Stochastic viability of second generation biofuel chains: micro-economic spatial modeling in France

Laure Bamière, Vincent Martinet, Christophe Gouel and Elodie Lecadre
INRA, UMR-210 Economie Publique, 78850 Thiverval-Grignon, France

Paper prepared for presentation at the EAAE 2011 Congress
Change and Uncertainty
Challenges for Agriculture,
Food and Natural Resources

August 30 to September 2, 2011
ETH Zurich, Zurich, Switzerland

Abstract

Within an overall project to assess the ability of the agricultural sector to contribute to bioenergy production, we set out here to examine the economic and technological viability of a bioenergy facility in an uncertain economic context, using the stochastic viability approach. We consider two viability constraints: the facility demand for lignocellulosic feedstock has to be satisfied each year and the associated supply cost has to be lower than de profitability threshold of the facility. We assess the viability probability of various supplying strategies consisting in contracting a given share of the feedstock demand with perennial dedicated crops at the initial time and then in making up each year with annual dedicated crops or wood. The demand constraints and agricultural prices scenarios over the time horizon are introduced in an agricultural and forest biomass supply model, which in turns determines the supply cost per MWh and computes the viability probabilities of the various contract strategies. A sensibility analysis to agricultural prices at initial time is performed. Results show that when they are around or under the median (of the 1993–2007 prices), the strategy consisting in contracting 100% of the feedstock supply with perennial dedicated crops is the best one.

keyword: Biofuel, Biomass production, Spatial economics, Stochastic viability, Monte Carlo simulation

1 Introduction

In a global context of greenhouse gases emissions mitigation and energy independance, biofuels are presented as an alternative to fossil fuels as an energy source. The European Union set the blending share of liquid biofuels and the share of renewable energy sources respectively at 10% and 20% in 2020 (CEC, 2008). Biomass has many factors in its favour: it is renewable; it can be cultivated in all regions; it can be converted into heat, electricity and biofuel; and it can be stored in huge quantities. An important question is then to determine to which extent the agricultural and the forest sector could contribute to the production of bioenergy.

This question has been addressed in several studies at a large scale, examining the global potential production without considering the economic conditions for this production to take place (see EEA (2006), Ericsson & Nilsson (2006) and Berndes et al. (2003) for a survey). Rozakis & Sourie (2005) examined the supply of first generation biofuels in France using a detailed micro-economic model of the agricultural sector, and the profitability of the biofuel chain in an uncertain economic context. However, the first generation of biofuels designated for transportation needs might not meet expectations, particularly in terms of agricultural acreage that can be made available for energy instead of food production, and these production targets could lead to a rise in food crops prices. Moreover, first generation biofuels appear not to be so promising in terms of environmental benefits as they initially did (Petersen, 2008), and biofuel production is thus subject to sustainability concerns (Scarlat & Dallemand, 2011). The second generation biofuel (cellulosic and ligno-cellulosic biomass, which includes agricultural and woody biomass) is advocated to be more compatible with the objectives of a sustainable agriculture development. Lignocellulosic biomass usually has higher energy content and yields for lower input levels.

Babcock et al. (2011) examined the market conditions for the emergence of a competitive cellulosic biofuel sector, and show that the competitiveness of the sector depends both on the institutional context (subsidies) and on the competition with the traditional ethanol chain. They emphasized that the feedstock price is a key driver of the production cost of second generation biofuels, this price being determined locally due to the fact that biomass transportation costs are high with respect to the biomass value and that there is no existing market for cellulosic biofuel feedstock. However, their study did not consider the local feedstock supply, while forecasts on the contribution of biomass in the future global energy supply varies widely, depending on the assumptions on land availability and yield levels (Berndes et al., 2003), and the delivery costs are an important factor of profitability (Graham et al., 2000).

Hellmann & Verburg (2008) used an aggregate top-down approach to assess the European production possibilities. But assessing the profitability of production facilities requires to account for the local context, along with the uncertainty on the price of agricultural commodities, and thus on the opportunity cost of local cellulosic feedstock. Ballarin et al. (2011) adopted a weighted goal programming model to assess the trade-offs between farmers' income and the *potential* bioenergy production at a regional scale, accounting for the environmental and agronomic local context, but without considering the production facilities explicitly, nor uncertainty in agricultural commodity prices, which would influence the actual production of bioenergy. Kocoloski et al. (2011) used a mixed integer programming model to define the optimal location of cellulosic ethanol refineries at the U.S. scale. Focusing on the transportation costs, they showed that the ethanol production costs vary with the local availability of biomass, which emphasizes the role of cellulosic ethanol facilities location on their profitability. Their study accounted for the response of biomass supply to the feedstock price and the land use competition with other commodities, but they did not model explicitly the local price formation for cellulosic biofuel feedstock nor the influence of other commodities price fluctuations on supply costs and quantities.

In this paper, we examine the economic and technological viability of a bioenergy facility in an uncertain economic context, both in terms of the capacity to supplying the facility with biomass and in terms of associated supply costs. For this purpose, we use the stochastic viability approach (De Lara & Doyen, 2008; De Lara & Martinet, 2009). We consider two viability constraints for a ligno-cellulosic bioenergy production facility. On the one hand, each year, the biomass supply to the plant has to be high enough to sustain energy production. On the other hand, the associated supply cost has to be lower than a threshold representing the profitability price of the facility. We assess the viability probability of various supplying strategies based on the proportion of contracted perennial crops, i.e., the probability with which these strategies make it possible to respect the constraints over time in a stochastic context for agricultural commodity prices. To describe the local agricultural context, we used a spatially explicit regional supply model for agricultural and forest lignocellulosic biomass. This model gives us the response of the production to fluctuating market prices. The approach was tested with data from the Champagne-Ardenne region (France), over a 13 years time period.

The paper is structured as follows. The methodological aspects involving the stochastic viability framework and the modeling approach are covered in section 2. The case study is described in section 3. Results are presented in section 4. Our conclusions are in section 5.

2 Methodology

2.1 Stochastic viability framework

Adopting the viewpoint of the ligno-cellulosic bioenergy facility, we look for the supplying strategies that maximize the technological and economic viability of the facility, under price uncertainty. For this purpose, we use the Stochastic Viability framework (De Lara & Doyen, 2008; De Lara & Martinet, 2009). The viability approach consists in examining the consistency of a dynamic system with a set of so-called viability constraints,[1] i.e., in determining if it is possible to satisfy the constraints over time, starting from a given initial state of the system (Aubin, 1991). In the stochastic framework, this is the *probability* of respecting these constraints over time which is of interest.

We consider here two viability constraints: i) the facility demand for lignocellulosic feedstock D (in primary energy equivalent) has to be satisfied each year and ii) the associated supply cost (mean cost per MWh) has to be lower than a threshold $\bar{p}$ representing the profitability of the process.

The facility supplying strategies consist in contracting a given share of the feedstock demand with perennial dedicated crops (q^{pc}) at the initial time $t_0 = 0$ for a contractual price p^{pc}; and then in satisfying

[1]Broadly speaking, the viability approach has connections with dynamic goal programming. However, the constraints are strict and there are no trade-offs between them, in the sense that they all have to be satisfied at all times.

the rest of the demand each year with annual dedicated crops or wood (q^{ac}) at a price $p^{ac}(t)$. The two viability constraints thus read as $q^{ac}+q^{pc}\geq D$ and $\left(p^{ac}q^{ac}+p^{pc}q^{pc}\right)/\left(q^{ac}+q^{pc}\right)\leq\bar{p}$. The higher q^{pc}, the higher the probability to satisfy the technological constraint but also the higher the perennial feedstock purchase price p^{pc}. We look for the supplying strategies that maximize the probability to satisfy both constraints over the planning horizon.

This viability probability is approximated by a frequency using Monte-Carlo simulations, i.e., we simulate a great number of agricultural price scenarios (one scenario being a sequences of prices for all commodities over the planning horizon) and examine the success frequency of each strategy across the scenarios.

Price scenarios are generated using a stochastic agricultural price model (see 2.2). The demand constraints, strategies and agricultural prices scenarios are introduced in an agricultural and forest biomass supply model, which in turns determines the mean supply cost per MWh and computes the viability probabilities of the various contract strategies (see 2.3).

2.2 Stochastic price scenarios

We assume that market prices for agricultural commodities can be represented as a VAR process. A VAR model makes it possible to represent the observed volatility level, the serial correlation (Deaton & Laroque, 1992) and the co-movement of agricultural prices (Pindyck & Rotemberg, 1990). The price level equation is

$$p_t = A + Bt + Cp_{t-1} + u_t, \qquad (1)$$

with p_t the vector of agricultural prices deflated by the United Nations Manufactures Unit Value index; A and B the coefficient vectors of exogenous variables: a constant and a trend; C the coefficient matrix; $E\left(u_t\right)=0$ and $E\left(u_t u_t'\right)=\Sigma_u$. We follow Beck (2001) by introducing a time trend that can account for the effect of productivity change or demand change on prices. For estimation, we use the Grilli & Yang (1988) commodity prices, updated by Pfaffenzeller et al. (2007). Prices are annual and extend from 1900 to 2003. We use price information on corn, palm oil and wheat. Given that markets for vegetable oils are known to be strongly interrelated (In & Inder, 1997), we use price information on palm oil in substitution for the oilseeds represented in the model: rapeseed and sunflower. A strong relationship exists also between wheat and barley (Dawson et al., 2006). We assume that barley, peas and horse bean prices follow wheat price trends.

Table 1: VAR estimates

	Wheat	Corn	Palm oil
time	-0.003^{***}	-0.004^{***}	-0.002^{*}
Wheat(-1)	0.568^{***}	-0.053	0.020
Corn(-1)	0.108	0.563^{***}	0.285^{**}
Palm oil(-1)	0.057	0.177^{**}	0.567^{***}
R^2	0.828	0.803	0.818
Covariance matrix of residuals:			
Wheat	0.024		
Corn	0.019	0.038	
Palm oil	0.006	0.016	0.041

The constant is omitted in the results. *, ** and *** denote significance at the 10%, 5% and 1% level.

The results are presented in Table 1. They show that agricultural prices have a positive first order correlation, a behavior which can be related to the effect of storage that tends to smooth shocks over several periods (Deaton & Laroque, 1992). It implies that a period of low (high) prices is most susceptible to be followed by low (high) prices. Lagged effects of one commodity over another are limited.

Agricultural prices will nonetheless move together because of common contemporaneous shocks, as is shown by the covariance matrix of residuals.

We use this estimation to simulate potential price trajectories, by drawing shocks from a centered multivariate normal distribution of covariance matrix Σ_u. We take the time trend off and we rescale the equations to the fifteen-year average of the case study local prices. Along with the simulated prices, we calculate the corresponding conditional expectations, which we used to endow farmers with rational expectations of next period prices. This results in a sequences of locally anticipated price series, which represent uncertainty scenarios.

2.3 A regional model for assessing biomass supply and associated costs

To assess the supply cost and viability of the bioenergy facility, we use a spatially explicit regional supply model for agricultural and forest lignocellulosic biomass, which has been initially developed in the framework of the ECOBIOM project [2]. It accounts for two spatial levels: the county and the region. The county has been chosen as the elementary unit as it is an administrative (sub) level for which data is available, and it provides the framework for locating biomass departure and delivery points at the county seats. It is characterized by soil composition, altitude, and the slope of forest stands. In our model it is the level at which production decisions occur, taking into account technical and economic constraints. The region is the relevant level when it comes to drawing the boundaries of the biomass supply area and studying the competition for resources arising when a bioenergy facility is being set up. It is the level at which transportation costs and logistics issues are accounted for.

The mathematical programming model maximizes the agricultural and forest income of the region (c.f. 2), taking into account transportation distances and costs from counties to the bioenergy facility, the facility demand D for biomass in primary energy equivalent (i.e. the technological viability constraint 4), soil characteristics, biomass and crop yields and production costs as well as available wood quantities per category, the related stumpage and harvesting costs, and the various potential uses of biomass (food, energy, industry or timber). Decision variables at the county level are the area of crop rotations, the harvested wood quantities per category, as well as the type, quantity and conditioning of biomass supplied to the bioenergy facility. We consider that, at the regional level, farmers are price takers for marketed commodities and take their land use decisions upon expected prices depending on past observations.

We present here a synthetic stylized version of the model, treating all commodities the same way. However, forest areas are actually independent from agricultural areas and wood products are described with quantities rather than with surfaces.

$$\max_{X_a, S_{i,a}} \sum_a \sum_i \left\{ p^i \left[Q_{i,a}(X_a) - S_{i,a} \right] - C_{i,a}(X_a) - T_{i,a}(S_{i,a}) \right\} , \tag{2}$$

$$\text{s.t.} \qquad \bar{X}_a - \sum_r X_{r,a} \geq 0, \qquad \forall a \tag{3}$$

$$\sum_a \sum_i S_{i,a} \rho_i - D \geq 0, \tag{4}$$

$$Q_{i,a}(X_a) - S_{i,a} \geq 0, \qquad \forall i, a \tag{5}$$

$$X_{r,a} \geq 0, \qquad \forall r, a \tag{6}$$

where $X_{r,a}$ is the area devoted to crop rotation r in county a, $S_{i,a}$ is the quantity of commodity i supplied by county a to the bioenergy facility (for these two matrix, the use of a single subscript means that we consider a subvector), $Q_{i,a}(X_a)$ and $C_{i,a}(X_a)$ are respectively the production and production cost

[2] ECOBIOM was financed by the French National Research Agency (ANR) under the National Research Programme on Bioenergy (PNRB) and coordinated by E. LeNET, FCBA.

functions of commodity i in county a depending on the land use X_a in that county, $T_{i,a}(S_{i,a})$ is the transportation cost function of biomass i supplied from county a to the facility, p^i and ρ_i are respectively the price and the lower heating value (MWh per ton) of commodity i. Constraints (3) represent the land availability in each county.

The dual value of the demand constraint (4) provides us with the opportunity cost of the last MWh delivered to the facility, i.e., the foregone revenue of the best production alternative plus biomass production and shipping costs. At initial time t0, this constraint is split, according to the supplying strategy, into a demand for perennial dedicated crops and a demand for annual dedicated crops or wood. We assume that the contractual price p^{pc} and the annual feedstock purchase price $p^{ac}(t0)$ are the dual values of respectively the former and the latter constraints. The areas in perennial crops are then removed from production in each county for the rest of the planning horizon, and the model is used recursively to determine $p^{ac}(t)$ and compute the mean supply cost per MWh for each year of each price scenario. It is the maximum mean supply cost per MWh over the planning horizon of each price scenario that is compared to the facility profitability threshold to assess the viability of the strategy.

3 Case study

This study addresses the issue of a bioenergy processing plant requiring a lignocellulosic biomass input equivalent to 1,000,000 MWh/year and setting-up in the French Champagne-Ardenne region.an agricultural and forest region. It is made up of 146 counties with both agricultural and forest activities, different types of ligno-cellulosic crops could be grown there and R&D activities in the field of second generation biofuels already exists there.

Model assumptions We assume here that i) agricultural and forest areas are independent, i.e., deforestation and afforestation are not allowed; ii) short rotation coppices (SRC) can only be grown on agricultural areas; iii)all biomass is already available at the county seat. We only account for the agricultural area of crop farms (Types of Farming 13 and14 in accordance with the FADN classification).

Soil and agricultural data We account for 7 soil types. Based on their agropedoclimatic characteristics, counties can grow 13 conventional crops and 5 dedicated crops : miscanthus, switchgrass, whole-plant triticale, fiber sorghum, and poplar SRC. Crops are combined into 29 crop rotations, among which 9 containing dedicated crops, plus poplar short rotation coppices. Crop rotations better take into account the preceding and following crop effects on yields, input consumptions (nitrogen balance for instance) and environmental impacts. Moreover, it facilitates the comparison of crop rotations (composed of annual crops) to perennial crops such as miscanthus, switchgrass, and short rotation coppice. We assume that farmers will substitute perennial crops for existing crop rotations, and annual dedicated crops will likely substitute to equivalent crops in crop rotations (whole-plant triticale substitutes to barley and fibre sorghum to maize). Regional data were collected and compared to compute average yields and production costs over 10 years (1997–2007) for conventional crops. The yields of dedicated crops were estimated based on first results from field trials. The associated production costs for perennial crops were used to compute an equivalent annual cost (with a 5% discount rate) over the whole rotation duration. Dedicated crops can be conditioned into silage or high density bales.

Forest data The annual wood volume available to harvesting per county depends on the characteristics of the existing forests (area, location, ownership, species, age of trees and slope of the plots).It was computed by the French Technological Institute for Forest, Cellulosis, and Building lumber (FCBA) based on 3 main data sources[3].For the Champagne-Ardenne region we have 60 harvestable wood categories and 5 types of conditioning (non-barked logs, long barked logs, short barked logs, bundles, and woodchips). Harvesting costs , stumpage as well as wood prices were provided for the region by the French Association of Forest Cooperatives (UCFF) and were harmonized with those from the French National Forestry Service (ONF).

Transportation data We used distances minimizing transportation time-what road haulage contractors tend to do.[4] Transportation costs per ton and kilometre were calculated using the trinomial formula from the "French National Road Center" (Centre National Routier, CNR), based on kilometric costs, hourly rates, and fixed costs as well as the type of vehicle which is being used. The choice of the vehicle depends on the type of biomass, its conditioning, the slope of the forest stand, and the distance to cover. We account for 8 types of vehicle, 5 for wood and 3 for crops.

Price scenarios The VAR model described in section 2.2 was used to simulate 500 anticipated price series (i.e., 500 price scenarios) over 15 years. Prices at $t0$ are the Champagne-Ardenne median prices for the 1993-2007 period. Barley, peas and horse bean prices follow wheat prices variations, whereas Rapeseed and sunflower prices follow those of palm oil prices and the price of the other crops (e.g. sugar beet, potatoes) remain constant. Wood prices are those of 2007. Contractual prices as well as the type and area of contracted perennial crops are fixed at $t0$, whereas model simulations to assess viability start at $t3$ when the facility is up and running.

Supplying strategies We compare 6 supplying strategies, consisting in contracting either 0, 20, 40, 60, 80 or 100% of the lignocellulosic feedstock demand (in primary energy equivalent) with perennial crops, i.e., miscanthus, switchgrass or poplar SRC in our study. The rest of the demand has to be fulfilled each year with wood or annual dedicated crops, i.e., whole plant triticale and fiber sorghum in our study.

4 Results

4.1 Agricultural land use and ligno-cellulosic biomass production

Switchgrass silage is the perennial biomass contracted by and delivered to the bioenergy plant. It is grown on the less fertile and profitable soil category of the region, as regards agricultural yields, and substitutes to the following rotations: rapeseed / wheat / whole-plant triticale (the rotation including a non-contracted annual dedicated crop) and corn / wheat / wheat / sunflower / wheat (the rotation usually grown on this soil type). Switchgrass is grown in two counties and its total area ranges from 3,516 ha to 17,582 ha depending on the contractual strategy (the larger the part of contracted biomass, the larger the area of switchgrass). Its opportunity cost ranges from 16.45 to 17.09 euros/Mwh (see table 2), i.e., from 76.37 to 79.35 euros/ton dry matter or from 939 to 976 euros/ha. The opportunity cost of the last MWh includes a 5.95 euros/MWh production and conditioning cost, 7.46 euros/MWh of foregone revenue due to crop rotation substitution and from 3 to 3.65 euros/MWh to deliver the biomass. It is noteworthy that in this benchmark case, the shadow price of the contracted biomass is always lower than the one of the annual biomass (see table 2). This means that it is less costly to supply the bioenergy plant with perennial dedicated biomass (i.e., swithgrass) than to use annual energy crops or wood.

Table 3 shows the type and quantity of annual biomass, in primary energy equivalent, supplied to the bioenergy plant on average over the 500 price scenarios. The larger the contractual biomass supply,

[3] The French National Forest Survey (IFN),the French National Geographical Institute (IGN), and the Regional Wood and Forest Department (SERFOB).

[4] Distancier intercommunal Route 500, INRA UMR 1041 CESAER, Dijon.

Table 2: Supplied biomass prices for the different strategies (€/MWh)

	sb0	sb20	sb40	sb60	sb80	sb100
Shadow price of the contracted biomass	–	16.45	16.45	17.09	17.09	17.09
Shadow price of the annual biomass for the base year	21.91	21.91	21.91	21.81	21.8	–

the smaller the annual one. The actual annual biomass supply within each scenario depends on the absolute and relative level of agricultural prices. When the ratio of corn over wheat prices decreases, fiber sorghum tends to substitute to corn in the corn/wheat/pea/wheat crop rotations on the soil type where maize has the lowest yield. When this ratio and the one of oilseeds over wheat prices increase, it is more profitable to grow whole plant triticale on soil types where it has high yields contrary to wheat, all the more than whole plant triticale has a higher energy yield per hectare than sorghum. Finally when agricultural prices are at a high, wood becomes the cheapest biomass source, starting with softwood woodchips. The facility can even be supplied with logs.

Table 3: Produced biomass in tons

		sb0	sb20	sb40	sb60	sb80
Triticale	(Whole plant)	99,645	76,849	54,798	33,433	15,808
Fiber	Sorghum	76,850	61,630	46,536	31,545	15,538
Softwood	Logs	66				
	Bundles	364	73	40	40	
	Woodchips	260,730	220,911	176,872	128,797	69,225
Hardwood	Woodchips	2,852	1,557	526	204	61

Fig. 1 describes the geographical origin of biomass, for three contractual strategies: "no contractual supply" strategy (sb0), 60% of supply contracted (sb60), and "total contractual supply" (sb100). When there is no contractual biomass supply, a large number of counties provide small quantities of dedicated annual energy crops, except three counties, each providing between 10% and 15% of the supply. These counties have poor soil quality, and the lowest opportunity cost. When the contractual part increases, the number of supplying counties decreases, and the share of the main suppliers increases. In the extreme case of a total conctracual supply, only two counties produce dedicated perennial crops (i.e., switchgrass), providing respectively 43% and 57% of the bioenergy plant supply.

4.2 Viability of the strategies

We now turn to the analysis of the viability of the various contractual supplying strategies. Fig. 2b exhibits the viability probability of a range of contractual strategies as a function of the profitability threshold price.

For a given profitability threshold price, higher contractual strategies result in higher viability probability. Setting contracts to ensure supply at a given cost is thus a good strategy to achieve the economic and technological viability of bioenergy plants in an uncertain economic context.

The strategy of total contractual supply exhibit a threshold effect: if the profitability threshold price is larger than the contractual price, the strategy is 100% viable (robustness). On the contrary, if the profitability threshold price is lower than the contractual price, the viability probability is nil. We thus have a *robustness threshold*.

The strategy of no contractual supply also has some asymptotic threshold effect, at a higher profitability threshold price level, corresponding to the highest opportunity cost of annual biomass supply over all price scenarios.[5] Partial contractual supply strategies exhibit a threshold effect at an intermediate

[5]In theory, there is no such upper bound, but in our Monte Carlo simulation approach, we explore a finite number of

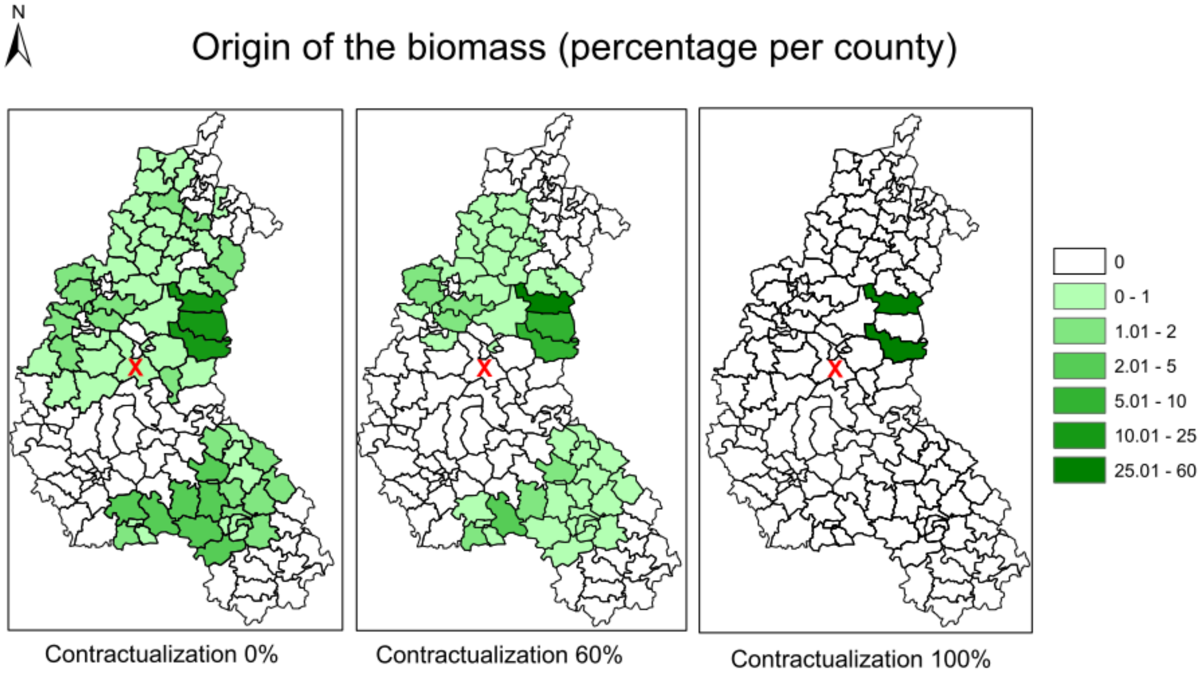

Figure 1: Biomass supply per county (percentage of total supply)

level, that may be interpreted as the weighted sum of the contractual (and thus not subject to uncertainty) price and the uncertain maximal opportunity cost. We interpret these thresholds as the *robustness threshold* of the various contractual strategies.

According to our simulations, and for a contractual price corresponding to the opportunity cost of perennial energy crops for a "medium year" (i.e., in the context of median commodity prices), contracting the biomass supply of the bioenergy facility is the strategy that maximizes the viability probability, i.e., the probability to satisfy both economic and technological constraints at all time over the planning horizon. To better understand these results, we examine how they are sensitive to the contracting price or, equivalently, to the economic context (in terms of agricultural commodity prices and opportunity cost to produce perennial crops).

4.3 Effect of the initial economic context

We performed a sensitivity analysis of our result to the initial contractual price, by the means of computing the opportunity cost of perennial crop supply in different economic contexts. We consider first a "low price" context, and then a "high price" context.

Lower contractual price case We performed the same simulations as in the previous analysis, but starting from a vector of lower agricultural prices corresponding to the 1st decile of 1993-2007 prices. When the contractual price is low, for example if it is set in an economic context characterized by low agricultural commodities prices and thus a low opportunity cost to contract, the viability probability of the considered strategies increases. Results are presented in Fig. 2a. A comparison of the contractual prices (opportunity cost of perennial energy crops) is provided in table 4.

The robustness threshold of the "no contract" strategy (sb0) does not change, but the more favorable initial economic context makes it possible to satisfy lower profitability threshold constraints with higher probability. The robustness threshold of the "total contract" strategy (sb100) is strongly reduced, as the

scenarios.

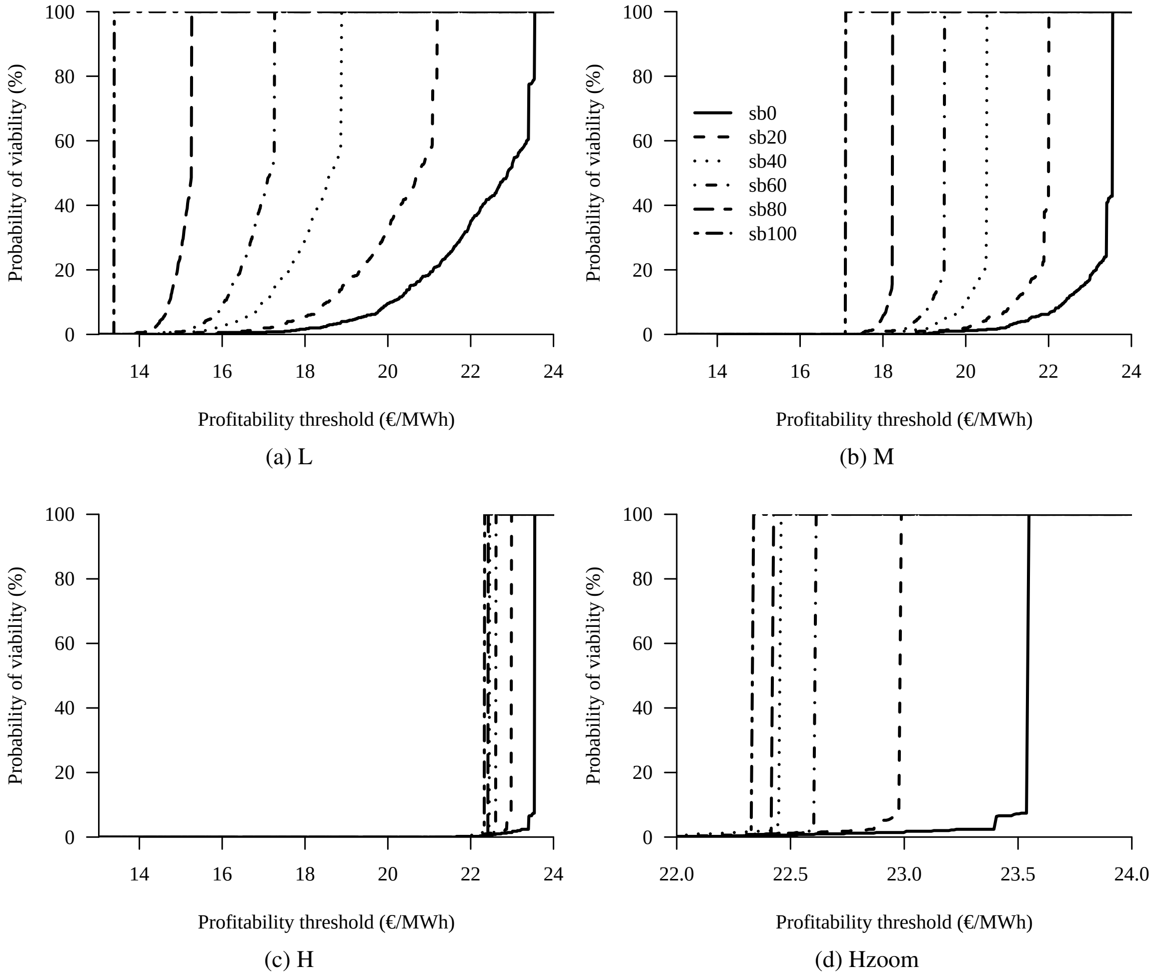

Figure 2: Viability probability as a function of the profitability threshold for a range of strategies

contractual price decreases. All intermediate strategies are thus favored in this direction. In terms of the nature of the supplied biomass, silage switchgrass is still the perennial crop contracted by the plant, at a cost ranging from 12.37 to 13.39 euros/MWh, and produced in the same counties on the same soil types. The annual biomass supply is mainly composed of fiber sorghum, as corn prices are low, but also contains whole plant triticale and in a very minor proportion wood.

Our results thus hold for a lower contractual price.

Higher contractual price case On the contrary, our results are modified when the contractual price is high, for example because it is set in a context of high agricultural commodity prices, with a high opportunity cost for the production of perennial energy crops. We performed the same simulations as in the benchmark case, but starting from a vector of higher agricultural prices corresponding to the 9th decile of 1993-2007 prices. Results are presented in Fig. 2c A comparison of the contractual prices (opportunity cost of perennial energy crops) is provided in table 4.

The 100% contractualization strategy is no longer the best one, at least for a large range on profitability thresholds. Fig. 2d presents a zoom of the results. One can see that the “total contract” strategy is still optimal for profitability thresholds larger than the contractual price, but that, for profitability thresholds lower than this level, positive viability probabilities are achievable with mixed strategies.

In terms of the nature of the supplied biomass, silage switchgrass is still the perennial crop contracted by the plant, at a cost ranging from 21.3 to 22.3 euros/MWh. However, contrary to the previous cases, it is provided by three counties on two different soil types. The difference in the foregone revenues on the two soil types is compensated by lower transportation costs from the new supplying county. The annual biomass supply is mainly composed of wood, as agricultural prices are high, but also contains whole plant triticale and fiber sorghum.

Table 4: Contractual price of perennial energy crop **(in euro/MWh)**

Strategy	sb20	sb40	sb60	sb80	sb100
Low contractual price	12.37	12.37	13.39	13.39	13.39
Benchmark case	16.45	16.45	17.09	17.09	17.09
High contractual price	21.31	21.31	22.29	22.33	22.33

5 Discussion and conclusion

Meeting the increasing targets of bioenergy production without harming the environment requires to develop viable second generation bioenergy chains. Such viability depends on both the local availability of biomass and the profitability of production. These elements are strongly influenced by the economic context and uncertain agricultural commodity prices, and the resulting opportunity cost of producing energy crops.

In the present paper, we used a stochastic viability approach to examine the economic and technological viability of a second generation bioenergy plant. We considered a technological constraint on the biomass supply, and an economic constraint on the per MWh supply cost. The profitability threshold characterizing this latter constraint was treated as a parameter, for sensitivity analysis. We examined the probability viability of various contractual supplying strategies, i.e., the probability with which these strategies respect the constraints over time. We showed that the “total contract” strategy, consisting in contracting all the biomass supply with perennial dedicated energy crops, maximizes the viability probability when the contracting price is not too high.

From a decision making point of view, our results suggest that the viability of second generation bioenergy facilities strongly depends on the availability and cost of local biomass supply. Setting contracts ensuring both the supplying of required quantities and its cost is an efficient strategy to limit the risk of non-viability related to the uncertain agricultural commodity price, at least when such contracts can be set at a sufficiently low price with respect to the profitability threshold.

In this study we assumed that the contractual price will equal the opportunity cost of the last MWh delivered to the plant. However it is probably underestimated for two reasons. First, in our simulations, dedicated biomass is sometimes grown on 100% of the crop growing farms area, whereas farmers are generally reluctant to introduce new crops massively. Second, farmers will probably ask for the price to be revised as it is a long-term contract. On the other hand wood supply can be contracted as well at a high scale, e.g, with a forest cooperative or the agency managing public forests. Another issue is that the biomass delivered to the plant is not always to be used as it is and may require a pre-treatment (drying, chipping etc.), inducing an extra cost that could change the optimal biomass supply. Logistics modeling could be improved as transportation and storage plays an important role in the competitiveness of bioenergy, due to the huge volumes to be transported and the need to supply the processing plant all over the year.

Kocoloski et al. (2011) showed that the facility size influence their optimal location and profitability. Future research could examine how the size of the bioenergy facilities modifies their viability.

References

Aubin, J.-P. (1991). *Viability theory*. Birkhäuser.

Babcock, B., Marette, S., & Tréguer, D. (2011). Opportunity for profitable investments in cellulosic biofuels. *Energy Policy*, 39(2), 714–719.

Ballarin, A., Vecchiato, D., Tempesta, T., Marangon, F., & Troiano, S. (2011). Biomass energy production in agriculture: A weighted goal programming analysis. *Energy Policy*, in press.

Beck, S. (2001). Autoregressive conditional heteroscedasticity in commodity spot prices. *Journal of Applied Econometrics*, 16(2), 115–132.

Berndes, G., Hoogwojk, M., & van den Broek, R. (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy*, 25, 1–28.

CEC (2008). *Proposal for a directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources*. Technical report, COM (2008) 19 final. European Commission, Brussels.

Dawson, P. J., Sanjuán, A. I., & White, B. (2006). Structural breaks and the relationship between barley and wheat futures prices on the London International Financial Futures Exchange. *Review of Agricultural Economics*, 28(4), 585–594.

De Lara, M. & Doyen, L. (2008). *Sustainable Management of Natural Resources. Mathematical Models and Methods*. Berlin: Springer-Verlag.

De Lara, M. & Martinet, V. (2009). Multi-criteria dynamic decision under uncertainty: A stochastic viability analysis and an application to sustainable fishery management. *Mathematical Biosciences*, 217, 118–124.

Deaton, A. & Laroque, G. (1992). On the behaviour of commodity prices. *Review of Economic Studies*, 59(1), 1–23.

EEA (2006). *How much bioenergy can Europe produce without harming the environment?* Technical report, European Environment Agency Report n°7/2006.

Ericsson, K. & Nilsson, L. (2006). Assessment of the potential biomass supply in europe using a resource-focused approach. *Biomass and Bioenergy*, 30, 1–15.

Graham, R., English, B., & Noon, C. (2000). A geographic information system-based modelling system for evaluating the cost of delivered energy crop feedstock. *Biomass and Bioenergy*, 18, 309–329.

Grilli, E. R. & Yang, M. C. (1988). Primary commodity prices, manufactured goods prices, and the terms of trade of developing countries: What the long run shows. *World Bank Economic Review*, 2(1), 1–47.

Hellmann, F. & Verburg, P. (2008). Spatially explicit modelling of biofuel crops in europe. *Biomass and Bioenergy*, in press, doi: 10.1016/j.biombioe.2008.09.003.

In, F. & Inder, B. (1997). Long-run relationships between world vegetable oil prices. *The Australian Journal of Agricultural and Resource Economics*, 41(4), 455–470.

Kocoloski, M., Griffin, M., & Matthews, S. (2011). Impacts of facility size and location decisions on ethanol production cost. *Energy Policy*, (39), 47–56.

Petersen, J. (2008). Energy production with agricultural biomass: environmental implications and analytical challenges. *European Review of Agricultural Economics*, 35, 385–408.

Pfaffenzeller, S., Newbold, P., & Rayner, A. (2007). A short note on updating the Grilli and Yang commodity price index. *World Bank Economic Review*, 21(1), 151–163.

Pindyck, R. S. & Rotemberg, J. (1990). The excess co-movement of commodity prices. *Economic Journal*, 100(403), 1173–1189.

Rozakis, S. & Sourie, J.-C. (2005). Micro-economic modelling of biofuel system in france to determine tax exemption policy under uncertainty. *Energy Policy*, 33, 171–182.

Scarlat, N. & Dallemand, J.-F. (2011). Recent developments of biofuels/bioenergy sustainability certification: A global review. *Energy Policy*, in press.