize the cost of the electricity (LCOE) generated or to maximise the NPV of the investment. In some cases, other objective functions are considered with the aim of reducing the pollutants and/or greenhouse gases emission or maximising the fraction of energy produced by RES. HOMER (Hybrid Optimisa-tion Model for Electric Renewables) is without doubt the most used software in this field of research [27] and a relevant number of recent works on design and operation of independent MGs were carried out using this tool [9,12,28,29]. This software, developed by NREL since 1995, allows simulating MGs with various genset configurations over a one year of operation by adopting a limited number of fixed heuristic dispatch strategies (i.e. Load Following and Cycle Charging) [30] and so without a real optimization of the MG management at the inner level problem. A similar approach was followed by Dufo-Lopez et al. [7] and Zhao et al. [8] with the definition of new control strategies applied to a MG located in Zaragoza and in Dongfushan Island respectively. Substantial improvements in terms of cost of energy reduction can be obtained with an optimization of the MG management [23]: this approach was followed by Wouters et al. [31] and Zhang et al. [32] who modelled the inner problem as a Unit commitment problem. Differently, Fossati et al. [33] defined the operating strategy of the programmable generators and the energy storage by fuzzy rules set by means of a GA while in Kyriakarakos et al. [34] the simulations were carried out with TRNSYS for the management of hybrid MG in a remote area. If any schedulable units are present in the grid (i.e. Ma et al. [10] and Shadmand and Balog [35]) the units operation is univocally defined and any management strategy is required. Among these approaches the unit commitment is the most powerful since it can easily handle various schedulable loads and multi-good systems while considering operational constraints and forecast on power production and consumption.

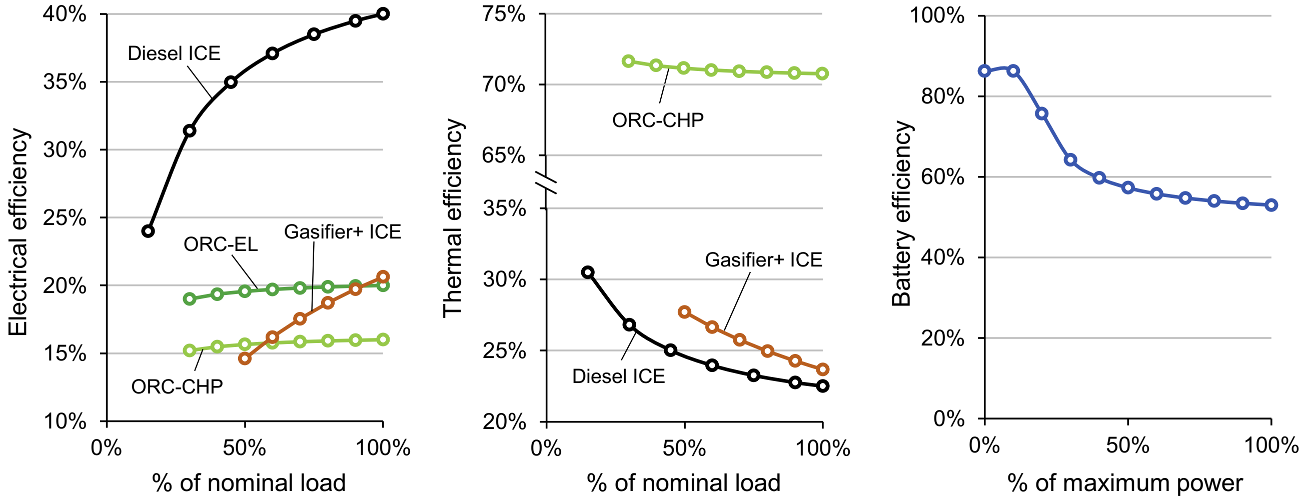

Fig. 3. Electrical and thermal efficiency for the programmable generators and battery efficiency.

Table 5
Properties of the goods and the storage systems present in the MG.

Good		Storage	Size	Self discharge (%)
AC	kW h	No	–	–
DC	kW h	Yes	Variable	0
Ground water	m^3	Yes	600	0
Potable water	m^3	Yes	100	0
LT-Heat	kW h	Yes	150	1
HT-Heat	kW h	Yes	100	1
Oil-Heat	min	Yes	20	2
Cooling	kW h	Yes	10	1
Woodchips	h	Yes	18	0

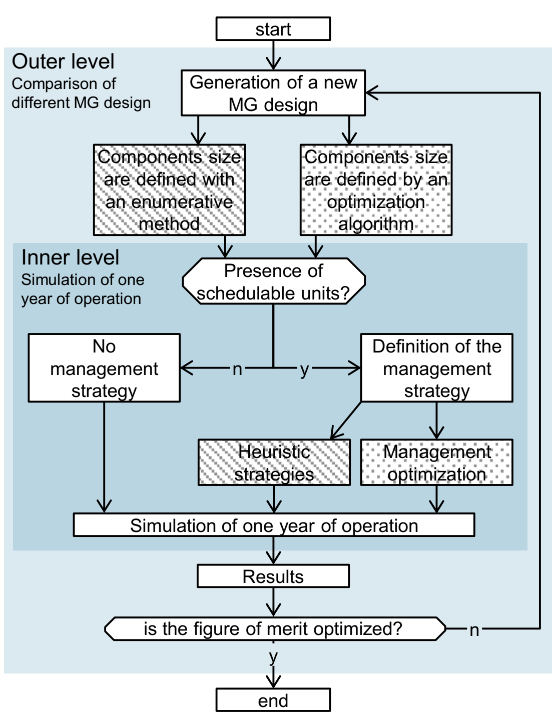

Fig. 4. Representation of the two levels scheme for the definition of the optimal microgrid design: dotted rectangles require the use of an optimization algorithm, line shaded ones the use of a heuristic/enumerative approach.

The outer problem instead is less critical and it can be faced by means of an optimization algorithm or by exploring a multidimensional grid obtained by the combination of discrete sizes of the generators and the storage system. The only exception is the work of Wouters et al. [31] where the optimal size of a generic CHP and the MG management are defined at the same hierarchical level.

4.1. Yearly simulation – optimal microgrid management definition (inner problem)

The techno-economic performance of a MG is strictly related to the way it is managed. Simulating the MG over a certain time span is the key factor to assess its operating costs, which are a relevant part of the overall cost of the system.

The simulations performed on this work are based on a mathematical model developed to ensure the most cost-effective management of a MG with different goods involved. As demonstrated in a previous work [23], this kind of approach has two main advantages: (i) a relevant saving can be reached in comparison with commonly adopted heuristic dispatch strategies and (ii) the management of complex systems with different goods can be handled with a very general formulation of the problem.

The model is based on a Unit Commitment problem, applied to a system where the demand of the different goods must be fulfilled in each time step. The schedule of each programmable unit is obtained solving a MILP problem with the aim of minimizing the overall variable cost of operation *OF*:

$$OF = \sum_{t \in T} \sum_{i \in U} \left[c_{t,i}^{fuel} + c_{t,i}^{O\&M} + c_{t,i}^{start\text{-}up} \right] + c_t^{wear} \quad (1)$$

where T is the set of time steps, U is the set of programmable units and c is the cost related to fuel consumption, variable O&M and start-ups. A monetary cost associated to the battery usage (*wear*) is considered as well. A referenced Ah aging model has been used to determine the wear cost of the battery in each time step as a function of the energy exchanged and its State of Charge (SOC) [36]. The objective function includes only monetary costs, but the balance of the different goods in the MG is implicitly considered with different sets of constraints. Similarly, technical operating constraints of the units (as ramps) or the level of the storages are described by additional equality constraints (see [23] for the extensive formulation). Diesel oil cost is assumed equal to 1 USD/litre considering local price and transportation, while the biomass cost is set equal 50 USD/ton.

Table 6
Summary of the recent publications on microgrid design optimization.

	Grid type	Yearly simulation inner problem		MG design outer problem		Energy source	Goods	Units		Storage
		Management strategy	Time step	Objective function	Solver			Schedulable	Not schedulable	
Montuori et al. [12]	GC/ SA					Diesel, NG, biomass	Electricity	Syngas ICE, diesel ICE, demand response	–	–
Patterson et al. [28]	SA	Predefined strategies (HOMER)	1 h	NPV	-NO- Parametric grid	Solar	Electricity heat	Electric vehicle, FC	PV	Battery hydrogen
Tao et al. [29]	SA					Wind, solar	Electricity	–	PV, WT	Battery
Castellanos et al. [9]	SA					Biogas, solar	Electricity	ICE, FC, electrolyzer	PV	Biogas, REDOX battery, Hydrogen
Dufo-Lopez et al. [7]	SA	Predefined strategies	1 h	LCOE GWP Pollutants	GA	Solar, wind, diesel	Electricity	ICE	PV, WT	Lead-acid
Zhao et al. [8]	SA	Predefined strategies	1 h	Cost %RES Pollutants	GA	Solar, wind, diesel	Electricity	ICE, seawater desalinator	PV, WT	Lead-acid, potable water
Wouters et al. [31]	GC/ SA	Unit Commitment	1 h	LCOE	MILP	Solar, wind, NG	Electricity, heat, cooling	Generic CHP	PV, WT	Battery
Zhang et al. [32]	GC	Unit Commitment	1 h	LCOE GWP	ε-method	NG	Electricity, heat, cooling	FC, ICE, stirling	–	Thermal storage
Fossati et al. [33]	GC	Unit commitment	1 h	LCOE	GA	Wind, diesel, NG	Electricity	FC, ICE, MT	WT	Lead-acid
Kyriakarakos et al. [34]	SA	TRNSYS	1 h	LCOE	PSO	Wind, solar	Electricity, hydrogen, potable water	FC, electrolyzer	PV, WT	Battery, hydrogen
Shadmad and Balog [35]	GC	Not required	10 s	LCOE	NSGA-II	Wind, solar	Electricity	–	PV, WT	Battery
Ma et al. [10]	SA	Not required	1 h	LCOE	GA	Wind, solar	Electricity	–	PV, WT	Pumped water

The actual management of the MG is obtained using a rolling horizon strategy and solving a MILP problem. The optimal schedule is followed just for 1 time-step; then, the forecasts of the production and the consumption of the different goods are updated, and the problem is solved again with the advantage of softening the impact of forecast uncertainties. The length of the time step is a parameter of great influence and a 1-h time-step is the common assumption for most of the studies in literature. In this work the simulations are carried out with a 10 min time-step with the advantage of catching the intermittent RES power fluctuations and the events which happen in a short time scale (i.e. units start-ups) but with the drawback of a dramatic increase of problem complexity and computational time. For this reason, a variable time step is used in this case to cover the whole time horizon, with the goal to exploit the beneficial effect of a fine time discretization with a satisfactory computational time [14]. A schematic represen-tation of the rolling-horizon with variable time-step used in this work is reported in Fig. 5. The time-step is progressively increased from 10 min to 4 h, covering a time horizon of 18 h in 16 time-steps with a limited computational time effort. As result, the near future is described with high accuracy while the farthest forecasts which are affected by a higher inaccuracy, are taken into account in an aggregate form. In spite of the adoption of a shorter time step, the results obtained by this approach cannot detect fluctuations below 10 min and regulations related to power quality, which would require a time-step around 1 s or less, are neglected in the simulation and are taken into account with an operating reserve constraints in the MILP problem [23].

In Fig. 6 a single day of simulation is represented for two MG configurations to highlight the capability of this approach in modelling fast fluctuations of generated and consumed power. A PV system (150 kW), a diesel ICE (200 kW) and a battery (200 kW h) are installed in both configurations. In the second one, a 100 kW biomass Gasifier+ICE is added to limit fossil fuel consumption. The fixed load follows the average profile in Fig. 1 but a consider-ably random fluctuation is added to catch a realistic trend of power

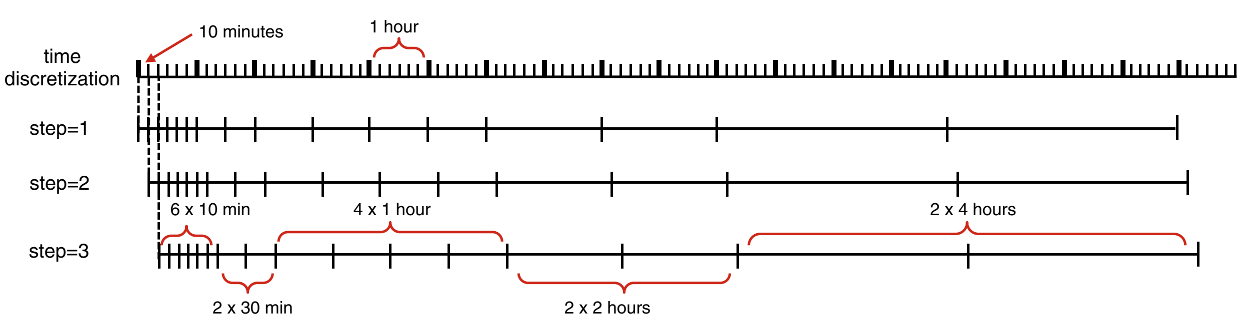

Fig. 5. Scheme of the rolling horizon variable time step discretization used in this work.

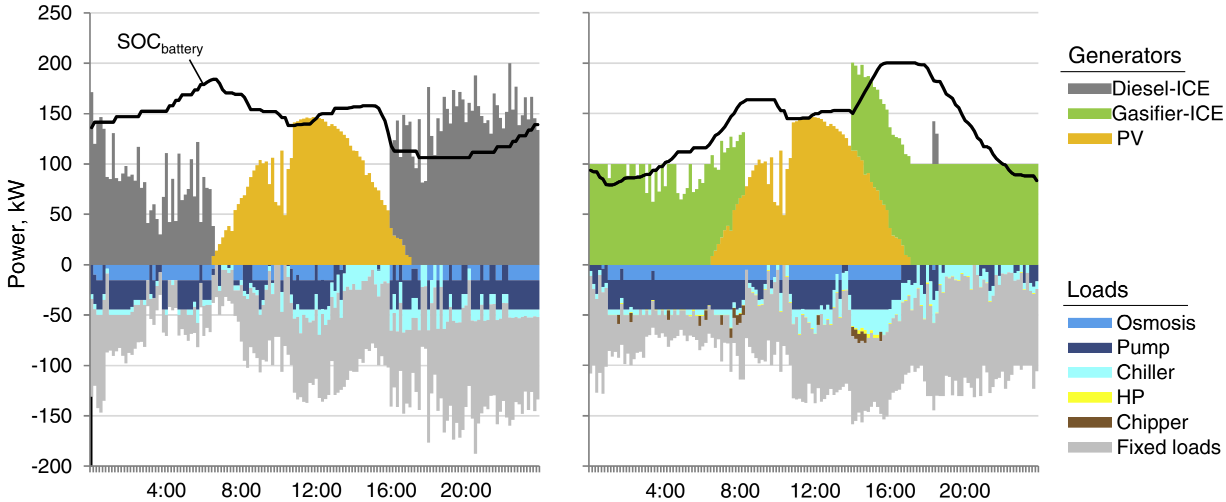

Fig. 6. Single day simulation with 10 min time step for two different MG configurations. (left) MG based on diesel-ICE and (right) MG provided with a biomass gasifier-ICE.

demand; PV production is not regular as well and a marked cloud passage can be noticed in the morning. In both cases the schedule of both the programmable loads and the dispatchable generators is defined by the EMS. The diesel engine mostly works in load following since it can cover the load peak by itself and it has a larger operation range compared to the gasifier system; as result the use of the battery is limited with small variation of the SOC level. On the contrary, the biomass based generator needs to run a higher number of hours storing energy into the battery in order to face the night power demand. In spite of this, the diesel engine must operate for 30 min around 19 pm to assist the gasifier. Another difference is related to the scheduling of the programmable loads: in the first case they are scheduled almost homogenously during the whole day to limit the off-design of the diesel engine and the wear of the battery during the central hours of the day; in the second case, they are mainly placed during the first eight hours of the day (when the fixed load is low) with the aim to run the gasifier close to the nominal condition. The programmable loads are not scheduled in the night to reduce the use of the diesel engine with economic and environmental advantages.

Although the application of variable time-steps considerably reduces the computational time, the resolution the MILP problem requires in average 1 s to determinate the optimal MG operation for the consecutive 10 min. The simulation of an entire year of operation (365 days) would need more than 10 h: a computational time effort that is not compatible with the objective of this work, which is the testing of a relevant number of MG configurations in order to find the most promising one. A representative year, made by 15 days has been defined to overcome this problem. As mentioned in previous chapter, the whole year has been split in three periods, representative of monsoon season, the dry winter and the intermediate seasons (pre and post monsoon). For each period the trends of the goods demand and of the solar radiation for 5 days have been created respecting the average values of each period. According to our results, 5 days is a good compromise between the good representation of the year (fluctuations of the goods demand and the sun radiation) and a relatively short simulated time span.

The operating cost over one year (C^{opex}) must take into account the availability of the components. During the year, the biomass-based generators are expected to be out of order for a certain number of days for scheduled maintenance and unpredictable failures: in these days the diesel ICE generator is used intensively to support the system and prevent power shortages. This additional operating cost is evaluated simulating the same system configuration (PV size, battery size) and assuming that the biomass-based generator is not available. We assumed an availability equal to 95% and 90% for ORC-based and Gasifier-based systems respectively since this parameter is in general higher for biomass combustion technologies in comparison with gasification ones [37].

4.2. Microgrid design – optimal genset definition (outer problem)

The LCOE is selected in this work as figure of merit to compare the economic performance of different MG configurations. This index, which is the average cost per kW h of useful electrical energy, includes both the operating and the capital costs, and helps to compare different configurations from an economic point of view. The LCOE is evaluated applying the cash flow method for the whole lifetime of the project (25 years). For the j-th year, the cash flow (CF) includes:

$$CF_j = \sum_{i \in U} \left[C_i^{inv} + C_i^{O\&M} \right] + C^{opex} \qquad (2)$$

where C_i^{inv} is the investment cost (equal to zero if in the jth year the unit i is not replaced), $C_i^{O\&M}$ is the fixed O&M cost of the unit i and C^{opex} is the operating cost evaluated by the yearly simulation. The assumptions at the base of this approach are that operation costs are constant during the whole lifetime of the project; this requires that performance decay of the units is not considered and that the goods demand is constant, as well as the fuel price and the O&M cost. For the discounted cash flow analysis, a discount rate of 9%has been chosen.

The economic assumptions for each component are reported in Table 7 as well as the life span. These data are mainly related to international manufacturers and retailers. Most of them have been obtained by public retail websites (internal combustion engines, lead-acid battery, PV and inverter) while the cost and the life span of the ORC system has been obtained by private communications with a world leading company in the sector. The only exception is the gasifier system, whose assumptions are related to the Indian context and supported by two references already cited in Section 2 [17,19]. Regarding O&M, the data about regular maintenance and the labour hours have been obtained by the above mentioned sources as well. The effect of the size on the investment cost is accounted with the exponential law in Eq. (3) [38] where the k coefficient (always smaller than 1) depends on the component

Table 7
Economic assumptions on the power generators and the energy storage (nominal size 100 kW).

	C^{inv}_{nom} USD	Scale factor (k) –	Fixed O&M USD/year	LT year
Diesel ICE	20,000	–	5000	10
PV	120,000	0.9	1120	15
Gasifier+ICE	180,000	0.7	18,000	8
Boiler+ORC	500,000	0.7	12,000	15
Lead-acid battery	19,000	0.9	380	10
Inverter	25,000	0.9	400	15

type: PV panels are modular and so a exponent equal to 0.9 is assumed while a lower value is adopted for Boiler+ORC and Gasifier+ICE because of the favourable scale economies. The nominal size for each unit is equal to 100 kW.

$$C_i^{inv} = C_{nom}^{inv}\left(\frac{size_i}{size_{nom}}\right)^k \tag{3}$$

The only exception is the lead-acid battery, whose lifetime (LT) strongly depends on the way it is operated as explained by Ah aging model. The battery LT is at maximum 10 years unless the wear prematurely depletes the capacity of the battery to store energy as reported in the following equation:

$$LT^{battery} = \min\left(10; \frac{C^{inv}_{battery}}{\sum c_t^{wear}}\right) \tag{4}$$

5. Results

In this study the research of the best MG design is realized with an enumerative approach instead of using an optimization algorithm in order to better describe the influence of the different variables on the final result. The size of the resulting multidimensional grid depends on both the MG configurations and the number of discrete sizes for each component. Three different cases are investigated: (i) the reference case with Diesel and PV, and two other configurations with the addition of (ii) a biomass boiler+ORC and a (iii) a gasifier+ICE. The size of the diesel ICE is equal to 200 kW for all the simulations since it must be able to cover the grid peak load by itself. The size of the PV ranges from 0 to 400 kW, battery from 0 to 500 kW h while ORC and Gasifier+ICE vary between 0 and 150 kW: a discrete step of 25 kW is assumed for the biomass-based generator size and 50 kW for PV and battery size.

All the simulations have been performed by an i5 2.6 GHz desktop computer with 8 GB RAM, using Gurobi as solver for MILP problems. Each step of the rolling horizon strategy requires in average 1 s. The computational time generally increases in the ORC cases, because of the presence of an additional good (oil-heat). However, because in real management the problem is solved only once every 10 min, the computational time is fully compatible with practical implementation.

5.1. Integration of PV plant

In this section the integration of a PV plant in a MG provided with a diesel ICE is investigated. The aim is to understand the effects of the presence of a non-programmable renewable energy generator in terms of MG operation and system economics. The specific cost of the energy generated by PV, omitting the energy storage system, is considerably lower than the Diesel one and hence, this solution can lead to a substantial reduction of LCOE although it entails the use of a battery system. The contour map in Fig. 7a shows the LCOE attainable by varying the size of the PV plant and the storage. It is possible to point out that the optimal battery size changes depending on the PV system; for small PV nominal power, battery is not required and the intermittent PV power is handled by a proper scheduling of both the programmable loads and the diesel engine. On the contrary, for a PV nominal power greater than 100 kW the use of a battery is mandatory to store the surplus of energy generated in the central hours of the day and to avoid energy dumping. The black line represents the locus of minimum LCOE varying the size of the PV plant and the detailed economic results for these cases are reported in Fig. 7b. Each group of stacked bars represents the LCOE breakup for a given PV size and optimal battery size: investment and operational costs are further divided in the contribution for each unit. A MG simply provided with a diesel ICE shows a very small investment and small O&M costs, but very high operational cost due to the use of an expensive fossil fuel (more than 95% of the LCOE). As result the LCOE is high, reaching a value of 295.1 USD/MW h. The introduction of a PV plant entails from one side a strong increase of the investment cost, mainly due to the PV panels followed by the inverter and the battery, and a slight increase of the maintenance

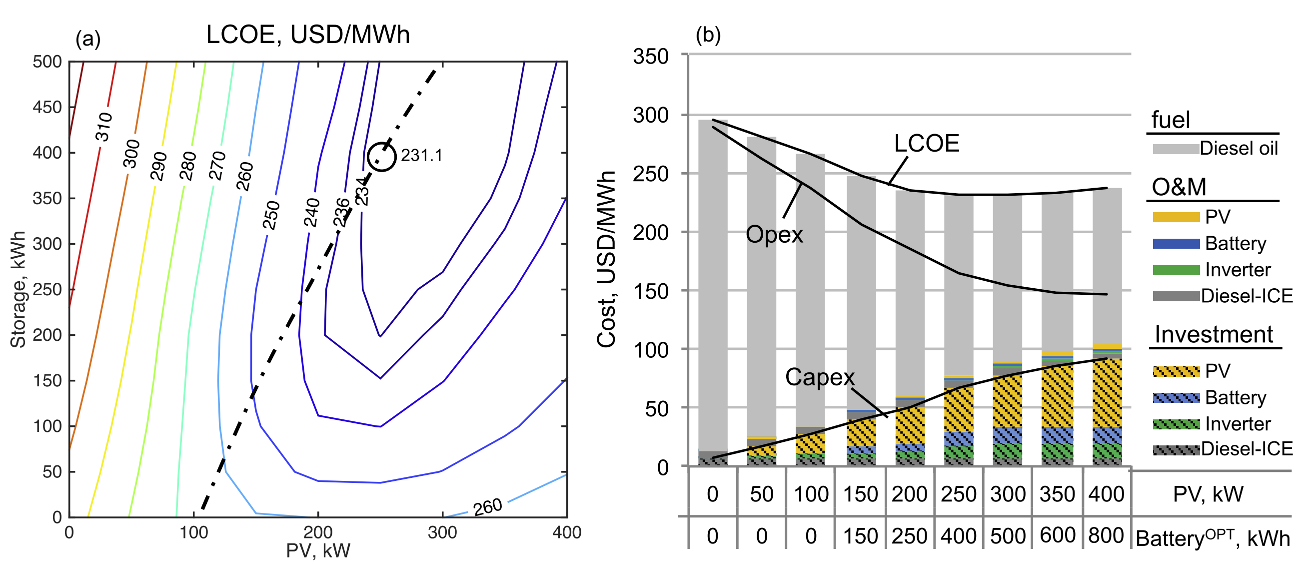

Fig. 7. LCOE results for Diesel+PV system; (a) LCOE map in function of PV and battery size and (b) breakup of LCOE varying PV size with optimal battery size.

costs. On the other side, the power production from a RES allows to reduce the consumption of fossil fuel with a relevant reduction of Opex cost. The trade-off between these two opposite effects leads to a minimum LCOE of 231.1 USD/MW h (−21.7% respect to the only-ICE case) for a 250 kW PV and 400 kW h battery. A further increase of the PV size allows for a less marked reduction of fossil fuel savings because the diesel engine works anyway a relevant number of hours following the load and limiting the use of the battery. The RES penetration increases almost proportionally with the PV size reaching a value of 46% for the optimal case.

5.2. Integration of biomass based generators

In this section the use of a biomass based generator is investigated with the aim to further reduce fossil fuel consumption and to increase the electricity generation by RES. Two biomass-based systems are compared: (i) a gasifier+syngas ICE and (ii) a biomass boiler+ORC. Their specific investment cost are remarkably higher than PV because the more complex system architecture and their relatively small present market. However, the dispatchability of these units can play a relevant role in the reduction of LCOE, partially substituting the diesel ICE in the role of base generator. Fig. 8a and c shows the trend of LCOE for the gasifier systems and the ORC respectively, varying the size of the biomass based generator and the PV plant; in each point the size of the battery is optimized. The two LCOE maps are very similar for the two cases (Gasifier system is in average cheaper of less than 5 USD/MW h) and common considerations can be addressed observing the trend of the minimum LCOE (dotted black line). Increasing the size of the biomass generator, the optimal size of the PV plant and the battery decreases because the use of a reasonably priced programmable generator allows for an easier MG management without the necessity to adopt big capacity storage. PV is detrimental for big size (150 kW) biomass generators while a small battery is always recommended. In Fig. 8b and d the LCOE breakup is reported for both cases. It is possible to note that the total investment cost is almost constant because the cost of the biomass generator is compensated by a reduction of PV plant size. Opex cost instead shows a minimum because for big size biomass based generators the higher investment cost is not repaid due to the limited number of

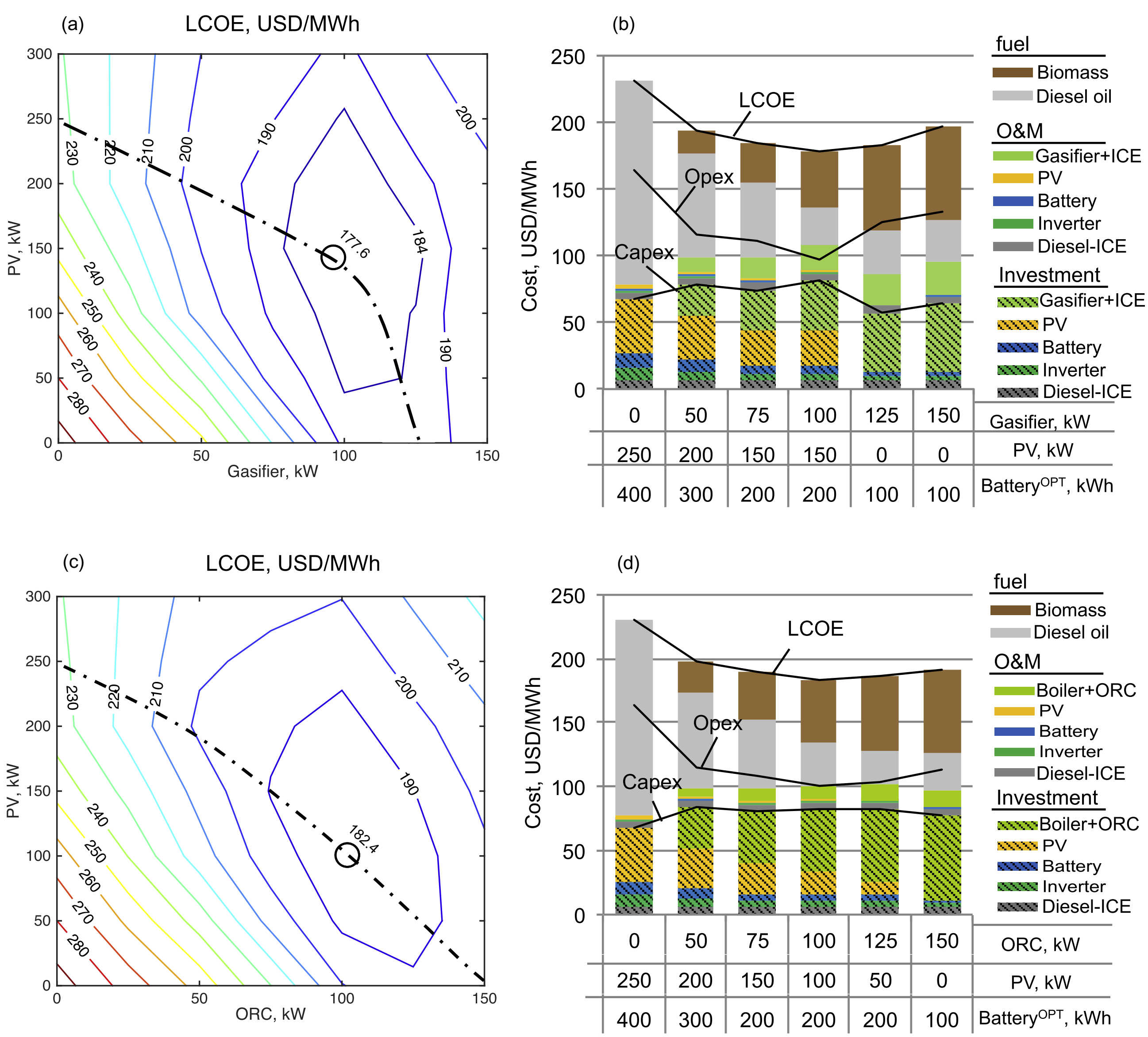

Fig. 8. LCOE results for gasifier system (a, b) and ORC system (c, d); (a, c) LCOE map in function of PV and generator size and (b, d) breakup of LCOE varying generator size with optimal PV and battery size.

Table 8
Optimal MG design for the three configuration analysed with information about the operation of the different components and the use of the battery. Diesel ICE size is 200 kW for all cases.

		Optimal sizes (kW, kW h)	CO_2 emission (kg/MW h)	LCOE (USD/MW h)		Load factor (–)	Daily start-ups (–)	Working hours (h)	Electricity generation (MW h)	Electricity to battery (MW h)
Diesel only	Battery	0	839.4	295.1	D-ICE	49.0%	-	8760	858.7	–
PV based system	PV	250	467.1	231.1	D-ICE	52%	1.45	4888	459.01	15.2
	Battery	400			PV	23%	–	–	528.5	177.6
ORC based system	Boiler	500	87.6	182.43	Boiler	79.0%	0.25	7815	–	–
	ORC	100			ORC	81.7%	2	7800	638.6	0.78
	PV	100			D-ICE	31.5%	2.08	492	51.5	0.08
	Battery	200			PV	23%	–	–	211.4	15.62
Gasifier based	Gasifier+ICE	100	108.21	177.61	Gas-ICE	90.8%	1.6	6079	552.1	15.6
	PV	150			D-ICE	25.6%	1	453	58.2	0.12
	Battery	200			PV	23%	–	–	317.1	49.0

operating hours. As a consequence, the LCOE trend has a minimum for both technologies; the optimal size for a gasifier system is slightly smaller than the ORC (100 kW vs 150 kW) according to its lower availability and higher off-design penalization. In the optimal configurations, the PV continues to play an important role with a nominal power of 100 kW and 150 kW respectively for ORC-based and Gasifier-based systems, providing an amount of cheap energy which can be easily matched by programmable loads. The Diesel engine is used in the energy-intensive seasons only for few hours at end of day and as backup generator when the biomass generator is out of order for maintenance or accidental failure. The optimal solutions show a RES share over 95% in both cases.

The final LCOE results are similar for both technologies but the generator management is considerably different, as reported in Table 8. The gasifier works with a higher average load factor respect to the ORC based system because of the higher part load penalization: this implies that the battery covers a more important role in load balancing as shown by the higher amount of energy stored in the battery coming by the programmable biomass based generator. The gasifier has in average more than one start-up every two days thanks to the faster start-up and because of the lower flexibility during operation. On the opposite, the ORC system exploits the additional degree of freedom offered by the oil storage: the boiler is shutdown with a lower frequency (1 start-up every 3 days in average) while the ORC shows a more intermit-tent operation following the load and using the heat stored in the oil tank.

5.3. Analysis of RES penetration cost

The results obtained in the simulations highlight the beneficial economic effect attainable by exploiting renewable energy sources whether intermittent (PV in this case) or dispatchable (biomass based generators) instead of fossil fuels. An additional investigation has been conducted to show the value of the dispatchability of a biomass-based system and the potential of hybrid solutions made by biomass and PV plants.

We calculated the specific cost of RES energy production for two MG configurations provided with a backup diesel engine and a single renewable energy power system: one with PV plant and the other with a Gasifier+ICE system. Different size of generators (and consequently of electricity generated) are investigated and the results are presented for the optimal size of the battery. The specific RES cost is calculated as the ratio between the life cost of the technology (generator plus the battery system) and the useful RES energy. This latter one is evaluated as the difference between the total electricity consumed by the village and the energy generated by the Diesel generator. This implies that the diesel engine never charges the battery and that the charge/discharge losses are totally allocated to the RES production: an assumption which is practically always verified as showed in the example in Table 8. In Fig. 9 three curves are presented: two for a PV system (in stand-alone and grid-connected configuration) and one for the biomass based plant.

As a general consideration, by increasing the installed power both stand-alone configurations show a trend formed by two different parts. Initially the specific cost of energy decreases, thanks to the favourable scale factor: the effect is more marked for PV plant since for small installed power (50 kW and 100 kW) battery is not required and grid balance is guaranteed by a correct manage-ment of schedulable loads. Increasing the RES share and hence the nominal RES installed power a bigger battery size is required leading to a specific cost increases: this figure soars for PV systems having a RES penetration higher than 20% (equivalent to 150 kW) while this effect is less pronounced for the biomass based system. The intermittency of solar source requires large energy storage

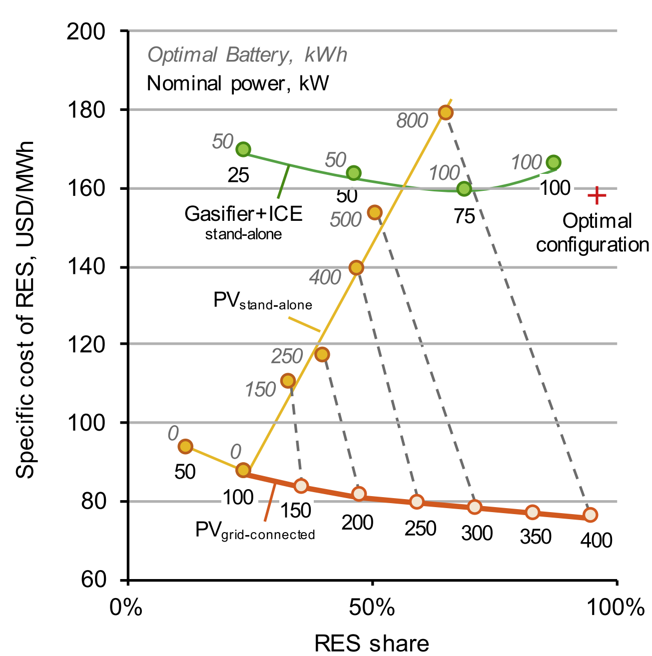

Fig. 9. Specific cost of RES production as function of RES penetration for three microgrid based respectively on PV (grid-connected or stand-alone) or a Gasifier +ICE system. For each marker, black figures refer to the nominal installed power while grey ones to the size of the optimal energy storage.

systems with a relevant part of energy lost in charge/discharge process. A qualitative evaluation of this additional cost can be obtained comparing two PV systems with the same installed power: one in stand-alone configuration and the other one grid-connected. The difference in RES penetration is due to effect of charge/discharge losses which are not faced by a grid connected PV since the entire energy produced is injected in the grid without any limitation. Regarding the gasifier system, the slope inversion starts at a higher RES penetration (70%) and has a lower intensity. In fact, thanks to the dispatchability relevant amounts of energy are easily manageable without huge energy storage and charging/discharging losses.

With the goal of increasing the RES penetration, a prohibitive RES energy cost is obtained for PV plants while values up to 87% can be obtained with a Gasifier+ICE system at a reasonable cost underling once again that the only cost-effective solution for high RES sharing is to rely on a renewable dispatchable generator. However, biomass based generators benefit by the integration of relatively small PV systems as shown by the optimal design (red cross) and intermittent generators can play a relevant role in lowering the LCOE and increasing the RES share.

6. Conclusions

In this work we investigated the potential of RES technologies in reducing the LCOE of stand-alone microgrids for rural electrification. PV and two biomass-based systems were investigated and several MG configurations have been optimized using a novel approach. The optimal management for each configuration is defined with a sequence of MILP problems based on a variable step rolling horizon approach allowing for forward-looking decisions and fast computation.

The selected case study is a rural village of 2000 inhabitants located in Patna district in the state of Bihar, India. We found that a proper mix of solar and biomass energy (with a reasonable size of energy storage and an optimized management of the schedulable loads) leads to a LCOE reduction of about 40% respect to a system based only on diesel generator. In addition, the RES share is strongly increased up to more than 95%, restricting the fossil fuel electricity production to the marginal role of back-up system. These results show the importance of using RES dispatchable gen-erators like biomass-based systems in stand-alone MGs and the benefits attainable in terms of cost reduction and RES share.

The results presented are obviously related to the assumptions we made (given in Tables 2, 3 and 7). In particular: different input data on specific cost of fuels (diesel oil and biomass), daily variation of electricity demand, solar radiation, etc. would lead to different solutions. For instance, the presence of a relevant cooling demand related to air conditioning, moving electricity demand peaks in the sunny hours, would favour PV and reduces the size of the battery. However, we performed many sensitivity analyses to address the robustness of the solution in relation to reasonable changes of the input data and we found that, even if the optimum generators size can slightly change as the share of energy sources, the qualitative trends of the results remains the same over a wide range of variation. The following general conclusions, are hence valid for a wide range of cases:

- The addition of solar PV yields a relevant contribution to decrease the LCOE, as well as emissions, but cannot completely replace the diesel production: the optimal (minimum LCOE) mix of diesel generator, PV and electric batteries still allocates a relevant role to fossil fuel, which actively acts to shave the battery charge/discharge fluxes and during the nocturnal hours. A higher RES share and a lower LCOE can be obtained only with an technology improvement of both PV panels (higher efficiency, lower cost) and energy storage (lower investment cost, smaller wear and longer life).
- Whenever biomass is available at reasonable cost, a better result is obtained with a RES dispatchable generator like a biomass Boiler+ORC or a biomass Gasifier+ICE, since they can almost totally replace the use of diesel engine, reducing the size of the electric storage and strongly increment the RES penetration. The possibility of reducing the LCOE strongly depends on the cost of these components, their efficiency and the cost of biomass.
- The best solution, in term of LCOE as well as RES penetration, is based on a proper mix of PV and biomass generators (with a reasonable size of energy storage and an optimized management of the schedulable loads), with a marginal role of back-up diesel generator. Varying the assumptions, the optimal mix may change leading to solutions with a different share of electricity produced by PV and by biomass but the beneficial effect of using a RES dispatchable generator is always confirmed except for the cases with a extremely high cost of the biomass.

Although this study is focused on small-scale rural electrification, similar considerations can be made for large regional and national grids which are experimenting issues in handling relevant share of intermittent RES coming from PV and wind plants. If electrical energy storage cost will not strongly decrease in the soon future, RES dispatchable power generators, as biomass systems or CSP with thermal storage, would likely play a more relevant role to reduce global greenhouse gases emissions and limit fossil fuel consumption also in on-grid application.

Acknowledgements

Solar data were obtained from the NASA Langley Research Center Atmospheric Science Data Center Surface meteorological and Solar Energy (SSE) web portal supported by the NASA LaRC POWER Project.

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