Bio-energy production in the sugar industry: an integrated modeling approach

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Abstract: *Recent reforms in the Common Agricultural Policy and the sugar regime caused serious concerns for the future of the European sugar industry. At the same time, the European Commission considers transportation bio-fuels as a key factor for reducing reliance on imported fuels, emission levels of greenhouse gases and to meet rural development goals. Matching the sugar sector with bio-ethanol production may create opportunities for sustainable management of the existing sugar industry infrastructure and also serve bio-fuel policy targets.*
A partial equilibrium economic model is used in order to evaluate the shift from sugar to bio-ethanol production in Thessaly, Greece. In the agricultural feedstock supply and industrial processing sub-models are articulated indicating optimal crop mix for farmers and the best technology configurations for industry. The joint ethanol-biogas option appears to be preferable using sugar beet and wheat, whereas capacity selected amounts at 120 kt of ethanol.

Keywords. Sugar beet, grain, ethanol, mathematical programming, Greece

1. Introduction

Bioenergy refers to the energy produced from biological sources or biomass. Biomass may either be burned directly or converted into liquid or gaseous fuel. Bio-energy production in the sugar industry includes mainly production of bioethanol for automotive fuel purposes. Ethanol is the most common biofuel worldwide, accounting for more than 85% of the total biofuel uses[1] .Ethanol is typically blended with gasoline in order to expand supply, increase the octane rating of gasoline, and make it a less polluting, cleaner burning fuel. Internal combustion engines optimized for operation on alcohol fuels are 20 per cent more energy-efficient than when operated on gasoline[2], and an engine designed specifically to run on ethanol can be 30 per cent more efficient[3].
Recent changes in European policies concerning the sugar and the bio-fuel sector, that complete 2003 Common Agricultural Policy (CAP) decoupling reform, create a favourable environment for ethanol production by ex-sugar factories in Europe. This paper undertakes an economic evaluation of alternative ethanol production schemes in Central Greece (Thessaly) using sugar beet and wheat. Ethanol production is simulated in a mathematical programming model that is coupled to an arable sector agricultural supply model. Agro-industry surplus is maximised subject to linear and non-linear constraints in order to determine optimal industry configuration and size as well as energy crop quantities and opportunity costs.

The paper is organised as follows: section 2 overviews the institutional environment and relevant policies. In section 3 technical options and information on sugar-to-ethanol transformation are detailed. Modeling methodology and the case study are presented in sections 4 and 5 respectively. Optimisation results and discussion are given in section 6, and section 7 comprises some concluding remarks and ideas for further research.

2. Institutional framework: CAP Reform and the European Sugar Industry

The creation of a common agricultural policy was proposed by the European Commission. It followed the signing of the Treaty of Rome in 1957, which established the Common Market. The Common Agricultural Policy (CAP) was agreed to at the Stresa conference in July 1958. The CAP established a common pricing system for all farmers in the member countries, and fixed agricultural prices above world market levels to protect farmers in member countries who generally had higher production costs than other world market producers.

The main purpose of the Common Market Organization (CMO) in the sugar sector when it was created in 1968, was to guarantee sugar producers a fair income to provide self-sufficiency in sugar throughout the Community. High prices paid by the consumers encouraged sugar production in Community and import levies were used to deter imports from non-EU countries. The essential features of the sugar regime were a support price (a guaranteed minimum prices to sugar growers and producers to support the market); production quotas to limit production and distribute it across the European community; tariffs and quotas on sugar imports from non-EU countries; and, subsidies to export the surplus of sugar production out of the European Union[4].

Strong support and protection given to the EU sugar sector had many different results. First, the EU became a net exporter of sugar as the supply expanded well beyond the demand. By driving a wedge between world market prices and prices prevailing inside the EU, the Sugar CMO originates a transfer of wealth from consumers to producers and refiners. Also, since the excess production was exported with refunds, sugar producers received the same revenues as they would selling the sugar inside the EU market. Such subsidized exports depressed world market prices, making other producers worse off. Since its creation in 1968, the CMO for sugar has changed only marginally. The first change was in 1975 following the United Kingdom’s accession, when the CMO incorporated that country’s previous commitments to certain African, Caribbean, and Pacific (ACP) countries to import raw cane sugar for refining and subsequent sale on the UK market. The second big modification came in 1995 following the Uruguay Round, with a restriction on export refunds. The CMO was adjusted by making provision to reduce quotas in the event that the limit on refunds meant that the available surplus on the Community market could no longer be exported with refund. Since then, in practice, if imports increased the market equilibrium was re-established by reducing Community quotas (reduction mechanism)[5,6].

However, CMOs success in making sugar one of the most profitable crops in many EU countries has succeeded in delaying reform proposals until recently. The principal causes for reforming the sugar program at 2005 are threefold: (1) the CAP reforms of 2003/04 moving from commodity support to direct area payments (that left sugar as the only major commodity unreformed) ; (2) the “Everything But Arms” (EBA)[1] agreement, allowing the 48 least developed countries duty-free access to the EU sugar market by 2009; and (3) a World Trade Organization (WTO) Panel ruling that found the EU sugar regime in violation of WTO export commitments. Additionally, the EU offer to eliminate export subsidies in the Doha Round of WTO negotiations played a role in shaping the reform proposal[7]. These events led to the European Commission’s proposal to drastically reform sugar in 2005.

The reform proposals were designed to continue with its recent reforms of the CAP and to meet its international obligations. The stated aims of the reform are (1) to encourage reductions in domestic sugar output, particularly in regions with high production costs or lower sugar beet yields; (2) to bring export subsidies in line with WTO commitments; (3) to dampen incentives for EU sugar imports from the EBA countries; and (4) to reduce the price gap between sugar and competing sweeteners to forestall the substitution of sugar. The basic features of the proposal are[8]:

[1] Traditionally, it has been admitted that the group of least developed countries (LDCs) should receive more favourable treatment than other developing countries. Gradually, market access for products from these countries has been fully liberalised. In February 2001, the Council adopted Regulation (EC) 416/2001, the so-called "EBA Regulation" ("Everything But Arms"), granting duty-free access to imports of all products from LDC's, except arms and munitions, without any quantitative restrictions (with the exception of bananas, sugar and rice for a limited period).

- Sugar price is reduced by 36 percent over a 4-year phase-in period beginning from 2006/07 (to ensure sustainable market balance, -20 percent in year one, -25 percent in year two, -30 percent in year three and -36 percent in year four).
- Minimum sugar beet price is reduced by 39.5 percent to €26.3/metric ton over the phase-in period.
- Sugar production quotas are not reduced except through a voluntary 4-year restructuring program where quota can be sold and retired. Payments for quota are €730/mt for 2006/07 and 2007/08; €625/mt for 2008/09 and €520/mt for 2009/10.
- Restructuring is financed by quota levies on producers and processors who do not sell quota. Total value of the restructuring fund is projected at €5.704 billion.
- Compensation is available to farmers at an average of 64.2 percent of the price cut. The aid is included in the Single Farm Payment and is linked to payments for compliance with environmental and land management standards.
- Establishment of a prohibitive super levy to be applied to over-quota production.
- Non-food sugar (sugar for the chemical and pharmaceutical industries and for the production of bioethanol) will be excluded from production quotas.

The new Common Market Organization in the sugar sector, which began in effect from July 2006, includes progressive reduction of prices of sugar and sugar beets as well as the reduction of quotas of sugar for each of EU country. These developments affected beet production dramatically, due to the sugar beet cultivation becoming economically disadvantageous and the sugar industries decreasing their production. According to estimates by the European Commission, total EU sugar production should fall to 12.2 million tons per year, which is equal to a decline of 43 per cent from the 2005 base year[8] . To achieve the target, based on estimates of the combined profitability of the industry (growers & manufacturers) the commission classified EU-25 sugar producing Member States into three groups, depending on their level of costs.

- Member States where sugar production is likely to be drastically reduced or even phased out: Greece, Ireland, Italy, Portugal;
- Member States in the border zone: Czech Republic, Spain, Denmark, Latvia, Lithuania, Hungary, Slovakia, Slovenia and Finland. In these MS, production is likely to be maintained but at a significantly lower level;
- Member States where the decrease in sugar production will be limited. It is even likely that overall production would not decrease in some MS: Austria, Belgium, France, Germany, the Netherlands, Poland, Sweden and the UK.

The main achievements of the first three years (2006 until 2009/10 (provisional status on January 2009)) of the restructuring is 5.77 million tones of quota renounced and out of 184 sugar factories, 79 have closed[9, 10]. Though the price for the consumer remained the same, the price for the producer reduced. According to EBA initiative there has been a reduction of import duties on sugar by 20% on 1 July 2006, by 50% on 1 July 2007, and by 80% on 1 July 2008 until their entire elimination on 1 July 2009[7]. In this situation the reference price has been dramatically reduced from €631.9 to €541.5 per ton from 1st of October 2008. Considering quota and duty free entrance of LDCs country to the EU market, the reference price from 1st of October 2009 will be €404.4 per ton[11].

3. Transformation from Sugar to Ethanol Production

Bio-ethanol can be produced from any feedstock that contains significant amounts of sugars or glucose polymers such as starch and cellulose that can be converted into glucose via hydrolysis. Sugar obtained from feedstock such as sugar beets, sugar cane and ‘molasses’, a by-product from sugar production, can be fermented directly. Starch from feed-stocks such as corn, potatoes, wheat, rye, barley and sorghum is a glucose polymer that must be hydrolyzed using enzymes to glucose monomers prior to fermentation.

With changes in the EU sugar regime, and with WTO ruling, the Common Market Organization in the EU has excluded sugar and sugar beet for non-food use (sugar for the chemical and pharmaceutical industries and for energy purposes) from production quota restriction. Simultaneously, the European Commission substantially promotes bio-fuels for environmental reasons and in order to ensure a minimal level of energy independence of EU. The States reduced their requirement for tax (the special tax in the petroleum products is basic source of income in all developed countries) when the fuel is from non-fossil origin, which renders competitive bio-fuels that usually cost twice as conventional fossil fuels. The EU sugar regime set compensation, by the EU regulation (EC) 320/ 2006 both for growers and industries. Compensation for producers and beet growers was set at amounts of €145.5M for restructuring, €43.6M for diversification and €123M for growers. In particular, it outlines that 100% of the restructuring compensation will be made available if full dismantling of production facilities occurs, while 75% of compensation will be made available if the option of partial dismantling of facilities is taken (i.e., a reduction of €36.4M if some facilities are retained)[12]. So, both the partial and complete transformation of production facility for bio-ethanol in the sugar industry is supported by the regulation and according to the requirement and commodity price, i.e. price ratio of sugar to ethanol, one can choose an optimal ratio between sugar and ethanol production.

Under the new CAP, the Greek sugar quota has reduced by 50.2 percent and the Hellenic Sugar Industry (HIS) has benefited by the amount of €118 million from the EU. In order for the HSI to accept the reduction of the quota by 50.2 percent, the EU has offered financial support to the Greek Industry to be spent for restructuring and investment. For Greece, the initial amount decided and agreed was at €118 million, of which to date 87 million have already been paid to HSI and the remaining 31 million will not be paid unless H.S.Co. finally implements its bio-ethanol program[13] .
The option of the H.S.Co. to convert altogether two sugar plants to ethanol production was announced in 2006, however despite consecutive calls to investors the process is still open and the sugar factories ceased operation without starting ethanol production. In this exercise we will evaluate the conversion of the sugar factory in Thessaly to ethanol, following two different configurations:

The first configuration comprises the raw biomass processing units that outflow their product after first transformation phase towards the Bio-ethanol production unit. The sugar-beet processing unit also produces pulp top shoots. Besides ethanol stillage from grain and sugar-beet being produced, the former is used to produce DDGS, the main by-product of the activity.

The second configuration includes a “biogas production unit” generating “green” electricity and heat out of pulp top shoots and stillage from sugar-beet. In this case steam and electricity previously bought are self-generated within the plant, whereas pulp is not sold anymore since it is used in the biogas unit.

4. Methodology and model specification

Models for optimisation of bio-energy conversion seek to determine plant size and technology. Detailed information is included on capital and administrative costs (which decrease with plant size), on variable conversion costs (proportional to the output), as well as on transport costs (increasing with plant size). Raw material costs are often assumed proportional to the output and biomass price is perfectly elastic thus constant no matter the quantity demanded by the plant. In other words, agriculture is not given special attention assuming that production is undertaken in homogeneous land and farm structures. A typical example of this engineering approach is a model by Nguyen and Price [14] on bio-ethanol from sugarcane and sweet sorghum in Australia. Analysis is sufficiently complicated concerning conversion using single or mixed crops and various transport costs, resulting in optimal ranges of size of the conversion plant. With regard to biomass raw material, cane and sweet sorghum prices and yields used are constant, assuming a simplified view of the agricultural supply.

Partial equilibrium micro-economic models are used to improve representation of the farm sector in agro-industry models and the introduction of energy crops in the crop mix. For example, Treguer and Sourie[15] have estimated the agricultural surplus generated by the production of energy crops including sugar beet-to-ethanol, and assessed how these new crops can help to maintain farmers’ income and farms’ structure. Rozakis and Sourie[16] built a partial equilibrium economic model in order to assist in the micro-economic analyses of the multi-chain system of the biofuel chain in France.

On this track, the present study aims at evaluating the conversion of a sugar factory to an ethanol production plant. It pays special attention to the fact that biomass cost increases with higher demand and also that capital costs per unit of output fall in bigger plants. Partial equilibrium agricultural sector modeling and engineering approaches, applied to the industrial model, are jointly exploited to determine the appropriate technical configuration and size of bio-ethanol plant, and at the same time raw material supply. The most efficient farmers will provide beet and grain at the lowest possible prices.

More specifically agriculture and industrial production are coupled in the frame of an integrated model actually containing two sub-models, namely the agricultural supply model and the ethanol production unit model. In the agricultural model, a large number of individual farms are articulated so that to adequately represent regional arable agriculture. Each farm selects a set of activities (cropping plan) in order to maximize gross margin. The farm planning is governed by resource availability, technical and policy constraints. Main constraints are:

available land (both total land area and area by land type such as irrigated, non irrigated etc.), irrigation water availability constraints, crop rotational constraints, environmental constraints, and so forth.

The demand curve for most crops is assumed to be perfectly elastic, i.e., the price of the crop assumed to be fixed and determined exogenously. This is a strong hypothesis that does not hold in the case of alfalfa. The demand curve of alfalfa has a negative slope, because this commodity is bulky and long-distance transport becomes complicated, so that its price is determined in the domestic market. There is a limit of quantity that can be sold in the domestic market, and demand depends on the quantity of ruminant livestock that consume it. Thus the agricultural supply model contains one quadratic term in the objective function.

Profit maximization of the industrial unit determines the optimal size and technical configuration of the plant, giving maximum income from sales of product and by-products and minimal cost of production. The main relationships shaping the feasible area of the industry model deal with capacity, sugar-beet to wheat ratio to ensure maximal duration of operation during the year (330 days), and capital cost linked to size (average capital cost is decreasing for increasing ethanol capacities). Usually size determination is modeled by binary or integer variables, as in a bio-energy application[17] that also mentions a number of studies of the same kind. In this study, since a continuous relationship is available[18] we preferred to introduce exponential terms (scale coefficients) in the objective function rendering the industrial module non-linear also. Furthermore, feedstock supply i.e., wheat and sugar beet produced in farms, have to satisfy industry needs (raw material demand should be greater than supply). A number of balance constraints concerning by-products, material inputs and environmental indices (such as water for irrigation) complete the constraint structure.

The integrated model combines both agricultural and industry objectives as its objective function represents total surplus that is equal to the sum of industry and agricultural sector surpluses. It is written in GAMS code and uses non-linear solvers. Algebraic notation of model constraints and objective function along with associated indices, parameters and decision variables are detailed in the appendix.

5. Case study

5.1. Agricultural Sector

It is assumed that farms holding sugar-beet quota and possessing considerable experience on its cultivation (since they had multi-year contracts with the sugar industry) will be the first and presumably most efficient suppliers of the ethanol plant with beet. The reason for choosing cotton cultivating farms beside sugar-beet is that an enormous number of farms cultivate this staple crop in the region. In order to ensure profitability for the ethanol plant it is important to spread capital and administrative charges over a longer period. It points out to the attractiveness of using mixed crops, in this case beet and grains, to extend the processing season that can thus count 330 days per year. The cultivation of irrigated wheat is considered to supply ethanol plant by grains, first because output is much higher than that of non-irrigated wheat, soft or hard, and secondly because it means extensive cotton cultivation replacing monoculture with cotton-wheat rotation[19].

In the present study we use data on farm structure, costs and yields from 2001-2002, i.e., under the old CAP is considered (scenario 1) then changes of CAP, i.e., new CAP element like decoupling of aid and cross compliance are introduced then in the model (scenario 2). Farms which cultivated at least one stremma (one tenth of a hectare) of cotton or at least one with sugar beet for the farming period 2001-2002 were selected for the study. A group of 344 arable farms out of all farms monitored by the Farm Accountant Data Network (FADN) satisfy the above constraint, representing in total 22,845 farms of the region.

The main crops cultivated by those farms are: Soft wheat, Hard wheat, Irrigated wheat, Maize, Tobacco, Cotton, Dry cotton, Sugar beet, Tomato, Potato, Alfalfa, feedstock maize and intercropped vetch to conform with the cross compliance term of the new CAP. Data used for the particular crop and for each agricultural farm sample were: output (kg/acre), prices (€), subsidy (€/kg and €/acre depending on the type of crop) and the variable costs (€/acre). Variable cost includes: Seeds and seedlings purchased, fertilizers and soil amelioratives, protection chemicals, fuels and lubricants, electrical energy, water, running maintenance of equipment, maintenance of buildings and landed improvements, salaries and social taxes, and wages of hired labour.

In figure 1, one can observe surfaces cultivated at the regional level by main crops in the base year 2002 as well as the optimal cropping plan for scenario 1 (CAP 2000). Model optimal results approach closely to observed surfaces forming a validation test proving the selected model specification can be used to perform predictions of the farmers' behavior under different parameters' sets. A national model of similar structure[20] passed successfully the validation test that increases confidence on non-linear sector models of Greek arable cropping systems. As a matter of fact, in the optimal solution when the model runs under the CAP 2003 regime (scenario 2) cotton cultivation is significantly decreased, replaced by maize, alfalfa and soft wheat. Also sugar beet almost disappears due to drastic price reductions.

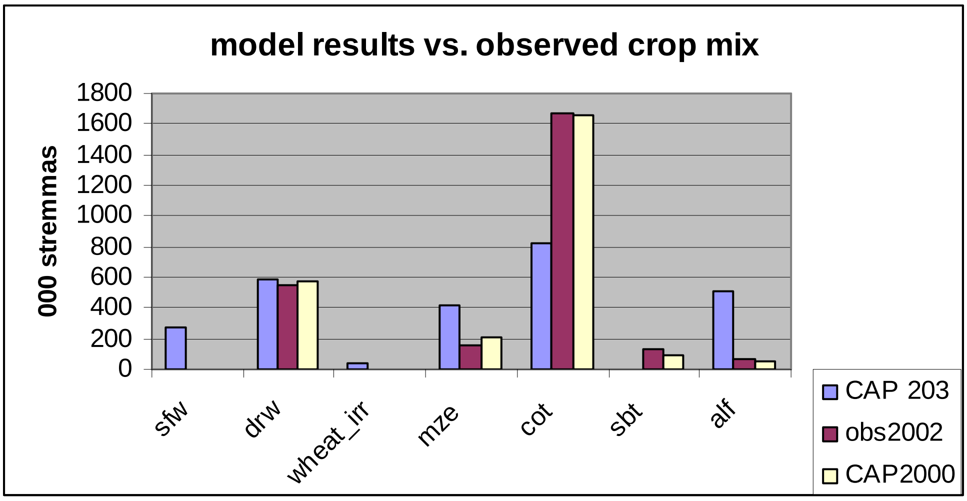

Figure 1. Observed and optimal crop surfaces at the regional level

5.2. Industry

Technical and economic data for the production process of ethanol and determination of various costs for the industry model are drilled by Soldatos and Kallivroussis[18] adapted to the conditions of ex-sugar factory in Thessaly by Maki [21]. Data include a transformation ratio from wheat and sugar beet to ethanol, corresponding prices and required quantities (per produced quantity of ethanol) of additional and auxiliary matters e.g. chemical substances, the requirements in electrical energy and steam and the corresponding costs, production rate of by-products and the sale prices of produced ethanol and by-products.

The base capacity of the unit (35000 t EtOH) determines the cost of investment, the cost of equipment, the requirements for the workforce and a line from costs (direct and indirect) that concerned the economic analysis as well as a pattern of the final cost of the first and auxiliary matters, the cost of electrical energy and steam, the cost of maintenance and other costs of operations that concern the production and the administrative support of the unit. A scale coefficient of 0.61 is used in an exponential function linking capital costs to plant capacity. Allowable range of capacities vary from 10000 to 120000 t. Capital costs are shown in Figure 2 illustrating a decreasing rate of increase of capital costs with increasing scale. This means decreasing average capital costs are associated with larger ethanol plants.

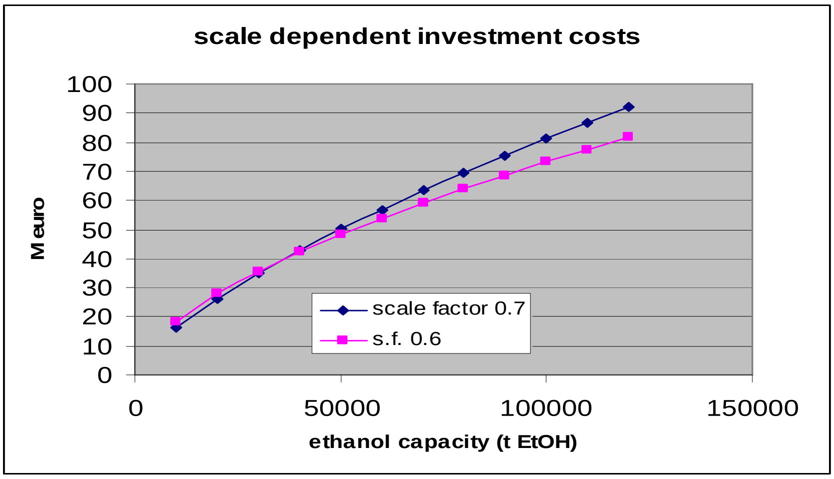

Figure 2. Investment cost of ethanol plant

6. Results and discussion

Parametric optimization of the integrated agro-industrial model determined the optimal crop mix for farmers as well as the best technology configuration for the industry and size of the plant. As expected, biomass costs increase and transformation costs decrease with capacity in any case. Biomass costs are endogenously given by the model (dual prices) resulting from changes in the crop mix to satisfy the increasing biomass demand from the industry. In figure 3 the evolution of optimal crop mix at the regional level for increasing ethanol plant sizes is presented, starting from the CAP 2003 optimal solution (for zero ethanol production presented in bar form in figure 2). Figures 4 and 5 illustrate results for capacities from 30 to 120 thousand tons of ethanol. All magnitudes are reported in average values per ton of ethanol.

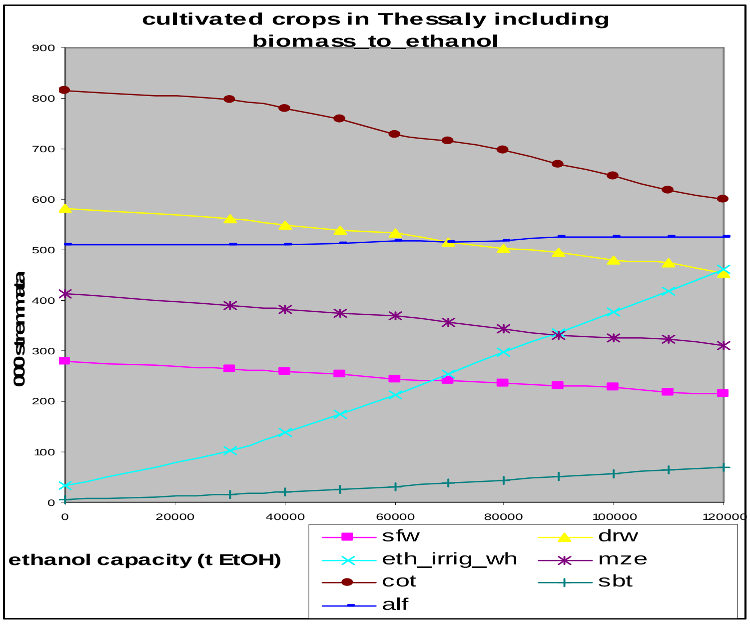

Figure 3. Evolution of cultivated surfaces by main food and energy crops.

Outflows (costs) consist of raw material costs (sugar beet and wheat), other variable input and labour cost as well as capital costs. Raw material cost is determined by the dual values of biomass demand satisfaction constraints for both energy crops, multiplied by respective quantities. The model maximizes total profits, thus it proposes the highest possible capacity. If we maximize average profit (profit per ton of ethanol) then lower than 120000 ton capacities are preferred although average profit is almost stable.

Key results of the model concerning the original configuration are presented in figure 4. One can observe that average costs always exceed average inflows. Total average cost is minimized in capacity range of 50-60 kt ethanol. Explicitly, average capital costs begin at 247 euro/t for small plants (30000 t) and decrease to 144 euro/t for maximal capacity (120000 t). Other variable costs (comprising labour and administrative expenses, chemical inputs and steam and electrical energy) start from a similar level for the small plant (249 euro/t), but unlike average capital costs they remain almost at the same level per unit for higher capacities (240 euro/t in 120000 t). Sugar-beet and wheat amount at almost 50% of total cost for small plants but this element increases to 57% for 120000 t plant.

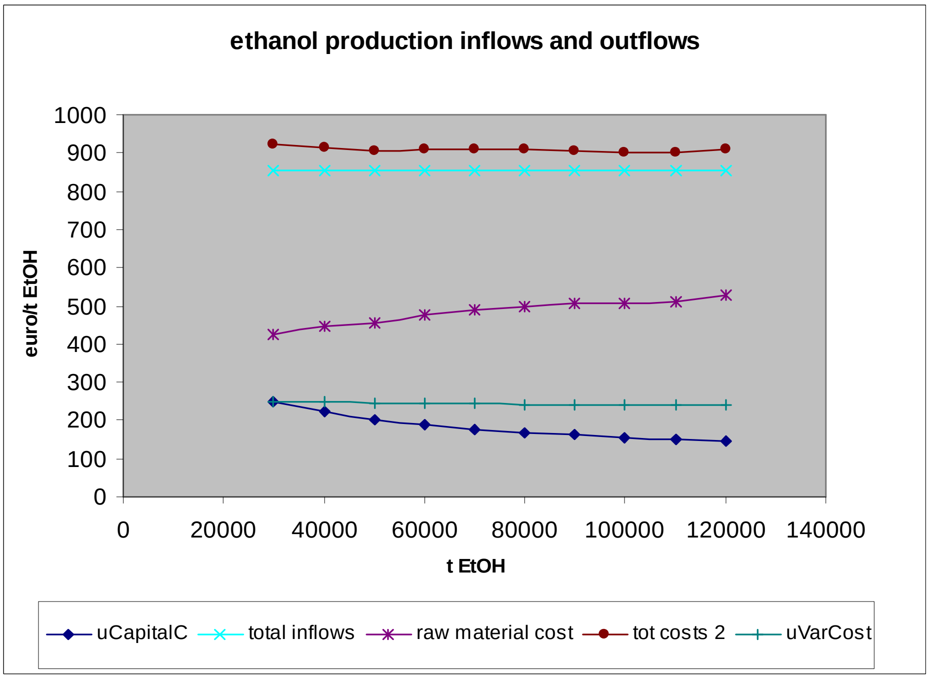

Figure 4. Inflows and outflows per unit of ethanol (configuration 1)

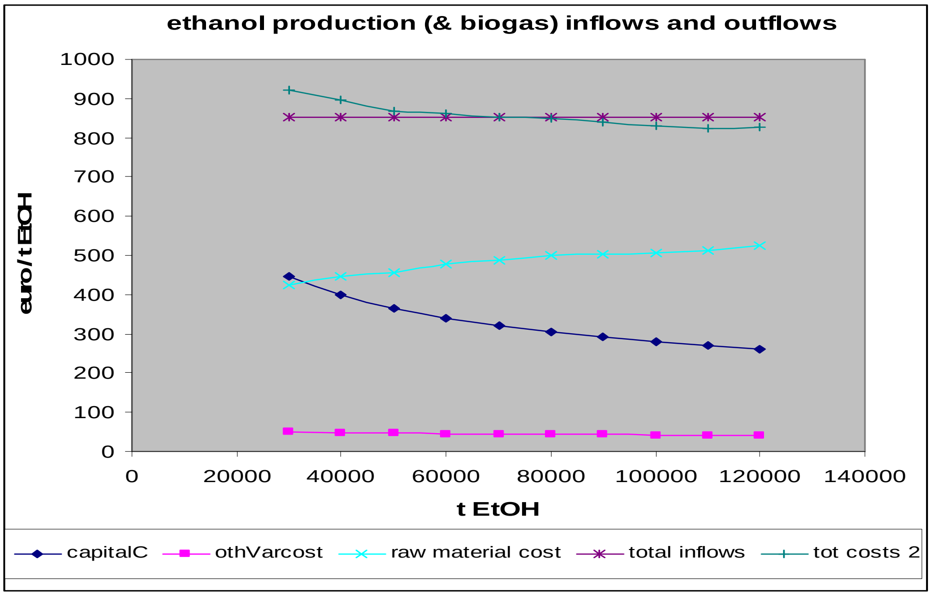

Figure 5. Inflows and outflows per unit of ethanol (configuration 2)

Concerning the configuration of ethanol plant with its own biogas facility results are considerably better, and they are presented in figure 5. Average cost curb intersects average inflows for plants up to 70000 t capacity. Capital costs are higher, as they incorporate investment cost of biogas unit beginning from 446 euro/t for small plants (30000 t) although rapidly decreasing to 260 euro/t for maximal capacity (120000 t). Other variable costs (which now only comprise labour and administrative expenses and chemical inputs as heat and electricity are produced by the biogas unit) start from a much lower level of 51 euro/t for the small plant and they decrease to 41 euro/t for higher capacities (120000 t). Sugar-beet and wheat amount at 46% of total cost for low quantities (small plant) but their part increases to 63% for the maximal capacity 120000 t plant. Maximum average and total profit is observed at the level of 120 000 tons, thus determining the optimal size of the plant.

7. Conclusions

This paper attempts an economic evaluation of bio-ethanol production in the context of the ex-sugar industry in Thessaly taking into consideration recent changes in the Common Market Organization for sugar in the E.U. and options considered by the Hellenic Sugar Industries.

It is assumed that industry uses both beet and grains to produce ethanol thus spreading fixed charges over greater production volume. An alternative scheme has also been evaluated where a biogas production unit consuming fermentation by-product satisfies the energy needs of the plant.

An integrated model articulating agricultural supply of biomass with its processing to ethanol maximizing total surplus determines the optimal production level. A plant configuration including abiogas facility proves to be more successful from an economic point of view. A plant of 120 kt ethanol represents optimal plant capacity, and is the highest one in the examined range.

Further research should be conducted to take into account uncertainty[16]. Uncertainty issues concerning not only demand side (ethanol and by-products price volatility) but also supply side (changing policy contexts and competitive crop price volatility) need to be addressed in order to determine ethanol profitability confidence levels. Also additional technical configurations including recent research findings on promising crops such as sorghum[21] could increase farmers' gains.

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9. Appendix

Mathematical specification of the Model

Indices:		
	j	Crops: {sfw: Soft Wheat, drw: Hard Wheat, wir: Irrigated Wheat, mze: Maize, mzf: Maize for fodder, tob: Tobacco, cot: Cotton, cotd: Dry Cotton, sbt: Sugar Beet, tom: Tomato, pot: Potato, alf: Alfalfa, vik: Intercropped vetch }
	k	Crop(s) having demand curve with negative slope
	r	Irrigated crops: {tob, cot, mzf, wir, pot, sbt, tom, mze, alf, cot}
	rot	Rotational crops: {mze, mzf, tob, sbt, cot, tom}
	$eth, ddgs, plp$	Ethanol, DDGS: Dried Distillers Grains with Soluble, Pulp

Model parameters:

p_j	Price of crop j
y_j	Yield of crop j
s_j	Subsidy on output of crop j
sub_j	Subsidy on area cultivated by the crop j
v_j	Variable cost of crop j
$P_{\{eth,\ ddgs,\ plp)}$	Price of ethanol, Distilled Dry Grain Solubles (DDGS), pulp
X	Total cultivable land surface of the farm
X_r	Available irrigated land area of the farm
w_f	Weight of farm
rot_coeff	Rotational coefficient
dec_surf	Decoupling surface
wt_j	Water requirement for crop j
wt_f	Water capacity of farm
wt_t	Total water quantity of the region
tr_{eth_wir}	Transformation rate from wheat to ethanol
tr_{eth_sbt}	Transformation rate from sugar beet to ethanol
q_{eth_base}	Reference capacity of 35000 tonnes

Decision variables:

x_j	Area cultivated by crop
$Q_{\{sbt,\ wir\}}$	Demand for sugar beet or wheat
$q_{\{eth\_wir,\ eth\_sbt\}}$	Quantity of ethanol produced from wheat or sugar-beet
$q_{\{eth,\ ddgs,\ plp\}}$	Total quantity of ethanol, DDGS or pulp produced in a year
tc_{ind}	Annual total cost of the industry

Objective: Maximization of Total Profit
The objective function of the integrated model is:

$$Max\sum_{j=1}^{n}((p_j+s_j)y_j+sub_j-v_j)x_j+\sum_{k=1}^{t}((\alpha-\beta\Sigma wy_kx_k)y_k-v_k)x_k+p_{eth}*q_{eth}+p_{ddgs}*q_{ddgs}+p_{plp}*q_{plp}-tc_{ind} \quad (1)$$

Subject to resource constraints:

Land constraint: Cultivated area may not exceed the total cultivable land area of the farm.

$$\sum_{j=1}^{n}x_j-x_{vik}\leq X \quad (2)$$

Irrigated land area constraints: Irrigated crops area may not exceed 10% more as of the total irrigated land area of the farm in 2002.

$$\sum x_r \leq 1.1 * X_r \tag{3}$$

Irrigation constrained: Water demand of the farm may not exceed to the water capacity (actual quantity) of the farm.

$$\sum wt_j * x_j \leq wt_f \tag{4}$$

Regional water constraint: Water demand for all farms of the region equal to the total water quantity of the region.

$$\sum f \sum wt_j * x_j = wt_t \tag{5}$$

<u>Subject to quota constraints:</u>

Constraint on cotton, sugar-beet and tobacco area: Crop area may not exceed areas cultivated cotton in 2002.

$$X_{crop} \leq coeff * X_{crop2002} \tag{6}$$

<u>Subject to flexibility constraints:</u>

Maize for fodder area constraint: Fodder maize cultivation area may not exceed by three times of maize cultivated area for fodder in 2002.

$$x_{mzf} \leq 3 * x_{mzf\,2002} \tag{7}$$

Potato cultivation area constraints: Potato cultivation area may not exceed 10% more as of the total potato cultivated area of the farm in 2002.

$$x_{pot} \leq 1.1 * x_{pot2002} \tag{8}$$

Tomato cultivation area constraints: Tomato cultivation area may not exceed 10% more as of the total tomato cultivated area of the farm in 2002.

$$x_{tom} \leq 1.1 * x_{tom2002} \tag{9}$$

<u>Subject to environmental and policy constraints:</u>

Constraints on alfalfa rotation area: Alfalfa area may not exceed rotational coefficient times total rotational cropped area.

$$x_{alf} \leq rot\_coeff * \sum x_{rot} \tag{10}$$

Environmental constraints: Rotational vetch cultivation may not less then decoupling surface deduced by alfalfa and multiplied by obligatory percentage.

$$x_{vik} \geq obligatorypercentage * (dec\_surf - x_{alf}) \tag{11}$$

Subject to biomass demand and supply constraints:

Wheat (sugar-beet) supply constraint: Wheat (sugar-beet) demand by the industry may not exceed the total supply of wheat (sugar-beet).

$$q_{wir} \leq \sum f \sum w * y_{wir} * x_{wir} \tag{12}$$

$$q_{sbt} \leq \sum f \sum w * y_{sbt} * x_{sbt} \tag{13}$$

Balance constraints:

Total quantity of ethanol will be equal to the sum of quantity ethanol produced from wheat and quantity ethanol produced from sugar beet.

$$q_{eth} = q_{eth\_wir} + q_{eth\_sbt} = tr_{eth\_wir} * q_{wir} + tr_{eth\_sbt} * q_{sbt} \tag{14}$$

Total quantity of DDGS will be equal to the demand of wheat multiplied by transformation rate from wheat to DDGS.

$$q_{ddgs} = tr_{ddgs\_wir} * q_{wir} \tag{15}$$

Total quantity of pulp will be equal to the demand of sugar beet multiplied by transformation rate from sugar beet to pulp.

$$q_{plp} = tr_{plp\_sbt} * q_{sbt} \tag{16}$$

Industry technical constraints:

Total capital cost is derived from expected capacity divided by reference capacity (35 000 t) exponent by scale factor (0.61) and multiplied by reference investment cost (12.4 M Euro) and accumulated other investment cost factor (3.41).

$$TotalCapitalCost = 3.41 \cdot \left(q_{eth} / q_{eth\_base}\right)^{0.61} \cdot 12.4 \tag{17}$$

Plant capacity constraint: Annual capacity of ethanol production of the plant (size of the plant) assumed to be between 10000 and 120000 ton.

$$10000 \geq q_{eth} \leq 120000 \tag{18}$$