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EXECUTIVE SUMMARY OF THE THESIS

Electrification of Gasification Reactors for Biomass-To-Methanol Plants: Techno-Economic Analysis

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

This Thesis Work explores the techno-economic feasibility of the electrification of gasifiers for Biomass-to-Methanol plants. Two state-of-the-art alternative paradigms for gasification are considered: a directly heated oxygen-blown gasifier and an indirectly heated one. Electrification is achieved by inserting resistive elements inside the gasification reactors to satisfy the requested thermal load through the Joule effect. Gasifiers, once equipped with the electric resistors, can operate alternately with the traditional operation, therefore based on the oxidation of part of the inlet biomass, in full electric mode or in hybrid configuration.

The scope of this research study is to perform a differential economic analysis of the aforementioned electrified plants with respect to the conventional ones to establish the set of conditions for a cost-effective investment. Depending on the type of gasifier, operating the plant with partial or complete aid of electrical resistances permits either to save biomass and obtaining biochar as extra product or to raise the Biomass-to-Methanol efficiency. In all cases, electrification allows to increase the plant carbon efficiency. After design and modelling of the biomass to methanol plants with process simulation software (Aspen Plus®), economic analysis is carried out considering the connection of the plants with the electric grid with variable electricity prices and with dedicated PV plants of different size.

2. Plant Modelling

BtMeOH plant, characterized by a 100 MWth (LHV based) biomass input, is composed of five sections: biomass pre-treatment, gasification, syngas cleaning and conditioning, methanol synthesis and heat recovery, as depicted in
Figure 1 [1] .

Two types of gasification reactors are analyzed: a directly heated oxygen-blown gasifier and an indirectly heated dual fluidized bed gasifier. In the direct configuration, operating at 870°C and 4 bar, reactor thermal load is satisfied through the heat generated by oxidation of biomass. The indirectly heated gasifier relies on a dual fluidized bed composed of a bubbling fluidized bed gasifier and a circulating fluidized bed combustor. An inert heat carrier composed by olivine is heated up in the air combustor and then recirculated in the fluidized bed, which operates at 815°C and 1.43 bar.

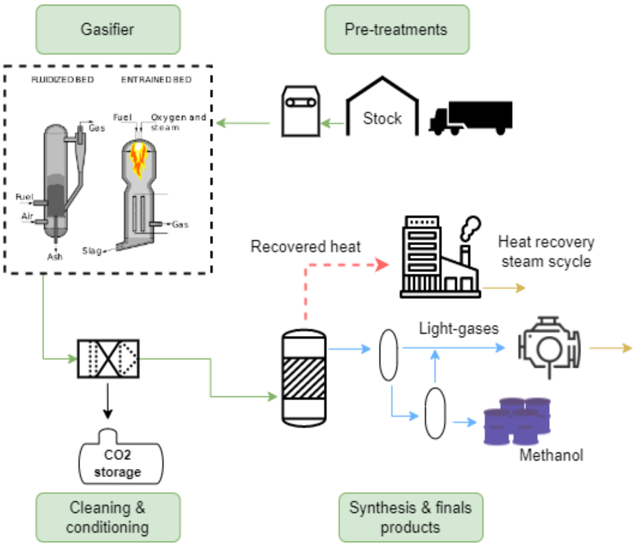

Figure 1: simplified general operative block scheme of Biomass-to-Methanol plant

Methanol synthesis process requires a syngas module M, Equation (1), equal to 2.05 at the inlet of the methanol synthesis section.

$$M = \frac{\dot{n}_{H2} - \dot{n}_{CO_2}}{\dot{n}_{CO} + \dot{n}_{CO_2}} \qquad (1)$$

To make the syngas compliant with this requirement, several unit operations are adopted in the syngas cleaning and conditioning sections, namely autothermal reforming, water gas shift and solvent-based CO_2 separation. High purity CO_2 separated from syngas is assumed to be permanently stored to achieve negative emissions. After conditioning, syngas is compressed and sent to the fuel synthesis section where it is converted to methanol with a 99.85% purity. The by-product of methanol purification, a purge stream mainly composed by hydrogen and unconverted hydrocarbons, is partially recirculated to maximize fuel output and partially burnt in an internal combustion engine (ICE) to avoid buildup of inert components in the system and recover chemical energy. Gasifiers, reboilers and CCS components require a continuous flow of low-pressure steam to operate. Hence, a one pressure level heat recovery steam cycle (HRSC) is integrated in the plants.

2.1. Gasifier model

The gasification section is controlled by an Aspen Plus® calculator that provides the outlet syngas composition. Direct plant calculator model is based on experimental data taken from an existing oxygen–blown reactor situated in Varkaus [2]; the model of the indirect one is calibrated to reproduce the syngas composition from the GoBiGas demonstration plant, Gothenburg [3]. The gasification models, depicted in the work of Poluzzi et al [2], exploit the partial chemical equilibrium of a WGS reaction to compute the syngas output composition. The fundamental parameters on which the modelling is supported are three and are reported in table *Table 1.*

- Recoverable residual char (RRC), defined as a percentage of the of the total carbon inlet.
- Gasifier temperature
- $pdelta = \log_{10} \frac{K_{eq}}{K(T)}$, which regulates the final composition with respect to equilibrium constant K_{eq}

Table 1: direct and indirect gasification model parameters

	Direct	**Indirect**
RRC	4,5%	17%
T Gasifier	870°C	815°C
pdelta	-0.16	-0.18

3. Electrification

The electrification of the two gasifiers prevents part of the chemical potential of biomass from being lost in oxidation, thus improving the biomass to fuel efficiency. Once the electrified operating model is configured, the system can modulate the thermal power provided with the electric resistances, allowing plant flexibility.

3.1. Direct Electrified Gasifier

Two alternative models are studied for the direct gasifier.
In the first one the implemented electrical resistances completely cover gasifier heat duty: oxy-combustion no longer occurs in the reactor. The following configuration is comparable to an indirect heating since it does not occur by modifying the internal composition of biomass and produced gas. With a strong assumption, modelling hypotheses depicted in section 3.2. for indirect plant are considered for the modelling of

the reactor. In this configuration resistances absorb at full load 23.45 MW of electric power, raising the total require power of the plant up to 29.8 MW.

In Model 2, a minor oxygen feed to the reactor is kept; in this way, even if most of the thermal power is provided with resistances inserted in the reactor, oxy-combustion still persists. It is hence possible to continue rely on the set of assumptions direct plant. To be compliant with Model 1, it is chosen to provide the same 23.45 MW of electric power to the resistors. Keeping the same original kinetics, some extra power is needed and, hence, is supplied with a stream of oxygen that passes from 1.93 kg/s (baseline case) to 0.42 kg/s.

In both the cases the absence/reduction of oxygen feeding to the gasifier leads to a lower CO_2 production inside the reactor. Since the model is based on the WGS chemical equilibrium, a minor presence of CO_2 leads to an increase of H_2, CO molar fraction and a decrease in H_2O molar fraction. A less oxidized syngas stream is then processed through the plant: the net effect is the decrease of CO_2 captured and an increase in methanol production. Comparing the two electrified models, Model 1 shows a higher biochar production, consequence of the higher recoverable residual char (0.49 kg/s vs 0.13 kg/s). However, in this way carbon availability for methanol synthesis production is reduced: methanol production passes from 4.21 kg/s (Model 2) to 3.88 kg/s (Model 1). Both cases show a higher production with respect to baseline case (3.28 kg/s).

It is possible to appreciate carbon redistribution through global carbon efficiency, calculated with Equation (2) and defined as the ratio between the carbon atoms in the products of the plant (i.e., biochar, methanol, and CO_2 captured) and the carbon atoms entering in the plant through biomass feedstock.

$$\eta_C[\%] = \frac{\sum \dot{n}_{product,i}\, x_{c,product,i}}{\dot{m}_{biomass}\, \frac{y_{c,biomass}}{MM_C}} \qquad (2)$$

In *Figure 4*, total carbon balance, calculated from Equation (2), is depicted as the degree of electrification increases; partial electrification results are obtained progressively decreasing the mass flow rate of oxygen as described in Model 2; the results obtained from Model 1 are reported with "triangles" to show the consequences of a different model application.

Methanol carbon efficiency (red line) increases from 36% to 46%, hence, a higher share of renewable carbon is transferred from biomass to the produced biofuel. Model 1 $\eta_{C_{MeOH}}$ reaches a lower value (43%) as expected from absolute production results; nonetheless, the higher biochar and CO_2 captured carbon efficiencies make the overall carbon efficiency constant (82%) for the two models.

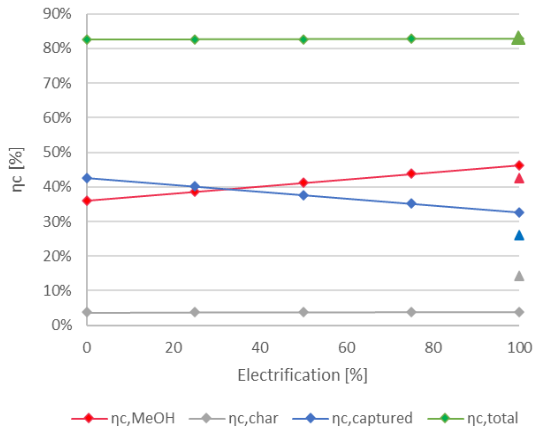

Figure 2: carbon efficiencies with respect to the electrification of the direct gasifier

3.2. Indirect Electrified Gasifier

In the indirect gasifier, depicted in *Figure 3*, the heating of the reactor is realised with the recirculation of an inert heat carrier, heated up in the combustor reactor, which oxidizes part of the biomass (additional fuel) and the residual char.

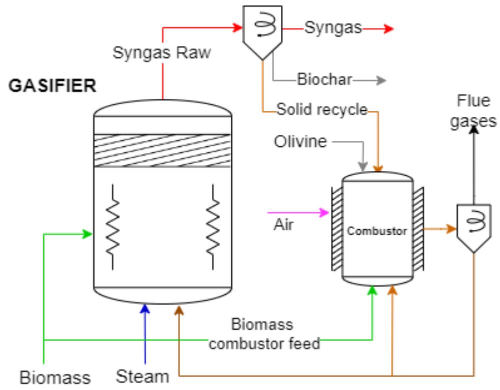

Figure 3: electrified dual fluidized bed

The electrification of this type of reactor entails the integration of electric elements in the gasifier; in this way it is possible, as the electric input increases, to progressively decrease the biomass flow entering the adiabatic combustor and extract the residual char from the reactor. The obtained model is set to maintain the same amount of biomass feed into the bubbling fluidized bed gasifier; the composition of the produced raw syngas is then unchanged and, hence, the

components downstream the gasifier does not change their operating points (i.e., no plant off-design). Resistances absorb at full load 17.89 MW of electric power, raising the total require power of the plant up to 23.77 MW.
As can be noted from *Figure 4*, three considered carbon efficiency, i.e., biochar, methanol, and CO_2 captured carbon efficiency, are reported; the overall value is increased from 59% to 82%, showing that electrification allows to reach the same global carbon efficiency of the direct gasifier. The first steps of electrification are obtained by reducing the biomass flow rate for combustion, resulting in higher methanol and captured CO_2 carbon efficiencies. When oxidized biomass approaches zero, increasing quantities of biochar are extracted. In this way the plant specific emissions are drastically reduced (from 979.8 to 63.43 gCO_2 emitted per kg of methanol), a stream of 0.91 kg/s of dry biomass is saved and a continuous production of 0.42 kg/s of biochar is obtained at full electrification.

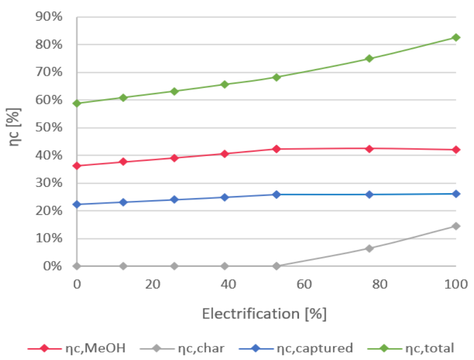

Figure 4: carbon efficiencies with respect to the electrification of the indirect gasifier

4. Thermodynamic results

To evaluate the plants performances, three main key performance indicators are used.
Global carbon efficiency is calculated with Equation (2), previously introduced.
Fuel efficiency is calculated as the ratio between the chemical power contents of plant products and the LHV biomass input, with the Equation (3).

$$\eta_{fuel}[\%] = \frac{\dot{m}_{methanol} LVH_{methanol}}{\dot{m}_{biomass,dry} LHV_{biomass,dry}} \quad (3)$$

CO_2 emission is computed as in Equation (2).

$$E_{CO_2}\left[\frac{gCO_2}{kg_{MeOH}}\right] = \frac{\dot{m}_{CO_2,emitted}}{\dot{m}_{MeOH}} \quad (2)$$

The obtained results for baseline non-electrified operation and fully electrified gasifiers are reported in *Table 2*.

Table 2: comparison between traditional and electric gasification modes KPIs

	Direct	E-Direct	Indirect	E-Indirect
η_{fuel}	63.51	81.50	63.95	74.36
η_C	82.56	82.82	58.69	82.63
E_{CO_2}	60.03	45.23	979.8	63.43

For the direct electrified configuration, it is possible to compute the marginal Power-to-methanol energy efficiency, reported in Equation (3).

$$\eta_{PtMeOH} = \frac{d\dot{m}_{MeOH} * LHV}{d\dot{P}_{el}} \quad (3)$$

The equation reports the differential variation of produced methanol chemical potential, LHV based, with respect to incremental electrical power requested. It is interesting to note that the value of 88%, obtained in the current research study, outweighs the corresponding value obtained in the work of Poluzzi et al. [4] with the addition of H_2.

5. Economic analysis

The economic analysis of the technical results is performed in a differential form that considered only the variations of costs and revenues between a yearly simulation of an electrified plant and the reference case one. In this way it is possible to assess in which framework of hypotheses the implementation of electric resistances is profitable.

5.1. Willingness to pay

To perform an hourly simulation, it is necessary to compute the "willingness to pay" of electricity, i.e. the breakeven electricity price (BEP) that makes it profitable to switch the gasifiers from baseline to electrified operation. BEP parameter assesses the trade-off between a higher product yield (larger incomes) and higher purchased electricity.
The general differential BEP function can be obtained from the equilibrium of the incremental differential revenues and costs, as depicted in Equation (6). For the considered plant

configurations, differential cost is represented by electricity, $d\dot{P}_{el}$ (differential power consumption), whereas differential revenues derive from the selling of the obtained products, $d\dot{m}_i$, at the assumed price $Price_i$.

$$BEP_{Price,el}\, d\dot{P}_{el} = \sum Price_i\, d\dot{m}_i \tag{6}$$

From the differential equilibrium performed for the direct plant is possible to compute that whenever the grid electricity price is lower than 50, 65, or 80 €/MWh (BEP respectively associated to a methanol price equal of 400, 500, 600 €/t), it is profitable to operate the plant in full electric mode; in the other case the gasifier is operated in the baseline mode.
For the indirect case, independent from methanol price, the threshold price for resistances utilization is instead constant and equal to 53 €/MWh.

5.2. Yearly simulation

The feasibility of the application of a solar field coupled with the production plant is simulated to ensure a renewable source of electricity. The adoption of a battery is considered as a strategy to operate energy time-shifting. The system is hence connected to three different sources of electricity: grid, solar field, and battery.
Energy flows are managed in this way:

- If the PV production does not cover the plant baseload consumption, electricity is taken from the grid. Plant is operated in baseline mode if grid price>BEP electricity; conversely, 100% of electrification is reached.
- When PV production exceeds the plant baseload demand, if grid electricity price>BEP, the electric power to the resistances is modulated according to the solar energy available. Conversely, 100% of electrification is reached purchasing from the grid the residual needed electricity.

During overcapacity hours, when solar production exceeds the maximum plant energy consumption, electricity is stored in the battery; conversely, during night hours, energy is taken from the battery. If the battery is fully charged the excess of electricity is sold to the grid at 40% of the PUN.

Figure 5 shows an example of how the energy flow is managed during the daytime hours (6 to 19) of day 01/01/2019 (assumptions: BEP=50 €/MWh, $Price_{MeOH}$=400 €/t, PV=80 MW, Battery=20 MWh).

At 6 am, the electricity price is below the BEP and no energy is produced from the solar field, so energy is taken from the grid. From the hour 7 to 16, the solar field is active and hence part of the load is satisfied by it. During hours 9-11, extra energy (solar field is over-dimensioned) flows to the battery till capacity is saturated; from that point on extra energy is sold on the grid. During hour 15, since solar field energy is not enough to sustain full electrification, residual energy is taken from the battery. During hour 16, EL_10% configuration is active, as consequence of a solar production higher with respect to baseload and a grid price higher than BEP. From hour 17 to 19, electricity price is higher than BEP with no energy production from the solar field; hence, plant is operated in baseline configuration with part of the energy that is taken in hour 17 and 18 from the battery.
The algorithm is used to simulate an entire year (8760 hours) of plant operation.

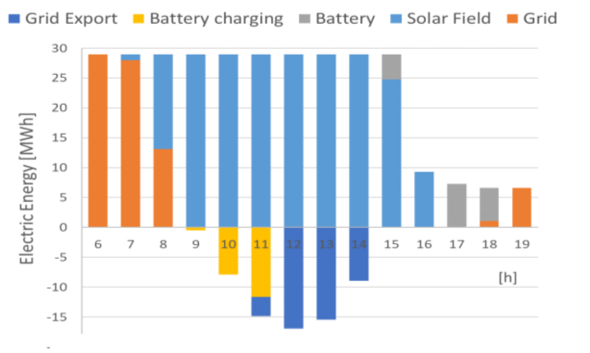

Figure 5: Energy flow management

5.3. Results

The following sensitivity analysis are performed:

- Grid price: PUN 2019 vs PUN 2021/2022[5] (Italian grid is assumed as decarbonized)
- Methanol price: 600 €/t - 400 €/t
- Solar field size: 0-30-50–65–80–100 MW
- Battery size: 1–2–3–4 equivalent hours of storage

For each set of assumption, the sizes of the solar field and the battery are varied, reporting the yearly production results. As an example, in *Table 3*, three indirect electrified configurations are compared to the baseline case (2021/2022 Italian grid). The reported results are obtained at fixed methanol production (104 kt/y) and fixed captured CO_2 (88 kt/y); electrify allows not only to obtain extra products, which repay the investment costs, but also reduce CO_2 emissions and grid dependence. Over-dimensioned PV fields permit to raise the resistances Capacity Factor (CF_{res}) even though in this way the percentage use of PV self-produced electricity is decreased (PV_{usage}), leading to higher share of electricity sold to the grid. Moreover, the equivalent hours of utilization of the battery, defined in Equation (7) as the ratio between annual energy stored and nominal power of resistors, is enhanced as PV and battery sizes are increased.

$$Heq_{batt}[h/y] = \frac{EE_{stored}\ [MWh/y]}{P_{nom\ res}\ [MW]} \quad (7)$$

Table 3: yearly simulation comparison

PV Size [MW] Battery storage	30 0h	65 1h	100 2h	Base case
$Biom_{saved}$ [kt/y]	11.0	13.5	14.4	0
$Biochar$ [kt/y]	3.05	5.08	5.76	0
$CO_{2\,emitted}$ [kt/y]	72.9	61.7	57.9	102
El_{grid} [GWh/y]	36.3	26.3	17.9	32
PV_{usage} [%]	99.6	78.8	61.8	-
CF_{res} [%]	20.6	33.1	37.5	-
Heq_{batt} [h/y]	0	411	878	-

In *Figure* 6 and *Figure* 7, the trends of Internal Rate of Return (IRR) and Net present Value (NPV) are reported as function of PV size (30-100 MW), for different Battery sizes (Indirect plant, 2021/2022 Italian grid).

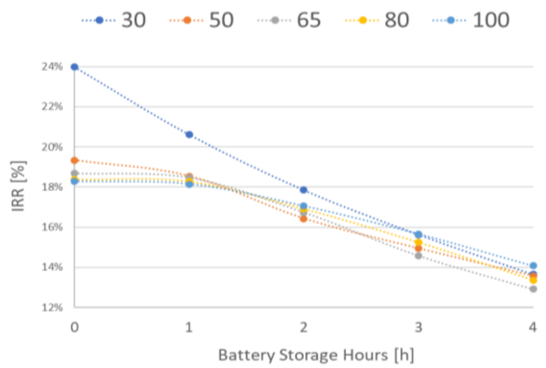

Figure 6: IRR with respect to battery storage hours

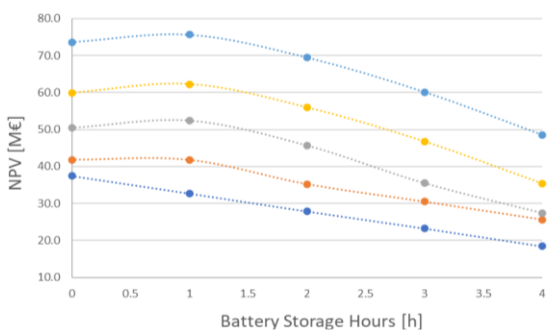

Figure 7: NPV with respect to battery storage hours

From the analysis of the diagrams derived by each set of assumptions, it is possible to state the following conclusions. Electrification is profitable if the average electrical price of grid electricity is comparable with break-even electricity price of the plants. Taking the 2019 Italian grid as a reference case (average electricity price of 52 €/MWh [5]), it was obtained that, thanks to a high number of hours of operation in electric mode, it is possible to significantly improve the revenues with respect to the baseline case. On the contrary, with a high grid electricity price (average electricity price of 300 €/MWh for 2021/2022 grid [5]), the solar field allows to cover the investment costs of the resistances. In these cases, it is necessary to deal with the trade-off between the maximization of NPV, obtained by increasing the size of the solar field, and maximization of the IRR, which shows greater values for smaller sizes. For both direct and indirect configurations, the most robust solution is the one that adopts a 30 MW solar field without battery. The investment cost of the battery in almost all cases exceeds the economic advantage that is derived by its adoption.

6. Conclusions

In this Thesis Work, the technical convenience derived from the adoption of electrified gasifiers in BtMeOH plants is demonstrated.

Indirect electrified solution demonstrates how a scarce resource such as renewable biomass can be efficiently exploited, transferring as much renewable carbon into biofuels as possible.

Power-to-methanol efficiency of 88%, obtained for the electrified direct configuration, suggests that, for this type of plants, electrify through electrical resistances inserted in the gasifier is preferable to electrify through hydrogen addition via electrolysers.

From the differential economic analysis, it can be concluded that the profitability of electrified plants is strictly related to low-price electricity availability. Nevertheless, the results show that electrified plants are already competitive simulating the operation of the plants with the 2019 Italian grid. It is predicted that future grids with higher penetration of renewable will show lower average prices and, hence, higher convenience for electrification. Furthermore, the sensitivity analysis has shown that the adoption of a solar field, whose cost is estimated to fall in the coming years, is important to gain independence from the grid prices and hedge against Black Swan events.

7. References

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