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# Irreversible investment, uncertainty, and ambiguity: The case of bioenergy sector

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# Irreversible investment, uncertainty, and ambiguity: The case of bioenergy sector

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**Abstract**

We analyse the decision of an agent to invest in industrial activities characterized by two forms of uncertainty: market size uncertainty and price uncertainty. We use bioenergy industries for an application of the model. Indeed, the sector is confronted to both, an uncertainty in relation to the arrival of an activity relying on the implementation of emerging renewable energy technology (second generation biofuel process) and an uncertainty linked to the variability of the price of biomass sold. We find the neglecting market size-related uncertainty would lead to an underestimation of the role of price uncertainty on the investment. Likewise, adding a price uncertainty may increase the investment when under both uncertainties the producer over values the selling prices. We demonstrate that the investment under price uncertainty is larger than the one under market size uncertainty when the producer's prior belief on the realization of the situation with a high price is higher than certain threshold. In addition, the ambiguity aversion on the price distribution also leads the producer to under-invest. We then discuss some political instruments that could ease the ability of the producer to invest in context of uncertainty and ambiguity.

Keywords: Ambiguity, Bioenergy, Irreversible investment, Real options theory, Uncertainty.

JEL Classification: D21, D81, Q42, Q57.

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# Introduction

The investments into renewable technologies are subjects to developments in order to reach the renewable energy target fixed to 20% by the European Union (EU) for 2020.[1] To reach the future targets set out by the EU, significant amounts of biomass and investments into biomass based technologies will be necessary. [2] Biomass is a key of the clean solid fuels development that need to be densified by pre-treatment process prior to transportation and storage. Biomass continues to be a resource that is limited, heterogeneous and not homogeneously spread. The torrefaction is an emerging pre-treatment process which transforms biomass in a high fuel quality input to produce bioenergy with conversion technologies. The investment in new pre-treatment units is the first step in the total biomass supply chain in order to save transport, material and handling costs for users.

Prospects for the development of pre-treatment, however, are affected by the high level of uncertainties that characterize biomass market. Currently, biomass market is characterized by two forms of uncertainty. First, an uncertainty in relation to the arrival of an activity relying on the implementation of emerging renewable energy technology, i.e., Biomass to Liquid (BTL) process, a conversion technology for second generation biomass based biofuels. Indeed, the technology and the complete chain are currently in the pilot stage. For economical reasons, it requires a large unit and needs some pre-treatment biomass resources co-processes to densify the widest range of biomass. In addition, the torrefied biomass can improve the efficiency of the final conversion stage. Secondly, an uncertainty in relation to the output price which is linked to the variability of the price of pre-treated biomass sold. Either the biomass is sold to heating or power units to substitute coal, the selling price should be indexed to coal price or the product is sold to BTL units to substitute fossil diesel and the price should be indexed to oil of which fluctuate even more sharply than the coal (Fuss & Szolgayová, 2009). So when the biomass producer has to decide his investment in the activity, he does not get initial knowledge on the number of potential buyers and on the selling price of his product. This naturally raises the issue of the effect of both uncertainties on the investment level.

To address this issue, we propose a real option approach (Schwartz & Trigeorgis, 2001). We consider a two-period model. With an incomplete information about the

[1]In 2007, the European Commission has fixed the renewable energy target in the EU's overall mix to 20% in the final energy consumption by 2020 regarding 1990. To reach this goal, the member states have adopted the pack energy-climate and renewable energy in particular (Parliament & the Council of the European Union, 2009) which defines the operational measures to develop 20% of renewable energies by 2020.

[2] Currently biomass delivers around 4% of the EU's primary energy (EEA, 2008).

selling price and the number of potential buyers in the market, the producer has to decide his investment for producing at the following period pre-treated biomass units. Investment expenditures in this specific industry are sunk costs so his investment is irreversible (Dixit & S.Pindyck, 1994). When dealing with irreversible investments in physical assets, real options theory (Dixit & S.Pindyck, 1994; Trigeorgis, 1996; Schwartz & Trigeorgis, 2001) offers a useful approach for the appreciation of uncertainties over time. Arrow & M.Kurz (1970) conducted pioneering work on irreversible investments under certainty. Their work was expanded through the introduction of uncertainty (Charles & Munro, 1985; Clark et al., 1985; Pindyck, 1981). The study of two uncertainties including an uncertainty about the number of buyers present on the market contributes to the irreversible investment literature. We extend our work by arguing that producers' decision making in pretreatment process is also influenced by aversion ambiguity that is on top of any existing risk aversion of a decision maker (Ellsberg, 1961). Ambiguity aversion relates to the aversion towards ambiguous prices of the torrefied biomass, specifically, the uncertainty regarding the probability distribution of prices when we have one buyer or two buyers for pre-treated biomass. The importance of ambiguity aversion in portfolio choice decisions is not new (e.g. Klibanoff et al. (2005); Gollier (2006)). However there is little evidence of its importance in capacity choice of an investor. Determining its contribution to how emerging industries contend with ambiguity aversion is an important line of research in entrepreneurial decision-making.

We find the neglecting market size-related uncertainty would lead to an underestimation of the role of price uncertainty on the investment. Likewise, adding a price uncertainty may increase the investment when under both uncertainties the producer over values the selling prices. Moreover, we demonstrate that the investment under price uncertainty is larger than the one under market size uncertainty when the producer's prior belief on the realization of the situation with a high price is higher than certain threshold. In addition, the ambiguity aversion on the price distribution also leads the producer to under-invest. We then discuss some political instruments that could ease the ability of the producer to invest in context of uncertainty and ambiguity.

The reminder of the paper is organized as follows. Section 1 provides empirical evidence of the scope of bioenergy market. Section 2 contains model description. Section 3 analyses both the optimal investment decision without ambiguity and the effect of uncertainty on this optimal decision. Section 4 examines the impact of ambiguity on strategy investment. Section 5 studies the policy prescriptions to reduce ex-ante uncertainties and concludes.

# 1 Motivation

## 1.1 Uncertainties related to the bioenergy market

The EU energy import is rising. Today, 53,8 % of the EU's energy needs are met by imported products (DG-Energy & Transport, 2009) and if domestic energy does not become more competitive in the next 20 to 30 years we will import 70% of the EU's energy needs (Commission, 2006). Energy-related GHG emissions remain dominant, accounting for 80 % of the total emissions, with the largest emitting sector being electricity and heat production, followed by transport in the EU-27 (EEA, 2008). Taking into account those threats, the EU is increasing policies favouring use of renewable energy sources. Furthermore as a substitute for transportation fuels and to make up for crude oil shortfall, biofuels will constitute a necessary supplementary offer. The EU set itself a minimum binding target of 10% biofuel use by 2020. The contribution brought by second-generation biofuels is regarded as equivalent to twice that of the other biofuels (Parliament & the Council of the European Union, 2009). Thus Europe and France develop second-generation biofuels technologies to offer a supplement to the first-generation biofuels offer. They will have an important role to play as soon as they are ready for the market.

Nevertheless, the conversion technologies for second generation lignocellulose based biofuels are note commercially available (IEA, 2008). Although gasification-based routes and the Fischer-Tropsch processes involve mature technologies already used at commercial scale, there is very limited experience in integrating biomass gasification with downstream processes for the production of liquid or gaseous transport fuels (Bioenergy, 2008). The technology and the complete chain are currently in the pilot/demo stage in Europe. Consequently, although parts of the technologies employed for the production of second generation biofuels have been used for other purposes for some time now, the entire production chain remains unproven on a large, commercial scale, thus remaining highly risky from the point of view of investors, as it is still often unknown in advance whether or not these technologies will ultimately work (Bole & Londo, 2009). First commercial units are expected to go on-line in the next few years (CHOREN, 2007; Berndes et al., 2009). For an investor who wants to build a torrefaction unit, he is faced to a technological uncertainty. The investor has the choice to sell his produce to two markets of which is uncertain, the BTL units. The moment of market implementation plays a key role. Here, he is faced to a second uncertainty, a price uncertainty which it is linked to the variability of the torrefied biomass prices sold, thus making the pay-off rather unpredictable.

Currently, the state-of-the-art of torrefaction process is mostly based on technical performance (Uslu et al., 2008; Berndes et al., 2009). The economic performances are unclear in a context with uncertainty on the pay-off and the development of BTL process. The available information mainly discusses the technology rather than the risk to invest for the producers in a torrefaction unit. However, the investor in pre-treatment process may be viewed as making decisions on expected demand with uncertainties on the structure of the market depending on the deployment of full scale plants and the energy sector to substitute coal inputs. Ex ante capacity choice clearly will depend upon the future demand. In an environment of incomplete uncertainty markets, the structure of uncertainties preferences will also be important to determine the optimal capacity. When dealing with irreversible investments in physical assets, real options theory (Dixit & S.Pindyck, 1994; Trigeorgis, 1996; Schwartz & Trigeorgis, 2001) offers a useful approach for the appreciation of uncertainties over time.

## 1.2 Ambiguity related to the selling price of the pre-treated biomass

We extend our work by arguing that producers' decision making in torrefaction process is also influenced by aversion ambiguity. It is generally assumed (Ellsberg, 1961) that decision makers dislike ambiguity, In the bioenergy sector, ambiguity aversion relates to the aversion towards ambiguous prices of the pre-treated biomass, specifically, the uncertainty regarding the probability distribution of prices when we have one buyer or two buyers for pre-treated biomass. Since investors must choose their capacity of production and since the probability distributions over selling prices of output are not always known, especially in the case of new BTL units, ambiguity aversion may be particularly important in their capacity choice decision. The importance of ambiguity aversion in portfolio choice decisions is not new (e.g. Klibanoff et al. (2005)). However there is little evidence of its importance in capacity choice of an investor. Determining its contribution to how emerging industries contend with ambiguity aversion is an important line of research in entrepreneurial decision-making. If ambiguity aversion matters, then policy makers can help via ex-ante mechanisms in which investors resolve the uncertainty through operational measures about the financial instruments for renewable energy from biomass, emerging technology research or resource availability. Because the policy prescriptions are different, the key for guiding policy is to know the relative importance of the behavioural effects to gear them towards alleviating the negative effects of uncertainty on the pre-treatment decision makers. Contrary to Chen & Epstein (2002); Klibanoff et al. (2005); Gollier (2006), we assume agents are not subjective expected utility maximizers but are, instead, ambiguity (or uncertainty) averse decision makers who maximize expected return. We then discuss the impact of ambiguity-aversion on the investment decision.

## 2 The model

We consider a two period model with a risk-neutral biomass producer. At period 0, the producer has the opportunity to invest $I \geq 0$ in a plant in order to produce pretreated biomass. He uses a production function of the form $q = f(I)$ in which $q$ is the aggregate output and $f$ is an increasing and concave function such that $f(0) = 0$. So, the producer requires $I$ units of investment for $q$ units of the torrefied biomass.

There are two possible states of the world: $A$ and $B$ associated to a market composed of one and two buyers, respectively. At period 0, the prior beliefs of the producer are $\psi$ on state $A$, and $1 - \psi$ on state $B$.

We assume that the producer does not know the future price of torrefied biomass $\tilde{P}_i$ in each state $i \in \{A, B\}$. However, in each state of the world, he is aware of there are two possible situations in the economy: a situation with a high price $\tilde{P}_i = \bar{P}_i$, and a situation with a low price $\tilde{P}_i = \underline{P}_i$. We have $\bar{P}_i > \underline{P}_i$ for all $i \in \{A, B\}$. The true value of the probability associated to the situation with a high price $\theta$ may be unknown. There may be subjective uncertainty (ambiguity) about what the probability $\theta$. Based on his subjective information, the producer associates a probability distribution $F(\theta)$ on $[\underline{\theta}, \bar{\theta}]$ which measures the subjective relevance of a particular $\theta$ probability. Following Klibanoff, Marinacci and Mukerji (2005), we describe the producer's behaviour towards ambiguity by a function $\phi$. An increasing and concave $\phi$ means that the producer is risk averse to ambiguity. Similarly, ambiguity neutrality is characterized by $\phi$ linear.

At period 1, if the producer has invested $I$, he produces $q$ units of torrefied biomass which yields a pay-off equal to $\tilde{P}_i q$ in state $i \in \{A, B\}$. From this pay-off must be subtracted the cost of production $C(q)$ which is an increasing and convex function and such that $C(0) = 0$.

So, with a discount factor $\beta < 1$ and $q = f(I)$, when there is no ambiguity on the $\theta$ parameter, the producer's expected pay-offs at period 0, $V_0(I, \psi, \theta)$ may be expressed as follows:

$$\begin{aligned} V_0(I,\psi,\theta) = \quad & -I + \beta\psi \left[\theta \left(\bar{P}_A f(I) - C(f(I))\right) + (1-\theta)\left(\underline{P}_A f(I) - C(f(I))\right)\right] \\ & + \beta(1-\psi) \left[\theta \left(\bar{P}_B f(I) - C(f(I))\right) + (1-\theta)\left(\underline{P}_B f(I) - C(f(I))\right)\right]. \end{aligned} \tag{1}$$

Likewise, when there is an ambiguity on the $\theta$ parameter, the producer's expected pay-offs at period 0, $W_0(I)$ is defined such that:

$$W_0(I) = \int_{\underline{\theta}}^{\bar{\theta}} \phi\left(V_0(I, \psi, \theta)\right) dF(\theta).$$

# 3 Investment decision without ambiguity

In this section, we consider that the producer is aware about the true value of $\theta$. There is no ambiguity on the $\theta$ parameter. At period 0, the producer has to choose his optimal investment $I$ for producing $q$ units of torrefied biomass. The optimal investment $I^*$ maximizes the expected pay-off $V_0(I, \psi, \theta)$. $I^*$ is the solution of the following program:

$$I^* \in arg \max_{I \geq 0} V_0(I, \psi, \theta).$$

Since for all $\theta$, $V_0(I, \psi, \theta)$ is concave with respect to I [3], the first order condition is expressed as follows:

$$\frac{1}{\beta f'(I^*)} + C'\left(f(I^*)\right) = \psi\left[\theta \bar{P}_A + (1-\theta)\underline{P}_A\right] + (1-\psi)\left[\theta \bar{P}_B + (1-\theta)\underline{P}_B\right]. \tag{2}$$

For all $\psi, \theta \in [0, 1]$, if for all $I > 0$, $V_0(I, \psi, \theta) \leq 0$ then we suppose the producer decides not to invest, i.e., $I^* = 0$. On the other hand, if there exists $I > 0$ such that $V_0(I, \psi, \theta) > 0$ then the producer invests $I^* > 0$ which is characterized by (2). Thus, the producer always invests unless the cost exceeds the benefit.

From (2), $I^*$ is clearly a function of $\psi$, $\theta$, $\bar{P}_A$, $\underline{P}_A$, $\bar{P}_B$, $\underline{P}_B$ and $\beta$: $I^* = I^*\left(\psi, \theta, \bar{P}_A, \underline{P}_A, \bar{P}_B, \underline{P}_B, \beta\right)$. We define both the expected price in state $i \in \{A, B\}$ and the expected price considering the uncertainty on the state of the situation, respectively, as follows:

$$E_\theta \tilde{P}_i = \theta \bar{P}_i + (1-\theta)\underline{P}_i \tag{3}$$

$$E_{\psi\theta} \tilde{P} = \psi E_\theta \tilde{P}_A + (1-\psi) E_\theta \tilde{P}_B. \tag{4}$$

We summarize in the following lemma the effects of those parameters on the optimal investment and we study the factors which lead the producer to invest or not.

**Lemma 1** *(i) A higher price in each state and for each situation, i.e., $\bar{P}_A$, $\underline{P}_A$, $\bar{P}_B$ or $\underline{P}_B$, or a higher prior belief on the state of the situation $\theta$ fosters investment*
*(ii) If $E_\theta \tilde{P}_A > E_\theta \tilde{P}_B$ then a higher prior belief on the size market $\psi$ fosters investment ; If $E_\theta \tilde{P}_A < E_\theta \tilde{P}_B$ then a higher prior belief on the size market $\psi$ decreases the producer's incentive for investing ; If $E_\theta \tilde{P}_A = E_\theta \tilde{P}_B$ then $\psi$ has no effect on the investment decision.*

[3] Proof in Appendix

*(iii) If $E_{\psi\theta}\tilde{P}f(I) > C(f(I))$ then a higher discount rate $\beta$ fosters the investment ; If $E_{\psi\theta}\tilde{P}f(I) < C(f(I))$ then a higher prior belief on the size market $\psi$ decreases the producer's incentive for investing ; If $E_{\psi\theta}\tilde{P}f(I) = C(f(I))$ then $\beta$ has no effect on the producer's decision.*

**Proof.** In Appendix ■

So a higher selling price encourages the producer's investment. Indeed, the opportunity to sell each unit to a higher price, and then getting a higher pay-off, leads the producer to make a larger investment. Moreover, selling prices are higher in a good situation than in a bad one. Hence, when the producer increases his prior belief on the realization of the good situation, he increases his investment.

Furthermore, a producer who thinks that the expected price in a market in which there are two buyers (is one buyer) is higher than the one where there is only one buyer (are two buyers) increases (decreases) his investment when his prior belief on the possibility that the market is composed of two buyers increases. So the influence on the investment decision of the producer's prior belief on the market size depends on the expected price by the producer. Since there is an uncertainty on the price, the producer may undervalue or overvalue the price which would lead him to under-invest or over-invest even if he has a good perception of the size market.

Finally, the discount rate effect on the investment decision depends on the return of the investment. If there is a positive-yield, the producer with a stronger preference for the present increases his investment. On the other hand, this producer reduces his investment when there is a negative-yield.

We present now the effect of price and market size uncertainties on the optimal investment decision. To do so, it is natural to compare the case of both uncertainties to a case of certainty in which $P \in \{\bar{P}_A, \underline{P}_A, \bar{P}_B, \underline{P}_B\}$. Moreover, we note the prior beliefs of the producer $\psi_A = \psi$ on state $A$, and $\psi_B = 1 - \psi$ on state $B$. Consequently, the case of certainty is constructed by considering that the producer knows both the future selling price and the size of the market. So the producer's expected pay-offs in the case of price uncertainty is represented by (1) and in the case of certainty may be expressed, respectively, as follows:

$$V_0^C(I) = -I + \beta\left[Pf(I) - C(f(I))\right) \text{ with } P \in \{\bar{P}_i, \underline{P}_i\}.$$

The first order condition is respectively to $I$:

$$\frac{1}{\beta f'(I_C^*)} + C'\left(f(I_C^*)\right) = P.$$

We now turn to compare the optimal investment in both cases. We get the following proposition.

**Proposition 1** *For $i, j \in \{A, B\}$ and $i \neq j$, if $E_\theta \tilde{P}_i > E_\theta \tilde{P}_j$ then:*
*(i) if $P = \bar{P}_i$ then $I^* \geq I_C^*$;*
*(ii) if $P = \underline{P}_j$ then $I_C^* \geq I^*$;*
*(iii) if $P = \bar{P}_j$ or $P = \underline{P}_i$ then if*

$$\psi_i \geq \frac{P - E_\theta \tilde{P}_j}{E_\theta \tilde{P}_i - E_\theta \tilde{P}_j}$$

*then $I^* \geq I_C^*$; otherwise $I_C^* > I^*$.*

**Proof.** In Appendix ■

Under both uncertainties, when the expected price in state $i$ is higher than in state $j$, the producer may over invest when he thinks that in state $i$ the price will be the largest. On the other hand, the producer may under invest when he thinks that the price in state $j$ is the lowest. The producer may over invest when he thinks that the price in state $i$ is the lowest or if the price in state $j$ is the highest but his prior belief in the realization of state $i$ is higher than a certain threshold. When price and market size uncertainties are combined, the optimal investment depends on the value of the price $P$. The investment under two uncertainties is larger than the one under certainty when the expected price in state $i$ is higher than in state $j$, for a low price in state $i$ and for high price in state $j$ but the prior on the realization of the state $i$ is higher than a certain threshold. The investment under two uncertainties is lower than under certainty when the producer thinks the certain price is the low price in state $j$. The expectation of a high or low selling price plays a major rule in the optimal capacity choice.

If we have one uncertainty on the price, i.e. $\psi = 0$ or $\psi = 1$, we rewrite the first order condition 2 as follows.

$$\frac{1}{\beta f'(I_{PU}^*)} + C'\left(f(I_{PU}^*)\right) = \theta \bar{P}_i + (1 - \theta)\underline{\mathrm{P}}_i.$$

We now compare the optimal investment in both cases. We find, there exists a threshold $\theta$ such as $\theta \geq \frac{P - \underline{\mathrm{P}}_i}{\bar{P}_i - \underline{\mathrm{P}}_i}$ for which $I_{PU}^* \geq I_C^*$, otherwise $I_C^* \geq I_{PU}^*$. If we are in a situation with high (low) price, the decision maker invests more (less) under price certainty than under uncertainty. In a favourable context, price uncertainty reduces the optimal amount of installed capacity as Pindyck (1988) proved it , whereas in an unfavourable context, uncertainty leads to higher values of the project. Dangl (1999) demonstrates the same result with numerical investigations: the optimal installed capacity increases much with uncertainty.

On the other hand, if we have only the size market uncertainty, i.e. $\theta = 0$ or $\theta = 1$, we rewrite the first order condition (2) as follows.

$$\frac{1}{\beta f'(I^*_{MSU})} + C'\left(f(I^*_{MSU})\right) = \psi P_A + (1-\psi)P_B.$$

The case of certainty is defined as previously with $P \in \{P_A, P_B\}$. We now compare the optimal investment in both cases. From proposition 2, we deduce that for $i, j \in \{A, B\}$ and $i \neq j$, if $P_i > P_j$ then: if $P = P_j$ then $I^*_{MSU} \geq I^*_C$; otherwise if $P = P_i$ then $I^*_C > I^*_{MSU}$. Market size uncertainty effect on the investment decision depends on the level of the price in each market. If the price in the market with one (two) buyer(s) is higher than the one with two(one) buyers, market size uncertainty increases investment if he thinks that the selling price is the lowest. Actually, under market size uncertainty, the producer may over invest because he thinks that the market in which the price is the lowest has more chance to occur. On the other hand, if the price in the market with one (two) buyer(s) is higher than the one with two(one) buyers, market size uncertainty decreases investment if the selling price is equal to the highest.

We now divide the effect of both uncertainties. We then propose to compare the case of both uncertainties to a case with one of the two uncertainties. Taking into account the results of the proposition, we get the following proposition.

**Proposition 2** *(i) For $i, j \in \{A, B\}$ and $i \neq j$, when the producer knows that state $i$ will occur then: if $E_\theta \tilde{P}_i \geq E_\theta \tilde{P}_j$ then $I^* \geq I^*_{PU}$ ; otherwise $I^*_{PU} > I^*$.*
*(ii)If the producer knows that the situation with a high price $P = \bar{P}_j$ will occur then $I^*_{MSU} \geq I^*$, while if he knows that the situation with a low price $P = \underline{P}_i$ will occur then $I^* > I^*_{MSU}$.*

**Proof.** In Appendix ■

Adding a market size uncertainty increases the investement when the expected price with both uncertainties is higher than one with only price uncertainty what ever the producer thinks about the level of the selling price. It may be underestimated when the selling price is the highest. However, the investment decreases when the expected price with both uncertainties is lower than the one with only price uncertainty. The neglecting market size-related uncertainty would lead to an underestimation of the role of price uncertainty. Likewise, adding a price uncertainty may increase the investment when under both uncertainties the producer over values the selling prices.

Finally, we propose to compare the producer's optimal investment decision in the price uncertainty case and in the market size uncertainty case. We then define two producers: producer 1 who has to invest under price uncertainty, and producer 2 who has to choose his investment under market size uncertainty. We obtain the next proposition.

**Proposition 3** *For $i, j \in \{A, B\}$ and $i \neq j$,*
*(i) if producer 1 knows that state $i$ will occur while producer 2 knows that the price is high then: if $\bar{P}_j \geq \bar{P}_i$ then $I^*_{MSU} > I^*_{PU}$; otherwise if*

$$\theta \geq \frac{\psi \bar{P}_A + (1-\psi)\bar{P}_B - \underline{P}_i}{\bar{P}_i - \underline{P}_i}$$

*then $I^*_{PU} > I^*_{MSU}$; otherwise $I^*_{MSU} > I^*_{PU}$.*
*(ii) if producer 1 knows that state $i$ will occur while producer 2 knows that the price is low then: if $\underline{P}_i \geq \underline{P}_j$ then $I^*_{PU} > I^*_{MSU}$; otherwise if*

$$\theta \geq \frac{\psi \underline{P}_A + (1-\psi)\underline{P}_B - \underline{P}_i}{\bar{P}_i - \underline{P}_i}$$

*then $I^*_{PU} > I^*_{MSU}$; otherwise $I^*_{MSU} > I^*_{PU}$.*

**Proof.** In Appendix ■

The investment under price uncertainty is larger than the one under market size uncertainty when the producer's prior belief on the realization of the situation with a high price is higher than certain threshold.

From propositions 1, 2 and 3, we obtain the following summary. When $E_\theta \tilde{P}_i > E_\theta \tilde{P}_j$ then :

Table 1: Summary of the effects of uncertainties in the investment

| Case | Conditions | | Ranking |
|---|---|---|---|
| 1 | $P = \underline{P}_i$ and $\underline{P}_i \leq \underline{P}_j$ | $\psi_i \geq \frac{P - E_\theta \tilde{P}_j}{E_\theta \tilde{P}_i - E_\theta \tilde{P}_j}$ and $\theta \geq \frac{\psi \underline{P}_A + (1-\psi)\underline{P}_B - \underline{P}_i}{\bar{P}_i - \underline{P}_i}$ | $I^* \geq I^*_{PU} > I^*_{MSU} \geq I^*_C$ |
| 2 | | $\psi_i \geq \frac{P - E_\theta \tilde{P}_j}{E_\theta \tilde{P}_i - E_\theta \tilde{P}_j}$ and $\theta \leq \frac{\psi \underline{P}_A + (1-\psi)\underline{P}_B - \underline{P}_i}{\bar{P}_i - \underline{P}_i}$ | $I^* > I^*_{MSU} > I^*_{PU} \geq I^*_C$ |
| 3 | $P = \bar{P}_i$ and $\bar{P}_j \geq \bar{P}_i$ | $\forall \psi_i$ and $\forall \theta$ | $I^*_{MSU} \geq I^* \geq I^*_{PU} \geq I^*_C$ |
| 4 | $P = \underline{P}_j$ and $\underline{P}_j \leq \underline{P}_i$ | $\forall \psi_i$, $\theta \geq \frac{\psi \underline{P}_A + (1-\psi)\underline{P}_B - \underline{P}_i}{\bar{P}_i - \underline{P}_i}$ | $I^*_{PU} \geq I^*_C \geq I^* > I^*_{MSU}$ |
| 5 | $P = \bar{P}_j$ and $\bar{P}_j \leq \bar{P}_i$ | $\psi_i \leq \frac{P - E_\theta \tilde{P}_j}{E_\theta \tilde{P}_i - E_\theta \tilde{P}_j}$ and $\theta \leq \frac{\psi \bar{P}_A + (1-\psi)\bar{P}_B - \underline{P}_i}{\bar{P}_i - \underline{P}_i}$ | $I^*_{MSU} \geq I^*_C \geq I^*_{PU} \geq I^*$ |
| 6 | $P = \bar{P}_j$ and $\bar{P}_j \geq \bar{P}_i$ | $\psi_i \leq \frac{P - E_\theta \tilde{P}_j}{E_\theta \tilde{P}_i - E_\theta \tilde{P}_j}$ and $\forall \theta$ | $I^*_C > I^*_{MSU} > I^*_{PU} \geq I^*$ |

When the optimal capacity choice under uncertainty is lower than under certainty, uncertainties reduce the optimal amount of installed capacity as Pindyck (1988) proved it. However, in few cases, the producer may over invest. First, uncertainties increase the investment when the producer thinks that the price in state $i$ is the lowest but his prior believes in the realization of the good situation and in the realization of state $i$ are higher than certain thresholds. Actually, under price and market uncertainties, the producer may over invest because of his confidence on the realization of the situation with a high price and the state $i$.

Then , both cases with two uncertainties or with the market size uncertainty only increase the investment when the producer thinks that the price in state $i$ is the highest. The price uncertainty plays also a main rule in the optimal investment choice capacity.

When the capacity decision is taken only under price uncertainty, the producer over invests when he thinks that the price in state $j$ is the lowest but his prior belief in the realization of the good situation is higher than a certain threshold. In this case, he is more sensitive to the market size than the price uncertainty.

As long as the producer's prior beliefs in the realization of the good situation and in the realization of state $i$ are lower than certain thresholds, he over invests only when the capacity is chosen under market size uncertainty and when he thinks that the price in state $j$ is the highest but lower than in state $i$. Finally, when the price in state $j$ becomes higher, the producer under-invests whatever the number of uncertainty.

# 4 Impact of ambiguity on the investment strategy

The ambiguity approach sets aside the assumption of a single set of state probabilities. Instead, agents' beliefs are represented not as a single probability measure on the set of states but as a set of probability measures. Ambiguity is a condition in which the probabilities of events are either not uniquely assigned or are unknown. Such a framework is relevant for investment decisions given the results of Heath & Tversky (1991): the ambiguity aversion is particularly strong in cases where people feel that their competence in assessing the relevant probabilities is low.

We suppose the producer is averse to ambiguity. Indeed, his ambiguity aversion relates to the aversion towards ambiguous prices of the torrefied biomass, specifically, the uncertainty regarding the probability distribution of prices when we have one buyer or two buyers for torrefied biomass. Since investors must choose their capacity of production and since the probability distributions over selling prices of output are not always known, especially in the case of new BTL units, ambiguity aversion may be particularly important in their capacity choice decision. Therefore, we are interested in understanding how investment capacity choice is affected by ambiguity aversion.

We extend the model of decision making by reflecting explicitly the circumstance that the decision maker is uncertain about the prior relevant to his decision. Indeed, the investor can worry that he may not take the good decision ex ante because he has relatively vague idea as to what the true probability about the selling price is. The fact to sell the output to $i$ for $i \in \{A, B\}$ has a return $\tilde{\Pi}_i$ whose distribution is ambiguous in the sense that is sensitive to $F(\theta)$ whose distribution is unknown. He has ambiguity aversion about ex ante evaluations. The subjective belief $\psi$ characterizes this perception of ambiguity of the decision maker. The expected pay-off of the project is also:

$$\tilde{V}_0 = -I + \beta[\psi\tilde{\Pi}_A + (1-\psi)\tilde{\Pi}_B]$$

with $\tilde{\Pi}_i = \tilde{P}_i q - C(q)$. $\tilde{P}_i$ follows a subjectively plausible probability distribution $F(\theta)$. In each state of the world, there are two possible situations in the economy: a situation with a high price $\tilde{P}_i = \bar{P}_i$, and a situation with a low price $\tilde{P}_i = \underline{P}_i$. The good situation occurs with probability $\theta$, so the bad situation occurs with probability $(1-\theta)$. The investor must choose how much invest in the capacity to maximize the value of the project. Following (Klibanoff et al., 2005), we assume that the preferences of the investor exhibit smooth ambiguity aversion. For each plausible probability distribution $F$, the investor computes the expected pay-off $V_0(I, \psi, \theta)$ conditional to $F$ being the true distribution. For a given investment I, the welfare of the agent is measured by (1). The shape of $\phi$ describes the investor's attitude towards ambiguity (or parameter uncertainty). A linear $\phi$ means that the investor is neutral to ambiguity. On the contrary, a concave $\phi$ is synonymous of ambiguity aversion. The investor's problem is :

$$\max_I W_0(I) = \int_{\underline{\theta}}^{\bar{\theta}} \phi[V_0(I, \psi, \theta)] dF(\theta)$$

The first order condition is respectively to $I$:

$$\int_{\underline{\theta}}^{\bar{\theta}} \phi'(V_0(I^*, \psi, \theta)) \frac{\partial V_0(I^*, \psi, \theta)}{\partial I} dF(\theta) = 0$$

where

$$\frac{\partial V_0(I^*, \psi, \theta)}{\partial I} = -1 + \beta f'(I) E_{\psi\theta}\tilde{P} - \beta f'(I) C'(f(I)) \tag{5}$$

with (3) and (4).

**Proposition 4** *If $\phi$ is twice continuously differentiable, the decision maker displays smooth ambiguity aversion. Then he invests less than if he was smoothly ambiguity neutral. The both uncertainties on the selling price and on the emerging BTL technology development decrease the capacity choice of the decision maker in the pre-treatement process.*

**Proof.** In Appendix ■

Due to ambiguity, the investor in torrefaction process choices a weaker capacity for his units than if he is ambiguity neutral. Ambiguity aversion leads the investor to evaluate probabilities distribution according to the least-favourable state, in this case the lowest pay-off. This behaviour could have consequences on the development of emerging BTL process. Indeed, as mentioned before, the pre-treatment could enhance the deployment of BTL process because it may improve the economics of the overall production chain. If the producer under-invests, the buyer has the risk not to be provided in quantity. The buyers of the torrefied biomass perceive uncertainty about the availability of their inputs. They would be reluctant to invest in the new renewable energy process.

Models for predicting consumers' choices suggests that consumers not only consider ambiguity in making decisions under uncertainty, but are willing to pay to avoid it or to seek it (Kahn & Sarin, 1988). In our case, the producer may will to reduce or avoid ambiguity by doing study of the price volatility of the torrefied biomass. Policy makers could help investors via ex-ante mechanisms (Engle-Warnick et al., 2008) to resolve the price and market uncertainties.

# 5 Policy implications

The EU set a minimum binding target of 10% biofuel use by 2020. Second generation biofuels may help to reach this goal. In this case, investment in pre-treatment units will be required to supply for the BTL units. A low level of investment may have negative impacts on the second generation biofuel production. It would be better to avoid an under-investment.

An increase ambiguity implies the firm is less confident in the prospect of the price level and make the producer under-invest. We may derive from proposition 4 that to encourage the development of emerging renewable energy technologies based on biomass, the regulator should strive to reduce the ambiguity on the price volatility by reducing or eliminating uncertainty in future BTL process development. More precisely, the task of the regulator could consist in announcing incorporation targets for the second-generation biofuels. It would incite investment in BTL units and reduce uncertainty in relation to market size for the torrefied biomass producers. Let's policy makers promote the development of second generation conversion technologies by introducing specific targets for second generation biofuels and R&D supports. We would like to know the consequences on the capacity choice in torrefaction units. From table 1, we obtain the following results.

Regarding the optimal capacity choice under uncertainty, the producer may over invests when he thinks the price will be the lowest and under-invests when it will be the highest. However, the large amount of investment in BTL units would lead investors to insure their supply in torrefied biomass. Near-term markets for the ligno-cellulosic feedstocks might be created and contracts might be established between torrefied biomass and second generation biofuels producers. Moreover, if we compare on the present biofuel policies in the EU, Member States have put in place mechanisms as feed in tariffs in biofuels for binding the 10% of biofuels in transport (MEEDDAT, 2010; Henri Prévot & Gagey, 2005). We can assume second generation biofuels may also benefit from the economical instruments to promote biofuels in order to be competitive with fossil oil prices. An assumed price level for the output of BTL units will tend to torrefied biomass contracts. The price of torrefied biomass could be indexed to another resource. By the way, the incorporation target policy reduce also the price uncertainty. Such initiatives could be complemented by initiatives that stimulate the development of lignocellulosic crops. Important initiatives include research on cultivation practices of perennial crops and adaptation of the EU common agricultural policy and spatial policies in order to accommodate them (Berndes et al., 2009).

To reduce the ambiguity on the price, policy makers have also announced call for tenders for combined heating and electrical power plants fired by biomass. In France, three calls for tender in 2005, 2007 and 2009 have been announced for the purchase of energy produced by biomass cogeneration, in order to meet the ambitious targets France has set itself under the Grenelle Environment Forum (Borloo, 2010; Abadie & Fond, 2009). Thus, the price uncertainty for one of the two potential buyers of torrefied biomass disappears. Proposition 2 raises the question of the level of the price in each market.

# 6 Conclusion

In this paper, we assess the impact of two uncertainties and ambiguity on the investment strategy. We develop a formal model for decision making in which investors are neutral to risk and averse to ambiguity about the true distribution of torrefied biomass price. We analyse the optimal capacity choice in this model. We show analytically that the model has the following implications, which are consistent with the theoretical findings: (i) the producer always invests unless his cost exceeds his benefit. The opportunity to sell each unit to a higher price, and then getting a higher pay-off, leads him to make a larger investment; (ii) price uncertainty, market size uncertainty and the combination of these both uncertainties may lead the producer to under-investing ; (iii) in the presence of ambiguity about price and market size, then producers will under-invest in their units.

The main feature of this model is that it allows understanding the investor behaviour faced to two uncertainties and ambiguity. From a theoretical point of view, this paper is considered to provide some policy implications for member states that aim to encourage energy-related greenhouse gas emission reduction and renewable energy sources.

An attractive feature of the model is to determine how the risk and ambiguity aversions of the buyer will affect the investment strategy of torrefied biomass producers. Finally, it would be important to check empirically, near the potential investor (private forest owners, cooperatives...) the theoretical results obtained in our model and evaluate the degree of their ambiguity aversion.

# 7 Appendix

We first study the concavity of $V_0(I,\psi,\theta)$: We differentiate twice times $V_0(I,\psi,\theta)$ with respect to $I$, we obtain:

$$\frac{\partial^2 V_0(I,\psi,\theta)}{\partial I^2} = \beta\left[\frac{f''(I)}{f'(I)} - \beta C''\left(f(I)\right) f'^2(I)\right]$$

which is negative because $f$ is increasing and concave and $C$ is convex. Thus $V_0(I,\psi,\theta)$ is concave.

If for all $I > 0$ we have $V_0(I,\psi,\theta) \leq 0$, it is never profitable for the producer to invest. The producer's optimal investment is equal to zero.

On the other hand, if there exists $I > 0$ such that $V_0(I,\psi,\theta) > 0$, there exists a solution to the maximization of $V_0(I,\psi,\theta)$ with respect to $I$. The first order conditions characterized the producer's investment:

$$\frac{1}{\beta f'(I)} + C'\left(f(I)\right) = \psi\left[\theta \bar{P}_A + (1-\theta)\underline{P}_A\right] + (1-\psi)\left[\theta \bar{P}_B + (1-\theta)\underline{P}_B\right].$$

■

**Proof of Lemma 1**
**Proof of Part (i) of Lemma 1**

We differentiate equation (2) with respect to $\bar{P}_A$, $\underline{P}_A$, $\bar{P}_B$, $\underline{P}_B$ and $\theta$, respectively. We obtain:

$$\frac{\partial I^*}{\partial \bar{P}_A} = \frac{-\beta f'(I^*)^2 \psi\theta}{f''(I^*) - \beta f'^3(I^*)C''(f(I^*))},$$
$$\frac{\partial I^*}{\partial \underline{P}_A} = \frac{-\beta f'(I^*)^2 \psi(1-\theta)}{f''(I^*) - \beta f'^3(I^*)C''(f(I^*))},$$
$$\frac{\partial I^*}{\partial \bar{P}_B} = \frac{-\beta f'(I^*)^2 (1-\psi)\theta}{f''(I^*) - \beta f'^3(I^*)C''(f(I^*))},$$
$$\frac{\partial I^*}{\partial \underline{P}_B} = \frac{-\beta f'(I^*)^2 (1-\psi)(1-\theta)}{f''(I^*) - \beta f'^3(I^*)C''(f(I^*))},$$
and
$$\frac{\partial I^*}{\partial \theta} = \frac{-\beta f'(I^*)^2 \left[\psi(\bar{P}_A - \underline{P}_A) + (1-\psi)(\bar{P}_B - \underline{P}_B)\right]}{f''(I^*) - \beta f'^3(I^*)C''(f(I^*))}$$

which are positive. So $I^*$ is increasing with $\bar{P}_A$, $\underline{P}_A$, $\bar{P}_B$, $\underline{P}_B$ and $\theta$.

**Proof of Part (ii) of Lemma 1**

We differentiate equation (2) with respect to $\psi$. We obtain:

$$\frac{\partial I^*}{\partial \psi} = \frac{-\beta f'(I^*)^2 \left[E_\theta \tilde{P}_A - E_\theta \tilde{P}_B\right]}{f''(I^*) - \beta f'^3(I^*)C''(f(I^*))}. \tag{6}$$

If $E_\theta \tilde{P}_A > E_\theta \tilde{P}_B$ then equation (6) is positive implying that $I^*$ is increasing with $\psi$. If $E_\theta \tilde{P}_A < E_\theta \tilde{P}_B$ then equation (6) is negative implying that $I^*$ is decreasing with $\psi$. If $E_\theta \tilde{P}_A = E_\theta \tilde{P}_B$ then $\psi$ has no effect on $I^*$.

**Proof of Part (iii) of Lemma 1**

We differentiate equation (2) with respect to $\beta$. We obtain:

$$\frac{\partial I^*}{\partial \beta} = \frac{f'(I^*)^2 \left[E_{\psi\theta} \tilde{P} - C'(f(I^*))\right]}{f''(I^*) - \beta f'^3(I^*)C''(f(I^*))}. \tag{7}$$

If $E_{\psi\theta}\tilde{P} > C'(f(I^*))$ then equation (7) is positive implying that $I^*$ is increasing with $\beta$. If $E_{\psi\theta}\tilde{P} < C'(f(I^*))$ then equation (7) is negative implying that $I^*$ is decreasing with $\beta$. If $E_{\psi\theta}\tilde{P} = C'(f(I^*))$ then $\beta$ has no effect on $I^*$.

■

**Proof of Proposition 1**

We define $g(I) = \frac{1}{\beta f'(I)} + C'(f(I))$. We differentiate $g$ with respect to $I$, we get:

$$g'(I) = \frac{-f''(I)}{\beta f'^2(I)} + C''(f(I))\, f'(I)$$

which is positive because $f$ is increasing and concave, and $C$ is convex. So $g$ is increasing with $I$.

So we get that:

$$\begin{aligned} g(I^*_{PU}) \geq g(I^*_C) &\Leftrightarrow \theta \bar{P}_i + (1-\theta)\underline{P}_i \geq P \\ &\Leftrightarrow \theta \geq \tfrac{P-\underline{P}}{\bar{P}-\underline{P}} \\ &\Leftrightarrow I^*_{PU} \geq I^*_C. \end{aligned}$$

■

**Proof of Proposition 2**

Similar to the proof of Proposition 1, thus omitted.

■

**Proof of Proposition 3**

Similar to the proof of Proposition 2, thus omitted.

■

**Proof of Proposition 4**

The investor's problem is :

$$\max_I W(I) = \int_{\underline{\theta}}^{\bar{\theta}} \phi(V_0(I,\psi,\theta))dF(\theta)$$

with

$$\begin{aligned} V_0(I,\psi,\theta) = -I + \beta[\psi[\theta(\bar{P}_A f(I) - C(f(I))) + (1-\theta)(\underline{P}_A f(I) - C(f(I)))] \\ + (1-\psi)[\theta(\bar{P}_B f(I) - C(f(I))) + (1-\theta)(\underline{P}_B f(I) - C(f(I)))]] \end{aligned}$$

The first order condition is respectively to $I$:

$$\int_{\underline{\theta}}^{\bar{\theta}} \phi'(V_0(I^*,\psi,\theta))\frac{\partial V_0(I^*,\psi,\theta)}{\partial I} dF(\theta) = 0 \tag{8}$$

where

$$\frac{\partial V_0}{\partial I} = -1+f'(I)\beta[\psi(\theta \mathrm{P}_A+(1-\theta)\underline{\mathrm{P}}_A)+(1-\psi)(\theta \mathrm{P}_B+(1-\theta)\underline{\mathrm{P}}_B)]-\beta f'(I)C'(f(I)) \quad (9)$$

(9) becomes:

$$\frac{\partial V_0}{\partial I} = -1 + \beta f'(I) E_{\psi\theta}\tilde{P} - \beta f'(I)C'(f(I)) \quad (10)$$

with (3) and (4). (8) is also equivalent to:

$$EW(I) = \int_{\underline{\theta}}^{\theta} \phi'(V_0(I^*, \psi, \theta))[-1 + \beta f'(I)(E_{\psi\theta}\tilde{P}) - \beta f'(I)C'(f(I))]dF(\theta)$$

with

$$\Delta(\theta) = \phi'(V(I^*, \psi, \theta))$$
$$\Lambda(\theta) = [-1 + \beta f'(I)E_{\psi\theta}\tilde{P} - \beta f'(I)C'(f(I))]$$

and so:

$$EW(I) = \int_{\underline{\theta}}^{\bar{\theta}} \Delta(\theta)\Lambda(\theta)dF(\theta)$$

Then the covariance is defined as follows:

$$cov(\Delta(\theta), \Lambda(\theta)) = E(\Delta(\theta)\Lambda(\theta)) - E(\Delta(\theta))E(\Lambda(\theta))$$

If $E^{I^*}(\Delta(\theta)\Lambda(\theta)) = 0$ thus

$$cov(\Delta(\theta), \Lambda(\theta)) + E(\Delta(\theta))E(\Lambda(\theta)) = 0$$

We distinguish two cases in function the shape of $\phi$. Following (Klibanoff et al., 2005), a function $\phi$ is linear is equivalent to say the decision maker is smoothly ambiguity neutral. If the function $\phi$ is concave, the decision maker displays smooth ambiguity aversion. The goal is to compare the amount of investment in function the smooth ambiguity aversion of the decision maker.

If the function $\phi$ is linear, $\phi'$ is a constant and for a smoothly ambiguity neutral decision maker, $E^{IN}(\Delta(\theta))$=0. Thus:

$$cov(\Delta(\theta), \Lambda(\theta)) = E^{IN}(\Delta(\theta)\Lambda(\theta))$$

- If $cov(\Delta(\theta), \Lambda(\theta)) < 0$ then:

$$E^{IN}(\Delta(\theta)\Lambda(\theta)) < 0$$

But we have supposed that $E^{I^*}(\Delta(\theta)\Lambda(\theta)) = 0$ so $J^*(I^N) < J^*(I^*)$ with

$$J^*(I^N) = E^{IN}(\Delta(\theta)\Lambda(\theta))$$
$$J^*(I^*) = E^{I^*}(\Delta(\theta)\Lambda(\theta))$$

If $\phi$ is concave and $\phi$ is twice continuously differentiable then $J^*$ is a decreasing function so $I^N > I^*$.

- If $cov(\Delta(\theta), \Lambda(\theta)) > 0$, then $I^* > I^N$

Thus we are interested in evaluating the sign of the covariance. We also evaluate the derivative sign of $\Delta(\theta)$ and $\Lambda(\theta)$ with respect to the variable $\theta$:

- $Sign(\frac{\partial(\Delta(\theta))}{\partial\theta})$

$$\begin{aligned}\frac{\partial(\Delta(\theta))}{\partial\theta} &= \frac{\phi'(V_0(I,\psi,\theta))}{\partial\theta} \\ &= \phi''(V_0(I,\psi,\theta)\frac{\partial V_0}{\partial\theta}\end{aligned}$$

where

$$\frac{\partial V_0}{\partial\theta} = \beta[\psi(\bar{P}_A - \underline{P}_A)f(I) + (1-\psi)(\bar{P}_B - \underline{P}_B)f(I)]$$

Since $\Phi''(V_0(I,\psi,\theta)) < 0$, $(\bar{P}_i - \underline{P}_i) > 0$ and $\frac{\partial V_0}{\partial\theta} > 0$ then:

$$\frac{\partial(\Delta(\theta))}{\partial\theta} < 0$$

- $Sign(\frac{\partial(\Lambda(\theta))}{\partial\theta})$

$$\frac{\partial(\Lambda(\theta))}{\partial\theta} = \beta f'(I)\frac{E_{\psi\theta}\tilde{P}}{\partial\theta}$$

where

$$\begin{aligned}\frac{E_{\psi\theta}\tilde{P}}{\partial\theta} &= \psi(E_\theta\tilde{P_A})' + (1-\psi)(E_\theta\tilde{P_B})' \\ &= \psi(\bar{P}_A - \underline{P}_A) + (1-\psi)(\bar{P}_B - \underline{P}_B)\end{aligned}$$

Since $\beta f'(I) > 0$ and $\frac{E_{\psi\theta}\tilde{P}}{\partial\theta} > 0$ then

$$\frac{\partial(\Lambda(\theta))}{\partial\theta} > 0$$

Finally, the covariance is negative. We conclude that if $\phi$ is concave and twice continuously differentiable then $J^*$ is a decreasing function so $I^N > I^*$.

■

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