Integration of renewable energy in microgrids coordinated with demand response resources: Economic evaluation of a biomass gasification plant by Homer Simulator

Lina Montuori (*) (a), Manuel Alcázar-Ortega (a), Carlos Álvarez-Bel (b), Alex Domijan (a)

(a) State University of New York at Buffalo
Department of Electrical Engineering, 230 Davis Hall, 14260 Buffalo, NY (USA)
(linamont@buffalo.edu)

(b) Universidad Politécnica de Valencia, Institute for Energy Engineering
Camino de Vera, s/n, edificio 8E, escalera F, 5ª planta 46022 Valencia (SPAIN)

Abstract

This paper deals with how Demand Response can contribute to the better integration of renewable energy resources such as wind power, solar, small hydro, biomass and CHP. In particular, an economic evaluation performed by means of the micro-power optimization model HOMER Energy has been done, considering a micro-grid supplied by a biomass gasification power plant, operating isolated to the grid and in comparison with other generation technologies. Different scenarios have been simulated considering variations in the power production of the gasified biomass generator and different solutions to guarantee the balance generation/consumption are analyzed, demonstrating as using demand response resources is much more profitable than producing this energy by other conventional technologies by using fossil fuels.

[*] Corresponding Author: Lina Montuori. State University of New York at Buffalo. Department of Electrical Engineering, 230 Davis Hall, 14260 Buffalo, NY (USA) Tel. 716-418930 email: linamont@buffalo.edu

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1. Introduction

The use of renewable energy sources (RES) and a more efficient use of energy have been increasing in the world some years ago, mainly motivated for a growing environmental awareness in order to reduce green-house gases emissions and the increase of fuel prices that drives up the prices of energy [1]. Energy policies are promoting energy efficiency, distributed generation and renewable energy resources, increasing production from distributed generation like wind power, solar, small hydro, biomass and combined head and power (CHP). The production from wind and photovoltaic units is governed by the availability of the primary energy source and, moreover, there is often no correlation between the production and the local consumption.

In order to contribute to solve this problem, demand response (DR), understood as the ability of customers to modify their usual consumption profile as a reaction to different electricity prices in different periods of time [2], [3], [4], [5] must be considered in order to improve the performance of power systems and, consequently, to reduce the content of CO_2 in the atmosphere [6]. Reductions in the load when prices are high, disconnection of unnecessary load, management of devices to improve energy efficiency, etc. are actions to be considered within the overall power grid control.

Microgrids are small electrical distribution systems that connect multiple customers to multiple distributed sources of generation and storage [7]. This new concept of distributed generation means a novel approach to the management of electricity systems that, conversely to the traditional configuration based on large generation plants, resides on the connection of small modular generation units to the medium and low voltage grids. Renewable generators, together with the energy storage devices and DR, constitute a solution to the randomness of renewable energy sources.

Several previous studies have shown the potential of DR activities integrated with intermittent energy resources like wind energy and photovoltaic into an electricity system [8], [9], [10], [11], [12],

[13]. However, the integration of DR with the power production using the biomass resource remains unexplored.

The integration of RES and DR in microgrids requires the development of adequate tools to properly evaluate the produced impact since a technical, economic and environmental point of view. In this framework, authors have studied and evaluated different scenarios in order to analyze about how DR resources can contribute to properly integrate the variability of renewable generation resources since an economic point of view. The most active country in DR issues has been traditionally the US, and especially some areas as New York, New England or California [14]. However, this concept has become a very promising field in Europe during the last years, and particularly in countries as United Kingdom, Italy or Spain, where the development of DR programs is fortunately emerging nowadays and they are being demonstrated very useful due to their singular peninsular grids [15].

In order to develop the research presented in this paper, authors have studied the behavior of the biomass plant developed in the laboratory of the Institute for Energy Engineering of the Polytechnic University of Valencia (UPV) during 2012 [16]. Nowadays, biomass is considered as the renewable energy source with the highest potential to contribute to the energy needs of modern society for both the developed and developing economies world-wide [17], [18], [19]. Energy obtained from biomass, based on short rotation forestry and other energy crops, can significantly contribute to reach the objectives of the Kyoto Agreement in reducing the greenhouse gases emissions (GHG) and minimizing problems related to the climate change [20]. One example is the application of bio-fuels produced from biomass for the generation of electricity, which ensures the achievement of a negative carbon intensity of energy and the reduction of the total amount currently emitted (9-38%) [21], [22].

However, although the utilization of biomass feedstock holds great interest and it is expected that the participation of biomass-derived energy contributes in about 1500 EJ by 2050 to the world's energy supply, some technical issues need to be addressed, especially regarding to the cost-efficient transformation into usable energy forms [23]. In order to make progress in this field, this paper proposes the synergistic integration between the thermo-chemical process of biomass gasification for the power production and demand response, providing a micro-power system that is economic and efficiently viable compared to other existing technologies.

Previous studies on this field, applied to some Asian counties such as China and others, highlight the great potential of the crop residues to meet the energy demand. However, the unequally distribution across regions and the randomness of the biomass crop arise as an important barrier which still needs the support of governmental energy policies [24] for their diffusion. Moreover, it has been demonstrated in different studies applied to such different regions as Canada [25] or developing countries in Asia [26] that the limited availability of biomass, as well as the need of a large-scale importation of biofuels and wood pellets would be essential in order to properly supply the demand in these areas. In this framework, the challenge addressed through the present analysis is to explore the economic benefits of the utilization of demand response resources for the energy management of a micro-power system supplied by a biomass power plant in order to guarantee the systematic exploitation of this renewable source and a reliable power production, avoiding the expensive storage of feedstock and the uncertain and variable public subsidies.

This research includes an economic evaluation by means of the micro-power optimization model HOMER Energy. In this part, a feasibility analysis of the biomass gasification plant has been performed considering different scenarios, operating as isolated in comparison with other generation technologies, taking into account real prices of electricity and existing DR programs in different parts of the world.

The paper is organized as follows. The methodology developed and applied in order to perform the economic analysis is presented in Section 2, while Section 3 defines in detail the technical and economical inputs and outputs used to feed the hybrid power microgrid model based on Homer Simulator. The economic feasibility of the hybrid energy system is analyzed in Section 4 in order to assess the economic impact of the load flexibility of energy consumers in a stand-alone microgrid supplied by a biomass power plant and, finally, conclusions of this research are discussed in Section 5.

2. Methodology for the economic analysis

The economic analysis presented in this paper has been done by means of the simulation software HOMER energy. This modeling tool, developed by the National Renewable Energy Laboratory of the United States, is based on energy balance calculus. Once electrical and thermal loads are specified, the model searches for a combination of generation resources, including RES, in order to supply such loads at a minimum cost [27].

One important contribution of the authors is that the model has been adapted in order to consider also the participation of the demand side so as to integrate the variation of renewable resources by means of the modification of the usual pattern of consumption of electricity customers connected to a microgrid isolated from grid.

The schema shown in Figure 1 represents the different technology options considered in the experimental model, which is the subject of this work.

Multiple technology options are compared for a power system design. The configuration of the schema of the stand-alone system includes the primary load (consumers) and power generators supplied by diesel, natural gas and synthesis gas coming from gasified biomass (syngas).

The methodology used for the economic analysis, based on the algorithm of Homer Simulator, considers the following steps, as it is shown in Figure 2:

- Step 1: Definition of the primary load. In order to have a real load curve for the study, the primary load considered in the present study was measured at the fitness center at the UPV. The considered load curve was obtained by measuring the total power demanded by the building during the whole year 2011 in a quarter-hourly basis. UPV has developed an Integral Management and Control System (IMCS) called DERD (Distributed Energy Resources and Demand), which is able to measure and control the different facilities and buildings at the UPV [28], [29].These data were synthesized and adapted to be used in Homer in a hourly timescale for a period of one year (8760 values).
- Step 2: Selection of the equipment to consider. In this phase, components of the system needs to be defined and specified. In our case, syngas, diesel and natural engines were selected.

- Step 3: Characterization of each component of the equipment. In order to make this simulation as realistic as possible, the following variables of these engines need to be characterized: Investment costs, fuel and efficiency curves and CO2 emissions. Emission factors considered for this analysis can be provided to the simulator, as well as using default values.
- Step 4: Description of the properties of resources . For each of the considered resources of the system (diesel, natural gas and biomass for the microgrid under study), such properties as fuel costs, LHV, carbon content and other similar characteristics needs to be defined. In addition, for the particular case of biomass, the annual availability of this resource needs to be also defined.
- Step 5: Selection of the DR programs. DR programs to be considered needs to be parameterized. This is done by defining such economic parameters as DR prices, operation market prices or fossil fuel costs for alternative dual resources.
- Step 6: Selection of economic inputs. Economic inputs to be selected in the simulator include the annual interest rate and the project lifetime.
- Step 7: Simulations. In this study, different scenarios have been considered and different simulations have been carried out to evaluate the benefits of using biomass to produce electricity and DR to guarantee the balance between generation and demand.
- Step 8: Sensitivity analysis. After simulating, a sensibility analysis is carried out so as to study the influence that the variation of power energy supplied by the gasified biomass generator has on the economic feasibility of the considered hybrid system, taking into account both the increment of generation supplied by conventional technologies and the decrement of demand provided by customers. For each considered scenario, the variation of power supplied by the biomass engine in a specific range has been considered in order to evaluate how the reduction of power supplied by such renewable resource affects the total cost of the energy supplied to the microgrid.
- Step 9. Assessment of results. The last step of the methodology includes the analysis of results obtained in simulations performed in steps 7 and 8 considering the different

configuration abovementioned, and including the technical, economic and environmental point of view.

3. Hybrid power micro-grid system modeling

The contribution of demand response on the integration of biomass resources when the power supplied by such renewable resources varies has been assessed. In particular, the effect of the participation of demand response in order to guarantee the balance generation/consumption when the power production of a biomass gasification plant decreases is evaluated

3.1. Technical and economic characteristics of the equipments. Model inputs

The electric load to be satisfied considered in the different simulations and shown in Figure 3, corresponds to the real power demanded by the Sports Building located at the UPV in Spain.

Inputs related to the biomass generator have been obtained from an experimental plant designed and implemented in the laboratory of the Institute for Energy Engineering of Valencia (IIE) and in the framework of the "International Project for the Sustainable Energy in Developing Countries" to supply electricity to an isolated area in the Democratic Republic of Congo [23]. The plant consists of a fixed bed reactor plant coupled to an internal motor engine fuelled by syngas, as shown in Figure 4.

In particular, a FG Wilson UG14P1 generator has been used to produce electricity by using syngas [30]. This experimental plant was developed. The characteristics of this generator, shown in Table 1, were experimentally determined during the tests performed at the laboratory of the IIE.

This economic analysis evaluates the possible savings that could be obtained by producing electricity with biomass instead of using fossil fuels and considering demand response resources for balancing purposes. In order to do this, the electrical production with syngas has been compared with the following generators, described in Table 1:

- FG Wilson P13.5-4 generator powered by diesel
- FG Wilson UG14P1 generator powered by natural gas

Considered engines are applicable for supplying continuous electrical power (at variable load) instead of using electricity from the grid. The model considers no limitation to the annual hours of operation and an overload power of 10%. Although the selection of a diesel generator could not seem a good option due to the cost of the fuel, considering this technology is interesting because it is able to quickly start and stop at certain times of a day, satisfying some particular consumption during specific periods (i.e., peak demand).

As mentioned previously, resources used in this application have been biomass in form of syngas, natural gas and diesel. The availability of biomass regarding its quantity, quality and price, is a frequent problem when dealing with any energy project, mainly due to the absence of a biomass resource market. Otherwise, it must be noted that the biomass generated in a region could not be completely collected due to the difficult access, structure of the plant, difficult management or because it is used for other applications. Consequently, only the biomass used for producing energy in a central plant, called “available biomass” is here taken into account.

The used biomass waste was composed of lingo-cellulosic pellets due to their chemical characteristics, summarized in Table 2, such as their higher energy density and lower moisture content if they are compared with other forms of biomass as wood chips [31] [32]. Since pellets are compact, they are easy handling, transporting and manipulating. Moreover, the process of pellets feeding to the gasifier can be automated for working in a continuous way.

Recent studies [33] [34] show that not only industrialized countries such as USA and European countries generate energy from biomass, but most of the biomass use occurs in highly populated rural areas of developing countries like Kenya, India, China or Congo [35] [36]. In particular, in the Democratic Republic of the Congo, country for which the experimental plant used in this research was designed and developed, only 9% of the 65 million Congolese people have the opportunity to use electric power. This critical energy scenario opens up enormous possibilities for the dissemination of installations of gasified biomass. In this type of facilities using biomass for power generation, increased demand and lower resource limitations in the quality of combustion result in significant reductions in cost [37].

The following simulations have been developed estimating an average value for diesel and natural gas resources, based on the latest data provided by “The world bank” database [38] regarding developing countries. The cost of diesel is estimated equal to 0.8 €/l and the cost of natural gas to 0.6 €/m3. Regarding the biomass resource, the wide availability of lingo-cellulosic biomass in these areas and the low costs of transportation and processing allow to estimate the cost of raw biomass to be equal to 22 €/ton. The different costs considered have are included in Table 3.

3.2. Definition of scenarios

A significant increase in the spread of the biomass gasification technology may be facilitated through the use of DR, so that the proper integration between the gasification for power generation and DR may guarantee a more adequate reliability in electricity production with biomass. Based on this, the present evaluation has been performed by considering different four scenarios in a microgrid isolated from the grid with different generators fed respectively with fossil fuels such as natural gas and diesel, and, biomass as renewable fuel. These four scenarios are defined by the following characteristics:

-Scenario 1: This is the base scenario which will be used as baseline to compare the rest of scenarios. In this one, the total load is supplied by the microgrid where all the generators produce electricity up to their nominal power, according to economic criteria.

-Scenario 2: The power that the renewable generator is able to produce is reduced up to 75% of its nominal power, so that the total load must be supplied by the other generators.

-Scenario 3: It is similar to scenario 2 but the production of the renewable generator is reduced up to 50% of its nominal power.

-Scenario 4: The renewable generator cannot produce any power value, so that the total load is supplied with only not renewable resources.

3.3. Economic output

The economic outputs provided by Homer, for each simulation are the following:

- Initial capital cost
- Annualized capital cost
- Annualized replacement cost.
- O&M (operation and maintenance) cost for each component of the system
- Fuel cost
- Annualized total cost

The project lifetime of the simulations was fixed in 15 years and the interest rate was neglected. The project lifetime is used to calculate the annualized replacement cost and the annualized capital cost of each component, as well as the total net present cost (NPC) of the system

The total NPC is the main economic output obtained with HOMER and it is used to rank all the configurations of the different scenarios here analyzed.

The net present cost is calculated by using the following expression:

$$NPC = \frac{\sum C_{ann,tot}}{CRF(R_{proj})} \quad (1)$$

where:

- $C_{ann,tot}$ is the total annualized cost (€/yr)
- CRF is the capital recovery factor (yr)
- R_{proj} is the project lifetime (yr)

The CRF is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows) and it is given by the expression:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (2)$$

where:

- i is the real interest rate
- N is the number of years considered for the recovery of the investment

In a first analysis, the NPC for different configurations of the microgrid has been calculated in order to study the economic reliability of renewable generation compared to traditional one depending of the variation of the power energy production. During a second analysis, results obtained from the different scenarios described above have been determined taking into account that when a problem appears and the syngas generator cannot completely supply its nominal power, the rest of generators in the microgrid must supply the difference in order to completely supply the load connected to the microgrid. Consequently, an over cost arises due to the fact that the energy produced with the other technologies is more expensive. This extra cost, expressed in €/kWh, has been calculated by means of the following expression:

$$\Delta C = \frac{Cv_i - Cv_1}{h_i - h_1} = \frac{\Delta Cv_i}{\Delta h_i} \quad (3)$$

Where:

- ΔCv_i (€/kW) is the difference between the variable costs of electricity (fuel and operation and maintenance) in the situation "i" and the base case with the syngas generator working at full load.
- Δh_i (h) is the difference between the operating hours in the situation "i" and the number of hours when the syngas generator is working at full load.

By (3), the over cost produced in the extreme situations of failure of the syngas generator is evaluated by considering that other generators supply the difference. However, there is another possibility that must be considered: this possibility is based not on the increment of conventional generation, but on the reduction of load that customers enrolled in a kind of DR programs could provide. If the demand side is able to guarantee the balance generation/consumption by reducing load in a cheaper way than the rest of generators by producing more power, this solution will be preferred. Therefore, in this simulation it is necessary to evaluate if the demand appears to be the most convenient solution.

4. Economic feasibility of the hybrid energy system. Discussion and Results

4.1. Integration of biomass renewable energy in a microgrid

Table 4 shows the technical results of the simulations performed with Homer Energy for the different scenarios. These technical results include the number of working hours, the fuel consumption and the electricity produced for each scenario. Two situations have been considered for each scenario, whether the natural gas generator (G2) or the diesel generator (G3) is producing the extra required power. The economic evaluation between the base scenario and the rest of scenarios has been done by comparing the variable costs between each couple of situations as the fix costs (investments) will be the same in both scenarios. These costs include the cost of the fuel and the operation and maintenance cost.

Regarding the economic results of this analysis, summarized in Table 5, they show that the production of electricity through the gasified biomass is more convenient than the production through traditional fossil fuels. The NPC of electricity production by biomass results to be lower than by conventional electric generators. When the electric power generated by gasified biomass decreases, the NPC for different configurations of the microgrid increases, in particular with the diesel generator, which shows the most expensive results.

Results obtained from scenarios 2, 3 and 4 have been compared to scenario 1 (case base), where all the generators are able to provide their nominal power. Table 6 shows the mean extra cost per kWh due to the decrement of electricity produced by gasified biomass and the subsequent increment in the power generation by other sources, as it has been explained before.

Consequently, values shown in Table 6 represent the average price that should be paid to not renewable generators per each kWh that they produce when the syngas generator reduces production.

4.2. Integration of demand response programs

In this simulation three programs currently active in the US for residential and small customers (which according to the reducible power considered in our microgrid would be the most realistic case) are considered [14]:

- “Demand Bidding Summer Discount Plan”, offered by the Southern California Edison. Participants present bids to reduce their load from noon to 8:00 pm on weekdays. Payments are on the order of $0.50 per kWh of real power reduction (about 0.35 €/kWh)
- “Voluntary Load Response Program”. This is the most popular program offered by Commonwealth Edison in Illinois. On average, participants are paid $0.25 per kWh reduced (about 0.18 €/kWh), depending on the hourly energy market
- “Cool Currents program”. This program is offered by the Detroit Edison Energy Company in Michigan and it is based on a direct payment to customers of $0.02 per interruption. The mean interruptible power is about 0.85 kW per unit, and the

duration of interruptions is 15 minutes, that means an average payment of $0.10 per kWh (0.08€/kWh).

In all of cases, the price paid to customers participating in the different demand response programs is lower than the cost of producing additional power to supply the total load consumption.

Actually, prices are bounded between 0.44 and 0.52 €/kWh for natural gas, and between 0.52 and 0.62 €/kWh for diesel. Considering the prices for different demand response programs as included, customers use to participate in such programs for lower prices.

4.3. Benefit evaluations for customers and the power system

The benefit can be evaluated based on the hypothesis considered in [14] that customers will manage their loads when the payments obtained from the system are 50% or more than the cost of the offered amount of power, according to the weighted average price in its electricity contract. The average price that customers may pay can be calculated by considering the fix and variable costs detailed in Table 5, taking an amortization period of 15 years for the capital cost and the total annual consumption of 23,360 kWh/year of the load connected to the microgrid. Then, the average prices shown in Table 7 are obtained.

Considering that customers will provide demand response services when they obtain a payment equivalent to prices shown in Table 7, the avoided cost for the system when demand response is used to cover reductions in the energy produced by the syngas generator can be evaluated. Results are shown in Table 8.

The cost of energy when the other generators are used has been calculated as the product of the additional energy that is generated (equal to the energy that the syngas generator is reducing the generation) and the average prices shown in Table 6 for the Scenario 2, as reductions are lower than the 25% of the total energy production.

Once again it is confirmed the economic profitability of using demand response resources. Table 8 shows that payments to customers reducing their consumption would be equivalent to the 66.9% and 56.1% of the cost if generators of natural gas or diesel, respectively, produce the same energy. That means an avoided cost for the system of 33.1% and 43.9%, respectively.

As it has been seen in these examples, it is demonstrated that using DR resources in order to balance the generation and the consumption of a microgrid is much more profitable than producing this energy by other conventional technologies by using fossil fuels. Additional benefits are the improvement of the efficiency in the microgrid as the total energy consumed is reduced, the reduction of energy loses in the grid because the transmitted power is lower, and the subsequent reduction in the carbon footprint as the energy produced by means of fossil fuel generators is also reduced.

5. Conclusions

The comparison between the power generation of a stand-alone system supplied by biomass, natural gas and a diesel engine underlines that when the electric power generated by gasified biomass decreases, the NPC for different configurations of the microgrid increases, especially with the diesel generator, that shows the most expensive results. In particular:

- The NPC for the microgrid is 108 k€/year when the biomass plant is working at full load, which is the minimum compared to other situations where the biomass plant is working at a different regime
- The NPC increases up to 218 k€/year when the biomass production is neglected, that means an increment in this index for the system higher than 100%

On the other hand, the convenience of using DR resources in order to balance the system generation/consumption when a reduction in the power supplied by the gasified biomass generator occurs is enhanced by this research:

- The participation of DR resources to solve unbalances in a non-connected microgrid is economically the most profitable option not only for customers, which receive an incentive and pay less for the energy that consumes, but also for the microgrid as a whole, which reduces the total operation cost, the energy loses in the grid and the carbon footprint
- In isolated microgrids, the cost of supplying the variability of renewable resources with other conventional resources is more expensive than requiring the participation of customers to reduce the total load in the microgrid.

These aspects have been numerically demonstrated by means of simulations with Homer

Energy, considering the characteristics of existing DR programs offered by different electrical companies worldwide. In all of cases the cost of demand response participation is lower than the cost of producing more energy with the available resources in the microgrid. In particular:

- Prices for additional power production supplied with conventional technologies for the microgrid has been calculated, being bounded between 0.44 and 0.53 €/kWh for natural gas, and between 0.52 and 0.62 €/kWh for diesel.
- Considering the prices for different DR programs as it has been indicated, customers use to participate in such programs for lower prices. According to the hypothesis considered in this research and the simulations above mentioned, payments to customers reducing their consumption would be equivalent to the 67% and 56% of the cost if generators of natural gas or diesel, respectively, produce the same amount of energy. That means an avoided cost for the system of 33% and 44%, respectively.

These figures demonstrate as the integration of renewable generation fuelled by biomass and DR resources in microgrids improves the global efficiency of the power system, reducing the energy losses with the subsequent reduction in the carbon footprint.

6. References

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