



Techno-economic optimization model for polygeneration hybrid energy storage systems using biogas and batteries



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ARTICLE INFO

Article history:

Received 17 April 2020

Received in revised form

28 September 2020

Accepted 6 December 2020

Available online 8 December 2020

Keywords:

Hybrid energy storage

Dispatch strategy

Bio-solar polygeneration

ABSTRACT

Renewable energy polygeneration systems are a viable alternative to fossil-fuel based systems, but storage solutions may be necessary when aiming for high sustainability and autonomy. As each storage technology has different strengths and weaknesses, combinations of various storage solutions may lead to better techno-economic performance than singular approaches. To this purpose, an optimization model including a novel dispatch control strategy for a hybrid energy storage system (HESS) is proposed, which uses biogas for long-term and batteries for short-term storage. The model optimizes for minimum lifetime costs while exploiting the biomass resources with maximum efficiency and quantifying the additional solar and battery capacities needed. It is applied in a case study with an innovative biomass-based polygeneration system in a rural locality of Bolivia to serve electricity, potable water, and bio-slurry as fertilizer. The results indicate that even with maximized efficiency of the biomass resource conversion, large PV and battery capacities are necessary to satisfy the electricity demand of the locality. Despite of the high investment costs, the biomass-based polygeneration system would cost 22% less over the project lifetime than the fossil-fuel based reference system while being less dependent on fuel price changes. It would also reduce CO₂-emissions by over 98%.

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1. Introduction

The need for a transition towards more sustainable energies has been recognized globally with various technologies competing while also complementing each other to provide more sustainable and secure energy-related services [1,2]. Amongst these technologies, small-scale biogas has gained increasing interest as a low-emission and locally available energy carrier with ecological and socio-economic benefits for developing regions in Africa, South-East Asia and Latin America [3]. With rising living standards, the usage of biogas as a cooking fuel may no longer be sufficient and advanced energy-related services like electricity will be in higher demand. However, despite of high scientific interest in small-scale

biogas electricity generation [4], a broad-scale penetration of rural areas has not been observed [5]. This may be due to the drawbacks of higher complexity and increased capital costs outweighing the benefits. The concept of polygeneration offers the possibility of dramatically increasing the benefits by providing several energy-related services rendered with a relatively modest addition of complexity [6,7]. By increasing the total energy efficiency of the biogas systems and hence reducing losses, polygeneration also maximizes the utilization of the limited biogas resources. Such polygeneration systems serve apart from electricity also other energy-related services like hot water, cooling, or potable water by further using the heat inevitably produced in the biogas combustion process. In consequence, biomass-based polygeneration systems can decrease oil dependency and lower Greenhouse Gas (GHG) emissions [8]. Solar technologies like Photovoltaics (PV) can be added to decrease the amount of biogas usage and batteries can be used to extend the services of the solar energy beyond sunshine hours [9]. Despite the lower electric efficiencies, small-scale biogas-

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based systems may prove to be the most efficient method to use biomass due to smaller transport paths compared to large systems [10].

Several authors have proposed specific small-scale poly-generation systems using biogas, water purification, solar and/or storage technologies: Kyriakarakos et al. [11] proposed a poly-generation system consisting of 4.8 kWp PV panels, a 3 kW wind turbine and a 1 kW fuel cell to generate electricity and to desalinate water with reverse osmosis technology. The system uses a Proton Exchange Membrane electrolyser to produce hydrogen as a transport fuel as well as batteries to cover electric loads for 3 days. Based on particle swarm optimization the results show that the optimal system is economically feasible for an off-grid island system with a probability of 90%, depending on fuel price fluctuations. Gazda et al. [12] developed an algorithm for biogas-based CCHP systems with various RES (Renewable Energy Sources) to evaluate the energetic and ecologic efficiencies of facilities in the agri-food sector like distilleries, waste digesters, juice storage facilities etc. Using a 750 kW_e biogas engine and ca. 228 kW PV panels, the system could lower GHG emissions by up to 67.4% and Primary Energy Savings (PES) by up to 65%. A heat storage tank has been considered, but electricity or biogas storage were not mentioned. Focusing on the Italian market and primarily on financial analyses Carlini et al. [13] calculated a payback time of 9 years for a 100 kW_e biogas-fuelled CHP plant but five years for a 500 kW_e CHP plant. It is mentioned that these results are highly dependent from the financial incentives set by the surrounding political institutions. However, they identify a trend that larger plants tend to recover the investment costs faster. For dairy farms in central Bolivia Villarroel-Schneider et al. [14] proposed a biogas-based polygeneration plant with a 40 kW_e engine producing electricity, cooling for milk refrigeration and heat for bio-slurry drying, which could then be used as fertilizer. When compared to the highly subsidized fossil fuel-based energy solutions in Bolivia, the proposed system seems to be competitive showing a payback period of 3.5 years when requiring just 15% subsidies on the investment costs. The paper underlines the potential of biogas-based systems for rural regions as well as the economic complexities due to fluctuating prices.

A polygeneration system based on a plug-flow digester unit connected to a 10 kW_e Internal Combustion Engine (ICE) to produce electricity, cooking gas and 20L/h of drinking water via air-gap membrane distillation (MD) has been devised by Khan et al. [15]. The system has been optimized for economic performance and a payback period of less than 4 years has been calculated. The biogas production could be increased through a recovery system transferring heat from the MD units to the anaerobic digester (AD). In a related study, the system has been further enhanced using 12 kW PV panels and approx. 10 kWh of batteries [16]. This enabled the system to serve nearly twice as many households with higher electricity demands highlighting the potentials of both, hybrid energy sources and storage technologies for polygeneration systems.

Due to the increasing penetration of RES into all electricity sectors and their inherent fluctuating nature, flexible storage solutions gain increasing interest. An extensive review on hybrid energy storage (HES) solutions of all sizes has been published by Bocklisch [17], who proposes several combinations of short-term and long-term storage technologies. A similarly interesting review concentrating specifically on micro-grids has been presented by Hajiaghasi et al. [18], who highlight amongst others the importance of capacity sizing. Both reviews clearly identify the complementing capabilities of short-term (e.g. supercapacitors) and long-term (e.g. Compressed Air Energy Storage (CAES))

technologies, however the storage potential of biomass resources (like biogas) has not been mentioned. Although several authors do consider biogas fuelled engines as back-ups for rural renewable energy systems, the details of the biogas storage control strategy are often neglected. For example, Amin Vaziri Rad et al. compare energy systems composed of PV panels, wind turbines, a biogas generator and hydrogen-driven fuel cells, which are supported by batteries and a hydrogen tank [19]. The results indicate that an off-grid system consisting only of PV panels, batteries and a biogas generator outperform all other combinations economically. However, the details of the biogas storage are not elaborated further. Nonetheless, Azzuni et al. identified a positive relationship of gas storage facilities towards energy security [20].

Despite the high interest in biogas-fuelled off-grid systems and their many benefits, no optimization method for biogas storage and batteries has been reported yet. Such a system could use the biogas for long-term storage (i.e. days to weeks), while the batteries could serve low short-term demands (i.e. several hours) and hence would allow for the biogas engine to operate at maximum efficiency as frequently as possible. Additionally, the system could be enhanced with PV panels, hence allowing for electricity service during maintenance downtime of gas system components as well as for surpassing the energetic limitation of the biomass resources. The aim of this paper is to facilitate the design of polygeneration with a hybrid energy storage system (HES) using biogas by developing a versatile model. Additionally, the benefits and drawbacks are to be analysed based on a case study. Hence, the scientific contribution of this paper is twofold:

1. Firstly, a novel model for economic optimization for a HES using biogas storage coupled to a biogas ICE and batteries, is presented. The model applies a dispatch control algorithm, which can take into account photovoltaic energy as an additional energy source, so that even with insufficient biomass resources a given demand load can be satisfied. In order to allow for a highly efficient system design, the model calculates the thermal energy recovered from the engine.
2. Secondly, an innovative polygeneration system has been designed to identify the benefits of a HES employing biogas and batteries controlled by the algorithm. By adding a MD subsystem, the energy efficiency of the total system is further increased and a second service is provided for an off-grid locality in Bolivia. Further considering the fertilizer in form of bio-slurry, the polygeneration system can provide up to three energy-related services: electricity, potable water, and fertilizer. The system is scrutinized with a techno-economic analysis in comparison with a diesel-based reference system in a case study.

After this introduction, the model approach is explained and one of many possible polygeneration layouts is presented in section 2. In section 3, the parameters and variables for the case study are described. The economic, energetic, as well as ecologic results are shown in section 4. The results and the model are discussed in section 5. Finally, conclusions on the algorithm and on the proposed polygeneration system are drawn in section 6.

1 Model and strategy description

The model aims to minimise the costs of the project over its lifetime. For this the Net Present Costs (NPC) are used, which are defined as follows in equation (1):

$$\begin{aligned}
 NPC &= \sum_{t=0}^n \frac{R_t}{(1+i)^t} \\
 &= \sum_{t=0}^n \sum_{j=1}^j \frac{CC_j + RC_j + OM_j + FC_j + SR_j}{(1+i)^t}
 \end{aligned} \quad (1)$$

where R_t are the cashflows for year t , i is the real discount rate and n represents the project lifetime. For each component j , R_t is composed of all capital costs CC_j , replacement costs RC_j , costs and revenues for operation & maintenance OM_j , fuel costs FC_j , and salvage revenues SR_j . The optimization problem can be expressed as shown in equation Eqn 2:

$$\min NPC \quad \text{subject to } E_{cs} \leq E_{cs,max} \quad (2)$$

where E_{cs} is the annual capacity shortage, where the energy system cannot satisfy the total electricity demand of the client, and $E_{cs,max}$ is the maximum annual capacity shortage permitted to the system. As the NPC is determined by component size and component utilization, the model simulates in an iterative process the system performance for each component size as predetermined in a given search space. For a more general comparison of the economic performance in relationship to the energetic output the Levelized Cost Of Energy (LCOE) is used and calculated as follows in equation (3):

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \quad (3)$$

where $C_{ann,tot}$ are the annualized cost of the system [in \$/yr] and E_{served} is the total electrical load served for one year [in kWh/yr]. To calculate $C_{ann,tot}$ equation (4) is used:

$$C_{ann,tot} = \frac{i \times (1+i)^n}{(1+i)^n - 1} \times NPC \quad (4)$$

where i , n , and NPC are defined the same as for equation (1). For the ecologic performance of the optimal system, the total mass of CO_2 -emissions $m_{CO_2,tot}$ is considered using equation (5):

$$m_{CO_2,tot} = m_{CO_2,transp} + m_{CO_2,comb} \quad (5)$$

where $m_{CO_2,transp}$ and $m_{CO_2,comb}$ are the masses of emissions due to transport and combustion of fuel, respectively. The fuel used m_{biog} in relation to the electric output by the engine is calculated as shown in equation (6):

$$m_{biog} = (IC \times P_{gen,max} + Slope \times P_{load}) \times t \quad (6)$$

where IC is the Interception coefficient [in kg/(h·kW_{rated})], $Slope$ is the fuel slope [in kg/(h·kW)], P_{load} is the electric load supplied by the engine [in kW], $P_{gen,max}$ is the peak load capacity of the engine [in kW], and t is the duration of one time step [in h]. With the electrical output of the engine depending on its partial load behaviour also its thermal output is varying according to electricity generated.

The model employs a unique dispatch strategy based on IF-THEN statements, which allows for optimal utilization of local biomass resources. Although there are similar control algorithms for HESS [21,22], none have been developed for the combination of two independent energy storage modes (chemical/biogas and electrochemical/batteries) for an optimization model of a poly-generation system. A graphic visualization of the algorithm is given in the supplementary material. The objective of the algorithm is to

operate the biomass engine as often as possible at maximum load and hence at maximum electric efficiency. The control algorithm operates according to the following order:

1. Check the state of storage of the biogas system. If the biomass storage is 10% below its technical upper limit, the algorithm will signal to release biogas to the engine.
2. Check the state of charge of the battery system.
3. Compare the electric load (after PV panels if included) with the capacities of battery discharge, converter discharge, and generator output.
4. Finally, the algorithm sets the generator output and the battery discharging or charging power. In case some load demand cannot be met the algorithm calculates the unmet load. Similarly, in case unused surplus power is generated, which can neither be used directly nor stored in the batteries, the model calculates the excess power.

A block diagram with a generic polygeneration system layout is shown in Fig. 1 and the optimization and analysis procedure of the model is shown in Fig. 2. The model is based on MATLAB (Version R2019a) and the Hybrid Optimization Model for Multiple Energy Resources HOMER (Version Pro 3.12.4). HOMER allows for a brute-force optimization approach running hundreds of simulations for all selected component sizes of the proposed polygeneration system. The connection to MATLAB allows for a more specific control of the energy storage and generation devices as well as for more precise calculations for the heat recovery. To validate the model behaviour under varying conditions firstly a white box testing approach with boundary value testing has been chosen with the results presented in the supplementary material [23]. Secondly, the model has been tested using results from a previous case study of a polygeneration system. The new dispatch (ND) control strategy has been used in a CCHP model and compared to the two most common strategies: load following (LF) and cycle charging (CC) [24]. The CCHP model has been presented in a previous study by Wegener et al. [25]. For the simulation, all input parameters have been kept equal while only the sizing of the biomass combustion system, the batteries, and the converter are being determined by the optimization model. Unlimited biogas supply is assumed and the PV panel capacity remains fixed.

The optimal component sizes for each strategy are shown in Table 1 and key results are shown in Fig. 3. Without biogas limitation, the ND strategy performs economically between the LF and the CC. However, the ND strategy requires less fuel and less engine operation time as the engine operates at higher efficiencies compared to the other two strategies. The results underline the universal applicability of the model and show that it optimizes biomass exploitation as aimed for.

2. Case description

2.1. Current electricity and water demand

For the case study, the locality of El Sena in Pando, Bolivia, has been chosen. In the reference case, the electricity demand of the inhabitants is covered by diesel-fuelled generators. These generators imply high GHG emissions and instability due to long fuel transport chains using unsecured roads. According to data from the national electricity agency (Autoridad de Fiscalización y Control Social de Electricidad) of Bolivia the total electricity demand of the village in 2016 was 1342.4 MWh with peaking values during the major harvest season in October [26]. For the daily demand profile, a typical demand profile of a rural community has been used with random variabilities of $\pm 10\%$ from day-to-day and $\pm 10\%$ from hour-

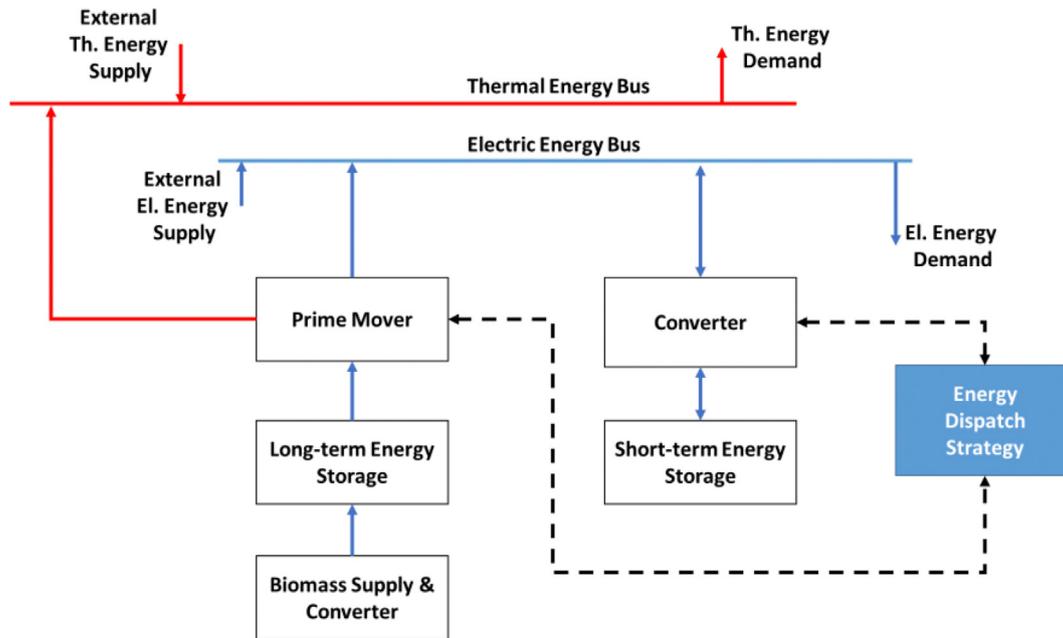


Fig. 1. Block diagram of a generic polygeneration system using the dispatch strategy.

to-hour [27]. The yearly electricity demand is shown in Fig. 4 and an exemplary weekly electricity demand for the first week in January is shown Fig. 5.

Additionally, the locality suffers from insufficient potable water provision as does the entire region of Pando [28]. This can cause higher infant mortality rates, more frequent malaria infections, and more cases of pneumonia. However, the production of potable water within the concept of polygeneration systems is especially attractive for remote areas with insufficient water access [29]. Therefore, the polygeneration system has been enhanced with a water purification subsystem based on thermally driven MD technology. For the potable water demand, a daily minimum of 3 l per person as proposed by the World Health Organisation's guidelines for drinking water has been assumed [30]. With a population of 8,258, this means a potable water demand of 24,774 l/day for the entire locality.

2.2. RES potential and costs

As shown in Table 2, the biogas potential has been calculated based on the amount of animals and humans in the locality registered by the national statistics institute of Bolivia [31,32]. A collection factor has been added to account for any losses during the collection and transportation processes. The biogas price has been calculated based on the local average cow dung price with a value of 10 USD/ton [14]. An average transport distance of 50 km has been assumed due to the proximity of nearby localities and conservative average transport costs of 6.5 USD/t for manure and liquid slurry have been used in the calculations [33]. Considering further a price of 10 USD/t for cow dung [14], an average dry matter ratio of 20% and average biogas yield of 0.3 m³/kg DM (s. Table 3), a biogas price of 0.28 USD/Nm³ has been calculated.

The monthly average values for solar global horizontal irradiance (GHI) and the clearness are provided by the NASA Surface meteorology and Solar Energy database and are shown in Fig. 6 [34]. The clearness index indicates how much of the extra-terrestrial horizontal radiation arrives on a horizontal surface on

the earth. With an annual average radiation of 4.84 kWh/m²/day and an annual average clearness index of 0.50, the potential for solar energy can be considered as rather high.

2.3. Polygeneration system design

The polygeneration system designed for the case study is shown in Fig. 7. The biomass is transformed into biogas in the AD, where also bio-slurry is produced as a side-product, which can be used later as fertilizer. The biogas leaving the AD is cleaned using various technologies (filter, cyclones, scrubber etc.) and then pumped to the biogas storage dome. Whenever the engine is started, biogas is drawn by the gas engine and combusted to generate electricity and heat. In the first heat exchanger (HEX), the heat of the exhaust gases is transferred to the cooling liquid and the gases are then emitted into the environment. In the second HEX, the heat between the engine cooling circuit and the feed water circuit for water purification is exchanged. The heated feed water is pumped into various MD units where it is evaporated, then pressed through a hydrophobic membrane, and eventually condensed using a cooling plate. The cold side of the MD unit is connected to the AD in order to keep the AD at optimal temperatures above 35 °C. A schematic diagram of the MD separation process is shown in Fig. 8 and another explanatory figure can be found in the supplementary material. A very informative and more detailed description of the purification process used in air gap MD systems has been provided by Noor et al. [38]. In case the cooling liquid is too hot, the temperature of the engine cooling liquid is further lowered for optimal engine cooling conditions in the third HEX and then returned to the engine. The kinetic energy of the engine shaft is transformed into electricity within the generator. The electric control system based on the dispatch control decides when to use the engine and/or the batteries to satisfy the electricity demand. The DC of the batteries and the PV panels is converted to AC using the converter and vice versa when excess energy from the engine is stored in the batteries [39].

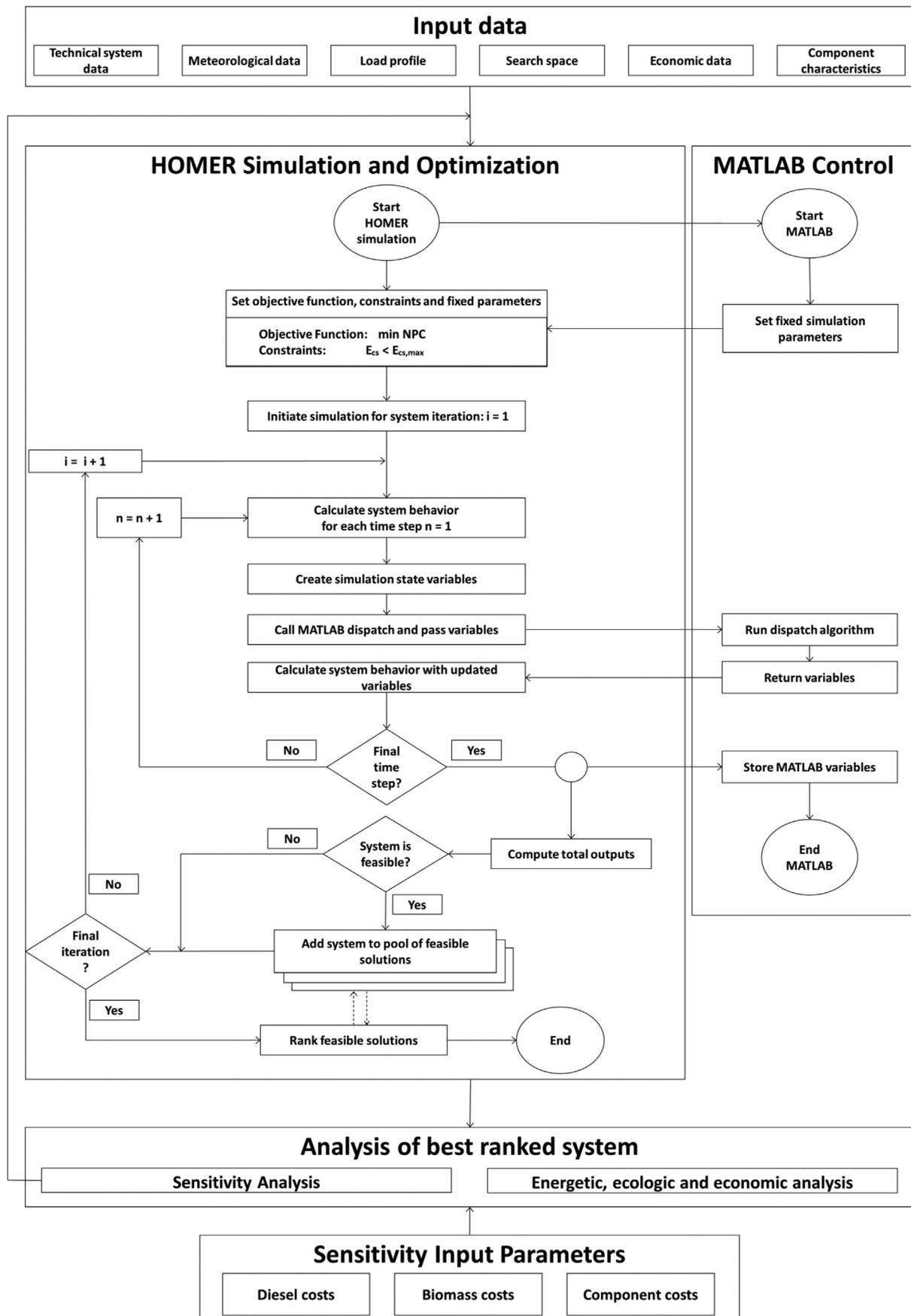


Fig. 2. Optimization and analysis procedure of the best ranked system.

Table 1
Optimal component sizes of different dispatch strategies.

Strategy/Comp. Size	Bio-Eng. (kW)	Batteries (kWh)	Converter (kW)	PV cap. (kW)
LF	56	317	56	85
CC	40	365	45	85
ND	46	272	40	85

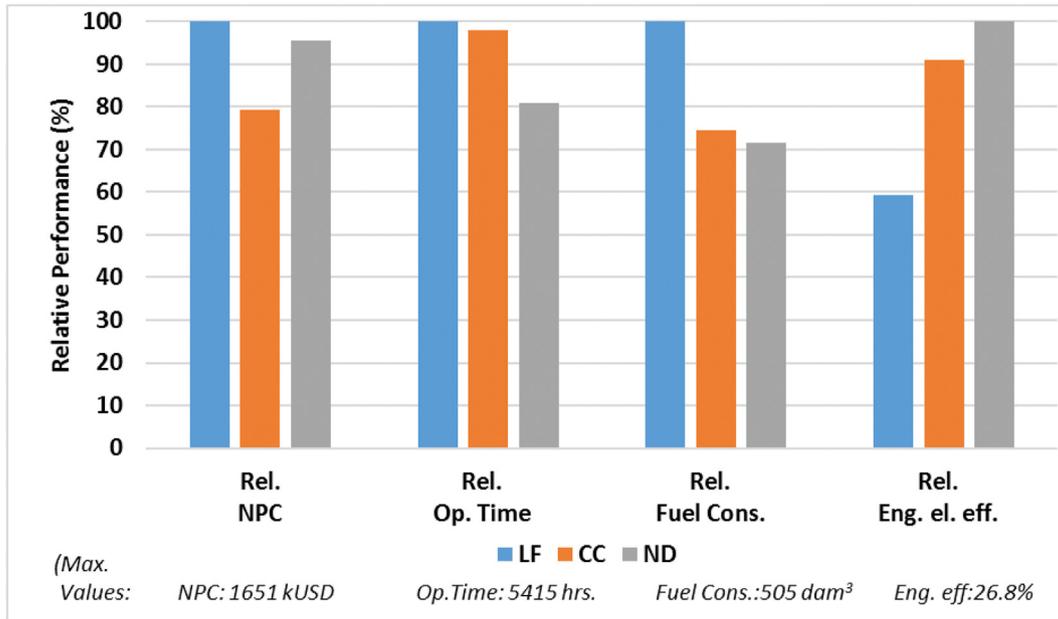


Fig. 3. System and component performance for various operating strategies.

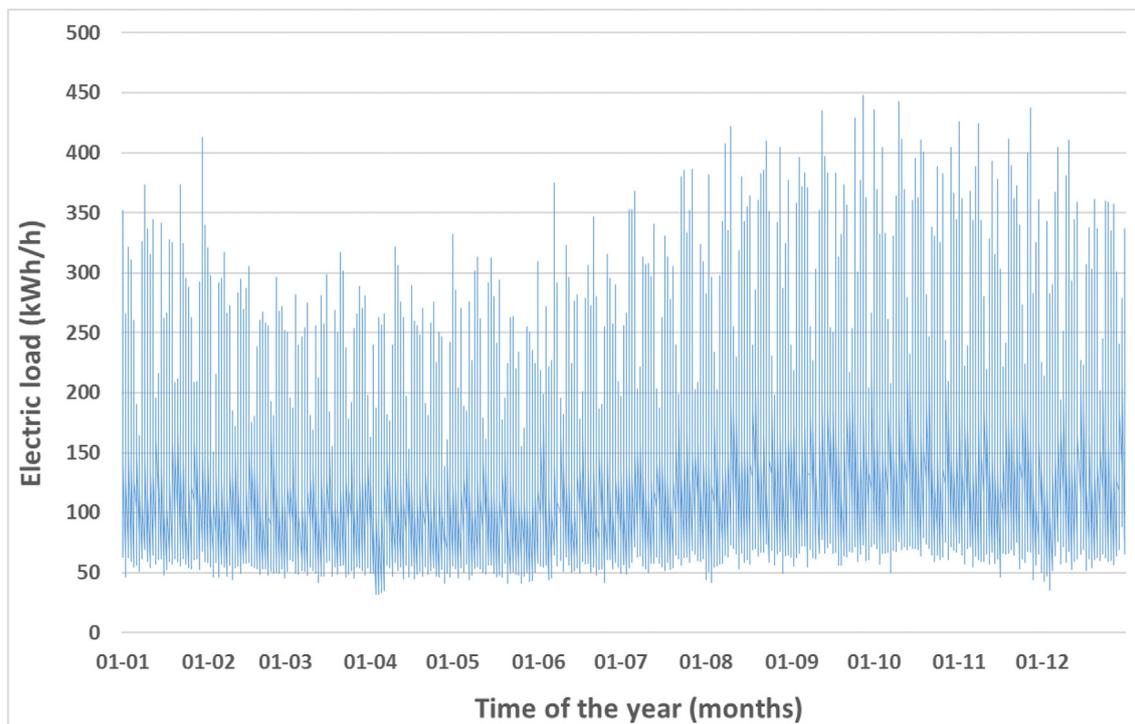


Fig. 4. Hourly electricity demand for one year.

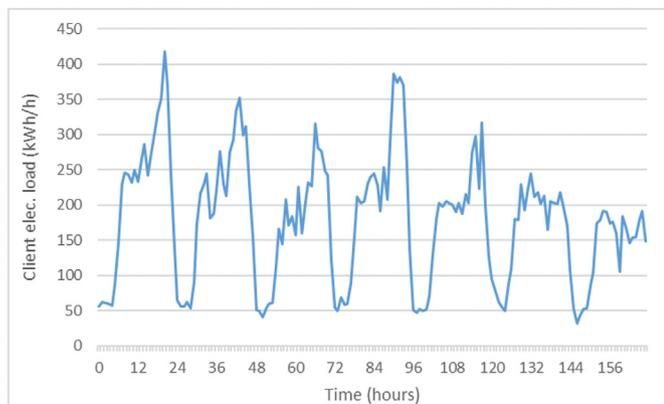


Fig. 5. Electricity demand for the first week in October (Monday to Sunday).

2.4. Technical inputs

Key technical variables for the model are shown in Table 3. The size of the AD has been calculated to 150 Nm³ based on the biomass availability shown in Table 2 and values provided by Teymoori Hamzehkolaei et al. [40]. The biogas production has been randomized with an hourly fluctuation of ±5% to account for inevitable process disturbances [41]. Furthermore, to account for downtimes, either scheduled (e.g. regular maintenance) or unscheduled (e.g. unexpected breakdowns), the biogas production has been set to zero for four days during three different occasions within the year (on the 1st of April, 1st of August and 1st of December) [42]. It has been assumed that the produced biogas has always the same chemical composition and hence the same LHV of 6.9 kWh/m³. For the additional electric load due to the AD system and gas storage, a value of 0.7 kWh per Nm³ of biogas stored has been assumed [43,44]. The dimensions of a biogas storage dome are based on a technical data sheet by Sattler Ceno TOP-TEX GmbH [45].

The engine performance based on the Patruus 370 BG CHP model by 2G Energy AG [46,47] is shown in Fig. 9. Exemplary values for HEx mass flows, temperatures, and heat transfers for a 370 kW_e engine at full load are shown in the supplementary materials. Thermal efficiencies have been assumed to be 90% for the HEx and 90% for the MD unit [48]. Other losses (e.g. due to distribution) have been neglected. The minimum value of ΔT employed in the system is 3.16 K for the heat transfer between the jacket fluid and the heating circuit. In the simulations, all values have been adjusted proportionally depending on the optimal engine size calculated by the model.

2.5. Economic inputs

For the different parameters, values from scientific and

Table 2
Biomass sources and production parameters.

	Bovine Animals	Poultry	Pigs	Human excrement	Organic food waste	Totals
Number	730 [32]	7287 [32]	646 [32]	8258 [31]	8258 [31]	
Daily production (kg/source/day) [35]	8	0.08	2	0.5	0.1 ^a	
Dry matter (DM) [35]	16%	17%	25%	20%	34%	
Biogas yield per DM (m ³ /kg DM) [35]	0.2–0.3	0.25–0.5	0.35–0.8	0.35–0.5	0.55	
Biogas yield per prod.(m ³ /producer/day)	0.320 [35]	0.010 [35]	0.128 [35]	0.040 [35]	0.019 [36]	
Collection factor	0.9	0.9	0.9	0.5	0.5	
Total biogas yield volume (m ³ /day)	210.2	65.6	74.4	165.2	77.2	592.6
Total biogas yield energy (kWh/day) ^b	1460.0	455.4	516.8	1146.9	536.2	4115.4

^a With daily production = waste per human (0.2 kg/day)xorganic waste ratio (50%) [36].

^b With an average energy value of 25 MJ/m³ or 6.9 kWh/m³ [37].

commercial references have been used as shown in Table 4. Due to the rural environment with complicated access, additional transport and installation obstacles may arise during initial construction as well as for replacement. To account for these uncertain parameters, additional reserve costs of 500 kUSD have been assumed based on the authors' experience with previous systems. For transport, the costs for renting trucks with drivers have been considered [33]. As the farmers can bring their biomass to sell it profitably, it has been assumed that they cover the transport costs of biomass and bio-slurry. For the bio-slurry, it has therefore been assumed that the bio-slurry will be distributed to the farmers in exchange for the transport costs. For the diesel price, the diesel opportunity price (1 UDS/l) has been chosen, which approximately represents the price for diesel on the international market [57].

3. Results

3.1. Economic

The optimal component sizes for the polygeneration and the reference system are shown in Table 5. Although peak demand reaches up to 450 kW, demand values above 330 kW occur less than 1% of the time, which is the maximum permitted by the capacity shortage constraint. Hence in the reference case a 330 kW_e is sufficient. Notably, the peak power output of the PV system exceeds the maximum conversion capacity of the converters so that nearly 500 MWh/year of excessive PV power are generated, which neither can be stored nor used directly. A larger converter or more batteries could prevent this albeit with an increase in costs. The required size of the PV panels would be equivalent to the size of one large football field [53]. The parasitic load to due biogas processing and water purification is equivalent to approx. 10% of the client load of the locality.

The NPC for each component and for each category is shown in Fig. 10. The total costs over the lifetime of 20 years for the polygeneration system are nearly 2 MUSD smaller than for the reference system equivalent to savings of more than 22%. This can be attributed mostly to the revenue from the water sales as well as diminutive costs for biomass compared to diesel. However, the capital investment costs as well as the replacement costs exceed those of the reference system by several million USD. At the end of the project lifetime, the salvage value of the battery system is approx.1 MUSD indicating that this set of batteries could still operate for several years after project termination. In direct comparison the LCOE of the polygeneration system is 27.4% lower with 0.297 \$/kWh compared to 0.409 \$/kWh for the reference system. The relatively larger difference in LCOE compared to NPC can be attributed mostly to the larger amount of electricity served by the polygeneration system, which is not accounted for by the NPC.

Table 3
Summary of the technical component input data.

Component	Further characteristics
Anaerobic Digester (AD) system	Biogas composition: 60% CH ₄ : 40% CO ₂ [15] Biogas LHV: 6.9 kWh/m ³ [37] Digester Volume: 150 Nm ³ [40] Average hourly biogas production: 24.7 Nm ³ /h [40] Hourly fluctuation in production: ±5% [41] Yearly Downtime: 3 × 96 h [42] Mass transformation: 8% Biogas: 92% Slurry (s. Table 2) Electric load for pumps, clean-up, separation etc.: 0.7 kWh/Nm ³ _{bio} [43,44] Lifetime: 20 years [16]
Biogas storage system	Type: SATTLER double membrane gas storage dome tank - B9 127/250 [45] Dome volume: 3840 m ³ (diameter: 21.1 m, height: 15.9 m) [45] Max. pressure: 20 mbar (low pressure zone) [45]
Biogas Engine CHP system	Based on Patruus 370 BG CHP system [46] Max. electric efficiency: 38% [13,46] Recovered thermal heat: 70% (Approx. thermal efficiency of 47%) [46] Total efficiency: 84% [46] Heating water outlet circuit temperature: 90 °C [46] Lifetime: 15,000 h [49]
Water Purification system	Air gap membrane lifetime: approx. 5 years [48] Remaining Air gap membrane distillation (MD) equipment: 20 years [48] Specific thermal consumption: 800 kWh/m ³ [48] Specific electricity consumption: 0.35 kWh/m ³ [48] Heat transfer to cooling circuit: 90% [48]
Battery system	Based on Generic 1 kWh Li-Ion battery model Depth of Discharge: 80% (equivalent to minimum SOC of 20%) [50] Approx. life cycles: 10,000 [51]
Converter	Hybrid converters Lifetime: 15 years [52]
PV system	Generic flat plate model Derating factor: 83% (equivalent to an electric efficiency of 17%) [53] Peak capacity per area: 170 W/m ² [53] Lifetime: 25 years [53]
Diesel Engine reference system	Max. electric efficiency: 35% [54] Min. partial load: 40% [55] Lifetime: 15,000 h [56]
System constraints	Maximum capacity shortage $E_{cs,max}$: 1% Operating reserve: 10%

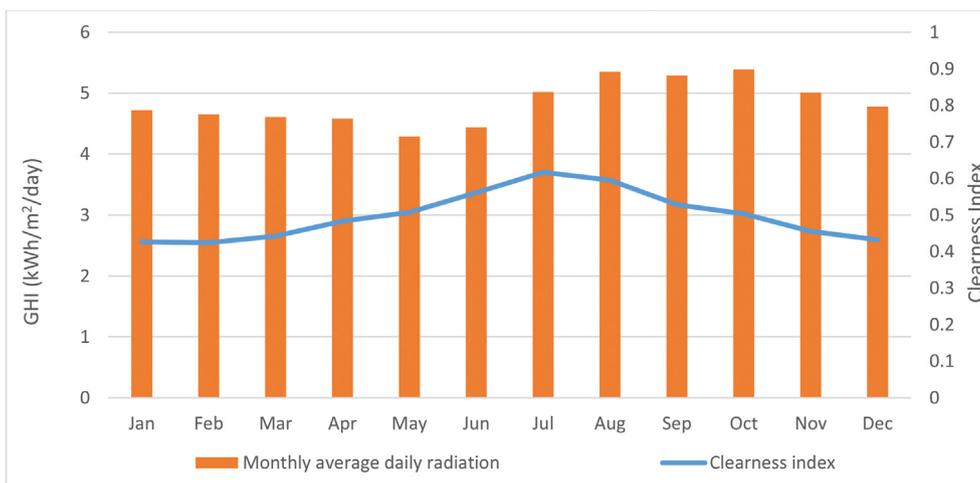


Fig. 6. Global horizontal irradiance (GHI) and clearness index for El Sena.

3.2. Energetic

An exemplary electricity generation curve for one week in October is shown in Fig. 11. For most days, the PV panels generate enough power during the day to simultaneously charge the batteries as well as to serve the electricity demand. After sunny days, the batteries can serve most of the demand with the engine operating only in the morning hours. However, after days with less PV output

the engine has to start more often to serve the load while most often charging the batteries as well.

A summary of the yearly system inputs and outputs is given in Table 6. The extra demand for biogas storage and water purification raises the electricity demand slightly. As the biogas production only stops during maintenance days, bio-slurry is constantly produced at around 334 kg/h, while potable water production occurs only sporadically when enough heat from the engine can be utilized. The

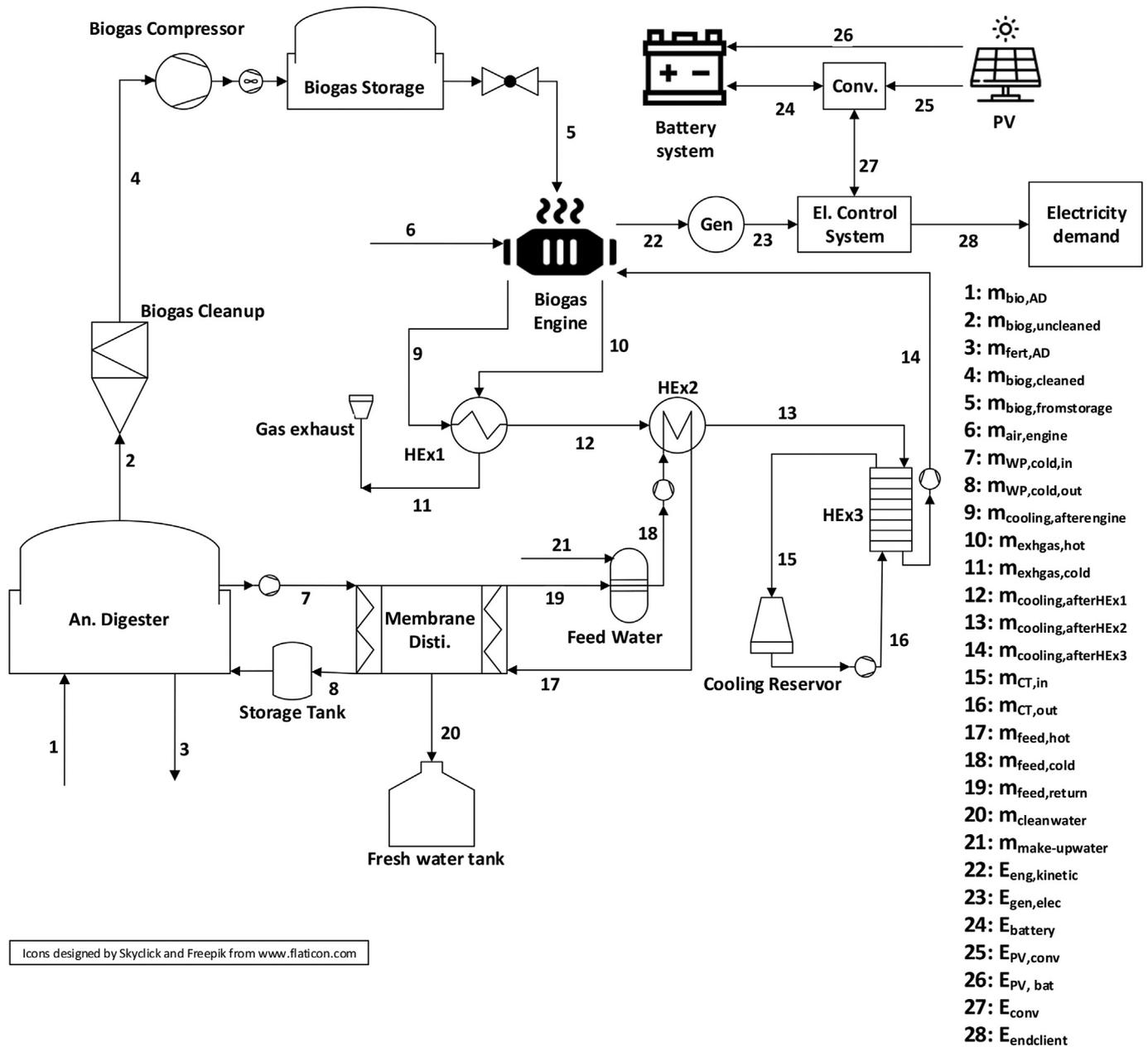


Fig. 7. System sketch of a particular bio-solar polygeneration system with hybrid storage.

total potable water production would amount to 800 m³ per year equivalent to approx. 8.8% of the locality's potable water demand.

3.3. Ecologic

More than 3000 t/year of bio-slurry would be produced. With a max. load of 30 t [33], every three to four days one truck would have to collect biomass and redistribute the bio-slurry. The diesel consumption of the reference system would imply that a 30 t transport truck would have to arrive approximately every 12 days. As most petroleum in Bolivia is refined in the South, an average transport distance of 1350 km (distance from El Sena to Gualberto Villarroel Cochabamba Refinery) has been assumed. As shown in Table 7, the CO₂-emissions for the biomass system would lead to a reduction of more than 98% when compared to the reference system. The

difference in CO₂-emissions between the two systems is visualized in Fig. 12.

3.4. Sensitivity analysis

The results of the sensitivity analysis for the economic performance of the polygeneration system and of the reference system are shown in Fig. 13. The polygeneration system performs better or close the reference case system for all scenarios with capital costs at 75% and 100%. Only with capital costs of 125% and low fuel prices of 75%, the polygeneration system can be outperformed by the fossil fuel based system. However, while the capital costs will be known beforehand and the biomass costs are dependent on only regional factors, the costs for diesel are very dynamic and dependent on many national as well as international factors out of the

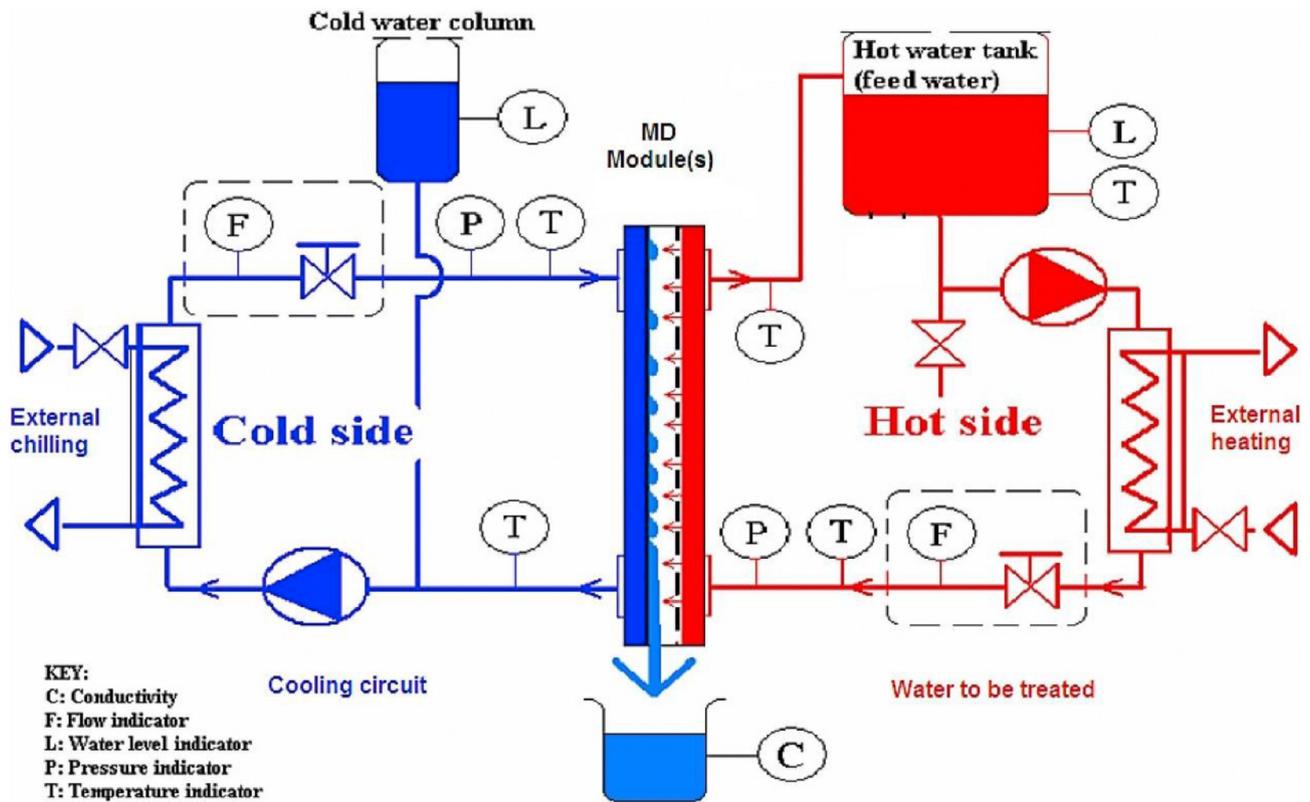


Fig. 8. Schematic flow diagram of an air gap MD separation process [38].

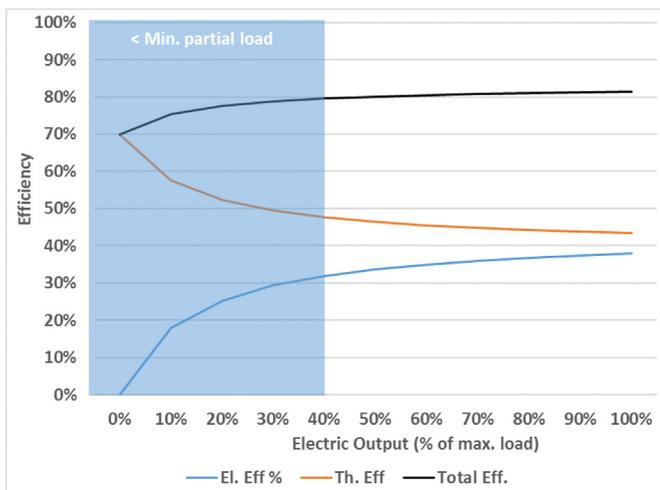


Fig. 9. Engine efficiencies for the reference engine with 370 kWp

municipality’s control. This leads to significant uncertainty for long-term financial planning.

4. Discussion

4.1. Polygeneration system

The biomass resources of the locality could not satisfy the electricity demand entirely, so that enhancing the system with solar technology is necessary when aiming for a 100% renewable energy system. In consequence, the algorithm calculated that large

capacities of PV panels and batteries would be necessary. On the one hand, this leads to a flexible energy system, which relies on two different energy sources and hence is more resilient. On the other hand, this increases capital investment costs immensely, which could complicate the financing process when looking for public and private investors. Despite of the high capital investment costs, the polygeneration system has considerably lower project lifetime costs than the reference system. This is especially due to much lower fuel costs stemming from locally available biomass as well as due to the potable water sales, which would lower operation costs substantially. The sensitivity analysis showed that, when compared with the reference system, the polygeneration systems is much more robust towards changes in fuel prices but much more susceptible to changes in the capital investment costs. This indicates that once the polygeneration system is constructed the municipality will have a financially more secure and stable energy system. This is also why the sizing of the components and their consecutive costs are crucial for a cost-effective design of the entire system underlining the importance of the optimization algorithm.

Although the produced water could only satisfy 8% of the assumed minimum potable water demand of the locality, the provision of potable water at low costs is another incentive for the local administration to support the polygeneration system financially. The MD system can therefore be considered as a supplemental water supply system providing high quality water to clinics and other critical areas. A compromise between a bio-solar and a fossil-fuel based system could be contemplated, where the CO2-reduction potential may not be as high but the necessary investment costs could be lowered. A substitution of electricity from PV panels with more electricity from diesel combustion would also further increase the MD-subsystem operation time. This could also be a convenient solution in case the population and hence the

Table 4
Summary of the economic component input data.

Component	Characteristics
Anaerobic Digester (AD) and biogas storage system	Capital costs (for digester, clean-up, pumps etc.): 200 USD/m ³ [40]
Biogas Engine CHP system	Capital & Replacement costs: 200 USD/kW [40] O&M costs: 0.2 USD/kWh (Including AD and biogas storage system at 3000 working hours per year) [58] Biogas price: 0.28 USD/Nm ³ (s. chapter 2.1.2)
Water Purification system	High quality potable water price: 0.145 USD/l [59] MD unit capital & replacement costs: 390 USD/kWe (coupled to engine output) [16] MD unit attachments capital costs: 365 USD/kWe (coupled to engine output) [16]
Battery system	Capital & Replacement costs: 1000 USD/kWh [51] O&M costs: Negligible [50]
Converter system	Capital & Replacement costs: 700 USD/kW [60,61] O&M costs negligible [60]
PV system	Capital & Replacement costs: 1,800USD/kW [62] O&M costs: 10 USD/kWe/year [62]
Diesel Engine reference system	Diesel opportunity cost: 1 USD/l [57] Capital/Replacement costs: 200 USD [52] O&M: 0.03 USD/op. hour [52]
System economics	Inflation rate: 4% [63] Nominal discount rate: 6% [63] Fin. reserves for uncertainties & engineering: 500 kUSD (s. chapter 2.1.5) Project lifetime: 20 years

Table 5
Optimal system component parameters.

Component	Size	Yearly Production	Additional electricity expenses
PV system	1075 kW (-6320 m ² [53])	1602 MWh/yr (74%)	486 MWh/yr (excess)
Battery system	2250 kWh	556 MWh/yr (annual throughput)	49 MWh/yr (losses)
Converter system	450 kW	1876 MWh/yr (Inverter output)	138 MWh/yr (losses)
Biogas engine system	260 kW	554 MWh/yr (26%)	145 MWh/yr (parasitic demand)
MD unit system	Membrane area 16.7 m ² (18 modules)	800 m ³ /yr (= 2190 l/day)	
Reference Diesel system	330 kW	1337 MWh/yr	-

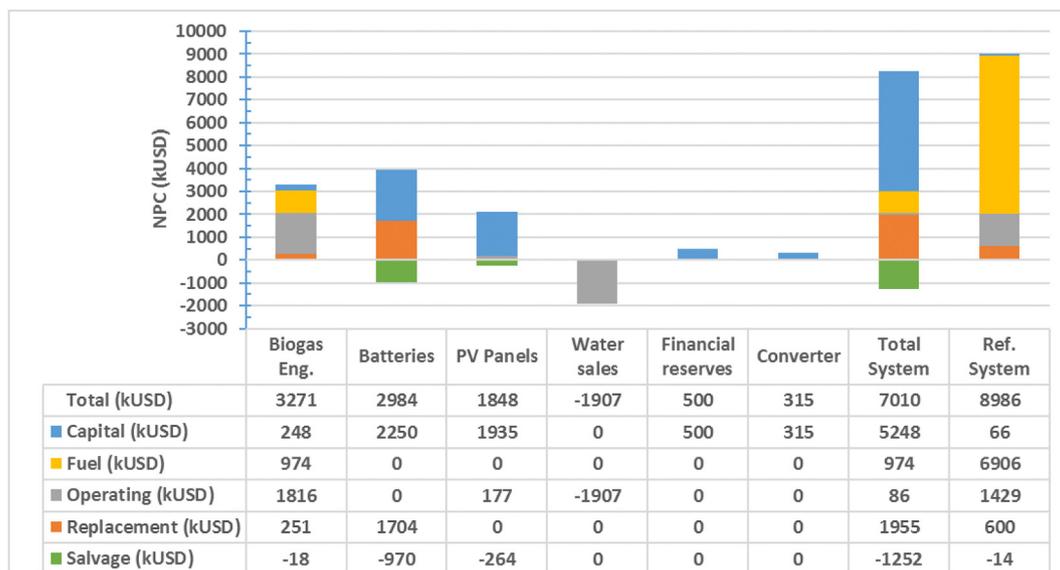


Fig. 10. Summary of the NPC values for the polygeneration system and the reference system.

electricity demand rises beyond the expected scope of this study. Introducing the bio-slurry redistribution system would close the nutrition cycle, but also require a well-adjusted system for mass and nutrition flows [66]. Depending on the business strategy, more sophisticated post-treatment of the digestate can be contemplated in order to produce high quality fertilizer. A selling price for the fertilizer could further improve the system economics. The

advanced technologies of the system would require several educational courses for local technicians and highly qualified personal as well as proper communication structures with the component manufactures for maintenance and reparation issues in order to operate the system safely. Considering further the complexity of the system, the planning and installation process should be carefully executed.

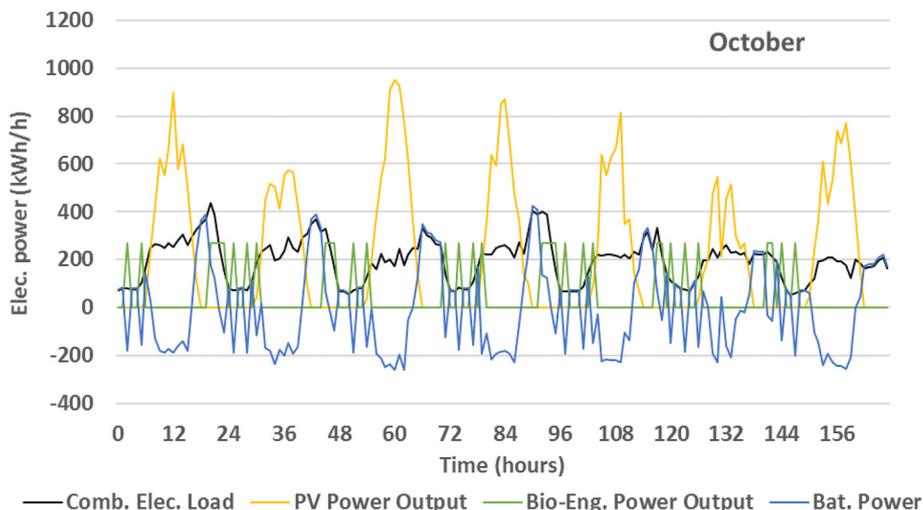


Fig. 11. Electric power load and generation for one week in high demand season (October).

Table 6
Summary of yearly system inputs and outputs.

Resources (Biomass system)	Input	Output
Biomass recollection (tonnes)	3177	–
Biogas combustion (tonnes)	254	–
Electricity production (MWh)	–	1,474 ^a
Potable water production (m ³)	–	800
Bio-slurry production (tonnes)	–	2923
Resources (Reference system)	Input	Output
Diesel combustion (tonnes)	344	–
Electricity production (MWh)	–	1337

^a Including parasitic load but excluding excess electricity and losses.

4.2. Dispatch control

The results of the validation and of the case study show that the algorithm successfully optimized the system for project lifetime costs given the limitations of biomass and solar resources as well as the need to serve the electricity demand. However, optimizing the economic performance of the system is just one of many possible optimization objectives with another option being minimizing CO₂-emissions. Even within the selection of economic parameters, a reduction of capital investments costs or operational costs may be favoured over project lifetime costs depending on the business strategy. Nonetheless, the algorithm can easily be adopted to optimize similar energy systems employing the strength of long- and short-term storage technologies (e.g. hydro-pump storage with

super-capacitors). Using MD for potable water generation is only one of several possible extensions for the system to reach high energy efficiency by transforming the waste heat of the engine. Other possible extensions like hot water generation, room heating, refrigeration etc. can be considered depending on the system location and demand characteristics.

A considerable trade off of the control mechanism lies in the high flexibility it demands from the gas ICE, because sporadically turning the engine on and off leads to lower engine lifetime than continuous operation. When designing a polygeneration system with the help of the algorithm, it should be aimed for an engine that can withstand such exigencies. Nonetheless, modern gas engines used in the land transport sector should be able to comply easily with these requirements. Future investigations could also take into account a more dynamic biogas generation profile, where the biogas composition and hence the LHV value fluctuate. Alternatively, other less cost-oriented component size configurations could be studied, where a smaller biogas engine works more continuously and hence produces potable water more continuously, while the PV panels and batteries cover the major part of the electricity demand.

5. Conclusion

A model introducing a novel dispatch control strategy for the optimization of polygeneration HESS using biogas and batteries has been developed. The control algorithm regulates the two storage

Table 7
Emission calculation parameters.

Parameter name	Biomass system	Diesel system
Heavy Duty Vehicle (Truck) emissions [g CO ₂ /(t·km)]	40 [64]	40 [64]
Average one way distance [km]	50 (s. Chapter 3.1.2)	1350 (s. Chap.4.3)
Outbound trip total weight [t]	45 (biomass)	45 (diesel)
Return trip total weight [t]	43 (bio-slurry)	15 (empty) [64]
Yearly necessary trips	106	12
Yearly CO ₂ -emissions due to transport [t/yr]	18.6	38.9
Yearly combustion [t/yr]	254	419
CO ₂ -emissions due to combustion [t/m ³]	0 ^a	2.67 [65]
Yearly CO ₂ -emissions due to combustion [t/yr]	0	1119
Total yearly CO ₂ -emissions [t/yr]	19	1159

^a Considering biogas as a carbon neutral energy source [3]. It should be noted that any biogas leaks could lead to significant greenhouse gas effects due to the high methane content.

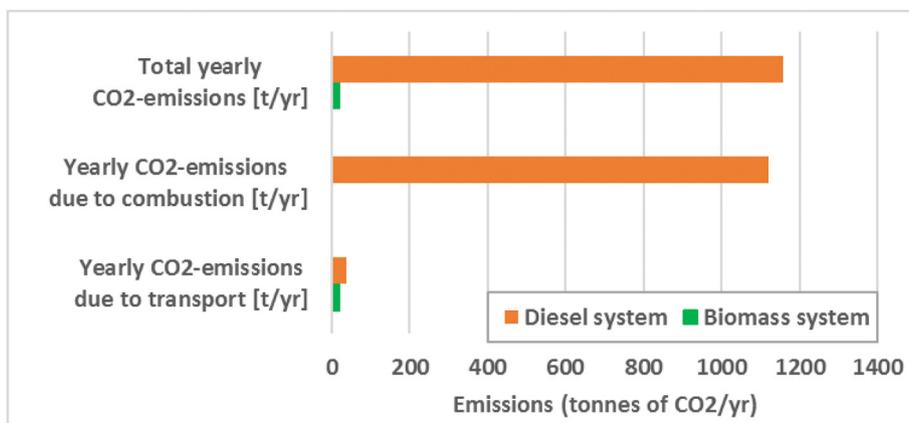


Fig. 12. Emission comparison for the reference and the polygeneration system.

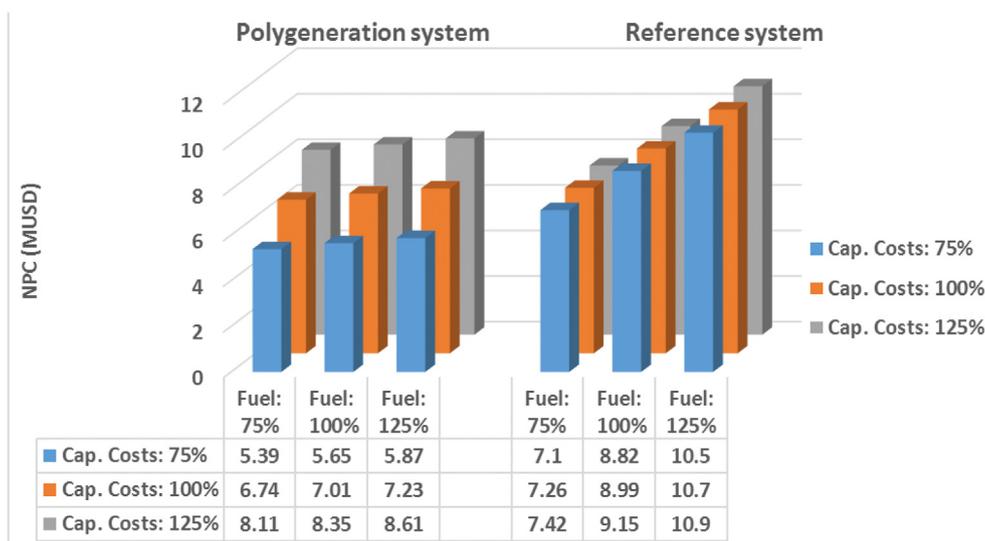


Fig. 13. NPCs of both systems with varying capital and fuel costs.

technologies with the aim to maximize capitalization on the biomass resources. The control strategy within the model allows for economic optimization of project lifetime costs under the constraints of biomass resource availability and electricity demand. If the amount of available biomass is insufficient to fulfil the electricity demand, PV panels and batteries are added as additional energy resource and storage options. The model calculates the residual thermal energy of the combustion process within the ICE in order to allow.) for a further increase in energy efficiency of the system via additional heat-driven energy-related services (e.g. water purification, heating, cooling, etc).

The model has been applied in a case study for a rural off-grid locality in Bolivia, where in the reference case a diesel-based system serves the electricity demand. The biogas potential has been calculated and a polygeneration system has been designed, which produces electricity, purified water, and fertilizer in form of bio-slurry. The polygeneration system performs economically much better than the reference system with 22% lower project lifetime costs and shows much more robustness towards fuel price changes according to the results of the sensitivity analysis. Nonetheless, high capital investment costs may be an obstacle for the realization of the project. As an additional advantage, CO₂-emissions could be reduced by more than 98% and the locality could achieve a much

more sustainable and autonomous energy and water supply system. The developed model can help scientists, engineers, and investors in the design process of renewable energy systems. Furthermore, it underlines that in rural areas smartly designed biomass-based polygeneration systems represent a viable economic alternative.

Author contributions

M.W. is the principal investigator of this work and wrote the manuscript. M.W. conceived and designed the control algorithm and system layout. J.V–S. has contributed greatly to the literature research. J. V–S., A.I., A.M. (Anders Malmquist), A.M. (Andrew Martin) and V.M. contributed to data analysis work and manuscript structuring. All authors revised and approved the manuscript for publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been conducted in collaboration between UPC (Universitat Politècnica de Catalunya) and KTH Royal Institute of Technology, funded through Erasmus Mundus Joint Doctoral Programme SELECT+, the support of which is gratefully acknowledged. The project STANDUP for Energy provided resources for supervision of this study. AI acknowledges support from Spanish project MOET_BIA2016-77675-R.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.energy.2020.119544>.

Appendix

Nomenclature

$m_{\text{bio,AD}}$	biomass to AD
$m_{\text{biog, uncleaned}}$	uncleaned biogas mass from AD
$m_{\text{fert,AD}}$	fertilizer mass from the AD
$m_{\text{biog, cleaned}}$	cleaned biogas mass from biogas clean-up
$m_{\text{biog, fromstorage}}$	biogas mass from biogas storage
$m_{\text{air, engine}}$	air mass to engine
$m_{\text{WP,cold,in}}$	mass of cold water into water purifier
$m_{\text{WP,cold,out}}$	mass of cold water out of water purifier
$m_{\text{cooling, afterengine}}$	mass of cooling water after engine
$m_{\text{exhgas,hot}}$	mass of exhaust gas after engine
$m_{\text{exhgas, cold}}$	mass of exhaust gas after HEX1
$m_{\text{cooling, afterHEX1}}$	mass of cooling water after HEX1
$m_{\text{cooling, afterHEX2}}$	mass of cooling water after HEX2
$m_{\text{cooling, afterHEX3}}$	mass of cooling water after HEX3
$m_{\text{CT,in}}$	mass of water into cooling tower
$m_{\text{CT,out}}$	mass of water out of cooling tower
$m_{\text{feed,hot}}$	mass of hot feed water into water purifier
$m_{\text{feed, cold}}$	mass of cold feed water into HEX2
$m_{\text{feed, return}}$	mass of cold feed water from water purifier
$m_{\text{cleanwater}}$	mass of cleaned water
$m_{\text{make-upwater}}$	mass of make-up water
$E_{\text{eng, kinetic}}$	kinetic energy of the engine
$E_{\text{gen, elec}}$	electric energy of the generator
E_{battery}	energy into or out of the batteries
$E_{\text{PV,conv}}$	energy from the PV panels to the converter
$E_{\text{PV, bat}}$	energy from the PV panels directly to the batteries
E_{conv}	energy into or out of the converter
$E_{\text{endclient}}$	electric energy provided to the client

Abbreviations

AC/DC	Alternating Current/Direct Current
AD	Anaerobic Digester
CAES	Compressed Air Energy Storage
CC	Cycle Charging
CHP	Combined Heat and Power
CCHP	Combined Cooling, Heat and Power
LCOE	Levelized Cost Of Energy
LF	Load Following
ICE	Internal Combustion Engine
GHG	Greenhouse Gases
GHI	Global Horizontal Irradiation
PV	Photovoltaic
HES	Hybrid Energy Storage
HESS	Hybrid Energy Storage System
HEX	Heat Exchanger
MD	Membrane Distillation

ND	New Dispatch
RES	Renewable Energy Sources
PES	Primary Energy Savings

References

- [1] IRENA, International Renewable Energy Agency (IRENA). Global energy Transformation: a Roadmap to 2050. 2019. [https://doi.org/10.1002/\(Sici\)1097-0029\(19990915\)46:6<398::Aid-Jemt8>3.0.Co;2-H](https://doi.org/10.1002/(Sici)1097-0029(19990915)46:6<398::Aid-Jemt8>3.0.Co;2-H).
- [2] OECD. OECD green Growth studies vol. 104; 2012. <https://doi.org/10.1787/9789264115118-en>.
- [3] International Renewable Energy Agency (IRENA). Measuring small-scale biogas capacity and production. 2016.
- [4] Dong L, Liu H, Riffat S. Development of small-scale and micro-scale biomass-fuelled CHP systems – a literature review. *Appl Therm Eng* 2009;29:2119–26. <https://doi.org/10.1016/j.applthermaleng.2008.12.004>.
- [5] Dimpl E. Small-scale electricity generation from biomass. Experience with small-scale technologies for basic energy supply- Part I: biomass Gasification. *Biomass Gasif*; 2011.
- [6] Murugan S, Horák B. Tri and polygeneration systems - a review. *Renew Sustain Energy Rev* 2016. <https://doi.org/10.1016/j.rser.2016.01.127>.
- [7] Serra LM, Lozano MA, Ramos J, Ensinas AV, Nebra SA. Polygeneration and efficient use of natural resources. *Energy* 2009;34:575–86. <https://doi.org/10.1016/j.energy.2008.08.013>.
- [8] Joelsson JM, Gustavsson L. Reduction of CO2 emission and oil dependency with biomass-based polygeneration. *Biomass Bioenergy* 2010;34:967–84. <https://doi.org/10.1016/j.biombioe.2010.02.005>.
- [9] Wegener M, Malmquist A, Isalgué A, Martin A. Biomass-fired combined cooling, heating and power for small scale applications – a review. *Renew Sustain Energy Rev* 2018;96:392–410. <https://doi.org/10.1016/j.rser.2018.07.044>.
- [10] National Research Council (US) Chemical Sciences. Heat and power production from biomass. Oppor. Obs. Large-scale biomass Util. Role Chem. Sci. Eng. Communities A work. Summ. National Academies Press (US); 2012. <https://doi.org/10.17226/14683>.
- [11] Kyriakarakos G, Dounis AI, Rozakis S, Arvanitis KG, Papadakis G. Polygeneration microgrids: a viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. *Appl Energy* 2011;88:4517–26. <https://doi.org/10.1016/j.apenergy.2011.05.038>.
- [12] Gazda W, Stanek W. Energy and environmental assessment of integrated biogas trigeneration and photovoltaic plant as more sustainable industrial system. *Appl Energy* 2016;169:138–49. <https://doi.org/10.1016/j.apenergy.2016.02.037>.
- [13] Carlini M, Mosconi EM, Castellucci S, Villarini M, Colantoni A. An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste. *Energies* 2017;10:1165. <https://doi.org/10.3390/en10081165>.
- [14] Villarroel-Schneider J, Mainali B, Martí-Herrero J, Malmquist A, Martin A, Alejo L. Techno-economic study of a biogas based Polygeneration plant for small dairy farms in central Bolivia. In: Sayigh A, editor. *Renew. Energy sustain. Build.* London, Kingston-upon-Thames: Springer; 2020. https://doi.org/10.1007/978-3-030-18488-9_54.
- [15] Khan EU, Mainali B, Martin A, Silveira S. Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study. *Sustain Energy Technol Assessments* 2014;7:68–78. <https://doi.org/10.1016/j.seta.2014.03.004>.
- [16] Khan EU, Martin AR. Optimization of hybrid renewable energy polygeneration system with membrane distillation for rural households in Bangladesh. *Energy* 2015;93:1116–27. <https://doi.org/10.1016/j.energy.2015.09.109>.
- [17] Pérez-Navarro A, Alfonso D, Ariza HE, Cárcel J, Correcher A, Escrivá-Escrivá G, et al. Experimental verification of hybrid renewable systems as feasible energy sources. *Renew Energy* 2016;86:384–91. <https://doi.org/10.1016/j.renene.2015.08.030>.
- [18] Hajiaghahi S, Salemnia A, Hamzeh M. Hybrid energy storage system for microgrids applications: a review. *J Energy Storage* 2019;21:543–70. <https://doi.org/10.1016/j.est.2018.12.017>.
- [19] Rad MAV, Ghasempour R, Rahdan P, Mousavi S, Arastounia M. Techno-economic analysis of a hybrid power system based on the cost-effective hydrogen production method for rural electrification, a case study in Iran. *Energy* 2020;190:116421. <https://doi.org/10.1016/j.energy.2019.116421>.
- [20] Azzuni A, Breyer C. Energy security and energy storage technologies. *Energy Procedia* 2018;155:237–58.
- [21] Li J, Yang Q, Robinson F, Liang F, Zhang M, Yuan W. Design and test of a new droop control algorithm for a SMES/battery hybrid energy storage system. *Energy* 2017;118:1110–22. <https://doi.org/10.1016/j.energy.2016.10.130>.
- [22] Chong LW, Wong YW, Rajkumar RK, Rajkumar RK, Isa D. Hybrid energy storage systems and control strategies for stand-alone renewable energy power systems. *Renew Sustain Energy Rev* 2016;66:174–89. <https://doi.org/10.1016/j.rser.2016.07.059>.
- [23] Fisher MS. Software verification and validation: an engineering and scientific approach. 2007. <https://doi.org/10.1007/978-0-387-47939-2>.
- [24] Aziz A, Tajuddin M, Adzman M, Ramli M, Mekhilef S. Energy management and optimization of a PV/Diesel/Battery hybrid energy system using a combined dispatch strategy. *Sustainability* 2019;11:683. <https://doi.org/10.3390/>

- su11030683.
- [25] Wegener M, Isalgué A, Malmquist A, Martín A. 3E-Analysis of a bio-solar CCHP system for the andaman islands, India—a case study. *Energies* 2019;12:1113. <https://doi.org/10.3390/en12061113>.
- [26] Anuario Estadístico del sector eléctrico de la gestión 2016. 2017. p. 490. ぎょうせい. https://sawi.ae.gob.bo/docfly/app/webroot/uploads/JMG—2017-09-07-ANUARIO_AE_2016_web.pdf.
- [27] Paleta R, Pina A, Santos Silva CA. Polygeneration energy container: designing and testing energy services for remote developing communities. *IEEE Trans Sustain Energy* 2014;5:1348–55. <https://doi.org/10.1109/TSTE.2014.2308017>.
- [28] Pando lucha por la calidad plena del agua potable, en las cantidades suficientes - Sol de Pando | Diario Digital n.d. <http://www.soldepando.com/httpwww-soldepando-comp27092/> (accessed April 2, 2019).
- [29] Calise F, de Notaristefani di Vastogirardi G, Dentice d'Accadia M, Vicidomini M. Simulation of polygeneration systems. *Energy* 2018;163:290–337. <https://doi.org/10.1016/j.energy.2018.08.052>.
- [30] WHO. WHO guidelines for drinking-water quality - Fourth Edition vol. 38; 2011. [https://doi.org/10.1016/S1462-0758\(00\)00006-6](https://doi.org/10.1016/S1462-0758(00)00006-6).
- [31] de Estadística IN. Censo de Población y Vivienda 2012 - Pandovol. 202; 2015. www.ine.es.
- [32] Producción de carne y derivados de las principales especies ganaderas a nivel nacional 1990-2013. Bolivia: Instituto Nacional de Estadística; 2014.
- [33] Ghafoori E, Flynn PC, Feddes JJ. Pipeline vs. truck transport of beef cattle manure. *Biomass Bioenergy* 2007;31:168–75. <https://doi.org/10.1016/j.biombioe.2006.07.007>.
- [34] Surface meteorology and solar energy. n.d. <https://eosweb.larc.nasa.gov/sse/>. [Accessed 20 March 2019].
- [35] Msibi SS, Kornelius G. Potential for domestic biogas as household energy supply in South Africa. *J Energy South Afr* 2017;28. <https://doi.org/10.17159/2413-3051/2017/v28i2a1754>.
- [36] Agua M de Ma y. Diagnostico de la Gestión de Residuos Sólidos en Bolivia - Dirección de gestión Integral de Residuos Sólidos de Bolivia. (DGIRS); 2011.
- [37] Packer N, Al-Shemmeri T. Conventional and alternative power generation vol. 1. Wiley; 2018. <https://doi.org/10.1002/9781119479420>.
- [38] Noor Ie, Martin A, Dahl O. Water recovery from flue gas condensate in municipal solid waste fired cogeneration plants using membrane distillation. *Chem Eng J* 2020;399:125707. <https://doi.org/10.1016/j.cej.2020.125707>.
- [39] Schöpfer S, Tiefenbeck V, Staake T. Economic assessment of photovoltaic battery systems based on household load profiles. *Appl Energy* 2018;223:229–48. <https://doi.org/10.1016/j.apenergy.2018.03.185>.
- [40] Teymoori Hamzehkolaei F, Amjadi N. A techno-economic assessment for replacement of conventional fossil fuel based technologies in animal farms with biogas fueled CHP units. *Renew Energy* 2018;118:602–14. <https://doi.org/10.1016/j.renene.2017.11.054>.
- [41] Theuerl S, Klang J, Prochnow A, Theuerl S, Klang J, Prochnow A. Process disturbances in agricultural biogas production—causes, mechanisms and effects on the biogas microbiome: a review. *Energies* 2019;12:365. <https://doi.org/10.3390/en12030365>.
- [42] Pezzuolo A, Boscaro D, Sartori L, Marinello F. Energy parameters and feedstock management in farm-scale biogas plants: survey in the North-East of Italy. *Jelgava, Latvia: Eng. Rural Dev.*; 2017. p. 725–9. <https://doi.org/10.22616/ERDev2017.16.N146>.
- [43] Smyth BM, McCullough G, Hakawati R, Rooney D, De Rosa F. What is the most energy efficient route for biogas utilization: heat, electricity or transport? *Appl Energy* 2017;206:1076–87. <https://doi.org/10.1016/j.apenergy.2017.08.068>.
- [44] Smyth BM, Murphy JD, O'Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? *Renew Sustain Energy Rev* 2009;13:2349–60. <https://doi.org/10.1016/j.rser.2009.04.003>.
- [45] Sattler-Hightex_Company. Biogas storage tanks for each plant design. Report n.d. [http://infota.siss.cl/concesiones/empresas/AguasAndinas/03%20Observaciones%20a%20las%20bases/CD%20Obras%20Especiales%20AS/PTAS%20MAPOCHO/01%20Licitacin/02%20Oferta%20EDAM/Oferta%20Tecnica/c\)%20ET%20y%20Catalogos/Commercial%20brochures/Sattler/Biogas](http://infota.siss.cl/concesiones/empresas/AguasAndinas/03%20Observaciones%20a%20las%20bases/CD%20Obras%20Especiales%20AS/PTAS%20MAPOCHO/01%20Licitacin/02%20Oferta%20EDAM/Oferta%20Tecnica/c)%20ET%20y%20Catalogos/Commercial%20brochures/Sattler/Biogas). [Accessed 20 May 2019].
- [46] Technical specification patruus 370 BG. n.d. http://www.2g-energy.com/media/1820/tsp_patruus-370bg_60hz_480v_en.pdf. [Accessed 14 February 2019].
- [47] Biogas engine E 2842 LE 322 technical data for 60%-CH₄, 40%-CO₂ 2011. http://powercan200.pl/wp-content/uploads/2014/04/1106_E2842LE322_biog-eng.pdf. [Accessed 25 January 2019].
- [48] Woldemariam DM. District heating-driven membrane distillation for water purification in Industrial Applications. KTH - Royal University of Technology; 2017. 978-91-7729-414-6.
- [49] Bhattacharjee S, Dey A. Techno-economic performance evaluation of grid integrated PV-biomass hybrid power generation for rice mill. *Sustain Energy Technol Assessments* 2014;7:6–16. <https://doi.org/10.1016/j.seta.2014.02.005>.
- [50] Chatzivasileiadi A, Ampatzis E, Knight I. Characteristics of electrical energy storage technologies and their applications in buildings. *Renew Sustain Energy Rev* 2013;25:814–30. <https://doi.org/10.1016/j.rser.2013.05.023>.
- [51] International Renewable Energy Agency (IRENA). Electricity storage and renewables: costs and markets to 2030. 2017.
- [52] Hossain M, Mekhilef S, Olatomiwa L. Performance evaluation of a stand-alone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia. *Sustain Cities Soc* 2017;28:358–66. <https://doi.org/10.1016/j.scs.2016.10.008>.
- [53] Fraunhofer ISE. Aktuelle Fakten zur Photovoltaik in Deutschland 2019. www.pv-fakten.de. [Accessed 1 February 2019].
- [54] Pathways to a smarter power system. Elsevier; 2019. <https://doi.org/10.1016/c2017-0-03015-x>.
- [55] Huang C-H. Modified neural network for dynamic control and operation of a hybrid generation systems. *J Appl Res Technol* 2014;12:1154–64. [https://doi.org/10.1016/S1665-6423\(14\)71674-8](https://doi.org/10.1016/S1665-6423(14)71674-8).
- [56] Aziz AS, Tajuddin MFN, Adzman MR, Ramli MAM, Mekhilef S. Energy management and optimization of a PV/diesel/battery hybrid energy system using a combined dispatch strategy. *Sustain Times* 2019;11. <https://doi.org/10.3390/su11030683>.
- [57] Ministerio de Hidrocarburos y Energia. Plan Eléctrico del Estado Plurinacional de Bolivia 2025 vol. 159; 2014. <https://observatoriocdbolivia.files.wordpress.com/2015/08/peebol2025.pdf>. [Accessed 16 July 2019].
- [58] Lako P, Simbolotti G, Tosato G. Biomass for heat and power - technology Brief 2010. n.d. www.etsap.org. [Accessed 20 May 2019].
- [59] Embotelladoras publican precios del agua para frenar especulación - Diario Pagina Siete. n.d. <https://www.paginasiete.bo/sociedad/2016/12/14/embotelladoras-publican-precios-agua-para-frenar-especulacion-120342.html#!>. [Accessed 14 May 2019].
- [60] Ghaem Sigarchian S, Paleta R, Malmquist A, Pina A. Feasibility study of using a biogas engine as backup in a decentralized hybrid (PV/wind/battery) power generation system — case study Kenya. *Energy* 2015;90:1830–41. <https://doi.org/10.1016/j.energy.2015.07.008>.
- [61] Yoo K, Park E, Kim H, Ohm J, Yang T, Kim K, et al. Optimized renewable and sustainable electricity generation systems for ulleungdo island in South Korea. *Sustainability* 2014;6:7883–93. <https://doi.org/10.3390/su6117883>.
- [62] Irena. The power to change: solar and wind cost reduction potential to 2025. 2016.
- [63] Economic survey of Latin America and the Caribbean 2018 - Plurinational State of Bolivia. *Econ Comm Lat Am Caribb* n.d. https://repositorio.cepal.org/bitstream/handle/11362/43964/134/EEI2018_Bolivia_en.pdf (accessed February 15, 2019).
- [64] Hill Nikolas, Norris John, Felix Kirsch CD, (Ricardo-Aea), McGregor Neil, Ricardo Uk E. Pastori (Trt) Is (Tepr). Light weighting as a means of improving Heavy Duty Vehicles ' energy efficiency and overall CO₂ emissions. Rep DG Clim Action 2015;199. https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/heavy/docs/hdv_lightweighting_en.pdf. [Accessed 28 May 2019].
- [65] Valsecchi C, Brink P ten, Bassi S, Withana S, Lewis M, Best A, Rogers-Ganter H, T Kaphengst FO. Environmentally Harmful subsidies (EHS): Identification and assessment study contract 07.0307/2008/514349/ETU/G1 - Annex 5: Subsidy level indicators for the case studies. Inst Eur Environ Policy; 2009. http://ec.europa.eu/energy/publications/statistics/doc/2009_energy_transport_figures.pdf. [Accessed 3 June 2019].
- [66] Rolamo N, Järvinen M, Nissinen P, Sahlstedt K. Risk assessment of nutrient discharges from biogas production: Finland. Helsinki: Aalto University - School of Engineering; 2017.