Towards zero CO_2 emissions in the production of methanol from switchgrass. CO_2 to methanol .

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Abstract.

In this work an integrated facility is proposed that produces methanol from switchgrass and uses the captured CO_2 to enhance the production capacity by 50% via CO_2 hydrogenation. The process consists of two sections, biomass processing to syngas and its conversion to methanol, and the electrolytic section where hydrogen is produced to hydrogenate the CO_2 that has been captured during syngas cleaning. The integrated facility produces up to 207 Mgal/yr of methanol production and 318 kt/yr of oxygen, but requires a large amount of electricity to generate the hydrogen. As a result, it can only be used in regions where wind velocity is above 8 m/s and solar radiation is above 5 kWh/m^2 /day such as in the Midwest of US, certain regions in China or the South of Europe. The investment is high, around 1000 M€, but the production cost of methanol is promising 0.25-0.35 €/kg with a high production capacity.

Keywords: Solar Energy, Biomass, Wind power, Synthetic methane, Hydrogen

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1.-Introduction

Methanol is one of the most important chemical products and intermediates. It can be used as solvent, intermediate or raw material for a number of higher valued products, fuels or additives. Typically, methanol has been produced via natural gas reforming or coal gasification. The fossil based sources of methanol are its major weakness when used within biofuels production, for instance biodiesel. Methanol has been the alcohol of choice due to the fast reaction times and high conversions, but above all, for its low prices. However, it is possible to produce methanol from a number of wastes or renewable sources. For instance, Martín & Grossmann (2013) used the glycerol from biodiesel facilities to produce methanol, reducing the dependency on fossil based raw materials by half. Hernández and Martín (2016) produced it from biogas via dry reforming while using the CO_2 contained within it. It is also possible to produce it out of switchgrass. Martín and Grossmann (2016a) integrated the methanol produced out of switchgrass to provide the one needed for biodiesel production. Recently, CO_2 hydrogenation is receiving the attention of many researchers. Martín & Grossmann (2016b) integrated the production of biodiesel with solar PV to use the electricity and produce hydrogen that was used to hydrogenate the CO_2 from flue gases. However, in the production of any fuel from biomass gasification, a fraction of the biomass is lost as CO_2, actually, at least 0.675 kg of CO_2 are produced per kg of methanol produced depending on the gasification technology. While CO and CO_2 compete in the hydrogenation process, and have several issues if processed together with the same catalyst, we can hydrogenate them separately.

In this work, we integrate a facility for the production of methanol from biomass and reusing the CO_2 captured during syngas composition adjustment to increase the production of methanol. Hydrogen is needed for the reintegration of the CO_2 into the production chain. Thus, a section of water electrolysis using solar, photovoltaics (PV), wind and/or biogas energy is integrated to the biomass section for the production of that hydrogen. In this regard the process avoids any carbon storage or further sequestration, but requires the use of renewable energy for that CO_2 to be processed in a sustainable way. The manuscript is organized as follows. Section 2 describes the two sections of the process. Section 3 presents the main models developed for each of the units. Section 4 shows the main process results and suggest feasible allocations for a facility that uses renewable resources for the enhanced production of methanol.

2.-Process description.

The process consists of four sections: Switchgrass processing, water electrolysis, methanol synthesis from syngas and synthesis from CO_2. Figure 1 shows the scheme for the integrated facility. Apart from methanol, oxygen is a valuable secondary product

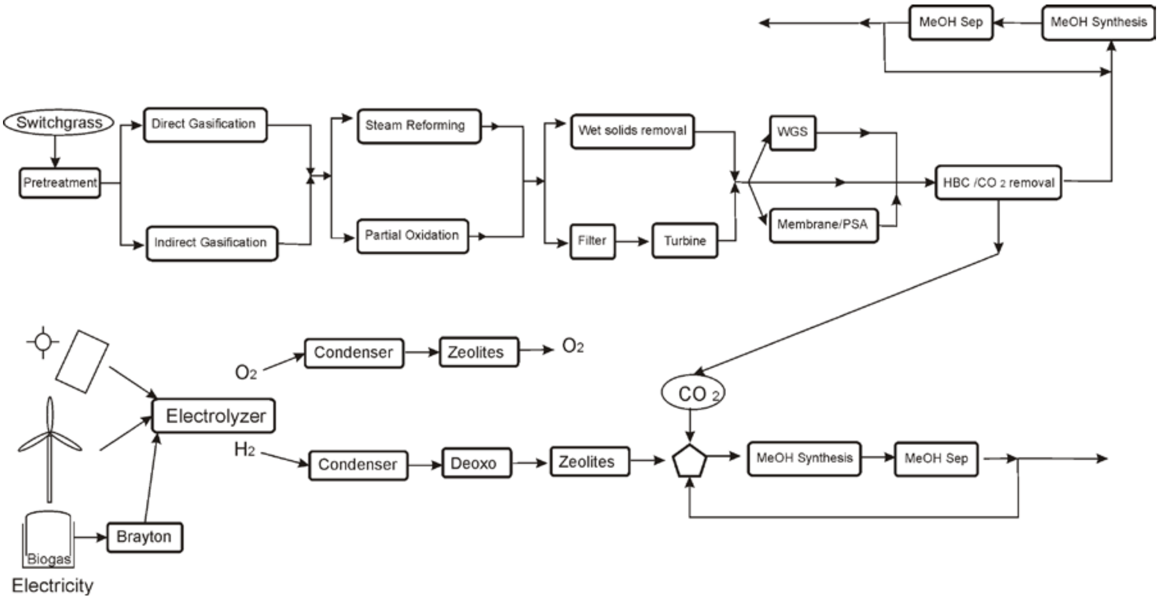

Figure 1.-Superstructure of the integrated process.

2.2.-Methanol Switchgrass

The idea is to use lignocellulosic raw materials to produce syngas that it is later converted into methanol. The switchgrass is gasified ro produced raw biosyngas. Next, the syngas is treated to remove hydrocarbons using reforming (steam or partial oxidation), followed by gas cleaning, to remove solids, and composition adjustment for the optimal production of methanol. The composition adjustmet has two steps, first, three technologies that can operated simultaneously to a fraction of the total flow such as water gas shift reaction, bypass and a membrane/PSA system is used to obtain the appropriate H_2 to CO ratio. Next, a fraction of the CO_2 must remain in the gas for methanol synthesis. Thus, a PSA system in used over a fraction of the gas flow to capture the excess. Most of the stages are common to previous papers (Martín & Grossmann, 2011; Vidal & Martín, 2015; Martín & Grossmann 2013) and therefore, for the sake of the length of the paper we do not go into the details here.

2.2.-CO_2 hydrogenation

The electrolyzer breaks down water into hydrogen and oxygen operating at 80ºC and 101 kPa. A solution of 25% of KOH is used as electrolyte (Genovee et al., 2009).

$$2\ H_2O \rightarrow 2\ H_2 + O_2 \qquad (1)$$

The energy for such an operation may come from wind, solar panels or the biogas generated. There are two product streams, the one consisting mainly of oxygen, that carries water vapor and traces of hydrogen, and the one that is mainly hydrogen. In both cases, we first remove water by condensation. For the oxygen stream, we further dehydrate it using a zeolite adsorber. Finally, the oxygen is compressed and stored. In the case of the hydrogen stream, after water condesation a deoxo stage is used to remove trazes of oxygen. In this process, a small amount of water is produced. Thus, the next stage consists of a zeolite bed for its dehydration (Davis and Martín, 2014a).

Once the hydrogen is purified, it is mixed with the CO_2 from the sour gases capture section in the biomass based part of the flowsheet The gas phase is adjusted in terms of pressure and temperature to the optimal operating conditions using a compressor and a heat exchanger. Methanol is produced based on a series of equilibria carried out over a catalyst. The optimal operating conditions (ratio of H_2 and CO_2 and operating temperature and pressure at the reactor) are optimized. The low conversion leads to the recovery of methanol using a flash separation and the recycle of the unreacted gases. Further details on the synthesis can be see in Martín and Grossmann (2016a).

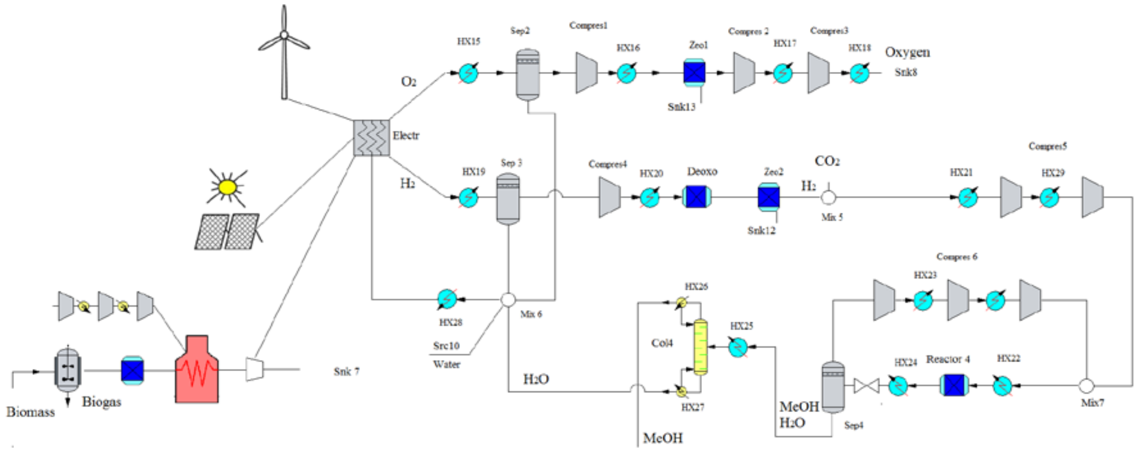

Figure 2.- Methanol production

3.- Modelling considerations

3.1.-Methanol production from Biomass

The details of the modelling for this section of the process can be seen in Martín and Grossmann, 2011, Vidal and Martín 2015 and Martín and Grossmann, 2013. The process model is formualted in terms of mass and energy balances, design equations, thermodynamic, chemical and phase equilibria as well as experimental data. Compression stages are modeled considering polytropic behavior and, when cooling down, water condenses. The gas phase is assumed to exit saturated. The pressure drop across each adsorbing bed is 10% of the inlet pressure. In Table 1 we summarize the modeling issues and we refer to previous work for further details

Table 1.- Modelling features of methanol production from switchgrass

Unit	Modelling approach	Fixed Operating conditions	Constraints
Gasification stage			
Indirect Gasifier	M& E Balances Experimental correlations	0.4 $kg_{steam}/kg_{dry\ biomass}$, 27 $kg_{olivine}/kg_{dry\ biomass}$, 1.6 bar. Char receices at least 4% of the O in biomass, 8,3 of S and 6.6 of N and the unconverted C and H	Gas composition correlations (Phillips et al. (2007),
Cyclon Gasifier - Combustor	Mass Balance	Recovery of all solids	
Combustor	M&E Balances	20% excess of air fed at 200ºC	Heat balance must hold with the one from the gasifier
Cyclon Gasifier - Combustor	Mass Balance	Recovery of all solids	
Electrostatic precipitator	Mass balances	99% ash removal 100% olivine removal	
Direct gasifier	M&E balances		Gas composition correlations from Eggeman (2005) and Zhu et al. (2009)
Cyclon direct gasifier	Mass balances	99.999 solids removal	
Reforming stage			
Steam reforming	M&E balances	Conversions given by (Phillips et al. (2007),	$C_nH_m + nH_2O \longrightarrow nCO + (\frac{m}{2} + n)H_2$ $NH_3 \longrightarrow \frac{1}{2}N_2 + \frac{3}{2}H_2$ Final temperature >300ºC Average temperature >600ºC
Partial oxidation	M&E balances	Conversions given by (Phillips et al. (2007) based on Vernon et al (1990) and Deutschmann and Schmidt (1998)	$C_nH_m + \frac{n}{2}O_2 \longrightarrow nCO + \frac{m}{2}H_2$

Table 1.- Modelling features of methanol production from switchgrass (cont)

Unit	Modelling approach	Fixed Operating conditions	Constraints
Cleaning stage			
Cold cleaning: Scrubber	M&E balances Flash calculations for saturation conditions	40ºC and 1.2 bar; 0.25 kg of water per m^3 of gas (Martelli et al., 2009) 100% Ammonia and solids removal	For low pressure gas
Hot cleaning: Ceramic filters	M&E Balances	Removal of solids 300ºC	For medium and high pressure gas
HBC, CO_2 and H_2S gas removal			
PSA adsorbent beds	Mass balances	25ºC 4.5 bar (Olofsson et al., 2005).	The previous cooling results in water condensation. Water is removed
Composition adjustment			
Water gas shift	M& E Balances Atomic balances Chemical equilibrium	4.5 bar	$\mathrm{CO} + \mathrm{H_2O} \longleftrightarrow CO_2 + H_2$ Equilibrium constant (Roh et al., 2010):
Bypass	Mass balance		
Membrane / PSA system	Mass balance	25ºC 4.5 bar (Olofsson et al., 2005). 100% recovery of hydrogen	The previous cooling results in water condensation. Water is removed
Methanol sysnthesis			
Reactor modelling	M& E Balances Atomic balances Chemical equilirbria		$CO + 2H_2 \leftrightarrow CH_3OH$ $CO_2 + H_2 \leftrightarrow CO + H_2O$ Equilibrium constants: Cherednichenko (1953) and Bisset (1977) 50-100 bar 200-300 ºC $1.75 \leq \frac{n_{H_2}}{n_{CO}} \leq 3$ (Ribeiro, 2010): CO_2 should be 2% to 8% (Lee, 2007) $1.5 \leq \frac{n_{H_2} - n_{CO_2}}{n_{CO} + n_{CO_2}} \leq 2.5$ (Marechal, 1997)
Flash separation	M&E Balances Flash calculations		
Methanol purification			
Molecular sieves	M&E balances	100% removal of water	

3.2.-Methanol production from electrolysis.

The critical point for the operation of the facility lies on the availability of solar, wind and the possibilities of biogas production to produce enough power to generate the hydrogen needed to hydrogenate the CO_2 captured. Typical range of wind velocities from 7-10 m/s and solar incidences, 1300-2000 kWh/m^2, assuming 75% efficiency, are considered to determine the allocations that provide the energy required for the production of hydrogen via electrolysis. Together with bounds on the typical sizes for wind farms, solar fields and biogas facilities.

-*Wind Turbine power:* We use the same turbine that in previous paper, GE 1.5sle type (Martín & Davis, 2014, SAM, 2013), whose model is given by eq (1) where P_{rated} =1500kW, v is the average wind velocity, a=8.322 and m=1/0.806.

$$P = \frac{P_{rated}}{1 + EXP\left(\frac{-(v-a)}{m}\right)} \tag{17}$$

Based on typical wind farms sizes (Farrel, 2011), the upper bound for the energy production using wind turbines is 125 MWe or 100 Turbines

-*Solar panel installation*: The PV panel provides 1kWp, corresponding with 8m^2. The installation cost ranges from 1700 to 4000 $/kWp installed with a target of 1000$/kWp. (http://www.nrel.gov/docs/fy12osti/53347.pdf , Maa β en et al 2011). Based on typical size of solar fields (http://en.wikipedia.org/wiki/Photovoltaic_power_station) the upper bound for the energy production using wind turbines is 250 MWe or 100000 panels due to area limitations.

-*Biogas based power:* A biogas based power facility is based on the anaerobic digestion of wastes for the production of a gas comprised mainly of methane and CO_2. The combustion of the biogas in a Brayton cycle produces energy. Based on typical production capacities of power from biogas, the upper bound considered is 50MW (Hahn, 2012)

Hydrogen production, purification and synthesis

For a detailed description of the model related to the production of hydrogen and oxygen we refer to Davis and Martín (2014b) and Martín and Grossmann (2016b). Table 2 shows the basic features of the units involved in this part of the integrated process.

Table 2.- Modelling features of methanol production from CO_2

Unit	Modelling approach	Fixed Operating conditions	Constraints
Electrolyzer	Experimental data	1 kg of hydrogen is 175,000 kJ 0.0124 kg H_2 per second per electrolizer (NEL Hydrogen AS 2012)	
Flash	Antoine correlations	25ºC 1bar	
Compressors	Thermodynamics, polytropic behaviour	efficiency of 0.85 k =1.4 (Walas, 1990).	
Zeolite water removal	Experimental data	5 bar Water removal ratio of 99.97%.	90ºC for hydrogen 25ºC for oxygen stream
Doxo reactor	M&E balances	90ºC Conversion of 99.97%	$2\ H_2 + O_2 \rightarrow 2\ H_2O$
Synthesis reactor	M&E balances Chemical Equilibria		$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$ $CO_2 + H_2 \leftrightarrow CO + H_2O$ Equilibria constants: (Chinchen et al., 1988). 50-100 bar 200-300 ºC

3.3.-Solution method

This facility has two sections. The first one produces methanol from biomass gasification via syngas. We could directly use the same solution for the biomass processing technology as in previous study, Martín & Grossmann (2016a). However, we prefer to compare again for our case.

In the production of methanol from switchgrass, a large amount of CO_2 is produced. Due to the energy intensive process required to obtain the hydrogen needed for its hydrogenation, instead of putting together the model for the biomass processing and the CO_2 hydrogenation sections, we split the problem into two. Otherwise, as we will see in the results, the use of different alternatives for biomass processing will not yield feasible results that can be compared and that can be confused with an inappropriate initialization of the NLP subproblem.

The first problem (P1) optimizes the objective function given by eq. (22) where methanol is produced from biomass. Power_ratio is the energy required to process a kilogram of CO_2.The methanol produced per kg of CO_2 is precomputed from the second section of the plant. Note that the more CO_2 produced, the more energy we require for the operation of the system. The cost of oxygen is assumed to be 0.021 €/kg, the steam price is 0.019€/kg and the cost of electricity of 0.06 €/kWh. We fix the processing capacity of the biomass section to 20 kg/s of switchgrass, so that further comparison with the use of CO_2 for algae growing is evaluated (Martín & Grossmann, 2016a)

$$Z = \mathrm{fc}\left(\mathrm{MetOH}\right)_{Biomass} + fc(MeOH)_{CO_2} - C_E \cdot \sum_{i=compresors} \mathrm{W}\left(\mathrm{Compres}_i\right) - C_S \cdot \mathrm{steam\_used} - C_{O_2} \cdot \mathrm{fc}\left(\mathrm{O2}\right) - C_E \cdot \mathrm{Power\_ratio} \cdot \mathrm{fc}\left(\mathrm{CO_2}\right); \qquad (22)$$

Subject to the model given in section 3.1 above. The model is formulated as a MINLP that has four topology options, namely, two gasifiers and two reforming modes.

The second problem, P2, uses the CO_2 captured during syngas production as a source for the production of methanol via its hydrogenation. The link between the biomass section and this one is given by the fact that the CO_2 captured is processed here, and the need to provide the electrical power for the biomass preprocessing stage and the compressors. Thus, the total power to be produced is as given by equation (33)

$$\mathrm{W}\left(\mathrm{Electrolizer}\right) + \sum_{i=compresors,H_2,O_2} \mathrm{W}\left(\mathrm{Compres}_i\right) + \mathrm{W}\left(Switchgass, \mathrm{sec}\,tion\right) = \mathrm{Power} \qquad (23)$$

The energy can be produced either using wind turbines, solar panels or biomass so that:

Power $\leq$ Power generated;

where

$$\text{Power generated} = \mathrm{n}_{\mathrm{aerogenerador}} \frac{\mathrm{P}_{\mathrm{nominal}}}{\left(1 + \exp\left(-\left(v - \mathrm{a}\right)/\mathrm{m}\right)\right)} + \mathrm{n}_{\mathrm{pannel}} \cdot \mathrm{Solar\_inc} \cdot \mathrm{A}_{\mathrm{pannel}} \cdot 3600 / \left(\mathrm{days}_{month} \cdot 24 \cdot 3600\right) + Energy_{Biogas} \qquad (24)$$

The objective function for this section is given by eq. (29) where the different terms are given by eqs (25-28):

$$C_{Wind} = \frac{1}{3} \cdot \frac{\mathrm{Wind}_{Invest} \cdot \mathrm{P}_{\mathrm{nominal}} \cdot \mathrm{n}_{wind\ turbines}}{time} + \mathrm{C}_{Operation,Wind} \cdot \mathrm{P}_{\mathrm{nominal}} \cdot \mathrm{n}_{wind\ turbines}; \qquad (25)$$

$$C_{Solar} = \frac{1}{3 \cdot time} \cdot \mathrm{n}_{\mathrm{panel}} \cdot \left(\mathrm{P}_{\mathrm{panel}} \cdot \mathrm{c}_{\mathrm{panel}} + \mathrm{A}_{\mathrm{pannel}} \cdot \mathrm{c}_{\mathrm{area}}\right); \qquad (26)$$

$$Biogas_{Investment} = 19352 \cdot \left(Energy_{Biogas} (\mathrm{kW})^{(-0.27)}\right); \qquad (27)$$

$$C_{Biogas} = \frac{1}{3 \cdot} \frac{Energy_{Biogas} \cdot \left(\mathrm{Biogas}_{Investment}\right) \cdot}{time} + C_{Operation,Biogas} \cdot Energy_{Biogas} \qquad (28)$$

$$Z = \mathrm{fc}\left(\mathrm{MeOH}\right)_{CO_2} - \mathrm{wind\_t} - \mathrm{solar\_t} - \mathrm{biogas\_t} + \mathrm{C_{O2}} \mathrm{fc}\left(\mathrm{O_2}\right) \qquad (29)$$

Subject to the model given in section 3.2. We may assume that the number of turbines, solar panels and electrolyzers is continuous since the cost is given by kW and the fact that a unit can be operating at a fraction of its design specifications.

Thus, the solution method is as follows. To compute the energy requirements to hydrogenate the captured CO_2, we first optimize P2 assuming $\mathrm{W}(Switchgass, \sec tion)$=0. With this we obtain a power_ratio of 25150 kJ/kg and a production of 0.727 kg of methanol per kg of CO_2. Next, using these values we optimize P1. We solve four NLP's of 2400 equations and 2700 variables each, one per gasifier technology and per reforming mode, to evaluate the optimal biomass processing. With the optimal topology for this section, we reoptimize P2 (540 eqs and 674 Vars) using the appropriate value for the power required by compressors and biomass preprocessing technologies and the CO_2 that is to be processed.

4.-Results and discussion

The key question regarding the selection between the use of solar and/or wind energy onshore depends on the costs, the energy availability and the technical limitations related to typical facility sizes. Over the last years a number of studies have gathered this information. The cost of wind turbines is 1600€/kW (Tegen et al. 2013 IRENA 2012). With regards to the PV panels, investment costs of 2300€/kW are assumed togewther with a cost for land and its preparation of typically 5.5 €/m^2.(Maaβen et al., 2011, http://www.fundacionsistema.com, Goodrich et al., 2012).The investment cost of the production of biogas is a function of its size. Using data from the literature (Hahn, 2012) . We have developed eq. (15). Furthermore, the operating costs of biogas production are in the range of 0.05-0.1€/kWh (http://www.suscon.org).

4.1.-Biomass processing technology.

A flow of 1700 t/d of biomass is processed. Following the procedure described in section three, it turns out that the optimal process is that which using indirect gasification followed by steam reforming. Actually, the use of direct gasification is the best option due to the large production capacity if it not were for the high production of CO_2, which eventually makes its hydrogenation infeasible due to the large energy consumption which prevents from using this option. Figure 3 shows the comparison between the values of the objective function for the four alternatives: Ferco Batelle indirect gasification & Steam reforming (FS);

Ferco Battelle & Partial oxidation (FO); Renugas direct gasification & Steam reforming (RS); Renugas & partial oxidation (RO). Using RS is infeasible for the high energy consumption under regular wind an solar availability.

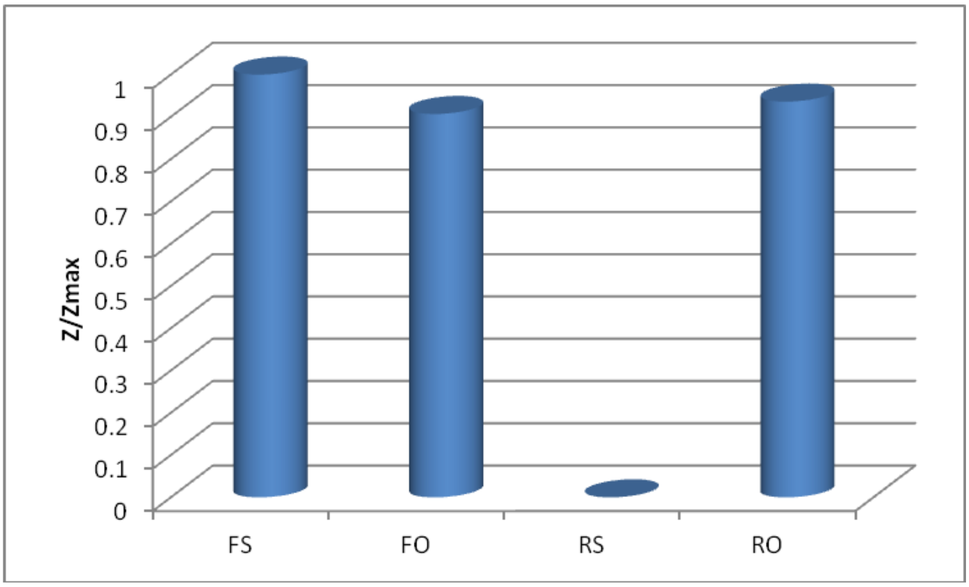

Figure 3.- Switchgrass processing topology optimization

4.2.-Plant location

Figure 4 describes the feasibility for the operation of the plant. As expected, higher wind velocities are needed for the plant to operate when the solar irradiation is lower. Based on this result, and assuming that the facility must be allocated in a single spot, and not producing the energy in several allocations, there are only a few feasible allocations worldwide (3TIER, 2015). Figure 5 shows the regions of the world where the integrated plant is feasible. Needless to say that we can produce the energy elsewhere and used it in our plant, the only thing is that it has to be renewable. For instance, we can produce electricity from wind in the UK and from solar in Arizona, however, that will not be feasible. On the other hand, we can still produce power from the sun in Arizona and from wind in the middle east of the US where the wind velocity is higher and locate the plant closer to the east, where higher biomass rates can be found. Due to the technical challenges in hydrogen storage, we need to produce the hydrogen in situ to hydrogenate the CO_2. Thus, we can alternatively produce power in separate allocations and transport it to the plant allocation for methanol production.

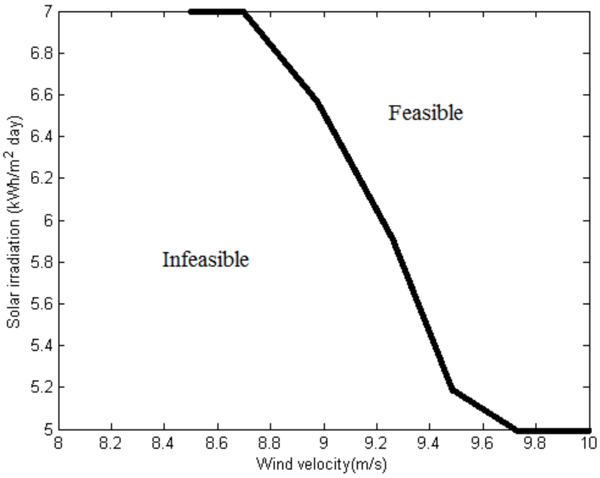

Figure 4.- Feasibility operation region

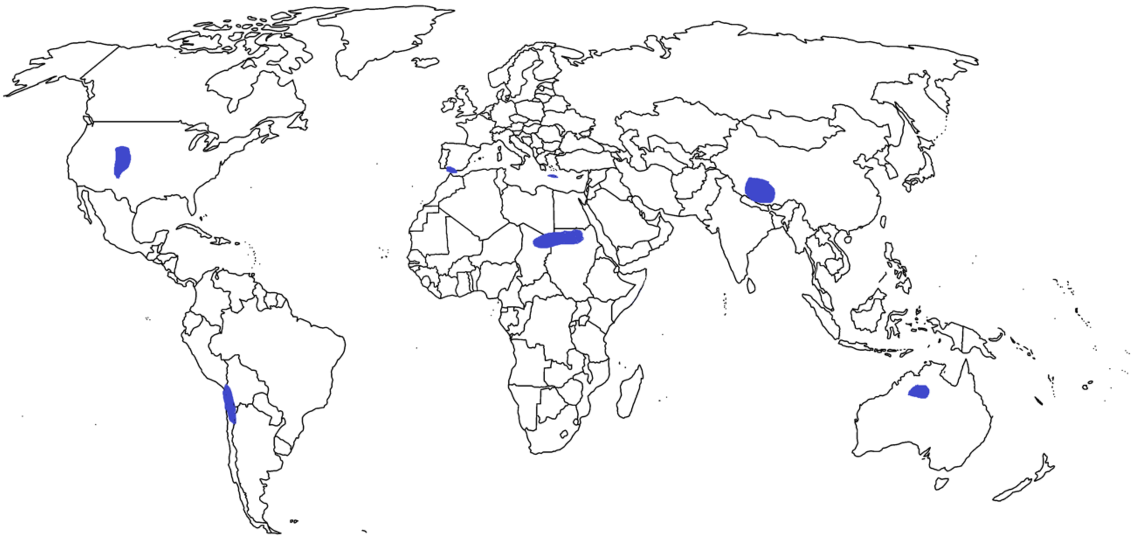

Figure 5.- Possible locations for the facility.

4.3.-Plant operation

In section 4.3.1. we describe the optimal operation of the plant in terms of the process parameters of the main units. In section 4.3.2 we describe the use of the different sources of energy. Finally, in section 4.3.3 of the results obtained in this work are compared with those where the CO_2 was used within algae production facilities for the simultaneous production of methanol and biodiesel.

4.3.1.-Process parameters.

The optimization of the production of methanol is split into the biomass processing facility and the CO_2 hydrogenation section. The main decision variables are the operation of the gasifier and combustor, the composition adjustment for the syngas and the operating conditions at the synthesis reactors. Table 3 shows the main results for these units. Not that the operating temperature for the production of methanol is suggested to be 200ºC but the pressure at the reactor changes from one section to the other depending on the catalysts. Finally, the power required for CO_2 hydration is 257 MW, which is quite large and conditions the further operation of the plant. Actually the production of CO_2 per kg of methanol in the biomass processing section is 0.71, which results in the need for a high flowrate of hydrogen.

Table 3.- Main operating parameters of the facility

Unit/Op. COndition	Gasifier /Combustor	WGSR	MetOH(Sw)	MetOH(SWB)	Electrolyzers	Power
T (ºC)	890/983	200	200	200		
P (bar)	1.6	5	92	52		
$\frac{H_2-CO_2}{CO+CO_2}$			2.25			
H_2/CO_2				3		
Steam (kg/kg$_{feed}$)	6.8/20	20.145/6.07				
Number					104	
Power consumption (MW)						257

4.3.2.-Energy usage distribution

Based on Figure 5, we compute the operating conditions of the plants located in the different points of the world, considering the fraction of energy from each source, wind, solar or biogas, and perform an economic analysis. Piping, insulation, instrumentation and utilities and chemicals represent 20%, 15%, 20% and 10% of the equipment cost (Matche, 2014; Sinnot, 1999). The land and buildings cost is estimated to be 12 M€, and raw material accounts for the biomass and the water, and we get credit out of the oxygen produced, 0.021€/kg. These items add up to the fixed cost. The fees represent 1% of the fixed cost to compute the direct cost. While the investment cost includes start up and engineering fees. We see that the investment is huge, due to the required energy consumption and the need for wind turbines and solar panels. We consider the labour costs, utilities (electricity and cooling water), chemicals (fertilizers, glycerol as credit), equipment maintenance and amortization (linear with time in 20 years), taxes, overheads (2.1% investment) and administration. Table 4 presents the results for the six feasible allocations. The production cost is promising around 0.35€/kg by the investment is quite high, around 1000M€, due to the need for energy to produce the renewable hydrogen.

Table 4.- Operating conditions of the plants

Plant/Characteristic	Solar availab (kW/m2/dia)	Wind Vel (m/s)	Wind (kW)	Solar (kW)	Biogas (kW)	Prod cost $/kg)	Investment (M€)
US	5.5	9.5	103550	103550	50000	0.34	960
Central Africa	7	9	73775	133333	50000	0.36	1001
South Spain	5.5	9.5	103550	103550	50000	0.34	960
Cyprus	5.5	9.5	103550	103550	50000	0.34	960
China	5.2	10	107110	100000	50000	0.34	956
Australia	7	8.5	73775	133333	50000	0.36	1001
Chile	7.5	9	62664	144444	50000	0.36	1016

4.4.-Comparison Algae use of CO_2 vs. other alternatives

Table 5 shows the two main integration opportunities for the production of methanol. We can either produce methanol and use it to produce biodiesel via algae growing (Martín and Grossmann, 2016b). In this case, the CO_2 produced in the switchgrass processing section is injected into the ponds and is captured by the algae. This solution, in spite of the processing problems regarding the ponds operation, required reasonable investment, around 180 M€, with a large liquid fuels production capacity. Alternatively, we can try to capture the CO_2 to enhance the production of methanol via hydrogenation as described in this paper. In this case, a large amount of energy is required to produce the hydrogen from water via electrolysis. The production capacity of liquids is similar to the one of the other facility, but the investment is far higher, almost an order of magnitude. The production cost is twice the value, but still competitive with current methanol

Table 5.- Integration alternatives

	Algae-Switchgrass	Switchgrass-Others
Prod capacity	205 Mgal/yr (69 Mgal/yr Biodiesel)	207 Mgal/yr (metanol)
Prod cost (€/gal)	0.49	1.01
Investment (M€)	180	1000
CO_2 capture	Switchgrass + 1.27 kg of CO_2 per kg of produced methanol	Switchgrass
Water fed	Swichgrass processing Algae processing unless wastewater is used. (1.8 kg/6.9kg biodiesel)	Swichgrass processing (24.835-3.824) kg water/ (20 kg/s of methanol)

5.-Conclusions

In this work we have designed an integrated facility for the enhanced production of methanol from switchgrass by capturing and hydrogenating the CO_2 that is released in the production of the syngas. The facility consists of biomass processing to syngas, gas clean up and composition adjustment followed by methanol synthesis. Water is split using electricity that is produced from biogas, solar PV or wind turbines to hydrogenate the CO_2 to methanol.

The production capacity increased by 50%, resulting in promising production costs, around 0.35€/kg. However there is an important drawback. The large amount of energy required leads to the need of large solar fields, wind farms and biogas production facilities. There are only a number of feasible locations for such facility. As a result the investment is large, around 1000M€.

The comparison among this facility and the one that uses alga to process that CO_2 is in favor of the use of algae, for its efficiency reducing the processing and investment costs.

6.-Nomeclature

a Adjustable parameter for the power curve (m/s)
A_{pannel} (m^2 /kWp) /8/
Biogas_E: Energy generated from biogas (kW)
c_{pane}l Investment per unit installed (€ / kWp)
c_{area} Investment per unit installed (€ / m^2)
Ci: Cost of item i
Cp: Constant heat capacity (kJ/kg ºC)
Daysm: Days in ta typical month. 30 days.
k: Politropic coefficient.
kp: Equilibrium constants
fc (i): Mass flow rate of species I (kg/s)
MW Molecular weight (kg/kmol)
ni: moles of species i

n_panel: Number of solar panels
n_turbines: Number of wind turbines
P_i : Partial pressure of component I (kPa)
m: Adjustable parameter for the power curve (m/s)
P_{panel} Nominal power per panel /1kWp/
$P_{nominal}$ Nominal Power of a turbine 1500 kW
power_ratio Ration power to mass of CO_2 required for methanol production kJ/kg.
$Op\_cost_{\_wind}$ Rent of the ground for the turbines (€ /kwh)
T: Temperature (K)
$T_{fercogas}$: Temperature at the gasifier (ºF)
Time: seconds in a year
v: Wind velocity (m/s)
$V_{cut:}$ Adjustable parameter for the power curve (m/s)
W: Electric power (kW)
$Wind_{invest}$ (€ / kW)
η: Efficiency
Z: Objective function (€/s)

Acknowledgement

The authors appreciate Salamanca Research for software licenses.

7.-References

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