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# TECHNO-ECONOMIC OPTIMIZATION OF A STAND-ALONE HYBRID MICROGRID FOR THE RURAL ELECTRIFICATION IN SUB SAHARAN AFRICA

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## ABSTRACT
This paper is focused on the design of a stand-alone microgrid for rural electrification. The aim of this work is to define the best mix of energy sources and the optimal size of the energy storage for a small isolated village on the Ghana seaside. We obtain the optimal solution by simulating one year of operation for several different combinations of prime movers and battery sizes and comparing the economic performance in terms of levelized cost of electricity. We adopt a rolling-horizon strategy to simulate the microgrid operation, which optimizes generators and loads schedule over a 12 hours time horizon. We solve a Mixed Integer Linear Programming problem for each time step, exploiting weather forecast for predicting the energy available from sun and wind and taking into account a realistic operation of each component like energy losses and costs during start-up of dispatchable generators and ageing cost for the battery. The optimal configuration found includes a 30 $kW_{el}$ wind turbine, a 60 $kW_{el}$ photovoltaic array, a 30 $kW_{el}$ biomass fired ORC and a 50 $kW_{el}$ diesel. The limited use of the diesel engine in the optimal solution demonstrates that energy access in a sustainable and economic way is possible even in rural contexts. Finally, two sensitivity analyses are presented varying the cost of the biomass and the error of wind speed forecast.

## INTRODUCTION AND SCOPE OF WORK
Providing a sustainable access to electricity in rural areas is one of the biggest energy challenges of the next years. The availability of electrical energy is fundamental for the improvement of life quality, for the production of drinkable water and for the conservation of perishables. It allows the growth of new employments and the possibility for women and children to dedicate more time to education instead of domestic activities [1]. In many countries worldwide the rural electrification is still underdeveloped because of the prohibitive cost of national grid extension. The use of stand-alone microgrid is recognized to be the most promising solution to face this issue. In the last twenty years several humanitarian projects have been launched with the goal to prove the suitability of stand-alone systems for rural electrification: most of them rely on diesel engines and electrical battery storage. Most of them have encountered a number of issues which have limited the spreading of their use. Affordability and availability of diesel engines, the necessity of maintenance and spare part deposit and, most of all, the high cost of fuel transport have led to systems with a relevant cost of the produced electricity. In most of the cases these projects have been abandoned while in the others, 30-40 years old engines are still running with detrimental effects on the ecosystem because of oil leakages on the ground and air pollution. The use of green energy sources in stand-alone microgrid is nowadays a topic of big interest since it would guarantee a sustainable access to energy and a competitive cost of the electricity. A number of journal papers investigates this concept integrating wind turbines and solar photovoltaic panels with a back-up internal combustion engine. Most of these studies are realized using a commercial software called HOMER [2] which allows the analysis of stand-alone grid with a large number of different components. This code is the only commercial option for the optimization of hybrid microgrids but it is based on a series of assumptions and approximations which strongly affect the final solution in terms of optimal design of the system and levelized cost of electricity. Main limits, in authors' opinion, are related to the lack in definition of components operational constraints and the use of a limited number of heuristic dispatch strategies. More advanced models, based on MILP problem and rolling-horizon approach, have been presented in literature and they represent today the state-of-the art in the optimization of microgrid management [3, 4]. With these models it is possible to determine the optimal grid operation taking into account weather forecast, a realistic operation of each component and a flexible dispatch strategy. The scope of this work is to demonstrate the adequacy of a comprehensive methodology for the optimization and the design of a hybrid stand-alone minigrid for the electrification of a rural villages with a test case on a small community on Ghana seaside, selected in base of the availability of energy demand profiles obtained in previous studies.

## NOMENCLATURE

*Acronyms*

| | | |
|---|---|---|
| ES | | Energy Storage |
| ICE | | Internal Combustion Engine |
| LCOE | [USD/MWh] | Levelized Cost of Electricity |
| MILP | | Mixed Integer Linear Programming |
| ORC | | Organic Rankine Cycle |
| PV | | Photovoltaic array |
| SOC | [%] | State of Charge |
| WT | | Wind Turbine |

*Variables*

| | | |
|---|---|---|
| C | [USD] | Cost |
| E | [kWh] | Energy produced/consumed |
| EL | [kWh] | Energy level of energy storage |
| H | [kWh/m$^2$/day] | Daily irradiance on tilted plain |
| w | [m/s] | wind speed |
| $T_h$ | [hour] | Time horizon |

*Subscripts*

| | |
|---|---|
| inv | Investment |
| O&M | Operation and Maintenance |
| nom | Nominal |
| Y | Year |

## MICROGRID DESCRIPTION

The reference case of this study is a rural village located in Ghana with approximately 1000 inhabitants. The schematic diagram of the standalone microgrid investigated is shown in Fig.1.

We classify electrical loads in two categories. The first one are primary loads, which must be met in each time step so that their time schedule cannot be modified by grid management optimization; the average daily trend of power required from each primary load and their aggregate demand are shown in Fig.2.

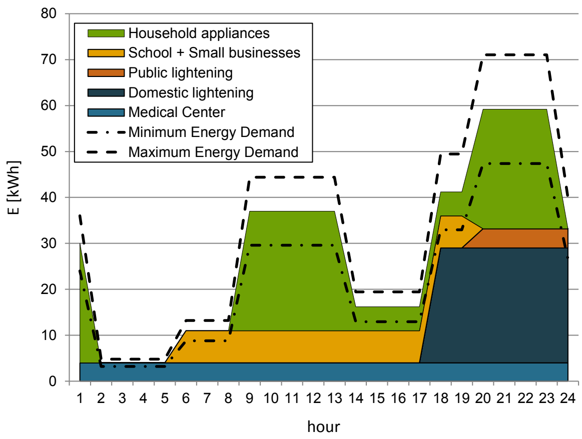


**Figure 2** - Daily average trend of each primary load demand and aggregate demand range

On the opposite, the energy request of schedulable loads can be met over a certain time horizon and their schedule is defined by the dispatch strategy algorithm. In this case, an osmosis plant and an icemaker are the schedulable loads while the primary loads are domestic consumptions. Schedulable loads data are reported in Table 1.

| | | Osmosis | Icemaker |
|---|---|---|---|
| Rated Power | [kW] | 7.2 | 7.5 |
| Minimum Power | [kW] | 3.6 | 3.75 |
| Start-up energy cost | [kWh] | 0 | 0.05 |
| Auto-loss factor | [%] | 0 | 1 |
| Minimum running time | [hour] | 1 | 2 |
| Daily energy demand | [kWh/day] | 55 | 82.39 |

**Table 1** - Technical data of the schedulable loads

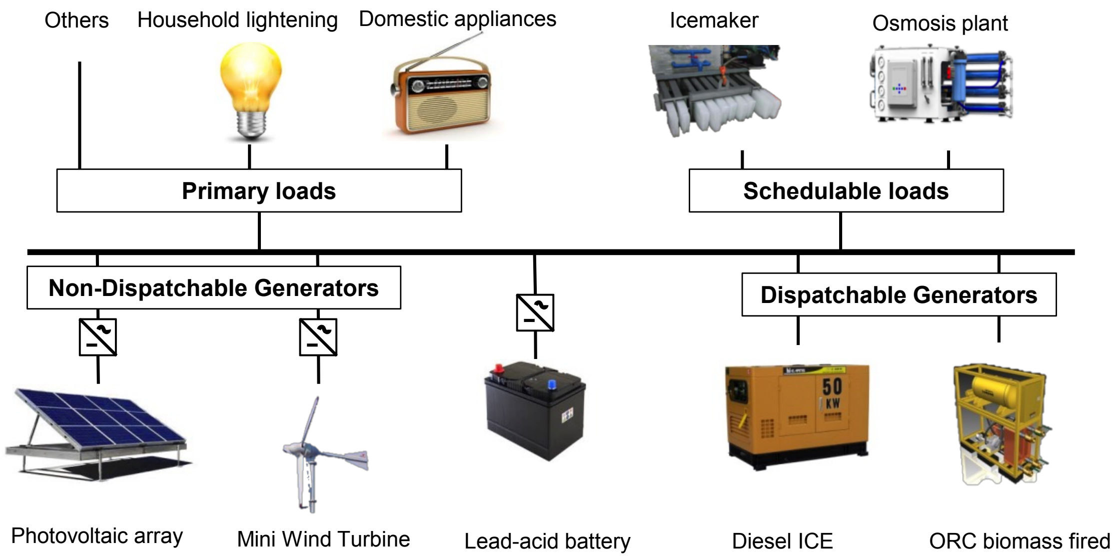


**Figure 1** – Schematic representation of the stand-alone hybrid microgrid studied in this work.

Two non dispatchable generators are considered in this work: photovoltaic panels and a small wind turbine. They allow for power production with negligible operation costs and no environmental impact. They are extremely attractive in rural context where the sustainability of the project is fundamental. Power is produced when the primary energy source is available (sun or wind) and they are not regulated by the power management system.

The power supplied by the PV array during a generic hour $t$ is calculated by eq. (1):

$$E_t^{PV} = \frac{H_t}{H_{ref}} E_{nom}^{PV} \eta_{BOS} \qquad (1)$$

where $H_t$ is the global irradiation on tilted surface (10° in this case), $H_{ref}$ is the reference irradiation (1000 W/m$^2$), $E_{PV,nom}$ is the power produced by the PV array in reference condition and $\eta_{BOS}$ is the balance of system efficiency (90%).

The power supplied by the WT during a generic hour $t$ is instead calculated by eq.(2):

$$E_t^{WT} = \begin{cases} 0, & w_t < w_{cutin} / \ w_t > w_{cutoff} \\ E_{nom}^{WT} \left(\frac{w_t}{w_{rtd}}\right)^3, & w_{cutin} \leq w_t \leq w_{rated} \\ E_{nom}^{WT}, & w_{rated} \leq w_t \leq w_{cutoff} \end{cases} \qquad (2)$$

where $w_t$ is the wind speed in hour t, $w_{cutin}$ is the cut-in wind speed (equal to 3.5 m/s), $w_{rtd}$ is the rated output wind speed (equal to 11 m/s), $w_{cutoff}$ is the cut-off wind speed (equal to 20 m/s) and $E_{WT,nom}$ is the rated power of the WT.

Monthly average daily availability of wind and sun in the site where the village is located, as obtained by hystorical meteo data, are reported in Fig.3.

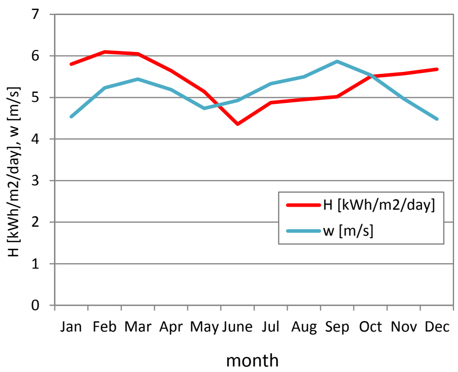


**Figure 3** – monthly average values for solar irradiation and wind speed

Dispatchable generators can be switched on and produce power when it is needed, playing an important role in microgrid operation. If they are properly used, they can reduce the size of non dispachable generators and battery storage, as well as avoid energy shortage of the battery and limit the energy wasted because of battery inefficiencies. In this case a traditional diesel Internal Combustion Engine (ICE) and an Organic Rankine Cycle (ORC) coupled with a biomass boiler cover this role. The last one is proposed as a renewable dispatchable alternative to fossil fuel generators for remote area energy supply. Part-load performances of both generators are reported in Fig.4: even if the ORC+boiler average efficiency is much lower than the ICE one, the availability of cheap wood biomass (70 USD/ton) and high cost of Diesel fuel (1 USD/liter) make this technology a valid solution to decrease operation cost and to limit the use of fossil fuel of the microgrid.

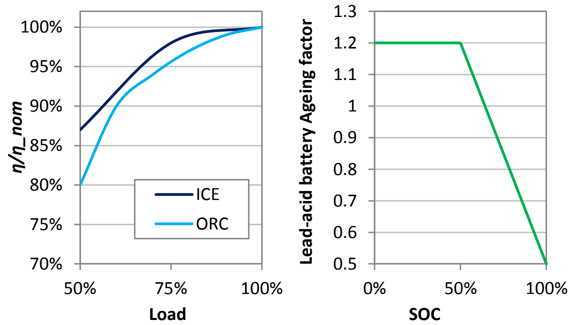


**Figure 4** - Part-load efficiency curves in relation to the nominal efficiency of the ICE and the ORC and the relationship between ageing factor and the SOC for lead-acid battery

Finally, energy storage is needed to ensure stable working conditions of the microgrid. In fact, it allows covering the energy demand when the energy production is not sufficient, while it can limit and possibly avoid energy dissipation when the energy supply exceeds the consumption. In this case a lead-acid battery is taken into consideration. Charge and discharge efficiencies are assumed to be equal to 80% and an ageing model is implemented to evaluate lifetime of the battery. The weighted *Ah-model* [5] is used to estimate the ageing of the component, assuming that the lifetime of the battery is affected by working conditions and attributing different ageing factors to different state of charge as reported in Fig 4.

## DESCRIPTION OF THE DISPATCH STRATEGY

Economic performance and operating costs of a microgrid are strictly related to the power management system which controls the schedulable loads and the dispatchable generators. A proper dispatch strategy is needed to ensure that energy demand is fulfilled while avoiding critical conditions as energy and power shortages. Load-following and set-point are the most common dispatch strategies used in standalone microgrid simulation [6]: in both cases, the operations of the dispatchable generators are chosen using only the actual values of energy demand and the SOC of the battery. Forecasts of energy production and consumption in the following hours are not considered.
In this paper, a more flexible and more farsighted dispatch strategy is implemented to simulate microgrid operation, The approach uses a rolling-horizon strategy based on a long-term optimization via Mixed Integer

Linear Programming (MILP). A similar approach has been proposed in literature [4] but here a more detailed description of components operation is considered.
The optimal schedule of each component (dispatchable generators, schedulable loads, energy storage) is obtained minimizing overall operating costs over a certain time horizon ($T_h$) considering the operational constraints of each the microgrid components. Forecasts of energy demand by primary loads and energy production by non-dispatchable generators over the whole time horizon are required to properly assess the schedule of the controllable components. The objective function to be minimized embeds a penalty term proportional to unmet energy demand and the actual operating costs. These last include fuel consumption, operation and maintenance and start-up cost for dispatchable generators and ageing cost for battery. Minimum number of running hours and maximum number of daily start-ups are few of the operational constraints that are introduced in the model. The grid management problem is formulated as a MILP in AMPL language [7] and solved with Gurobi [8].
At the beginning of each hour, the MILP is solved to obtain the optimal schedule for next $T_h$ hours; we follow the resulting schedule only during the first hour, then we update forecasts and solve the problem again in order to take into account more recent and reliable information.
A two days management obtained with the previously described approach is reported in fig.5. The microgrid set of generators is made of a 30 $kW_{el}$ PV, a 30 $kW_{el}$ WT, a 30 $kW_{el}$ biomass ORC and a 50 $kW_{el}$ diesel ICE, with a 50 kWh lead-acid battery. We adopt a time horizon of 12 hours. The first day is characterized by a massive energy production by non-dispatchable generators: the energy surplus, partially shaved by the schedulable loads, is stored in the battery and the ORC is switched on only during nocturnal hours when the energy consumption of primary loads is relevant. The second day experiences a very low energy supply by both wind and sun: in this case the ORC generator runs during the whole day, covering the daily energy demand and charging the battery up to a state of charge equal to 84%. During nocturnal hours, the ORC supply is not sufficient, so also the Diesel generator is switched on in order to cover the load consumption.
Thanks to a proper usage of dispatchable generators and schedulable loads, the strategy adopted allows to obtain a flattening of energy fluxes from and to the battery. This leads to a better economic performance because battery wear is limited and energy wasting related to inefficiencies in charge and discharge process of the battery are partially avoided.

## YEARLY SIMULATION RESULTS

With the aim to define the optimal microgrid design different combinations of generators and battery sizes are investigated and compared on the basis of one year of operation. From monthly average data of solar irradiation and wind speed the hourly values are numerically produced in order to respect the overall mean value for each period but providing days with large differences in the sun and wind patterns.
The component sizes considered in this study are reported in Table 2 with the corresponding investment cost and the O&M costs. The cost of the 50$kW_{el}$ back up ICE is 16500 USD with O&M cost of 0.32 USD/$kW_{el}$. Lead batteries sizes are 50, 150 and 250 kWh with a specific cost of 220 USD/$kWh_{el}$.

| | PV | | WT | | ORC | | |
|---|---|---|---|---|---|---|---|
| Size [kW] | $C_{inv}$ [kUSD] | $C_{O\&M}$ [USD/y] | $C_{inv}$ [kUSD] | $C_{O\&M}$ [USD/y] | $C_{inv}$ [kUSD] | $\eta_{nom}$ [%] | $C_{O\&M}$ [USD/y] |
| 15 | - | - | - | - | 90.3 | 11.5 | 0.04 |
| 30 | 56.9 | 58 | 67.0 | 250 | 158.3 | 12 | 0.07 |
| 60 | 106.0 | 108 | 118.5 | 440 | 277.5 | 13.9 | 0.13 |
| 90 | 152.8 | 156 | 165.0 | 615 | - | - | - |

**Table 2** – Investment and O&M costs for the renewable energies generators depending on the installed power

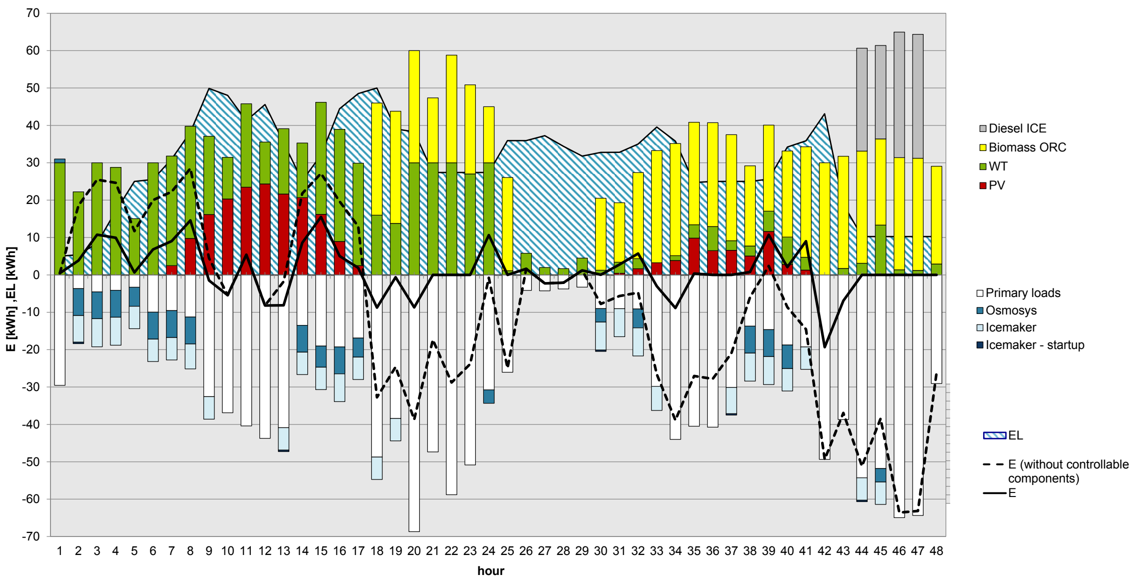


**Figure 5** - Hourly energy pattern of each components in a two-days microgrid management with the rolling horizon strategy.

In total 192 cases are investigated and results are reported in Fig 6 where three different charts are reported for a microgrid without ORC (Fig 6.a) and for ORC size of 30 $kW_{el}$. (Fig 6.b) and 60 $kW_{el}$ (Fig 6.c). Each point is representative of a specific generator set with the optimal battery size.
The results obtained without the use of the ORC show the impact of variable renewable energies (PV and WT) on the overall LCOE. Higher is the renewable installed power lower is the energy produced with the ICE with a relevant money savings and a strong reduction of the LCOE. Optimal solution (90 $kW_{el}$ WT and 60 $kW_{el}$ PV, 150 kWh ES) is found for variable energies generators sizes close to the maximum ones, however in this case more than 23% of the total energy is produced with fossil fuels and the ICE is not strictly limited to back up operations with detrimental effects on the environment. Furthermore the high share of energy produced by non dispatchable energy sources requires a large battery.
The adoption of a renewable dispatchable generator like the biomass ORC allows a further reduction of the ICE use because of the lower cost of the fuel. The optimal solution is obtained for the following component sizes: 60 $kW_{el}$ PV,30 $kW_{el}$ WT, 30 $kW_{el}$ ORC, 50 kWh ES with a good repartition of the energy produced by ORC (~37%) and by variable sources PV and WT (~53%). The ICE produces less than 10% of the total energy and the relevant share of energy from dispatchable generators allows to reduce the optimal size of the battery down to 50kWh.
Solutions with a smaller penetration of variable renewable energies have higher LCE because the increase of the ICE running hours and the high fossil fuel consumption. On the other side, big size of both WT and PV leads to an increase of LCOE because the necessity of a larger energy storage to face the the variability of both sun and wind and to decouple the energy production and the energy consumption.
It is finally interesting to note that with a 60 $kW_{el}$ ORC the optimal LCOE is higher than the previous one because the high investment cost is not justified by the resulting decrease of operational costs. However, the optimal solutions in this case are obtained with zero consumption of fossil fuel and an energy production totally from renewable sources.

## SENSITIVITY ANALYSIS

The influence of the assumptions about components cost and operational constraints can be very relevant and strongly affect simulation results in terms of final LCOE and optimal grid design. In particular the biomass cost has a big impact on the optimal ORC size and the optimal dispatch strategy. All the previous microgrid designs have been tested with different biomass costs and the breakdown of the LCOE for the optimal solutions is reported in Fig. 7 highlighting the different weight of investment and operational costs. Increasing the biomass cost from the reference cost of 70 USD/ton leads to an optimal solution in which ORC is not installed and the PV and WT sizes are increased; a bigger share from variable sources requires a larger battery size whose cost share increases. For a limited biomass cost decrease (down to 60 USD/ton), instead, the optimal size of the generators does not change respect to the basic scenario but a consistent part of diesel cost is shifted to biomass purchase and to install a bigger battery. Finally, for a further decrease of the biomass cost, a microgrid provided with a 60 $kW_{el}$ ORC able to cover the whole energy demand becomes the more convenient solution.

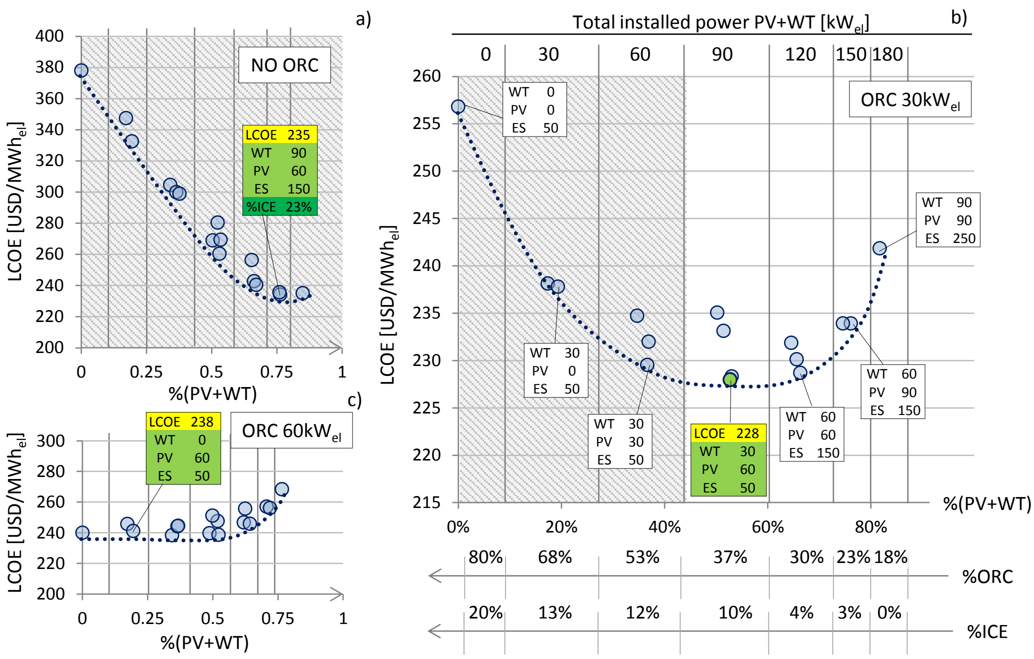


**Figure 6** – Yearly results for different microgrid design. In the boxes the optimal components sizes are reported. The grey shaded area highlights the solutions with more than 10% of the total energy produced by the ICE

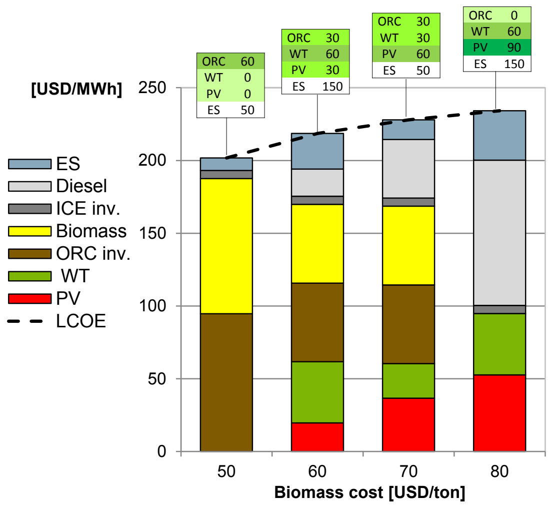


**Figure 7** - Optimal components size (table above), LCOE and influence of fuels and investment costs of each component in cost breakdown for different values of biomass cost.

A second sensitivity analysis is performed varying the accuracy on wind speed forecast and observing the effects on the actual LCOE. An error on prediction of loads consumptions or power generation leads to a definition of a schedule that, relying on inaccurate forecast, is not optimal. However the rolling horizon approach partially faces this problem: every hour the forecast is updated and the algorithm can partly remedy the inaccurate scheduling in previous steps. In particular the effect of a random error is almost negligible since it slightly varies the global energy forecast along the horizon period. To exasperate the effect of a forecast error different yearly simulations for the optimal micro grid configuration have been performed considering different amounts of error in wind speed (positive or negative for all the time steps). It has been assumed that the error in the first hour of the $T_h$ is zero and its absolute value increases linearly until it reaches the maximum value in the last hour of $T_h$. The effects on the results of different maximum absolute errors are reported in Fig. 8. Both overestimation and underestimation of the wind speed, (and so the energy production by the WT), lead to an increase of the LCOE and the grid operation cost, because energy production is partially shifted from the ORC to the ICE in order to face the scheduling errors. The wrong prediction affects also the battery operation: in fact some energy is wasted, because of battery saturation and larger inefficiencies occur, related to more relevant charge and in discharge processes.

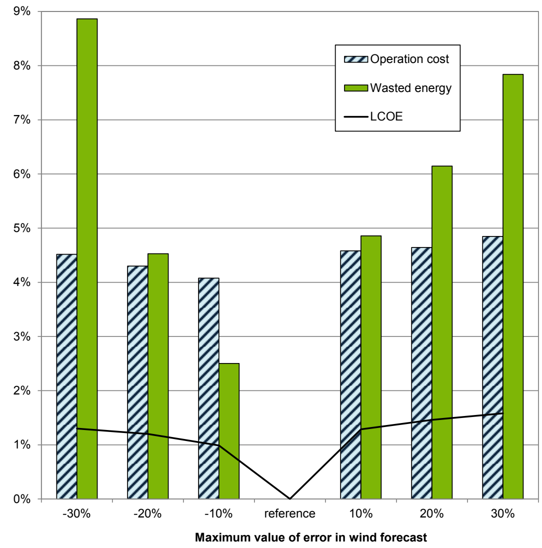


**Figure 8** - Percentage increase of LCOE, wasted energy and operation cost for different values of forecast error for a fixed microgrid (60 kW PV, 30 kW WT, 30 kW ORC, 50 kW ICE, 50 kWh ES)

## CONCLUSIONS

The novel method described in the paper, enables a better design procedure for an isolated microgrid. In particular, the investigated test case demonstrates the potential advantages in terms of LCOE reduction with the optimization of components size and with a proper procedure to allocate schedulable loads and prime movers operation. The method can be usefull both in selecting the proper prime movers combination and in managing the microgrid.

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