SWEET SORGHUM TO PRODUCE IN ITALY SUSTAINABLE ETHANOL, ELECTRICITY AND HEAT IN DECENTRALISED SMALL-MEDIUM BIOREFINERY

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ABSTRACT: Sweet sorghum is an interesting energy crop for the southern regions of the EU: its processing allows to obtain from the sugar juice sustainable ethanol and from the by-products (i.e. bagasse, vinasse) electricity and heat. The profit derives from the sale of ethanol and electricity and from the removal of costs for the purchase of primary heat source (i.e. self-utilisation of the produced heat). With this approach the plant is a proper biorefinery and the technical-economic feasibility promotes also small-medium plants. The chain model was finalised in Italy engaging representative of all the main stakeholders: farmers, agricultural associations and consortia, SME, fuel processors and related associations, fuel distributors, representatives of public authorities, policy makers, banks and researchers. In the developed chain model the biorefinery has a capacity of 10,000 t/year and the cultivation of 3,800 hectares within 15 km from the plant is required. The internal rate of return (15 years) is higher than 20%. The obtained ethanol is certified as sustainable in accordance with Directive 2009/28/CE and the Italian legislative decree n. 28/2011 (GHGs emissions saving 63%) and it is competitive to contribute in reaching the target to 2020.

Keywords: sustainability, sweet sorghum, ethanol, electricity, heat, biorefinery.

1 INTRODUCTION

Taking into consideration the indications of the Directive 2009/28/CE for the promotion of the renewable energy sources and the related targets by 2020, sweet sorghum (*Sorghum bicolor* (L.) Moench) can play a strategic role as bioenergy crop in Italy and in the southern regions of the EU [1]. In fact sweet sorghum is a C4 plant and it is characterized by high biomass yields, large amount of free sugars in the stems and low input requirements because of its high water, nitrogen and radiation use efficiency [2-10]. In addition it has a wide adaptability to different environments [1]. For these characteristics sweet sorghum is considered one of the most efficient crops to convert atmospheric CO_2 into sugars and biomass [1].

For its applications in the bioenergy sector, sweet sorghum is a multipurpose crop. Free sugars extracted from the stems are fermentable in ethanol and residual crushed biomass (i.e. bagasse) can be burned in CHP plant to obtain electricity and heat. With regards to the yields, in the Po Valley conditions (Italy) sweet sorghum produces 55-70 t/ha wb of stems and 6-8 t/ha of fermentable sugars without irrigation [11-12]. Grain can be obtained for the food chain (5-8 t/ha in the Po Valley) [13]. At this aim specific agricultural machineries are being tested for the automatic separation of grain during the harvesting operation and genetic researches are directed to select hybrids with high yields in stems, sugars and grain at the same time. The high genetic variability of sweet sorghum favours these selections: till now 4,000 varieties have been identified worldwide, allowing significant improvement of the yields in the future [14]. To complete the exploitation of the crop, vinasse deriving from the processing of sugars in ethanol (i.e. distillation phase) can produce biogas through the anaerobic digestion and the obtained biogas can be converted in electricity and heat in a CHP plant.

The possibility of exploiting the whole biomass of sweet sorghum to produce ethanol and other energy commodities, after its high economic viability that has been demonstrated, offers a new sustainable path for the production of ethanol, which is considered a strategic fuel for the transport sector [1, 14-19].

Basing on these considerations in the framework of the SWEETHANOL project, supported by the European Commission in the context of the Intelligent Energy Europe program, a chain model to use sweet sorghum as energy crop to supply a small-medium biorefinery (capacity 10,000 tons anhydrous ethanol per year) was studied. Different case studies were analysed in the three countries of the project consortium (Italy, Greece, Spain) and the results obtained in the Italian specific situations are reported here.

2 MATERIALS AND METHODS

The chain model was developed fitting to the Italian situation of the Po Valley the decentralized ethanol production, which is already implemented in India by the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT).

The developed chain model was validated through the discussion about its contents with the stakeholders. Five discussion workshops were carried out in Italy to this aim: three technical workshops (i.e. one in Turin and two in Padua), one administrative (i.e. in Udine) and the last one, characterized by an intersectorial approach directed to finalize the eventual criticisms (i.e. in Padua). The geographic localization of the events was chosen basing on the actual possibility to cultivate sweet sorghum in rotation with maize and in marginal lands, where the economic viability is guaranteed.

In the technical workshops were discussed the following topics: cultivation of sweet sorghum in the Po Valley (e.g. biomass and sugar yield, irrigation and fertilizers requirements, mechanization), range of supplying and related logistics (e.g. number of agricultural machineries, number of kilometers driven, timing of supplying), processing in ethanol (e.g. crushing, fermentation, distillation, rectification, dehydration), energetic exploitation of by-products. The technical details discussed with the stakeholders were obtained in the contest of the MULTISORGO project, supported by the Italian Ministry of the Agriculture. In the administrative workshop the laws and the authorization required to start up new entrepreneurships were discussed. In the intersectorial workshop all the contribution were implemented in the final model.

The stakeholders engaged in the discussion events were: farmers, agricultural associations (e.g. Coldiretti), agricultural consortia (e.g. Consorzi Agrari d'Italia S.p.A.), seeds companies (e.g. Assosementi, KWS Italia S.p.A.), SME and fuel processors (e.g. M&G Group – Chemtex Italia S.r.l., Bertolino Group) and their associations (e.g. Assocostieri), fuel distributors (e.g. LyondellBasell Italia), researchers (e.g. ENEA, universities of Florence, Padua, Udine and Turin, CRA-ENG), investors (e.g. BCC of Friuli Venezia Giulia), representatives of public authorities (e.g. Italian Ministry of the Economic Development, Custom Agency).

The economic viability of the chain model was verified through the internal rate of return (IRR), payback and net present value (NPV). In the costs item were considered: investment costs (i.e. buildings, equipment, extraordinary maintenance, overheads 5%, technical costs 5%, unforeseen expenses 4%), purchase of biomass (i.e. 33 €/t, based on the current maize price), utilities for industrial users (i.e. electricity, water, discharge of waste water, waste disposal) and other costs, such as chemicals, handling of the biomass, O&M, insurance, maintenance. In the income items were considered: selling of anhydrous ethanol (1,000 €/t), selling of the electricity to the grid (average value of 0.22 €/kWh for 15 years, considering the price of electricity plus the renewable energy production subsidy, in accordance with the present Italian law for the electricity produced from biomass). The sensitivity analyses were carried out varying the price of the biomass in the range 20-35 €/t, the price of the ethanol in the range 500-1,000 €/t and the comprehensive electricity energy price in the range 0.18-0.28 €/kWh and verifying the consequent values for the IRR: the economic viability was attributed for values higher than 20%.

The GHGs emissions saving for the ethanol obtained from sweet sorghum in the considered chain model was calculated basing on the public tool produced by the project BIOGRACE, supported by the European Commission in the contest of the Intelligent Energy Europe program; this tool is downloadable from the website www.biograce.net. The sheets of ethanol from sugarcane, ethanol from corn and ethanol from wheat were fitted to the sweet sorghum cultivation and processing. The input values for the cultivation derived from sweet sorghum really tested in Italy in the contest of the MULTISORGO project [20]. The vinasse reported in the sugarcane sheet is considered as digested matter deriving from the anaerobic digestion of the vinasse from the fermentation of the sweet sorghum juice. The seeding material value was inserted in the sheet "User defined standard values" and it was utilised instead of the standard value of sugarcane. The field N_2O emissions were calculated in the specific sheet of BIOGRACE tool with the values relative to the really tested sweet sorghum in Italy in the contest of the MULTISORGO project. This first part of the sheet gave the e_{ec} value. The transport section and the e_{td} value relative to the transport of vinasse and sorghum fresh matter were calculated with values deriving from the sweet sorghum cultivation trials made in Italy in the contest of the MULTISORGO project. The section of ethanol plant was filled in with calculated values from the sweet sorghum elaborated model, considering the obtained tons of ethanol per hectare (2.67 t/ha), the conversion factor of ethanol in MJ/kg (26.81), the calculation of MJ of sorghum per hectare per year (316,680): these data gave the value of yield ethanol of 0.226 $MJ_{etOH}/MJ_{sorghum}$. The by-products are completely reused in the process (i.e. vinasse for anaerobic digestion and bagasse for combustion plant). Considering the data from the sheet of wheat ethanol with straw burnt in CHP, the data for CHP plant of sweet sorghum model were calculated. The values of consumed electricity and the surplus of power to sell to the grid were inserted in the sheet, without considering the steam from CHP, which is completely reused in the processing plant. Out from this section the e_p value was obtained. Automatically the allocation of over main and by-products was calculated. The values for transport of ethanol from plant to EU were considered as zero, because the plant is supposed to be already in the EU. The EU internal transport was considered as 300 km and the other values like energy consumption of depot, the filling station were left the same of sugarcane. The LUC was not considered because in the model sweet sorghum is cultivated in the fields where usually maize or other crops are cultivated and in marginal lands. From this modified sheet derived the final value in percentage of reduction emissions of GHGs.

3 THE CHAIN MODEL PROPOSED IN ITALY FOR THE PO VALLEY

The main working hypotheses applied in this chain model and agreed with the stakeholders are summarized in the Table I.

Table I: Working hypotheses applied in the chain model

Working hypotheses	
Capacity	10,000 t/ha as anhydrous ethanol (99.7% w/w)
Required fields	3,800 ha
Localization	Po Valley (Italy)
Seeding	May
Harvesting	Sept-Oct
Biomass yield	65 t/ha wb (moisture 72%)
Sugar yield	6.5 t/ha
Fertilization	100 kg N/ha 60 kg P_2O_5/ha 60 kg K_2O/ha
Irrigation	no irrigation
Climate characteristics	temperate oceanic climate 670 mm (May-Sept 2010, in Udine, Friuli Venezia Giulia region)
Ethanol yield	2.67 t/ha
Range of supply	15 km from the biorefinery
Harvesting window	40 days (Aug-Sept)
Working time	330 days/year, 24 hours/day
Investment cost	30 million €

3.1 Agricultural section of the chain

In the considered model sweet sorghum is cultivated in rotation with maize and in some marginal lands. As regards with the first option, sweet sorghum contributes to reduce the supply of nitrogen to the soil, because its demand is the half that of maize (Tab. I), and consequently its cultivation is an indirect measure to contrast the eutrophication. Sweet sorghum is suitable to grow in marginal lands, but the choice to use them is subordinated to economic considerations specific for each site. In fact in some cases farmers prefer to do not work these lands, because the attainable yields do not justify the incurred operating costs. Then it is plausible that only a part of the available marginal lands guarantees the economic viability for the farmers. In order to plan the chain in one specific territory both contributions (i.e. rotation with maize and use of marginal lands) have to be integrated and in the model it has been assumed that the supply of the biorefinery is guaranteed with 10,000 hectares dedicated to the chain, of which 3,800 hectares actually cultivated every year. The hypothesized range of 15 km allows the supply in the situation of the Po Valley.

In the considered climate the seeding starts from May and the harvesting is in the period of August-September. The logistics of the harvesting is a critical aspect for the supplying timing of the biorefinery and for the sugars preservation, because it is carried out in a short window, which can be of 40 days at maximum, choosing varieties with different growth cycles, short (70-90 days) and long (110-120 days). The developed model suggests the employment of 4 yards, utilizing in total 4 mower-shredder-charger machines and 24 farm tractors with dumper (capacity 50 m^3/dumper). One simulation has been performed to verify this assumption. In this simulation the fields have been located with the following logic, which is consistent with the situation in the considered territory in terms of distribution of farms and cultivated crops:

35% of the fields within 5 km from the biorefinery;
44% between 6 and 11 km from the biorefinery;
21% between 12 and 15 km from the biorefinery.

This simulation confirms that the hypothesised logistics is able to supply the biorefinery with a traffic of 15 tractors per hour in the harvesting period. The obtained result is held acceptable.

3.2 Biorefinery

The scheme of the biorefinery is shown in the Figure 1.

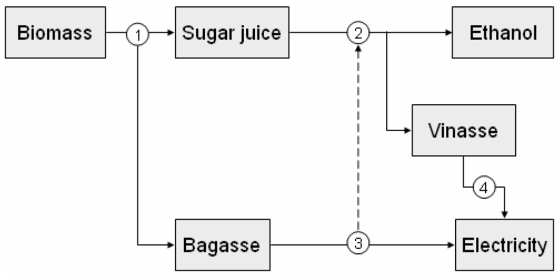


Figure 1: Scheme of the biorefinery
Legend:
1 = crushing unit
2 = processing of the sugar juice in ethanol
3 = drying and burning of the bagasse in CHP plant (electrical power 4.20 MW)
4 = anaerobic digestion of the vinasse and burning of the obtained biogas in CHP plant (electrical power 0.75 MW)

Sweet sorghum is supplied to the plant as chopped biomass and the sugar juice is immediately separated in the crushing unit, in order to avoid significant loss of sugar (Fig. 2).

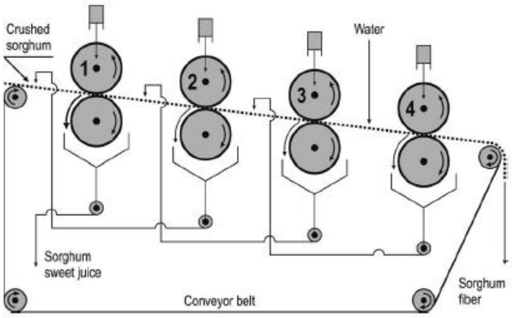


Figure 2: Crushing unit [21]

The sugar concentration obtained in the juice with the considered variety and with the extraction efficiency of the applied technology is about 12%. In order to supply the biorefinery for all the year, the sugar juice is concentrated to have a stable syrup: the concentration to 45% allows the storage for 3 months, the concentration to 80% extends the storage time up to 11 months. The waste water from the concentration unit can be discharged in surface water body, respecting the limits of the Italian law.

Before the alcoholic fermentation, the stored sugar juice is diluted to 18%. The fermentation is carried out in batch with yeasts (*Saccharomyces cerevisiae*) in their optimal conditions. The fermented medium (ethanol 7% p/p) is distilled and rectified. The azeotropic ethanol is dehydrated in molecular sieves unit and the anhydrous ethanol is one of the final products of the biorefinery.

3.3 Biorefinery: electricity and heat from the by-products

Bagasse is the by-product of the crushing operation. Basing on the considered working hypotheses the characterization of the bagasse is reported in the Table II.

Table II: Bagasse characterization

Bagasse characterization	
Moisture	50-55%
Residual sugars	6-7%
Cellulose	16-18%
Hemicellulose	11-13%
Lignin	7-9%
LHV (moisture 10%)	4.0-4.4 kWh/kg

In the considered model bagasse is stored at the biorefinery and it is dried up to final moisture of 10% before the exploitation. The dried bagasse is burned in CHP plant, constituted by a biomass steam generator and a steam turbine: thermal efficiency 0.9, heat of vaporisation (λ) 716.76 kcal/kg, electrical power 4.20 MW. Unlike the other units, this one works 340 days per year.

Vinasse is the by-product of the distillation and rectification unit. Basing on the working hypotheses, its chemical characterization is reported in the Table III.

Table III: Vinasse characterization (average values)

Vinasse characterization	
Dry matter	6-7%
Volatile matter	85-90%
BOD_5	40-50 gO_2/l
COD	70-90 gO_2/l
Nitrogen	750-850 mg/l
Phosphorous	1.5-2.5 g/l
pH	4.4-4.6

Vinasse is converted in biogas through anaerobic digestion, mixing this feedstock with other substrates as inoculum (e.g. manure). The expected biogas yield is 570 Nm^3/t of volatile matter. The obtained biogas is burned in CHP plant made of a turbine with electrical efficiency 34% and electrical power 0.75 MW.

A further energy recovery derives from the concentration unit, because, when the harvesting ends, the high heat consumption of this units ends and the residual steam is able to feed a turbine (electric power 0.43 MW), contributing to the total energy balance of the biorefinery.

For both by-products electricity is sold to the grid as final product of the biorefinery and heat is recovered and used for self-consumption, especially for the concentration, distillation and bagasse drying units.

In this model the selling of heat through a district heating network is not foreseen.

3.4 Economic viability

The results of the economic analysis indicate the viability of the considered initiative (Tab. IV).

Table IV: Economic analysis

Economic indicators	
IRR (15 year)	21.6%
Payback	6 years
NPV (15 years)	40.3 million €

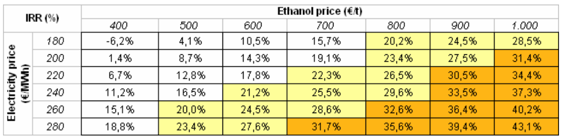
The economic analysis was completed with a sensitivity analyses to evaluate the incidence of the main variables on the viability: the price of biomass, which must be high enough to ensure the long-term supplying of the plant, the price of ethanol and the value of the all-inclusive tariff for the selling of the electricity to the grid.

In the figures on the side the results of the sensitivity analyses are reported (Fig. 3: price of biomass 20 €/t, Fig. 4: price of biomass 25 €/t, Fig. 5: price of biomass 30 €/t, Fig. 6: price of biomass 35 €/t).

As a general principle the sensitivity analyses suggest that the profitability is ensured with an ethanol price higher than 900 €/t and a value for the comprehensive electricity energy price of 0.26 €/kWh.

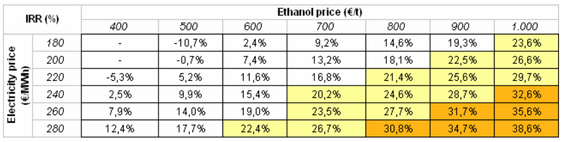
In these hypotheses up to 35 €/t can be paid to the farmers for the biomass supplying.

On the contrary, lower values for the selling of ethanol and electricity determine a decrease in the incomes, which can be obtained from the biomass suppliers, endangering the security of supplying.



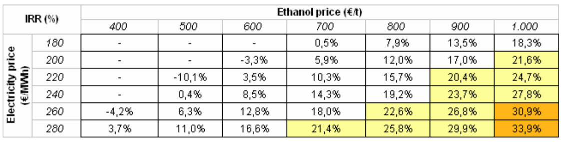
IRR (%)		Ethanol price (€/t)						
		400	500	600	700	800	900	1.000
Electricity price (€/MWh)	180	-6,2%	4,1%	10,5%	15,7%	20,2%	24,5%	28,5%
	200	1,4%	8,7%	14,3%	19,1%	23,4%	27,5%	31,4%
	220	6,7%	12,8%	17,8%	22,3%	26,5%	30,5%	34,4%
	240	11,2%	16,5%	21,2%	25,5%	29,6%	33,5%	37,3%
	260	15,1%	20,0%	24,5%	28,6%	32,6%	36,4%	40,2%
	280	18,8%	23,4%	27,6%	31,7%	35,6%	39,4%	43,1%

Figure 3: Sensitivity analysis with price of biomass 20 €/t. In yellow the values higher than 20% are evidenced and the darker are the better values



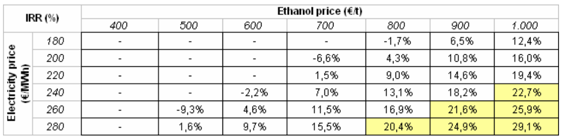
IRR (%)		Ethanol price (€/t)						
		400	500	600	700	800	900	1.000
Electricity price (€/MWh)	180	-	-10,7%	2,4%	9,2%	14,6%	19,3%	23,6%
	200	-	-0,7%	7,4%	13,2%	18,1%	22,5%	26,6%
	220	-5,3%	5,2%	11,6%	16,8%	21,4%	25,6%	29,7%
	240	2,5%	9,9%	15,4%	20,2%	24,6%	28,7%	32,6%
	260	7,9%	14,0%	19,0%	23,5%	27,7%	31,7%	35,6%
	280	12,4%	17,7%	22,4%	26,7%	30,8%	34,7%	38,6%

Figure 4: Sensitivity analysis with price of biomass 25 €/t. In yellow the values higher than 20% are evidenced and the darker are the better values



IRR (%)		Ethanol price (€/t)						
		400	500	600	700	800	900	1.000
Electricity price (€/MWh)	180	-	-	-	0,5%	7,9%	13,5%	18,3%
	200	-	-	-3,3%	5,9%	12,0%	17,0%	21,6%
	220	-	-10,1%	3,5%	10,3%	15,7%	20,4%	24,7%
	240	-	0,4%	8,5%	14,3%	19,2%	23,7%	27,8%
	260	-4,2%	6,3%	12,8%	18,0%	22,6%	26,8%	30,9%
	280	3,7%	11,0%	16,6%	21,4%	25,8%	29,9%	33,9%

Figure 5: Sensitivity analysis with price of biomass 30 €/t. In yellow the values higher than 20% are evidenced and the darker are the better values



IRR (%)		Ethanol price (€/t)						
		400	500	600	700	800	900	1.000
Electricity price (€/MWh)	180	-	-	-	-	-1,7%	6,5%	12,4%
	200	-	-	-	-6,6%	4,3%	10,8%	16,0%
	220	-	-	-	1,5%	9,0%	14,6%	19,4%
	240	-	-	-2,2%	7,0%	13,1%	18,2%	22,7%
	260	-	-9,3%	4,6%	11,5%	16,9%	21,6%	25,9%
	280	-	1,6%	9,7%	15,5%	20,4%	24,9%	29,1%

Figure 6: Sensitivity analysis with price of biomass 35 €/t. In yellow the values higher than 20% are evidenced and the darker are the better values

3.5 GHGs emissions saving

The results of the calculation of the GHGs emissions saving depend on each detail of the production of feedstock (including land use change and N_2O emissions), of its processing, of the exploitation and allocation of eventual by-products and of the transport and distribution of the obtained ethanol. In accordance with the applied working hypotheses and the assumptions explained in detail in the materials and methods, the ethanol produced from sweet sorghum determines a GHGs emissions saving of 63%.

The related values for the emissions from cultivation, processing and transport are reported in the Table V.

Table V: GHGs emissions for ethanol produced from sweet sorghum in the considered chain model

GHGs emissions	
Cultivation	29.9 g $CO_2eq/MJ_{ethanol}$
Processing	-1.8 g $CO_2eq/MJ_{ethanol}$
Transport and distribution	3.1 g $CO_2eq/MJ_{ethanol}$

The table V emphasizes that the processing phase has a negative contribution to the GHGs emissions because the energetic exploitation of the by-products is able to cover all the energy consumption of the plant. In fact heat is recovered for the self-consumption and electricity is sold to the grid for economic reasons (i.e. high value of the comprehensive electricity energy price for 15 years, in accordance with the Italian law), but a lower amount is bought from the grid.

4 CONCLUSIONS

The economic analyses and the environmental remarks indicate that the considered chain model to produce ethanol and other energy products from sweet sorghum is sustainable. Consequently its actual application in Italy, especially in the Po Valley, is viable and the obtained ethanol is able to contribute to achieve the target by 2020 for the transport (i.e. 10% of the energy consumption deriving from renewable energy sources).

The configuration, which appears optimal, foresees that the farmers are biomass suppliers with a double remuneration: one pre-financing at the supplying time, in order to cover the costs of cultivation and to guarantee a minimal profit (similar to that of the previous sowable crop) and one balance after the sharing of the industrial profits in order to improve the incomes to maintain the motivation and to preserve the security of supplying the biorefinery.

The investment costs to start up new entrepreneurship or to implement existing distilleries can derive by private investors (e.g. banks, investment funds, entrepreneurs) and/or by agricultural consortia.

As regards with the upgrading of the chain model, consequent to the future evolution of the ethanol market in direction of the 2nd generation biofuels, the possibility to implement the biorefinery with the processing of lignocellulosic feedstock was foreseen. In this hypothesis sweet sorghum is processed during the harvesting period, cultivating a lower agricultural surface. In the rest of the year other lignocellulosic feedstocks (mainly residual biomass) are converted in ethanol. From a technical point of view, the biorefinery requires a moderate adaptation: the previous units must be implemented with the sections of pretreatment and enzymatic hydrolysis and all the other facilities are able to continue to work equally.

Figure 7: Harvesting of sweet sorghum in the fields of Udine (Friuli Venezia Giulia region, Italy) (source: CETA)

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