E3S Web of Conferences **414**, 02015 (2023) https://doi.org/10.1051/e3sconf/202341402015
SUPEHR23

POWER TO GAS PLANT FOR THE PRODUCTION OF BIO-METHANE: TECHNO-ECONOMIC OPTIMIZATION

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Abstract. In this work, a power to bio-methane plant in which the biogas is produced from an anaerobic digester plant and the hydrogen is generated by using an electrolysis unit powered by a renewable plant (photovoltaic or wind-based), is designed and sized. The plant sizing is carried out by applying a techno-economic multi-objective black box optimization approach. A numerical code, built by using the Matlab software package, is used to evaluate components sizes and to assess plant costs. This code is implemented in an optimization workflow developed in the modeFRONTIER environment. This approach allows to identify the optimal size of the plants components with the aim of maximizing the annual bio-methane producibility and minimizing its levelized cost. The results show that for a low-price electricity scenario (45 €/MWh) the minimum levelized cost of bio-methane (LCOBM), equal to 84.6 €/MWh, is obtained adopting the PV-based configuration. On the contrary, considering an high-price scenario (135 €/MWh), the minimum LCOBM is obtained for the Wind-based plant and is equal to 34.9 €/MWh.

1 Introduction

The "power to gas" concept with the synthetic methane production, is a very promising approach for storing the renewable electricity by producing a fuel that can be easily distributed through widespread natural gas network. To this aim electrolytic hydrogen and carbon dioxide react to produce methane according to the Sabatier reaction [1]. As CO_2 source, an interesting option is the using of CO_2 coming from organic biomass conversion processes like the anaerobic digestion. The biogas direct methanation, in which biogas and hydrogen react for producing bio-methane, is a process able to produce up to 80% more methane in comparison to conventional biogas upgrading methods [2] by also assuring economic advantages in terms of lower investment and operating costs [3] since the biogas upgrading section is not needed. The attention to this bio-methane production technology is high as confirmed by the more recent technical literature [2],[4],[5]. In this contest the present work aims to study, from technical and economical points of view, "power to bio-methane" (PtBM) plants, by evaluating the optimal sizes of the components that allow to maximize the biomethane production according to the availability of the renewable sources, as well as to minimize the plant costs. Thus, this study is focused on the development of a techno-economic optimization model based on a numerical algorithm (Sizing Plant code), developed

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in Matlab environment, and a multi-objective genetic algorithm (pilOPT), available in modeFRONTIER software package.

2 Power to Bio-methane plant configuration

The concept layout of the power to bio-methane plant (PtBM) is illustrated in figure 1. The biogas (40% CO_2, 60% CH_4), produced by an anaerobic digester plant (based on the Bekon dry digestion technology [6]) and the green hydrogen, generated by using an electrolysis unit powered by a renewable power plant (a PV plant or a wind farm), react in a direct methanation unit for producing bio-methane. Thus, the main components of this plant are:

- The RES plant based on a PV power plant (the selected single module is a 560 W monocrystalline solar panel that has an efficiency of 20.5% at standard test conditions and is manufactured by Jinko Solar [7]) or a Wind farm (horizontal axis wind turbines with an efficiency ranging from 30% to 35% have been selected).
- The electrolysis unit (the selected PEMEL unit consists of modules of 1 MW_{DC}, operates at 20 bar and produces 16.8 kg/h with a specific energy consumption of 59.6 kWh/kg [8]).
- The direct biogas methanation unit, operating at 280 °C and 20 bar, based on a double pass design with the condensate removal after the first pass. The composition of the produced biomethane is CH_4 98.7%, H_2 0.9%, CO_2 0.3%, H_2O 0.1% [9], and the LHV (Low Heating Value) is equal to 49.7 MJ/kg (the molar ratio CO_2/H_2 is set equal to 4).
- The storage unit based on gas steel cylinders for hydrogen storage at 200 bar.
- The compression unit based on reciprocating compressors (this technology ensures good performances especially for high-pressure applications).

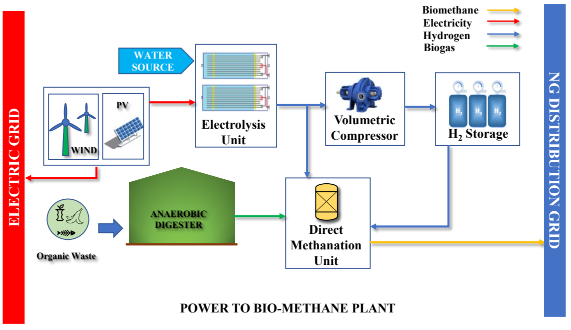

Fig. 1. Power to Bio-methane plant concept

3 Multi-objective Optimization approach: techno-economic design

The techno-economic optimization of the PtBM plants has been performed by developing a multi-objective model by using the modeFRONTIER (ESTECO Engineering) software package. The optimization problem is based on the evaluation of the variables, set as input variables, that satisfy the objectives and constraints established according to the design problem. The workflow of the techno-economic optimization model is reported in Figure 2. It is possible to notice the interconnected variable nodes (Input Variables), the defined application node (the Sizing Plant code is the solver) and the logic nodes (i.e. the Scheduling Start node). The input variables are the H_2 storage capacity and the RES plant size; the objectives are: i) maximizing the annual plant operating hours (OPH) and the annual biomethane production and ii) minimizing the annual electricity diverted to the grid and the levelized cost of bio-methane (LCOBM); the assumed constraint concerns the number of annual operating hours (fixed at 7500).

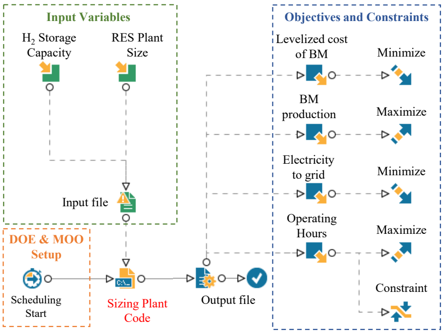

Fig. 2. Workflow of the optimization model.

The levelized cost of bio-methane (LCOBM) is calculated by using the equation:

$$LCOBM = \frac{\left(\sum_{n=1}^{N} C_{Inv,n,act} + \sum_{n=1}^{N} C_{Rep,n,act}\right) \cdot CRF + \sum_{n=1}^{N} C_{O\&M,n,act} - \sum_{n=1}^{N} R_{EGRID,n,act}}{\sum_{n=1}^{N} m_{BM,n}} \quad (1)$$

where $C_{Inv,n,act}$ and $C_{Rep,n,act}$ are the annualized and actualized plant investment costs and replacement costs, respectively, $C_{O\&M,n,act}$ refers to the actualized operating and maintenance costs, CRF is the Capital Recovery Factor, $R_{EGRID,n,act}$ is the actualized annual revenue due to the electricity excess selling and $m_{BM,n}$ is the annual bio-methane production. The terms in eq.1 are calculated by eqs 2-5 as in ref [7]:

$$C_{n,act} = \frac{C}{(1+I_r)^n} \quad (2) \qquad I_r = \frac{i-f}{1+f} \quad (3)$$

$$CRF = \frac{I_r \cdot (1+I_r)^n}{(1+I_r)^n - 1} \quad (4) \qquad R_{EGRID,n,act} = \frac{p_{el} \cdot E_{GRID,n}}{(1+I_r)^n} \quad (5)$$

In eq.5, p_{el} is the electricity price and $E_{GRID,n}$ is the annual electricity diverted to the grid. The plant lifetime (N), the nominal interest rate (i) and the expected inflation rate (f) are assumed equal to 20 years, 3% and 2% [10]. The main economic data are listed in Table 1**.**

Table 1. Economic data

Parameter	Unit	Investment cost (C_{Inv})	O&M cost ($C_{O\&M}$)
PV plant costs [11]	€/kW	405.5	1.58%· C_{Inv}
Wind plant costs [12]	€/kW	1260	1.1%· C_{Inv}
PEM Electrolyzer costs [7]	€/kW	1678	3%· C_{Inv}
Compression unit costs [13],[14]	€	$36079.54 \cdot P^{0.6038*}$	8%· C_{Inv}
H_2 storage system costs [15]	€/kg	490	3%· C_{Inv}
Methanation unit costs [16]	€/kW	450	3%· C_{Inv}
Biogas price [17]	€/m^3	-	0.243

* P is the Compression Unit size expressed in kW

The O&M costs have been calculated as percentage of the initial investment cost for each plant component. The replacement costs have been considered only for the compressor unit and the PEM electrolysis unit (after 10 years). These replacement costs are assumed equal to the 100% and 40% of the initial investment cost, respectively [18].

4 Techno-economic optimization results

The sizing optimization procedure has been applied to two case studies referring to the installation of solar and wind power plants, respectively. The selected installation site for the two PtBM plants is the Puglia Region (South of Italy). In order to perform the analysis, the data related to the solar irradiation (for the PV plant) and wind speed (for the wind farm) have been obtained by the database of the commercial software HOMER pro. The further input parameter needed for the modelling is the biogas mass flow rate, assigned equal to 500 Nm^3/h. Results of the sizing optimization procedure are the pairs of values: H_2 storage capacity and size of the renewable power plant (PV plant or of the Wind farm). These data represent the values that maximize the bio-methane production and minimize the electricity diverted to the grid for the fixed constraint related to the operating hours (7500 annual plant operating hours). Being the optimization problem classified as a multi-variable and multi-objective optimization problem, the results are available as a set of "optimal solutions" or a Pareto front. Figure 3 depicts the Pareto fronts for the two studied plant configurations. Along these fronts two points can be noticed: i) the point HSC_{min}, that is the optimal solution in terms of minimum hydrogen storage capacity (at the maximum RES plant size) and ii) the point $Size_{min}$, that refers to the optimal solution in terms of minimum RES plant size (at the maximum hydrogen storage capacity). In the PV-based plant configuration, these values are 794 kg (at the maximum plant size of 25 MW) and 18.8 MW (at maximum hydrogen storage capacity of 2000 kg), respectively. In the Wind-based plant configuration these values are 540 kg (at the maximum plant size of 25 MW) and 13.8 MW (at maximum hydrogen storage capacity of 2000 kg), respectively. In Figure 3 it is possible to highlight an "optimal design zone" that allows to restrict the range of the optimal solutions to values that represent a right compromise between the capacity of the H_2 storage and the size of the renewable power plant. By analysing the results, it is possible to highlight that if a wind farm is installed for realizing the PtBM plant, lower sizes of this renewable plant are needed in comparison with the sizes required in the case of the PV plant installation (a wind farm with a size in the range 15-20 MW vs a Photovoltaic plant with a size in the range 19-23 MW). Similarly, the range of the H_2 storage capacity is smaller in the wind-based configuration with respect to the PV-based plant configuration (700-1200 vs 900-1400 kg). Moreover, according to the Pareto front, it has been calculated that i) the bio-methane production is about in the range 1750-1950 tons per year and 1800-2200 tons per year for the PV-based and Wind-based plant configurations, respectively, ii) the electricity surplus diverted to the grid, varies between 9000-14000 MWh per year and between 12500-25000 MWh per year for the PV-based and Wind-based plant configurations, respectively.

The techno-economic design has been carried out according to the optimization workflow presented in Figure 2. The aim has been to find the pairs of values of H_2 storage capacity and RES plant size which allow to reach the minimum value of the LCOBM within the "optimal design zone" of the Pareto fronts, for both PV-based and Wind-based plant configurations. Furthermore, three different electricity price scenarios have been considered: i) low price (LP, $p_{el} = 45€/\text{MWh}$), ii) medium price (MP, $p_{el} = 90€/\text{MWh}$) and iii) high price (HP, $p_{el} = 135€/\text{MWh}$). Figure 4 shows the LCOBM values obtained for the optimal PV-based and Wind-based configurations, for each electricity price scenario. For the LP scenario, the LCOBM in the PV-based configuration is smaller than that of the Wind-based configuration (84.6 €/MWh vs. 89.7 €/MWh) due to the higher investment and overall O&M costs of the Wind plant with respect to the PV plant. On the contrary, for the MP and HP scenarios, the LCOBM values result smaller in the Wind-based configuration than those in the PV-based one, thanks to the greater electricity surplus that implies higher revenues. The minimum value of the LCOBM is equal to 34.9 €/MWh. With respect to the RES plant size and the H_2 storage capacity, the PV-based configuration shows the same pairs of values for all scenarios (21.5

MW, 1080 kg). In the Wind-based configuration, the optimal pair of values result equal to 18.5 MW and 780 kg in the LP and MP scenarios and 20.0 MW and 680 kg in the HP scenario.

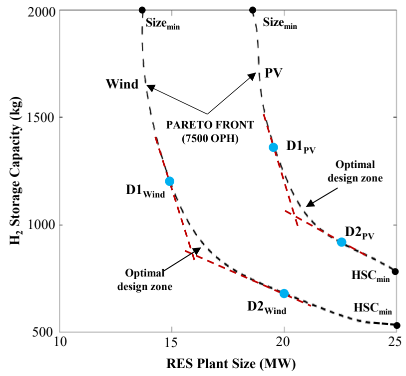

Fig. 3. Pareto fronts at 7500 OPH for PV-based and Wind-based configurations.

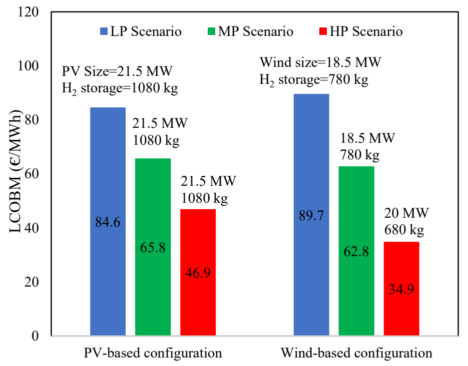

Fig. 4. LCOBM for the optimal PV-based and Wind-based configurations for different electricity price scenarios.

Table 2 shows the components sizes as well as the annual mass and energy balances of the PtBM plant configurations (PV-based and Wind-based) in the optimal design points and for the considered electricity price scenarios.

Table 2. Comparison of components' sizes, and annual energy and mass balances at the optimal design points which guarantee the minimum LCOBM for each electricity price scenario.

		PV-based configuration	**Wind-based configuration**	
PtBM Plant		**LP/MP/HP**	**LP/MP**	**HP**
RES plant size	MW	21.5	18.5	20
Biogas flow rate (at digester full load)	Nm^3/h	500	500	500
Annual Electric energy production	MWh	34054	42438	46960
Annual Electric energy to the grid	MWh	11961	18912	20845
Annual Biogas consumption	tons	3147	3494	3649
Electrolysis unit	kW	8000	6000	7000
Electrolytic Hydrogen production (at full load operation)	kg/h	134.9	101.2	118
Hydrogen to the methanation reactor (at full load operation)	kg/h	71	71	71
Hydrogen compression unit	kW	164	123	143
Hydrogen storage capacity	kg	1080	780	680
Methanation reactor production capacity	$MW_{th,LHV}$	4.92	4.92	4.92
Bio-methane production (at full load operation of the methanation reactor)	kg/h	355.8	355.8	355.8
Annual Electric energy consumption of the Electrolysis unit	MWh	22048	24526	25590
Annual Hydrogen production	tons	373.7	415.7	433.9
Annual Biomethane production	tons	1866.6	2072.9	2164

5 Conclusions

In this work, the techno-economic design of a biogas to methane plant has been carried out by applying a multi-objective black box optimization approach. In the analyzed plant, the biogas is produced from an anaerobic digester plant and the renewable hydrogen is generated by using an electrolysis unit powered by a RES plant (photovoltaic and wind). The plant sizing is performed by means of a numerical code built using the Matlab software package. This code is implemented in an optimization workflow developed in the modeFRONTIER environment. First, the technical optimization has been carried out in order to evaluate the optimal sizes of the RES plant and of the hydrogen storage system according to the maximum annual biomethane production, and the minimum annual electricity diverted to the grid. Results in terms of “Pareto fronts” have been obtained and an “optimal design zone” has been identified. The economic optimization has been carried out in order to identify, in the “optimal design zone”, the pairs of values of H_2 storage system size and RES plant size which allow to assure the minimum value of the LCOBM. Three different electricity price scenarios have been considered: i) low-price (45 €/MWh), ii) medium-price (90 €/MWh) and iii) high-price (135 €/MWh). The results show that the lowest and highest values of LCOBM are obtained for the Wind-based configuration by considering the high-price electricity scenario (34.9 €/MWh) and the low-price electricity scenario (89.7 €/MWh), respectively.

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