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# Energy and economical comparison of possible cultures for a total-integrated on-field biodiesel production

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**Abstract.**

This work is aimed at investigating the energy conversion effectiveness and the economical advantages of a total integrated solution for on-field biodiesel and electrical energy production. The system proposed here is based on the synergy of four sub-systems: a seed press for oil production, a downdraft gasifier, a biodiesel conversion plant and a Solid Oxide Fuel Cell (SOFC). Two possible culture rotations, suggested by literature review, were analyzed here from economical and energy balance points of view. Both the rotations were composed of oleaginous crops only, therefore the seeds collected from the different cultures were pressed, then the protein cake produced in the process was gasified in the downdraft reactor. The gasification process was modeled here, and its output suggested that, for a precise number of hectares, the syngas obtained through the cake gasification was enough for producing methanol required for oil-biodiesel conversion and feeding a 10-kW SOFC. The purge line in the methanol reactor was used in the SOFC as well. The system was simulated using ASPEN PLUS[TM] and MATLAB[TM] codes. Results of the SOFC and gasifier models underlined the capability of the fuel cell to work with this particular system, furthermore the whole system analysis suggested that the surface required for sustainability of the processes is a function of the rotation choice. In both cases little surfaces ranging from 11 to 21 hectares were found to be enough for system self-sustainability with a ROI under 7 years in all the operating conditions analyzed.

## 1. Introduction

Most of gasifiers for electrical and CHP applications are commonly coupled either with Organic Rankine Cycle (ORC) systems, Internal Combustion engines, Conventional and External Firing Gas Turbines (EFGT) or Stirling engines [1–6]. However, the efficiency of these systems is not as high as the one that can be obtained using advanced power generation systems such as Molten Carbonate Fuel Cells (MCFC) [7, 8] or Solid Oxide Fuel Cells (SOFC) [9–11]. For this kind of systems, a downdraft gasifier (DG) reactor is a suitable solution due to the low content of tar and particulate in its gas when compared with updraft, crossdraft or fluidized bed gasifiers [1, 2, 12, 13]. This feature optimizes the performance and the reliability of the SOFC subsystem that operates properly only when fed with clean syngas fuel [14].

This study starts from the feasibility analysis reported in [15], where a full integrated system for biodiesel production was proposed and its advantages were discussed. The previous work was based on a rotation of rapeseed-flax-sunflower, as suggested by [16]. All the crops composing this rotation could be used for oil production, but the major disadvantage

of this solution was the low oil productivity of flax seeds. Furthermore flax oil is a valuable product and its use for biodiesel conversion is disadvantageous. For this reason, a new rotation was proposed and its feasibility and sustainability were discussed in [17]. This solution substituted flax with soy. All these crops are adequate to Mediterranean zones, therefore the simulations were based on data obtained from literature about average oil production for these cultures in the Emilia Romagna region of Italy as reported in [15, 18–27].

The system layout is sketched in figure 1. The approach suggested here consisted in cultivating every year all the surface (evaluated on economical end energy balance basis) with a different culture. The collected seeds were converted into oil and protein cake by a mechanical process. The protein cake obtained as a by-product of the oil extraction was gasified to syngas in a downdraft stratified reactor. A small part of the syngas was converted to methanol in a chemical reactor while the rest of the gas fed a 10 kW SOFC. The methanol was then used in the transesterification of the PVO to produce biodiesel. The gasifier model was based on: ultimate analysis of the protein cake, dimensions and physical properties of the cake pellets and geometrical parameters of the gasifier. The geometrical and physical properties of the protein cake were obtained through a series of experimental analyses, the results of these analyses are reported in table 1. The biodiesel production process consisted of two stages: in a first reactor the syngas was converted into methanol; then in a different reactor PVO and methanol were mixed for biodiesel production. The methanol production conversion reactions were simulated with an equilibrium-based approach whereas the biodiesel production was modeled by a stoichiometric approach with a known conversion typical of the catalytic reactions. SOFC modeling is well described in literature [28–30], the model proposed here was based on the works of Bang-Møller and Rokni [28] for the cell reactions and Rami Salah El-Emam for the reformer [29].

The whole system model was obtained coupling all the models of the sub-systems. It allowed to calculate the mass of biodiesel and glycerin obtained every year and the electrical energy produced by the SOFC connected to the gasifier. An economical analysis was made to evaluate the return of the investment and the economical differences between the rotations proposed here.

## 2. Gasifier mathematical model

For the gasification reactions modeling, a kinetic model was used in order to predict zone lengths and gas composition. This model was created starting from the method developed by Reed and Markson [31] to predict the flaming pyrolysis zone length $l_p$ and the char reduction zone length $l_c$. The biomass properties used as input in this model are: moisture content $F_m$, biomass particle equivalent diameter $d_p$, area $A_g$ and height $H$ of the gasifier, density $F_d$ of the biomass, and void fraction $F_v$ in the biomass. Furthermore the model by Reed and Markson evaluates the heat transfer between particles located in the flaming pyrolysis layer using data by Reed and Markson themselves [31] or obtained from Huff [32]. One of the major output of this model is the char reduction time $t_c$. It was used here for coupling this model with the one presented and discussed by Wang and Kinoshita [33]. Wang's model consists of a kinetic system of differential equations that describes the mechanisms occurring in the char reduction zone. It starts from the evaluation of the effect of flaming pyrolysis on a particle homogeneously composed of equivalent biomass molecules $CH_\alpha O_\beta$. The system resolution requires the kinetic constants and biomass properties that were obtained from [34–36].

The resulting coupled model operates fixing a pressure $p$ of gasification and the equivalence ratio $ER$ of the reactor [1].
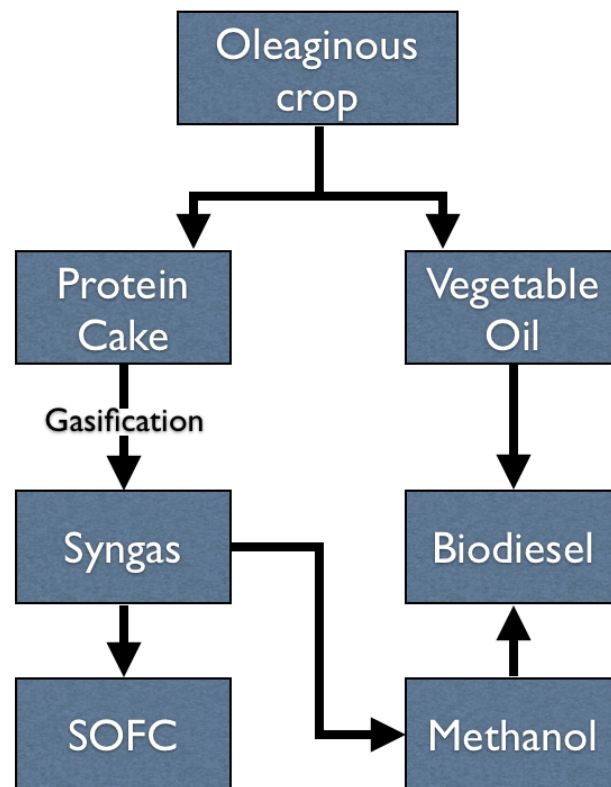
**Figure 1.** System layout

Table 1 lists the chemical, physical and geometrical properties of the protein cakes used as model input in this work: rapeseed, sunflower, soy and flax. Table 2 shows the geometrical and physical parameters of the gasifier. Furthermore, table 3 resumes the syngas compositions, $HHV_{syngas}$ and gasifier cold gas inefficiencies $\eta_{cold}$ for rapeseed, sunflower, soy and flax protein cakes. A complete discussion of the model used here can be found in [37].

**Table 1.** Protein cakes parameters

| Parameter | Rapeseed protein cake | Sunflower protein cake | Soy protein cake | Flax protein cake |
|---|---|---|---|---|
| Equivalent cake diameter $d_p$ | 0.01 m | 0.01 m | 0.01 m | 0.1 m |
| Density $F_d$ | 1.79 $kg/m^3$ | 1.79 $kg/m^3$ | 1.79 $kg/m^3$ | 1.79 $kg/m^3$ |
| Void fraction $F_v$ | 0.48 | 0.48 | 0.48 | 0.48 |
| Moisture | 10.8% | 10.8% | 10.8% | 10.8% |
| C (wt%) | 43.2% | 46.78% | 55.89% | 46.46% |
| H (wt%) | 6% | 6.425% | 6.57% | 5% |
| O (wt%) | 44.27% | 45.91% | 28.25% | 47.64% |
| N (wt%) | 5.6% | 0.88% | 9.29% | 0.6% |
| S (wt%) | 0.93% | 0 % | 0% | 0% |
| Ash (wt%) | 7.20% | 3.82% | 5.36% | 4.4% |
| $HHV_{bio,dry}$ | 15.37 MJ/kg | 16.76 MJ/kg | 21.34 MJ/kg | 17.15 MJ/kg |

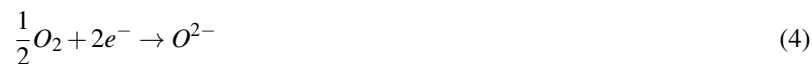**Table 2.** Parameters of the downdraft stratified gasifier

| Parameter | Value |
|---|---|
| Gasifier diameter $D_g$ | 0.28 m |
| Gasifier area $A_g$ | 0.0616 m$^2$ |
| Fixed bed height H | 0.4 m |
| Flaming pyrolysis temperature $T_s$ | 1173 K |
| Char reduction temperature T | 1073 K |
| Equivalence ratio ER [1] | 0.35 |
| Pressure in the gasifier p | 1 bar |

**Table 3.** Results of the gasification model

| Variable | Rapeseed | Sunflower | Soybean | Flax |
|---|---|---|---|---|
| $H_2$ [%vol] | 12.2 % | 12.42 % | 14.72 % | 14.96 % |
| $CO$ [%vol] | 13.98 % | 14.17 % | 17.38 % | 19.43 % |
| $CH_4$ [%vol] | 6.01 % | 5.92 % | 4.77 % | 3.11 % |
| $CO_2$ [%vol] | 17.86 % | 17.06 % | 11.78 % | 14.76 % |
| $N_2$ [%vol] | 50.31 % | 50.43 % | 51.35 % | 47.73 % |
| Syngas production per hectare | 5582 kg | 4328 kg | 10353 kg | 2012 kg |
| $HHV_{syngas}$ | 5.22 $MJ/Nm^3$ | 5.32 $MJ/Nm^3$ | 5.49 $MJ/Nm^3$ | 5.18 $MJ/Nm^3$ |
| $\eta_{cold}$ | 96.67 % | 96.41 % | 93.76% | 90.34% |

## 3. SOFC model

The SOFC model has been developed by Bang-Møller and Rokni [28]. This model did not take into account the recirculation of the exhaust in the anode. To overcome this issue, the reforming model presented by Rami Salah El-Emam et al. [29] was used in this work. The reforming of the fuel occurs near the anode. Here take place both the reforming of the methane (equation 1) and the water gas shift of the carbon monoxide (equation 2). The electrochemical reaction takes place in the anode and in the cathode. At the anode, the hydrogen reacts with the oxygen ions to form water and electrons according to the equation 3. At the cathode, the oxygen of the inlet air reacts with the electrons from the anode (equation 4) to form oxygen ions that they are conveyed to the anode through the solid oxide electrolyte. Equation 5 resumes the overall electrochemical reaction.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \tag{3}$$

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{4}$$

$$H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O \tag{5}$$

The mathematical modeling of reforming and electrochemical reactions are explained in [29] and [28] respectively. Using these models it was possible to calculate the electrical energy

production and the electrical efficiency for a given syngas inlet flow with a specific gas composition. The SOFC model parameters adopted in the simulations are reported in table 4.

**Table 4.** SOFC model parameters

| Description | Symbol | Value |
|---|---|---|
| Fuel utilization factor | $U_f$ | 0.85 |
| Recirculation factor | $r$ | 0.2 |
| Steam to carbon factor | $STC$ | 2.5 |
| Cathode air factor | $vent$ | 1.1 |
| Pressure ratio | $PR$ | 2.5 |
| Operating temperature | $T_{SOFC}$ | 1073.15 K |
| Anode pressure loss | $p_a$ | 500 Pa |
| Cathode pressure loss | $p_c$ | 1000 Pa |
| Current density | $i$ | 3000 mA cm$^{-2}$ |
| Active cell area | $A_{cell}$ | 81 cm$^2$ |
| Cells for each stack | $n_{cell,stack}$ | 75 cells |
| Number of stacks | $n_{stack}$ | 8 stacks |
| Electro-chemical parameters | Reported in [28] | |

## 4. Biodiesel production model

The modeling of syngas→methanol conversion and methanol+oil→biodiesel conversion were developed in ASPEN$^{TM}$ Plus software. The model used the data obtained from literature about the productivity of the mentioned cultures together with the data output of the kinetic model of the gasification process for the four different protein cakes. Once the amount of vegetable oil collected from every hectare of the different cultures was evaluated, ASPEN software was used first to calculate the amount of methanol required for complete oil conversion and then the volume of syngas necessary for the production of that very amount of methanol.

The biodiesel production model from vegetable oil and methanol reaction was based on the transesterification of triolein [38] reported in equation 6, the reactor was configured RSOITC and it was based on stoichiometric approach with a defined conversion rate (95%). The model thermodynamic activity is set in the software to 'universal quasi-chemical' as suggested by the presence of highly polar components.

$$TRIOLEIN + 3CH_3OH \rightarrow^{KOH} 3METHYL\ OLEATE + GLYCEROL \quad (6)$$

The syngas to methanol conversion was based on the following reactions [39]:

$$CO + 2H_2 \rightarrow CH_3OH \quad (7)$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad (8)$$

$$CO_2 + H_2O \rightarrow CO_2 + H_2 \quad (9)$$

The methanol conversion modeling was based on equilibrium reactor in ASPEN plus (REQUIL). The syngas composition suggested by the gasification model showed that the CO and $CO_2$ were in excess compared to hydrogen, therefore the molar flow rate of methanol produced in the reactor was limited by the conversion of $H_2$. For the operating conditions of

the reactor given in table 5 the hydrogen conversion was about 15%. The methanol production model parameters are reported in table 5). The whole system was resolved using 'Design Specification' function of Aspen Plus in order to obtain the flow-rate of syngas necessary for producing the methanol required for PVO conversion. Table 6 resumes the output of the ASPEN model together with the amount of syngas required for the process and the amount and the composition of the syngas purged after multiple recirculation. Figure 4 schematizes the process as reported in ASPEN$^{TM}$ plus.

**Table 5.** Parameters of the biodiesel production model

| Parameter | Value |
|---|---|
| Methanol reactor pressure | 76 bar |
| Methanol reactor temperature | 523.15 K |
| Recycle ratio | 8 |
| Biodiesel reactor pressure | 1 bar |
| Biodiesel reactor temperature | 343.15 K |

**Table 6.** Results of the biodiesel production model for 1 hectare of soil

| Variable | Rapeseed | Sunflower | Soy |
|---|---|---|---|
| Seeds | 4000 kg | 2800 kg | 3700 kg |
| PVO | 1840 kg | 1260 kg | 740 kg |
| Biodiesel | 1465 kg | 997 kg | 583 kg |
| Glycerin | 488 kg | 332 kg | 194 kg |
| Methanol required | 204 kg | 137 kg | 80 |
| Syngas required | 4160 kg | 2718 kg | 1173 |
| Syngas purged | 3956 kg | 2580 kg | 1093 |
| $H_2$ purged | 4.47 % | 4.42 % | 4.60% |
| CO purged | 11.22 % | 11.41 % | 14.24 % |
| $CH_4$ purged | 6.86 % | 6.78 % | 5.69 % |
| $CO_2$ purged | 19.88 % | 19.45 % | 14.01% |
| $N_2$ purged | 57.41 % | 57.76 % | 61.30 % |
| $HHV_{purged}$ | 4.16 MJ/N$m^3$ | 4.35 MJ/N$m^3$ | 4.33 MJ/N$m^3$ |

## 5. Results and discussion

### 5.1. Chemical balance

The first result that need to be discussed is the chemical balance of the system proposed. Figure 2 shows the differences in syngas production, syngas required for methanol production and syngas HHV. The value reported in figure 2 guaranteed, for all the cultures used in this study in biodiesel production, an excess of syngas. This gas excess is fundamental because it was the parameter used for evaluating the surface required for SOFC run over the year. More detailed data can be found in tables 6 and 7.
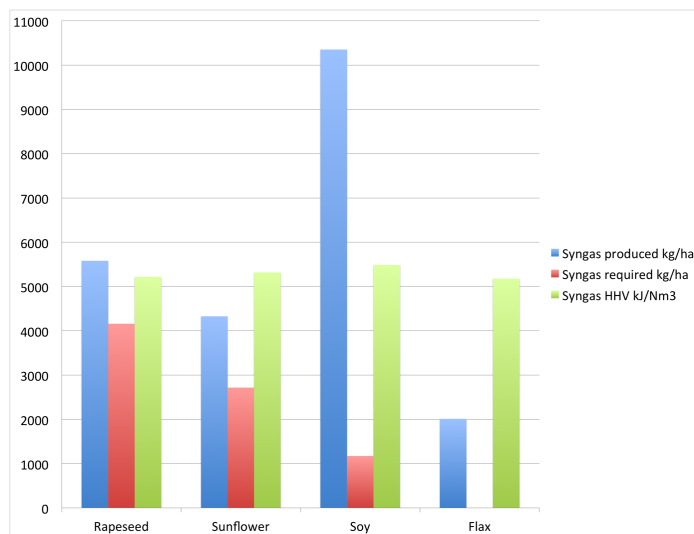
**Figure 2.** Syngas production, requirement and quality comparison

The heating values of the syngas obtained through gasification of the four protein cakes were founded to be all similar with an estimated value of about 5 MJ/Nm$^3$. Figure 2 together with the comparison reported in figure 3 underlined the differences between the soy and flax uses. Flax produced less protein cake and less oil, for this reason larger surfaces were required for reaching the sustainability of the system fixing the electrical power output to 10 kW. Soy was similar to flax from an oil production point of view but it had more protein cake that produced higher amount of syngas. Furthermore the proposed results outline two energy recovery features of the system proposed here: culture such as soy are characterized by high solid matter when compared with the oil production. With the approach proposed here this characteristic is not a disadvantage any more, because the gasification and electrical energy conversion of the solid matter compensate the low biodiesel production. Moreover in all the biodiesel conversion processes described here, even if the methanol reactor had a low conversion rate, the non-reacted gas chemical energy was not wasted because the purge line was connected with the SOFC. The waste heat coming from the methanol reactor and the SOFC could be used for several purposes such as heating up the biodiesel reactor, drying the cake and pre-heating the air entering the gasifier. If the heat produced by the processes will exceed the heat required for the mentioned processes, the system can be considered "high efficiency CHP", this solution guarantees a higher subsidy [40].

### 5.2. SOFC results

The results of the gasifier-SOFC system are reported in table 7, reporting the number of hours and the energy produced by one hectare of different crops. The data discussed here allowed the calculation of the number of hectares necessary as function of the number hours of plant running per day. The SOFC worked together with pure and purged syngas from the gasifier and methanol conversion reactors respectively. Because the higher the surface tilled, the less the specific cost of cultivation, the system considered only one crop a year. Furthermore, if the protein cake was properly stored, there was no need to use all the cake in the very year in which it was produced. For this reason the system was balanced working on the three year
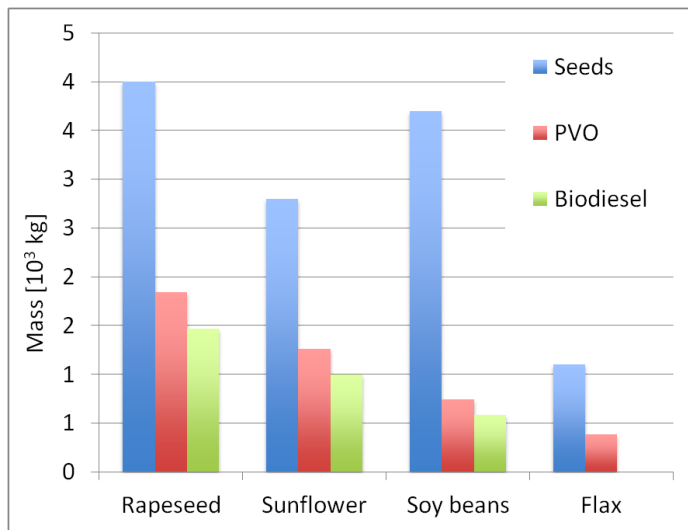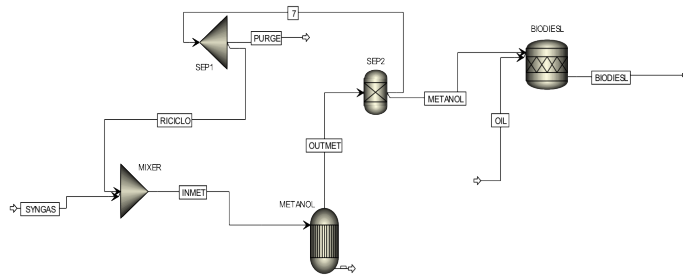
**Figure 3.** Productivity differences



**Figure 4.** Biodiesel production model in *ASPEN*$^{TM}$ plus software

rotation instead of an year by year approach. Figure 5 and figure 6 show the different values in terms of hours of operation of the SOFC for the three different cultures and for the two rotations proposed as a function of the surface tilled. Horizontal dashed lines were placed at 8760 and 13140 total hours in a 3-year time interval, that is the same as 2920 and 4380 hours per year, 8 or 12 hours a day depending on the point of view. The higher the number of hours to run the plant per year, the higher the surface required to ensure the feeding of the gasifier. The line with the higher slope is the cumulative line. In case of 12 hours a day of plant run the minimum surface required is 11 hectares for the soy-based rotation and 21 hectares for the flax-based rotation.

*5.3. Economical analysis*

As reported in [15], the analysis was based on a few conservative assumptions:

- The cost for oil extraction was evaluated starting from technology review of seed presses available on the market. The average specific consumption is 0.06 kWh/kg of seeds [41]. This electrical energy was absorbed from the grid and not self-consumed from the power
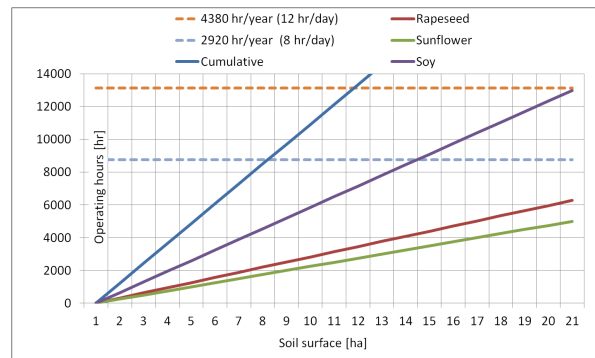
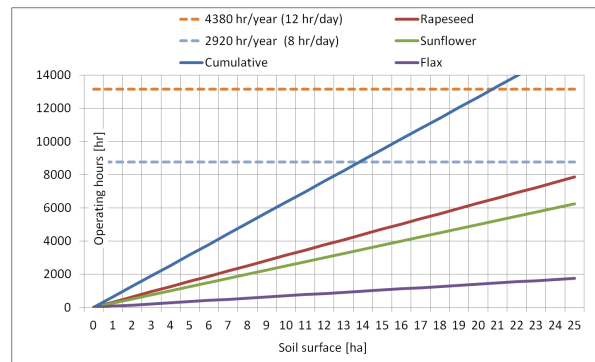**Figure 5.** Hours of plant running per hectare of tilled surface with rotation A



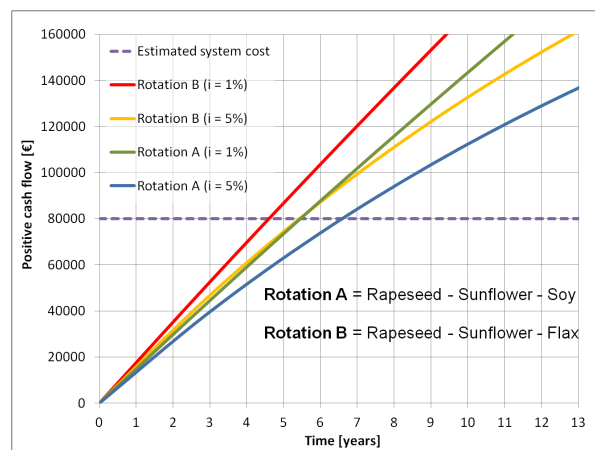**Figure 6.** Hours of plant running per hectare of tilled surface with rotation B



**Figure 7.** Net present value analysis

**Table 7.** SOFC output for 1 hectare of different cultures

| Output | Rapeseed | Sunflower | Soy | Flax |
|---|---|---|---|---|
| Gasified protein cake kg/ha | 2160 | 1540 | 2960 | 715 |
| Operating hours at 10 kWel | 314 | 250 | 650 | 70 |
| Energy produced kWh/ha | 3132 | 2503 | 6400 | 686 |
| SOFC electrical efficiency | 56.65 % | 56.18 % | 58.12 % | 58.56 % |

output of the SOFC. The considered cost for electricity at the current grid price for industrial uses was 0.1565 €/kWh$_{el}$ [42]).

- The costs for cultivating rapeseed, sunflower, flax and soy per hectare of soil are 680 €, 850 € , 500 € , 1245 € respectively. These costs were obtained as sum of seed, fertilization and farming costs [20, 27].

- This analysis did not take into account the electrical energy surplus obtainable through gasification of stalks and other vegetable byproducts of seeds crop. This surplus could be used for increasing the SOFC power output or together with the protein cake to increase the gasification performance.

- The income for sale of glycerin was 0.145 €/kg [43]).

- Other sources of electrical consumption were not taken into account in this study (i.e. compressor for methanol reactor pressurization).

The sale of biodiesel and electrical energy, the following parameters and subsidies were taken into account for 12 hours of plant running a day:

Biodiesel sale price set at 0.982 €/L (with biodiesel density < 0.90 kg/L), that is the current value on the Italian industrial market [44] and a feed-in tariff of electrical energy set at 0.297 €/kWh$_{el}$ for production from biomasses by means of small size plants thanks to a recent subsidy program in force in Italy (Ministerial Decree 06/07/2012 for the subsidy of electrical energy production from renewable sources different from photovoltaic systems [40])

For both the rotation proposed, this economical approach was found to yield a positive cash flow of about 45896 €/3year for rapeseed-sunflower-soy rotation, while the rapeseed-sunflower-flax rotation gives a cash flow of 54179 €/3year. On the other hand, the rotation with flax needed almost twice the surface required by the other rotation for being sustainable. Furthermore the rotation with flax needed to sell the flax oil, introducing the necessity to market an extra product when compared to the other solution. A conventional net present value analysis is showed in figure 7. It was based on an investment of about 80000 € ($I_0$) for the whole system and the capital cost was amortized within a period that range from 4.5 to 6.5 years depending on the rotation and the discount rate. Two possible discount rates (i) were considered in this study: 1% typical of alternative investments in government bonds (adjusted for inflation), and 5% typical of mortgage in Italy. The choice of the more suitable gasifier for this application, was determined by the characteristics of the protein cakes processed. For this non-conventional fuel an open core or an Imbert gasifier are good choices due to the capability of these reactors to process different kind of biomasses. The market offers different reactors for the power output size required in this work [45–47]. For cost estimations the All Power Labs GEK device was used as an example. The cost of the whole system was estimated on the following assumptions:

- Literature suggests a cost per kW of about 4000 € [48].

- A GEK 10 kW gasifier with bio-filter costs about 1500-2000 [46].
- The costs of the methanol and biodiesel production reactors and the seed-press was kept high (38000 €) in order to compensate possible extra costs for gas cleaning and SOFC maintenance [41, 49].

The following formula was used to calculate the net present value (NPV) at the N-th year as the sum of the discounted cash inflow in the years from 0 to N:

$$NPV = -I_0 + \sum_{n=0}^{N} \frac{(I_{bd+ee} - I_{seeds,cultivation} - I_{press\ el\ consumption})}{(1+i)^n} \tag{10}$$

It is interesting to find that 48% of all income of soy-based rotation comes from biodiesel, thus about 52% comes from electricity. In the flax-based rotation these values shift to 56% and 39% respectively (plus a 6% of income from the flax oil). Increasing the production of syngas and electrical energy through exploitation of stalks and other by products of seeds crop can thus improve significantly the cash flow.

## 6. Conclusions

The study discussed here demonstrated the capability of solid oxide fuel cells to be effectively used in systems such as the one proposed here. The presence of $CO_2$ and $N_2$ in the syngas seemed to affect the cell conversion efficiency within given limits, fixing the overall conversion rate to encouraging values. Furthermore two possible rotations are here modeled and discussed, substitution of flax with soy could drastically reduce the surface required for system self-sustainability without compromising the return of the investment. Future work will support the method proposed with accurate experimental campaign, trowing light on possible limits of the system such as capability to avoid ashes slagging in the gasifier or the effect of syngas composition fluctuations on methanol conversion rates. Once the system model is validated, different rotations can be simulated in order to maximize the profit.

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