**Does French Energy policy foster investments in the biomethane sector?**

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## Abstract

Biomethane from organic waste provides an opportunity for the simultaneous production of renewable energy and waste management. With auctions as an allocation policy for subsidies the complexity of decision-making process in biomethane sector arises from the uncertainty of the evolution of the natural gas price and anticipation of required improvements in the production costs. Also the level of the market premium an investor should apply for and the uncertainty of winning through auctions adds to the complexity. In addition, investments are irreversible and intended for long horizons of time. To study the investment behavior, we adopt a real options approach that allows the consideration of a dynamic framework in an uncertain context. We focus on biomethane in France and we analyze how the Plurennial Energy Programming presented in January 2019 by the French Government will impact its development. In our microeconomic analysis we show to which extent the willingness to invest depends on the type of uncertainty related to the evolution of natural gas prices or to the existence of competition, on the level of market premium or on the technological learning. Part of our results show that none of the ambitious ceiling prices for 2023 and 2028 seem attainable and larger installations are economically more attractive.

**Keywords:** Biomethane investment projects, natural gas price, subsidy, real options analysis, auctions.
**JEL Classification**: Q40, Q57, D81

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# 1. Introduction

To reach the climate goals, European Union (EU) and its member states seek to expand the part of renewable energy in the total energy supply. Renewable gases are expected to play an important role in the European Green Deal as the European Commission ambitions to reach climate neutrality by 2050 (European Commission, 2020). One of these renewable gases is biomethane, which is the result of an anaerobic digestion process of organic waste. After a purification process, the biomethane obtained has the same characteristics as natural gas and can be injected in the gas grid. Biomethane from organic waste can be seen as the crossing point of two important challenges that faces modern societies today: organic waste management and renewable energy production (Scarlat et.al, 2018). Following the definition of Holtermann (1972) biomethane can be seen as a mix of private and public good[4]. First, it allows establishing a local circular economy (urban or agricultural area) by producing biofuel from organic waste thereby integrating agricultural waste management and transport system (Vernay et. al., 2013, Lybæk et.al., 2014). Second, biomethane has the advantage to be a flexible energy carrier that is easily stored and can be dispatched at will for electricity production and to balance energy grids (Hochloff & Braun). However, biomethane installations incur high investment costs and are not yet competitive under current market conditions (Nevzorova and Kutcherov, 2019). Regulatory support schemes intended to realize economies of scale in this sector are currently implemented all-over Europe (Banja et al., 2019) but with the level of support following a decreasing trend (Scarlat et.al, 2018).

Since the 1990's the feed-in tariff has been one of the most widely applied energy policy (Solangi et al., 2011) for stimulating renewable energy. Nevertheless, FIT schemes fell victim of their own success and have been criticized for entailing unreasonable and uncontrollable cost (Leiren & Reimer, 2018). Auctions have been put forward as an alternative to FIT and are becoming an increasingly popular energy policy (Leiren & Reimer, 2018; REN21, 2017, p. 21) to promote renewable energy. Contrary to feed-in tariffs, auctions create competition which often leads to cost reductions for the support of renewable energy like wind and PV (Eberhard & Kåberger, 2016; IRENA and CEM, 2015; Lundberg, 2019). For example, auctions for wind in The Netherlands and Germany have led to significant price reductions (Marsden et.al., 2018). Moreover, by setting the available auction volume in advance the public budget made available can be controlled ex-ante, instead of ex-post. Hence, it is not without surprise that the EU (directive 2018/2001) plans the phasing out of feed-in tariffs policies in favor of auctions for renewable energy. A FIT policy for biomethane exists since 2011 which will be progressively replaced with auctions by 2023 in most of European countries (Germany, Italy, France, Belgium, Lithuania, etc.)

[4] Biomethane output can be defined as a private good. Waste management and energy system gains like increased flexibility and reduced carbon emissions can be seen as a public good

In this paper we focus on the case of France which has a big agricultural and food sector. The waste from these two sectors represent almost 60% of the total potential for biomethane in France (Ademe, 2013). In 2019, the French government presented the Plurennial Energy Programming (named PPE hereafter) for 2019-2023 and 2024-2028, a strategic document for the coordination of the energy transition. The objective is that biomethane accounts for 10% of the total gas consumption by 2030. In line with the EU directive 2018/2001, France plans to implement auctions for the allocation of support for biomethane as from 2023 (MTES, 2019). The scenario is to have two auction rounds per year with an auctioned volume of 350 GWh. Ceiling prices are to be set at 67 €/MWh as from 2023 and 60 €/MWh as from 2028.

The French proposal has generated debate and concern within the biomethane sector (Atee Club Biogaz, 2020). A first concern is that the established ceiling prices put pressure on the required cost reduction. The French policy makers expect a significant effect from technological learning. Indeed, the current production cost of biomethane is 95 euro/MWh on average compared to a natural gas price of around 10 euro/MWh (TTF, April 2020). Given that the biomethane sector is fairly young (first grid connection in 2014 (Ademe, 2019)), the biomethane sector believes that the proposed ceiling prices are too ambitious. A second concern is that the preparation of biomethane projects requires resources, time and complex stakeholder management. For example Skovsgaard & Jensen (2018) show that the power balance between farmers and energy convertors can make farmers reluctant to participate. And whereas with FIT's all the preparatory effort will bear fruit almost by default, this is not the case with auctions. With auctions and this risk of not winning may make small actors reluctant to participate compared to large companies with diverse project portfolios to disperse risk (Lundberg, 2019). Finally, whereas with FIT's the price level is a given, with auctions it becomes a strategic choice where a trade-off has to be made between profit and chance of winning. Although the auction provides for ceiling prices, it is up to the bidder to decide to what extent he wishes to bid lower than this ceiling price to increase the chance of winning. Overall, the complexity of the project valuation and decision-making process will increase with the implementation of auctions.

Our paper criticizes whether the French support scheme for biomethane is appropriate to reach set policy objective and proposes recommendations to foster the development of the biomethane sector in France. It does so by conducting a real options analysis. This approach has been widely used to evaluate the value of renewable energy projects under uncertainty (Kozlova, 2017; Lee & Shih, 2010, Liu et.al.(2019)). We argue that it makes it especially well-suited to evaluate the optimality for investment in biomethane under uncertainty that results from the evolution of natural gas prices and the introduction of the auction mechanism.

The contributions of our paper are twofold. First, it complements existing studies for the evaluation of biomethane investment projects by discussing how the price uncertainty and the technological learning can be integrated in such models. Most of previous works use classical cost-benefit analysis or Mixed Integer Linear Program. Conversely, we argue that the simultaneous consideration of natural gas prices' uncertainty and the learning curve of costs' evolution in an analytical model within a continuous-time framework allow a full treatment of the dynamic aspects of the decision to invest. Second, our paper contributes to the real options analysis applied to biogas projects (D'Alpaos, C, 2017; Di Corato & Moretto, 2011) by considering the context of auctions and the inherent strategic uncertainty. This feature, undoubtedly, adds complexity to the analytical development of the model.

We show that the introduction of auctions mechanism together with the market uncertainty given by the future evolution of natural gas prices reduces the optimal price that an investor would bid. This price is bounded from below by the Marshallian Price and from above by the optimal price with market uncertainty and the traditional price from auctions framework. Not surprisingly, this result is in line with the current policy objectives. However, given that the pricing strategy is highly dependent on the evolution of costs, we show that none of the ambitious ceiling prices for 2023 and 2028 seem attainable and larger installations are economically more attractive.

The remainder of the paper is structured as follows. Section 2 introduces the methodology used and the literature review. Section 3 presents the model and the determination of the optimality for investment extended with auction theory to evaluate the impact on decision making process. The section ends with a numerical illustration and discussion of the results. The fourth and last section brings in some policy implications of our modeling framework and concludes the paper.

## 2. Related literature

Our paper uses insights from different strands of economic literature: renewable energy investments, technological learning and auctions theory. Investments in renewable energy in general has been examined in numerous studies in recent years. Curtin et al., (2019), Kozlova & Collan, (2020), Ozorhon et al., (2018), Egli, (2020) and Yang et al., (2019) take qualitative angle by looking amongst others at barriers, decision criteria and stranded risk when it comes to investments in renewable energy. Other papers are more focused and use models to examine project valuation and investment. For the biogas sector in particular, the dominant approach for investigating investments is cost-benefit analysis based on net present value (e.g. Reise et al., 2011; Hochloff & Braun, 2014; Kalinichenko et al., 2017; Skovsgaard & Jensen, 2018; Zemo & Termansen, 2018). Please refer to Table 1 for a summary of the objective of each paper and the method used.

*Table 1 : Economic literature focusing on investments in biogas sector*

| **Article** | **Objective, flexibility** | **Method** |
|---|---|---|
| Reise et.al. (2011) | Understanding of the decision-making behavior of farmers: conversion threshold, subsidy, non-monetary, individual risk perception | Survey with hypothetical opportunity to invest |
| Hochloff & Braun | Focuses on biogas CHP in the electricity | Mixed Integer Linear Program |

| | | |
|---|---|---|
| (2014)) | market in control reserve markets. Cost and benefits of installing excess capacity | |
| Kalinichenko et al., (2017) | Clarify the procedural technique for sensitivity analysis of a biogas plant investment project; Compare NPV and PI | Classic NPV approach. Sensitivity analysis as function of: investment cost, discount rate, sales price, sales volume, economic plant life, biogas plant load factor |
| Skovsgaard & Jensen, (2018) | Optimal value chain (CHP or upgrade to methane). Flexibility: profit allocation, plant size, optimal substrate energy convertor type | Choice of value chain and focus on power balance between farmers and energy convertor/aggregator under different profit allocation schemes. |
| Zemo & Termansen, (2018) | Study the Danish farmers decision to invest in collective biogas projects<br>Necessary flexibilities: Distance farm – plant, Contract options, Cancel partnership, Free start-up consultancy | discrete choice experiment;<br>mixed logit model with flexible distribution |

Source: Own elaboration

Nevertheless, we argue that three important drivers of the decision to invest are omitted in these papers: sunk and irreversible investment, market uncertainties (on the demand, on output prices, on the overall return), and flexibility to wait. The timing and the irreversibility of costs make it important to get investment decisions right, while the presence of uncertainties makes it difficult to do so. In this context, we argue that economic analysis based only on cost-benefit analysis is insufficient. Instead, we propose a real options approach, a well-known decision tool from economic theory. This tool helps capturing the positive effect of uncertainties in the decision-making process by recognizing that arrival of new information through time adds value to an investment project, i.e. creates option values (Arrow and Fisher (1974), Henry (1974), Myers (1977), Trigeorgis (1993), Dixit and Pindyck (1994)). More particularly, the intuition underlying the real options concept is straightforward: there may be a value associated with the option to postpone a decision until some of uncertainty about the variables which influence it, is resolved.

The real options approach has gained popularity in recent years because of increased complexity of investment planning and project valuation associated with renewable energy (see Kozlova (2017) or Liu et al., (2019) for broad synthesis). Closer to our paper, Boomsma et.al. (2012) apply real options to investigate the timing and capacity choice for investment in wind. The uncertainties considered are steel prices for investment, and electricity price and subsidies that impacts revenues. The role of subsidies in green investments is also tackled by Bigerna et al., (2019). With market demand uncertainty, the paper investigates the role of subsidy level on renewable energy development in reaching the Italian government target. Nevertheless, only few papers apply a real option approach to investigate investments in biogas. For example, Di Corato & Moretto (2011) focus on the flexibility to change between different inputs, by assuming that the price of one input is uncertain while the other is held constant. They argue that the flexibility to switch between inputs adds value to the project in case of price fluctuations the input. More recently, D'Alpaos (2017) examines the profitability and timing to invest in biogas under uncertainty of the selling price on the Italian energy market.

Moreover, besides price uncertainty, we argue that changes in production costs also have to be considered in the framework to properly valuate biomethane investment projects. Decrease of production costs results from learning effects or learning-by-doing. This assumes that the performance of a technology improves as the experience with the technology accumulates (Wright, 1936). Junginger et al. (2006) investigate technological learning in the context of bioenergy systems. They argue that the investment costs for biogas plants are not the best measure for technological learning. First of all, the number of plants constructed is not enough to construct a reliable learning curve. And secondly, their study shows that learning doesn't only occur when new plants are built but also because plant performance improves with time. More recently, Junginger et al., (2020) provide a broad overview of tools and methods considering the role of experience curves in low-carbon energy technologies.

Finally, auctions have winners and losers which add to the uncertain environment. Most articles that examine auctions adopt an empirical approach like for example Lundberg ( 2019) or focus on design aspects (Gephart et al., 2017; Klemperer,  2002). This paper integrates auction theory to enrich the model framework in assessing the impact of uncertainty. Auction theory applies probability to assess the chance of winning. Auction theory was first described by Vickrey (1961). Vijay Krishna, (2002) describes several types of auctions and associated probability models in the book Auction Theory  (Vijay Krishna, 2002).  Real options and the consideration of strategic pricing in a competitive environment can be found in Lambrecht & Perraudin, (2003), Pawlina & Kort, (2005), Hsu & Lambrecht, (2007), Dosi & Moretto, (2010) and Cong, (2019). These works emphasize the idea that the competitive environment and uncertainty on the competitor's strategy distort the timeline of the option to invest and the direction of distortion is dependent on the increase or the decrease of the decision-makers payoff from exercising the options. In the first case, the authors observe an erosion of the option value to wait and an earlier exercise, whereas in the second case, the option is delayed.

This paper combines real options with auction theory in order to get insights in the decision-making process and policy implications in the case of French biomethane investment projects. More specifically, we contribute to the literature by simultaneously considering the price uncertainty, the learning curve effect and the additional risk coming from the threat of competitors in a decreasing price or reverse auctions context. We analyze the impact of these variables on the optimal decision to invest.

## 3. The Model

This section presents the development of the model by discussing the main assumptions and propositions. Before describing the main assumptions of the model, we present in Table 2 the main variables which are going to be used:

*Table 2 : Nomenclature of model parameters*

| Parameter / Variable | Symbol | Unit |
|---|---|---|
| Price of natural gas at time t | $P_t$ | € / MWh |
| Total revenue for selling biomethane | $P_r$ | € / MWh |
| Minimum required price for gas (Marshallian price) | $P_m$ | € / MWh |
| Optimal bidding price without uncertainty | $P_a$ | € / MWh |
| Optimal price with real options | $P^*$ | € / MWh |
| Optimal bidding price with uncertainty | $P^{**}$ | |
| Market premium | $S$ | € / MWh |
| Growth rate of price of natural gas | $\mu$ | % |
| Volatility of price of natural gas | $\sigma$ | % |
| Produced energy in year t | $q_t$ | GWh / y |
| Learning rate | $\gamma$ | - |
| Operational electricity costs | $c_e$ | € / MWh |
| Operational costs (exc. electricity) | $c_t$ | € / MWh |
| Profit at time t | $\pi_t$ | € |
| Solution of the quadratic equation | $\beta_1$ | - |
| Discount rate | $r$ | % |
| Unit investment costs or capital expenses | $K$ | € |
| Funding period | $T$ | Years |
| Option Value | $F$ | € |
| Cumulative Distribution Function | $cdf$ | % |
| Value of the Project | $V$ | € |
| Installed capacity | $Q$ | $Nm^3/h$ |
| Auction energy volume | $Q_a$ | GWh |
| Hazard rate | $\lambda$ | - |
| Net Present Value | $NPV$ | € |
| Number of bidders | $N$ | - |
| Bidder i | $i$ | |

### 3.1 Main assumptions

Our modeling framework relies on assumptions that we justify in this subsection.

***Assumption 1****:* The evolution of the price of natural gas can be characterized as a Geometric Brownian Motion. Our assumption of a GBM for natural gas prices follows (Schwartz, 1997), (Pindyck, 1999, 2003), Carmona and Ludkovski (2004). Formally, it is expressed as,

$$dP_t = \mu P_t dt + \sigma P_t dz \ \ , P_0 = P \qquad (1)$$

Where $dt$ is the time variation, $dz$ is the increment of a Wiener process. Thus, we have E $[dz]$ = 0 and Var $(dz)$ = $\epsilon_t dt$, $\epsilon_t$ is a normally distributed random variable (E$[\epsilon_t]$ = 0, Var$(\epsilon_t)$ = 1).

***Assumption 2:*** In continuation of the learning effect discussed previously, learning in our model is considered for the operational expenses like maintenance and operations. It is assumed that technological learning will not impact electricity consumption, except for some minor efficiency improvements. In addition, electricity costs are exogenous and expected to rise. This cost is thus modeled separately from the rest of the operational expenses. To integrate learning effect in the model we following Majd and Pindyck (1989) and Della Seta et al., (2012) who present the learning curve as follows:

$$c_t(q_t) = c_{\mathrm{t}} e^{-\gamma q_t} \qquad (2)$$

And the total operation expenses as:

$$OPEX = c_e + c_t(q_t) = c_e + c_{\mathrm{t}} e^{-\gamma q_t} \quad (3)$$

where $c_e$ is the cost for electricity. The parameter γ is the learning rate and is derived from expected cost reductions established by (ENEA, 2018).

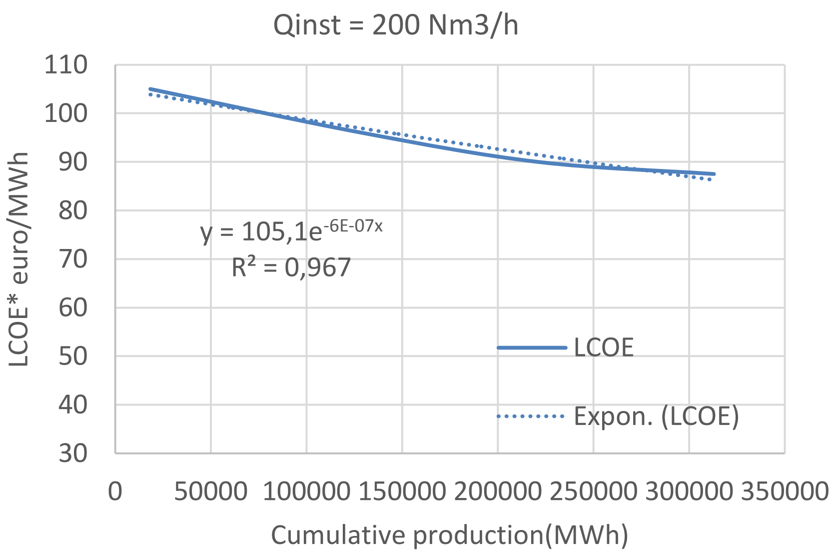


*Figure 1 : Example of learning rate of operation costs.*

***Assumption 3:*** We also consider a fixed market premium $S$ in addition to the natural gas price without a cap as illustrated in Figure 2 in the left.

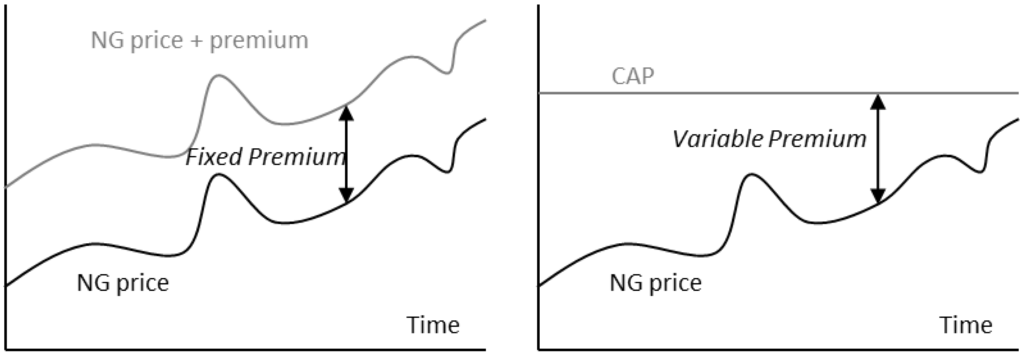


*Figure 2 : Fixed market premium (left) and variable market premium (right)*

Since the premium is added as a fixed value to the natural gas price it moves with its growth and volatility. Thus, the revenue stream $P_r$ can be expressed as:

$$P_r(t) = P_t + S \qquad (4)$$

***Assumption 4*** The option to invest does not come for free, implying some investment costs per unit of MWh, K. These costs are irreversible and they are due to land, labor, transport, equipment, interest loans and other external services.

***Assumption 5*** The horizon time for the decision process is finite and denoted with *T*. The discount rate is defined as $r$.

The investor decides to invest with respect to the observed value of natural gas price at date t, $P_t$. The higher this value, which encompasses the future expected values, the more the chance to invest. Because of investment and operating costs, the threshold of the value $P_t$ should be determined. In the following subsection, we analyze the investor's decision using dynamic programming.

### 3.2 What value for the option to invest in a biomethane installation?

Now we are able to analyze the investor’s problem. Investor’s objective is to maximize the expected total value of the biogas plant over its lifetime, by choosing at each date t, the optimal level of natural gas price, given the uncertainty on the evolution of natural gas prices, the level of subsidy and the operational constraints. Using the definition of $P_t$ in equation (1), we remind that the expected value of a variable following a geometric Brownian motion:

$$E[P_t] = P_0 e^{\mu t} \quad (3)$$

where the $P_0$ is the level of natural gas price at date t=0. Based on the assumptions presented in subsection 3.1. the instantaneous profit $\pi$ at any time $t$ is given by:

$$\pi_t = (P_t + S - c_t e^{-\gamma q_t} - c_e) \quad (4)$$

The net present value of the project can then be expressed as:

$$NPV(P_t, \gamma) = E\left[\int_0^T \left((P_t e^{\mu t} + S - c_t e^{-\gamma q_t} - c_e)Q\right)e^{-rt}\,dt - K \times Q\right] \qquad (5)$$

with $q_t = tQ$, by considering that the installation is producing up to the capacity.

$$NPV(P_t, \gamma) = \left(\frac{P_t(1-e^{-\delta T})}{\delta} + \frac{S(1-e^{-rT})}{r} - \frac{c_e(1-e^{-rT})}{r} - \frac{c_0(1-e^{-rT})}{\gamma Q + r}\right) Q - K \times Q \qquad (6)$$

With $\delta = r - \mu$. The value of the project is $NPV(P_t, \gamma)$ as a function of the stochastic natural gas price and continuous technological learning. We can now determine the option value $F$ of the project.

$$\mathrm{F} = \mathrm{Max}_{P^*}\, E\left[\int_0^T ((P_t + S - c_t e^{-\gamma q_t} - c_e)\,Q)e^{-rt}\,dt\right] \qquad (7)$$

Standard analysis shows that this option satisfies the ordinary differential equation $rF(P_t)dt = E[dF(P_t)]$ (Dixit, Pindyck, 1994). After applying value matching and smooth pasting conditions and solving for $P^*$ we obtain the following proposition for the option value to invest:

$$F(P_t, \gamma) = \begin{cases} AP_t^{\beta}, & P_t < P^* \\ \left(\frac{P_t(1-e^{-\delta T})}{\delta} + \frac{S(1-e^{-rT})}{r} - \frac{c_e(1-e^{-rT})}{r} - \frac{c_t(1-e^{-rT})}{\gamma Q + r}\right) Q - K \times Q, & P_t \geq P^* \end{cases} \qquad (8)$$

***Proposition 1****: The optimal price of natural gas for which investment is justified is given by the following equation:*

$$P^* = \frac{\beta}{\beta - 1}\left(\frac{C_0}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) + \frac{C_e - S}{r}(1 - e^{-rT}) + K\right)(\delta)(1 - e^{-\delta T})^{-1} \qquad (9)$$

***Proof*** *Appendix*

In other words, the investment is optimal if the level of natural gas prices is sufficiently high.

***Proposition 2****: The option value of natural gas for which investment is justified is given by the following equation:*

$$F = \frac{Q(1-e^{-\delta T})}{\delta\beta}\left[\frac{\beta}{\beta-1}\left(\frac{C_0}{\gamma Q+r}\left(1-e^{-(\gamma Q+r)T}\right)+\frac{C_e-S}{r}(1-e^{-rT})+K\right)(\delta)(1-e^{-\delta T})^{-1}\right]^{1-\beta} {P_t}^{\beta} \quad (10)$$

***Proof*** *Appendix*

Proposition 2 describes the value of the option as a function of the uncertainty of the natural gas price on the energy market. However, the right to invest has to be acquired through the auction mechanism.

### 3.3 Extension: auctions and uncertainty of winning

Having established the option value there remains the uncertainty of winning the auction. In an auction an investor is only sure about his own established value that allows him to generate a profit. But the investor is unsure about the private value that other bidders have established for the asset to be auctioned. Hence, there is an uncertainty of winning the auction. We assume that the bid prices follow an exponential distribution. The cumulative distribution for the bid price is then:

$$cdf(P^*) = 1 - e^{-\lambda P^*} \quad (11)$$

Here $P^{**}$ is the bid price and $\lambda$ is the hazard rate. Contrary to a classical auction wherein there is one product for sale and the price is ascending, auctions of energy projects are reverse auctions (bid as low as possible while still earning a profit) where the auctioneer is the buyer and bidders are the suppliers. A bidder $i$ offers an energy volume $Q_t$ and his optimal bid price $P^*$. He has the probability to win until the total volume put on the auction, expressed as $Q_a$, is sold. Therefore,

$$\sum_{i=1}^{n} Q_t^i \middle| P^{*i} \leq Q_a, \qquad \text{with } P^{*i} \text{ in ascending order} \qquad (12)$$

Hence, the auction can be considered as a Multiple Object Auction (Vijay Krishna, 2002) with identical objects (i.e. technologies), but with different sizes (offered volume $Q_t$). However, for simplicity we consider a single object auction. To determine the outcome of the bidding strategy we will follow the approach described by Vijay Krishna (2002). In a standard first price auction the goal is to bid as high as possible. The first-price auction description is adapted for reverse auctions. The immediate pay-off of the reverse auction is the difference between the optimal bid price $P^*$ of and the minimum established value of the object or the Marshallian price which we call $P_m$. The minimum price $P_m$ is defined as the price for which $NPV(P_t, \gamma)$ as formulated in equation (5) equals zero. For the immediate pay-off we then get,

$$\pi_i = \begin{cases} P^{*i} - P_m^i, & if\ P^{*i} < \ min_{i \neq j} P^{*j} \\ 0, & if\ P^{*i} > \ min_{i \neq j} P^{*j} \end{cases} \quad (13)$$

***Proposition 3****: In a classical auction framework, the bidding strategy for bidder* $i$ *can then be defined as (see* A.5 Outcome of bidding strategy*),*

$$P_a = \ P_m + \int_{P_m}^{\infty} 1 - \left[\frac{cdf(P^*)}{cdf(P_m)}\right]^N dP = \ P_m + \frac{1}{\lambda N} \quad (14)$$

Where N > 0 is the number of competitors and N+1 the number of total bidders. $\lambda$ is the hazard rate. For a given $\lambda$, $P^*_a$ tends to $P_m$ with increasing number of competitors N. In the limit of the hazard rate to infinity the value $P_a^*$ tends to $P_m$. We now have a lower boundary represented by $P_m$ and an upper boundary defined by $P_a^*$ , which is the maximum price that an investor may offer, i.e. the maximum mark-up that he hopes to receive given the uncertainty of winning. However, in this traditional framework of auction theory, the market uncertainty on the evolution of the value of the asset itself is ignored. Thus, in the following we consider the latter type of uncertainty in order to determine the optimal bid. With both types of uncertainty (exogenous evolution of natural gas prices and uncertainty of wining), the investor maximizes the new value of the opportunity to invest with respect to $P^{**}$

$$MaxE[H(P^{**}, N)] =$$
$$\left(\frac{1-cdf(P^{**})}{1-cdf(P)}\right)^N \left[\left(\left(\frac{P^{**}}{\delta}\left(1-e^{-\delta T}\right) + \frac{S-C_e}{r}\left(1-e^{-rT}\right) - \frac{c_t}{\gamma Q + r}\left(1-e^{-(\gamma Q + r)T}\right)\right) Q - K \times Q\right) \times \left(\frac{P}{P^{**}}\right)^\beta\right] + \left(1 - \left(\frac{1-cdf(P^{**})}{1-cdf(P)}\right)^N\right) \times 0, \quad (15)$$

Where $cdf(P^{**})$ is the cumulative distribution function of losing i.e. probability that the bid $P^{**}$ is smaller than the market clearing price, $P_t = P$ .

$$cdf = 1 - e^{-\lambda P^{**}}, \ Prob(P^{**} \leq P) \quad (16)$$

***Proposition 4****:* When natural gas price uncertainty is added to the classical auction context, the optimal price is given by:

$$P^{**} = -\frac{1}{2\,\mathrm{N}\lambda}\left(-\left(1-\beta-\mathrm{N}\lambda\frac{\left(\frac{S-C_e}{r}(1-e^{-rT})-\frac{c_t}{\gamma Q+r}(1-e^{-(\gamma Q+r)T})-K\right)\delta}{(1-e^{-\delta T})}\right)+\sqrt{\begin{array}{c}\left(1-\beta-\mathrm{N}\lambda\frac{\left(\frac{S-C_e}{r}(1-e^{-rT})-\frac{c_t}{\gamma Q+r}(1-e^{-(\gamma Q+r)T})-K\right)\delta}{(1-e^{-\delta T})}\right)^2 \\ -4\mathrm{N}\lambda\beta\frac{\left(\frac{S-C_e}{r}(1-e^{-rT})-\frac{c_t}{\gamma Q+r}(1-e^{-(\gamma Q+r)T})-K\right)\delta}{(1-e^{-\delta T})}\end{array}}\right) \qquad (17)$$

where $\lambda = \frac{pdf(P^{**})}{1-cdf(P^{**})}$ is the hazard rate of losing the auction.

***Proof*** *Appendix*

By taking the limits of $\lambda \geq 0$ we find that:

$$P_m \leq P^{**} \leq \min(P^*, P_a^*) \qquad (18)$$

The outcome of the bidding strategy under classical auctions as represented by equation (14) is the tradeoff between having the maximal possible gain and the chance of winning when there are N competitors. $P_a^*$ is the highest mark-up that an investor can ask. When the uncertainty on the evolution of natural gas prices is also taken into account, the investor is less willing to require this high return and proposes a lower price, $P^{**}$, for small values of the hazard rate of $\lambda$. The higher the competition, i.e. the higher the probability to lose and thus higher hazard rates, $P^*_a$ and $P^{**}$ tend to converge to the horizontal asymptote presented by the Marshallian price, $P_m$. This is further illustrated in section 3.4. Of course, an investor is free to choose to increase the probability of winning by taking more risks or take less risk but consequently decrease the probability of winning.

### 3.4 Numerical illustration

In order to study the properties of our previous Propositions with reference the French PPE we provide in the following subsubsection some numerical solutions.

#### 3.4.1 Data parameterization

To evaluate the landscape in which the biomethane sector has developed until now in France a few interviews with different stakeholders have been conducted (see appendix A.1: Interviews).[5] Likewise, most of our data for scenario analysis are based on estimations gathered from industry

5 To this purpose, a questionnaire was created with general questions concerning the organization's vision on the biomethane sector in France and their motivations to contribute to its development. More specific questions were aimed at challenges and opportunities and whether they were of a financial, technical or more social and political nature.

reports and interviews. With the model developed in section 0 we can perform a study of a benchmark case. As a benchmark we take the conditions for which it is optimal to invest today, given current market conditions in terms of the growth rate and volatility of the natural gas price. The market premium is set at a level for which an investor is indifferent between waiting and investing now. The price of natural gas for the benchmark case is the current price on the energy market, 7 € / MWh (TTF, April 4th 2020). The chosen capacity for the benchmark case is 200 $Nm^3/h$.[6] Data for CAPEX and OPEX are from actual but anonymous biomethane plants. Table 3 shows the data used for the benchmark cases.

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Installed capacity | Q | $Nm^3/h$ | 200 |
| Annual production | q | MWh | 16 872 |
| Natural gas price (TTF, 4/4/2020) | $P_t$ | € / MWh | 7.00 |
| - Annual growth rate [1)] | $\mu$ | % | 1,0 |
| - Annual volatility [1)] | $\sigma$ | % | 10 |
| Market premium (for 15 years) | $S_t$ | € / MWh | 79 |
| Unitary capital Expenses (CAPEX) | K | € / MWh | 326 |
| Operational Expenses (OPEX): | | | |
| - Electricity consumption | $C_e$ | € / MWh | 12,7 |
| - Other costs | $C_t$ | € / MWh | 46,2 |
| Discount rate | r | % | 3 |
| Technological learning rate (OPEX part) | $\gamma$ | - | 6E-7 |
| Period | T | years | 15 |

*Table 3 : Values for the benchmark study case. [1)] See A.2: Evolution gas price.*

In the following subsections we present the results for this benchmark case for different types of frameworks and uncertainties: deterministic evolution of gas prices, uncertainty in their evolution, competition and gas market uncertainty and competition without price uncertainty. For each case we present the bidding strategy when a fixed market premium is considered. Moreover, we make scenarios to test the impact of the PPE target and instruments (auctions) on bidding strategy.

### 3.4.2 Results

The graph in Figure 3 show the results.

6 Industry experts interviewed agree that the minimum size of a biomethane installation in order to be economically viable is approximately 100 Nm3/h under the current feed-in tariff energy policy. We have thus chosen a capacity of 200 Nm3/h for our benchmark case which represents the average capacity of biomethane installations in France. This is an important input for our analysis

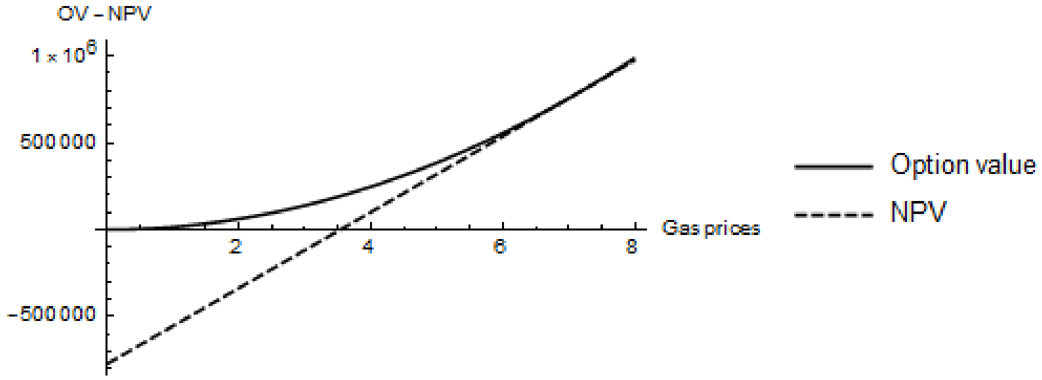


*Figure 3 : Option value curve F(P), and NPV as a function of the natural gas price: installed capacity is 200 $Nm^3/h$.*

The value of waiting is the difference between the option value and the curve NPV. The point where an investor is indifferent between investing and waiting is at a natural gas price of 7 €/MWh and thus defines the moment to invest. An overview of investment trigger prices for different project valuation methods is given in the following table:

*Table 4 : : Investment trigger prices for different project valuation methods.*

| General Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Installed capacity | K | $Nm^3/h$ | 200 |
| Annual production | Q | MWh | 16 872 |
| Market premium | $S_t$ | € / MWh | 79 |
| Project valuation Method | Symbol | Unit | Value |
| NPV = 0 $(\mu \neq 0, \sigma = 0, \gamma \neq 0)$ | | | |
| - Investment trigger | $P_m$ | € / MWh | 3.53 |
| - Total remuneration | $P_r$ | € / MWh | 82.54 |
| Real Options: F= V – I $(\mu \neq 0, \sigma \neq 0, \gamma \neq 0)$ | | | |
| - Investment trigger | $P^*$ | € / MWh | 7.075 |
| - Total remuneration | $P_r$ | € / MWh | 86.07 |
| Competition and market uncertainty: $(\mu \neq 0, \sigma \neq 0, \gamma \neq 0, \lambda \neq 0)$ | | | |
| Investment trigger | $P^{**}$ | € / MWh | 5.09 |
| Total remuneration | $P_r$ | € / MWh | 84.09 |
| Auctions without market uncertainty: $(\mu \neq 0, \sigma = 0, \gamma \neq 0, \lambda \neq 0)$ | | | |
| Investment trigger | $P_a$ | € / MWh | 7.53 |
| Total remuneration | $P_r$ | € / MWh | 86.53 |
| *Current feed-in tariff for reference* | *FIT* | *€ / MWh* | *105* |

A classical net present value approach including learning effects requires a natural gas price of 3,53 €/MWh for investment given a market premium of 79 €/MWh. Based on the real options approach an investor should invest when the gas price is 7,07 €/MWh.. The difference is explained by the fact that volatility is a measure for uncertainty which may delay the investment. Moreover, the expected time before investing is about 2.15 years. This implies that a significant level of market premium may accelerate the decision to invest in the short term.

$$E[t^*] = \frac{1}{\mu - \frac{1}{2} * \sigma^2} \mathrm{Ln}\left[ \frac{ \frac{\beta}{\beta-1} * \frac{ \frac{c_e - s}{r} * \left(1 - e^{-rT}\right) + \frac{c\left(1 - e^{-T(r+q\gamma)}\right)}{(r+q\gamma)} + k }{ \left(1 - e^{-T(r-\mu)}\right) } * (r-\mu) }{P} \right] \tag{19}$$

The real options results in terms of total immediate remuneration is 86 €/MWh, which is lower but in the range of current feed-in tariff conditions of 105 euro for 200 $Nm^3$/h installed capacity. This is explained by the fact that the future growth of the natural gas price and technological learning is valued. However, total remuneration might be higher than the current feed-in-tariff since the market premium is not capped in our model.

The optimal gas price for investment is established in the context of no competition. However, competition in auctions puts pressure on prices. We therefore need to evaluate the bidding strategy and see how this compares to the optimal price. The bidding strategy is a function of the hazard rate λ and N. This is represented in figures 7 and 8 below.

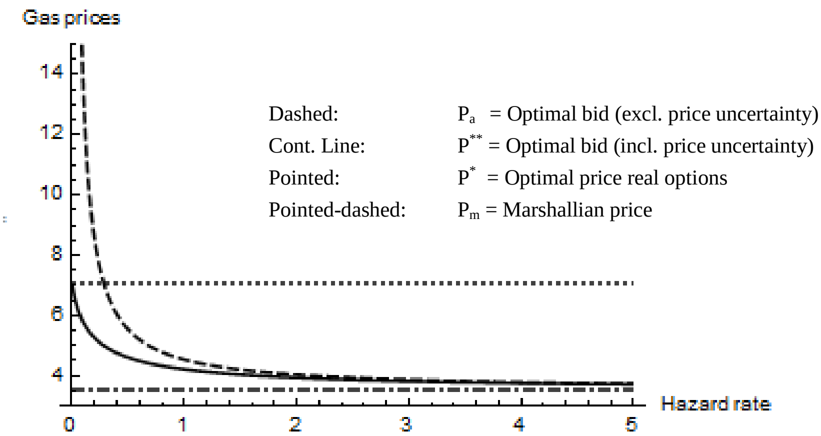


*Figure 7: Bid prices as a function of λ for the benchmark case*

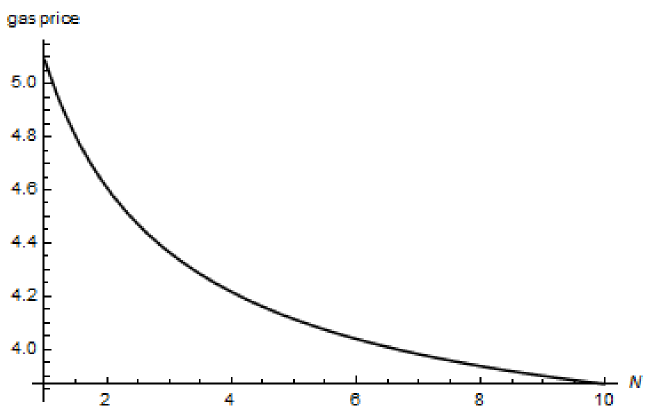


*Figure 8: Bid prices as a function of N-number of competitors for the benchmark case*

The higher the hazard rate the greater the probability that a competitor is willing to invest at a lower natural gas price. As can be intuitively expected the bidding strategy is to decide to invest at a lower natural gas price with increasing hazard rate (but given market premium). For the benchmark case it is possible to bid since the bidding strategy is equal or smaller than the current gas price of 7 €/MWh. When the lower boundary increases above the current gas price then there are no viable options to bid. We illustrate that the fixed market premium, combined with the natural gas price, is of comparable order of magnitude as the current feed-in tariff levels. This allows for the actors to participate in auctions if they would occur today. In the next section market premium levels are set to a level derived from the objectives in the PPE.

### 3.4.3 Scenarios

For the different scenarios the market premiums are based on the ceiling prices as mentioned in the PPE from which the current natural gas price is subtracted. These resulting premiums are defined as the maximum possible premiums in this report. Since the exact details of auctions are not known yet this is an assumption that might be different from what the French government intends to put in place. However, it allows for a starting point to evaluate the proposed energy policy and associated trigger prices for investment. The final remuneration for an investor is the natural gas price for a given moment in time to which the premium is added. Table 5 shows the results of the different numerical simulations

*Table 5 : Results of different auction scenario's. NPV is calculated for a gas price of 7 euro / MWh. The investment trigger is based on the real options analysis.*
*r = 3%, growth rate = 1%, volatility = 10%. (*reference of value of waiting = NPV )*

| *Scenario of costs trajectory* | Market premium *€ / MWh* | Installed Capacity *Nm3/h* | NPV (P = 7€ / MWh) *Meuro* | Option Value *Meuro* | Value of waiting* *%* | Invest trigger *€ / MWh* |
|---|---|---|---|---|---|---|
| 2023 Ambitious | 60 | 200 | -3.11 | 4.645 | > 100% | 42.49 |
| | | 300 | -3.72 | 6.096 | | 36.01 |
| 2023 Moderate | 76 | 200 | 0.14 | 1.384 | > 100% | 12.66 |
| | | 300 | 1.32 | 1.046 | | 6.18 |
| 2028 Ambitious | 53 | 200 | -4.54 | 6.072 | > 100% | 55.54 |
| | | 300 | -5.93 | 8.305 | | 49.05 |
| 2028 Moderate | 73 | 200 | -0.4 | 1.996 | > 100% | 18.26 |
| | | 300 | 0.37 | 1.993 | | 11.77 |

Only the moderate scenario for 2023 yields economically viable results. Either invest now based on a classical NPV analysis, or wait until the natural gas price reaches 12.66 €/MWh. The project values of big installations are greater than those of small installations which is expected conform to scale effects. The only project worth investing in now based on the criteria that the option value equals the project value is an installed capacity of 300 $Nm^3/h$ with a premium of 76 €/MWh. In addition, the moderate scenario 2028 yields a positive NPV for bigger installations. All other scenarios either have a negative NPV or investment triggers for the natural gas price which are unlikely to be reached within the next ten years.

However, in the context of auctions it is not necessarily the optimal price that is the winning value. Recall equation (14) which defines the bidding strategy for the optimal NG price as:

$$P_a = P_m + \frac{1}{\lambda N} \text{ (ref. 14)}$$

In the limit of the hazard rate to infinity the value $P^*_a$ and $P^{**}$ tend to $P_m$. Table 6 presents the optimal price and decision to bid for different scenarios.

*Table 6 : Bidding strategies and final decision (λ = 0.25, N=1)*

| *Scenario of costs trajectory* | Premium request | Capacity *Nm3/h* | Auctions (1) $P_a$ *€ / MWh* | Auctions (2) $P^{**}$ *€ / MWh* | Decision - |
|---|---|---|---|---|---|
| 2023 Ambitious | 60 | 200 | 25.24 | 24.25 | no bid |
| | | 300 | 22.00 | 20.89 | no bid |
| 2023 Moderate | 76 | 200 | 10.33 | 8.38 | no bid |
| | | 300 | 7.09 | 4.43 | Bid $P^{**} < P_t$ |
| 2028 Ambitious | 53 | 200 | 31.77 | 30.95 | no bid |
| | | 300 | 28.52 | 27.63 | no bid |
| 2028 Moderate | 73 | 200 | 13.3 | 11.48 | no bid |
| | | 300 | 9.88 | 7.87 | no bid |

Overall, the market premiums applied and derived from the PPE objectives are challenging, especially for the ambitious cost trajectory scenarios. As can be intuitively expected it is clear that bigger installed capacities are economically the most attractive. But for only case it would be interesting to bid now. None of the ambitious scenarios seems feasible by 2023, given the current price of 7 €/MWh. However, it is fair to assume that the scenario "2023 ambitious cost trajectory" and capacities 200 and 300 can be achievable within the next ten years. This observation is in line with interviews. The goal of auctions is to create competition and should lead to decreased demand for a premium as we have seen with the auctions for wind farms. However, the results in Table 6 leave little space for lower premium requests. Hence, they have not been simulated with the model.

### 3.4.4 Sensitivity analysis

Parameters for the sensitivity analysis are the discount rate, growth rate, volatility, learning rate, market premium and electricity costs to study the impact on the investment trigger P*. The benchmark case from section 3.4.1 is used as reference. The growth rate and the volatility are exogenous parameters that depend on the market and that impacts the investment trigger P*. The discount rate is partly exogenous and partly endogenous. Exogenous, since cost of capital of debt depends on the banks and their risk evaluation of biomethane projects. Endogenous, since it depends on the expected rate of return of investors coupled to technical risks. The learning rate can only partially be controlled by the biomethane sector, since the room for innovation depends also on regulations.

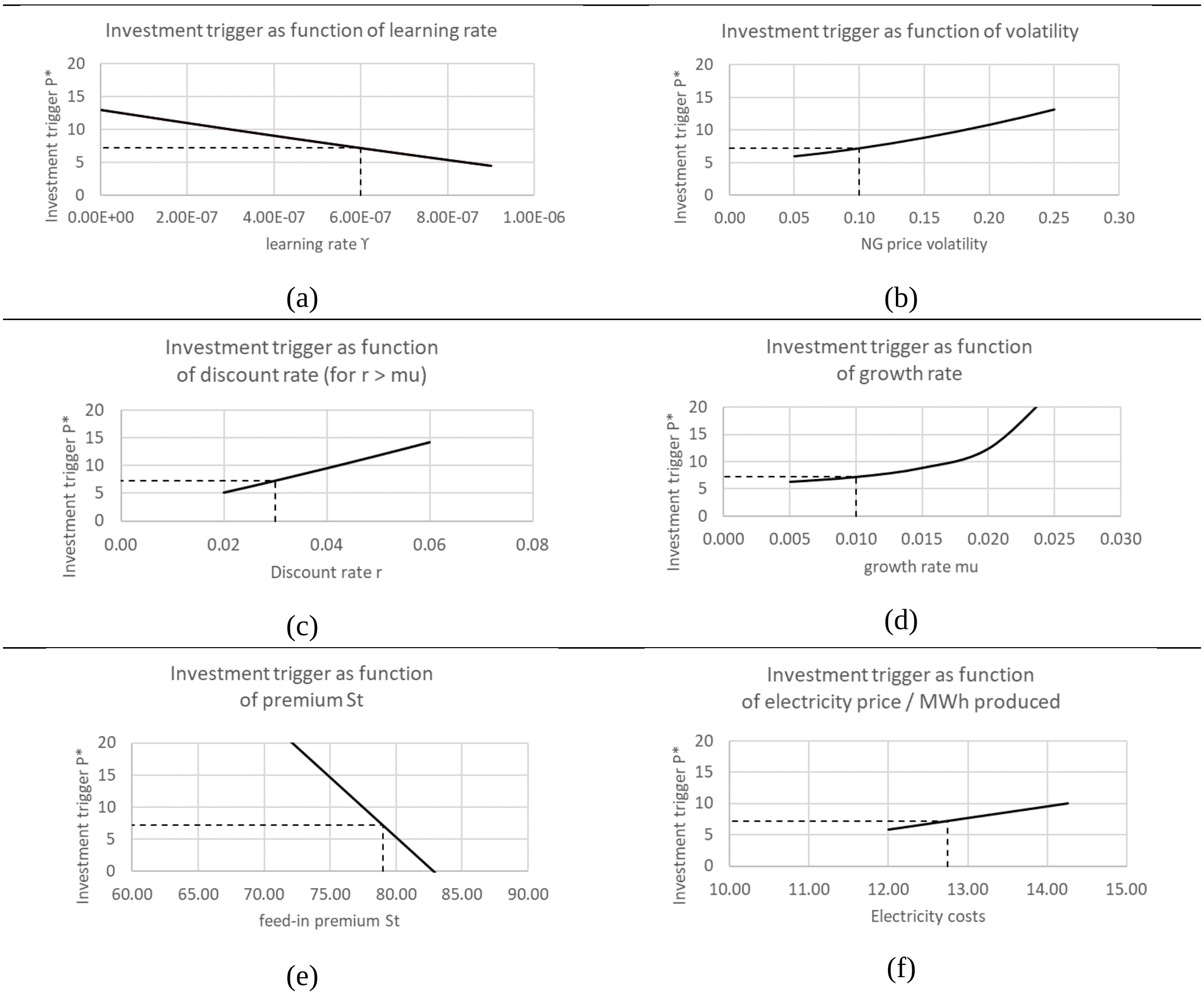


*Figure 4 : Sensitivity analysis of different parameters for the benchmark case of 200 Nm$^3$/h.*

A change in the market premium has the biggest impact on the investment trigger. This is not surprising since the market premium is a significant part of the remuneration on top of the market price of natural gas. Next to the market premium the discount rate has a significant impact on the investment trigger. By changing the discount rate from 5% to 6% the investment trigger doubles. This stresses the importance that the ceiling price needs to be set with great attention and rigor. Even a ceiling price that is slightly to low can have major consequences for investment decisions. In fact, compared to the market premium all other parameters seem almost not important. Up until a growth rate of 1.5% it's impact on the investment triggers is important but not extreme. A higher growth rate pushes up the investment trigger since future expected returns are higher, making it worthwhile to wait. The volatility of the gas price shows a similar impact as the growth rate. A higher volatility however represents either higher or lower returns which is a reflection of the uncertainty of future revenues. As a result, the investment trigger increases, as real options theory tells us.

Out of the six parameters analyzed, the learning rate is the only parameter that is only partially in control of the biomethane sector. If the trajectory as presented by the PPE is not achieved the consequences for investment decisions are considerable. Last but not least, the evolution of the electricity price is not to be ignored either. An increase of the current electricity price with 25% doubles the investment trigger. An important conclusion from the sensitivity analysis is that many parameters that significantly impact investment are exogenous to the sector itself.

## 4. Policy implications and conclusion

We examine the implementation of the auction mechanism as a policy to allocate subsidies to biomethane projects and criticize whether this policy is suitable to reach the target of 10% of the gas consumption by 2030. To this end a real options approach is applied combined with technological learning and auction theory. The presented evaluation concludes that the ambitious cost trajectory will not lead economically viable projects by 2023. This would mean that the French government will auction less than 350 GWh per year. In its current form, the proposed energy policy can lead to a stagnation of the development of biomethane projects or worse, bring the sector to a halt. Either, there are too few (large scale) installations offered during the auctions that are economically viable given the ambitious cost trajectory. This would hamper competition which is the intrinsic objective of auctions. Or, the ambitious cost trajectory is hardly met, which means that the French Government will reduce the energy volume for the auction.

Either way, results from the real option analysis conducted in this paper indicate that the target of 10% will be hard to achieve by 2030. What the model result reveals is that even with a high number of participants to the auction, the proposed ambitious ceiling prices will be difficult to obtain. More particularly, two effects can be noticed: on the one hand, the market uncertainty related to the evolution of natural gas prices may increase the trigger price necessary to motivate the investment and on the other hand, the increasing number of competitors may reduce the bid prices. Since the complexity and risk of losing might refrain farmers to participate, it is likely that the number of participants is not satisfactory, reducing competition and leading to higher prices. If this happens, it may lead to exclusion from auctions or even cancellation of the auction followed by a new auction with higher ceiling prices but lower volumes (i.e. < 350 GWh). This adds to the risk since the process has to start over for which new costs have to be incurred by the participants. Overall, the proposed policy does not create a fruitful environment for the development of biomethane and its opportunities related to systems integration as mentioned in section 2. We believe that the proposed auction mechanism only valorizes biomethane as a private good and not the public part.

The microeconomic analysis in section 3 is based on different assumptions. First of all, the model has only integrated operational learning. Although operational costs are equally or even more important than capital costs, future research should look into integrating learning related to capital expenses. Second, there is a fixed market premium that is added to the price of natural gas. This premium is thus not capped and moves with the evolution of the gas price. Future research should focus on a model in which the market premium is capped during the funding period. However, a capped premium limits revenue compared to a fixed premium which will lead to even less favorable conditions for investment than presented in this paper. With regard to the uncertainty of winning two aspects are worth investigating further in future research. It is assumed that the bid prices are exponentially distributed. This is fair to assume in so far that according to the probability density function there is a bigger chance to have low bids than to have higher bids.

Regarding the policy and the promotion of biomethane there are options as a way forward. The most obvious is to increase the ceiling price, albeit equivalent auction volume, as presented in the PPE. They should be reevaluated and an objective should be set that is challenging but feasible. Second, as with the European Directive for electricity (1997) and gas (1998) to create competition, auctions could be implemented in phases with decreasing eligibility. This might be foreseen, but to date these details are not known which adds to the uncertain environment. A radical implementation of auctions for all sizes risks stagnating the development of the biogas sector.

Another approach could be to take a more holistic angle, especially in the wake of post-lockdown and economic relaunch situation. Although very often price is the only criteria in auctions the EU guideline 2014/25/EU allows other award criteria. The price criteria only recognize biomethane as a private good. Other criteria could thus be implemented that recognize the system integration aspect of biomethane and give flexibility to investors to look for diversification. These improvements are worth considering to continue fostering a friendly climate for biomethane investments.

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# Appendix

## A.1: Interviews

**List of organizations and people interviewed**

| Organization | Setting | Date | Duration |
|---|---|---|---|
| Waste Water Treatment Plant | Face to face | 13/2/2019 | 45 min. |
| Energy provider and distribution system operator | Face to face | 19/3/2019 | 45 min. |
| Biogas manufacturer | Telephone | 3/4/2019 | 1h, 15min |
| ADEME: Agency for environment and energy management | Face to face | 8/4/2019 | 35 min. |
| AURA-EE: Regional agency for environment and energy | Telephone | 9/4/2019 | 30 min. |
| FNSEA: National Federation of Agricultural Holders' Unions | Telephone | 16/7/2019 | 40 min. |

## A.2: Evolution gas price

<u>Gas prices and premium</u>

Sources:

- From 1984: (*BP - Statistical Review Data*, n.d.)
- From 1987: (BP, 2018)

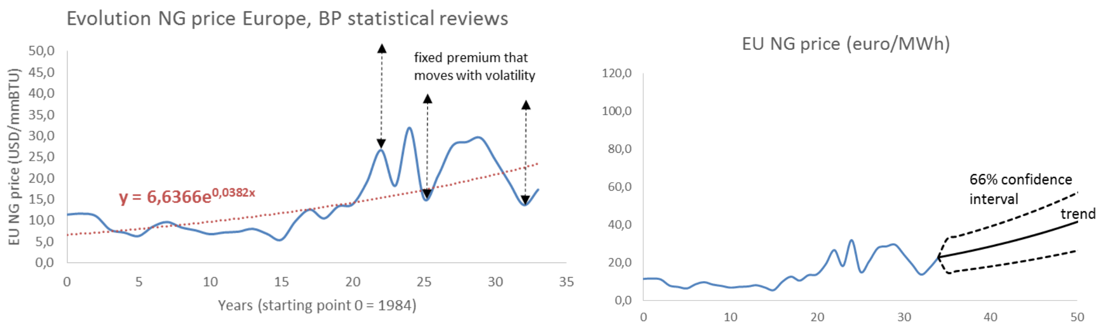
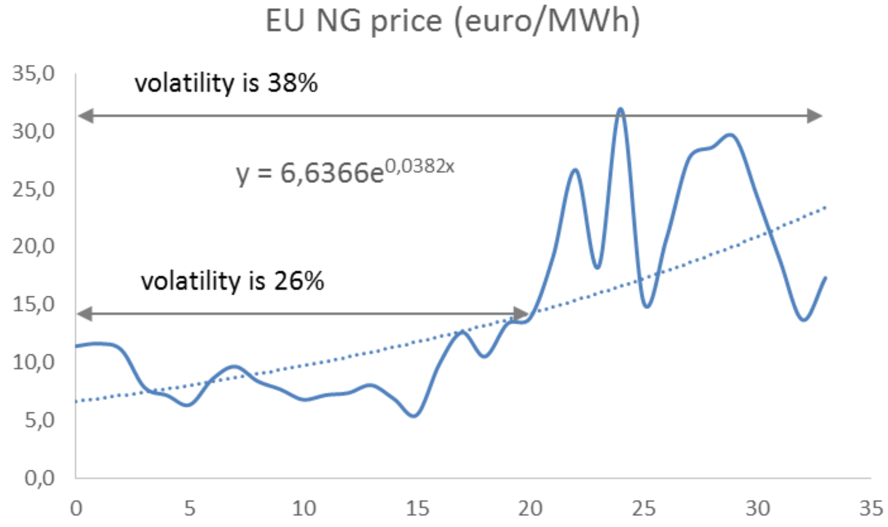


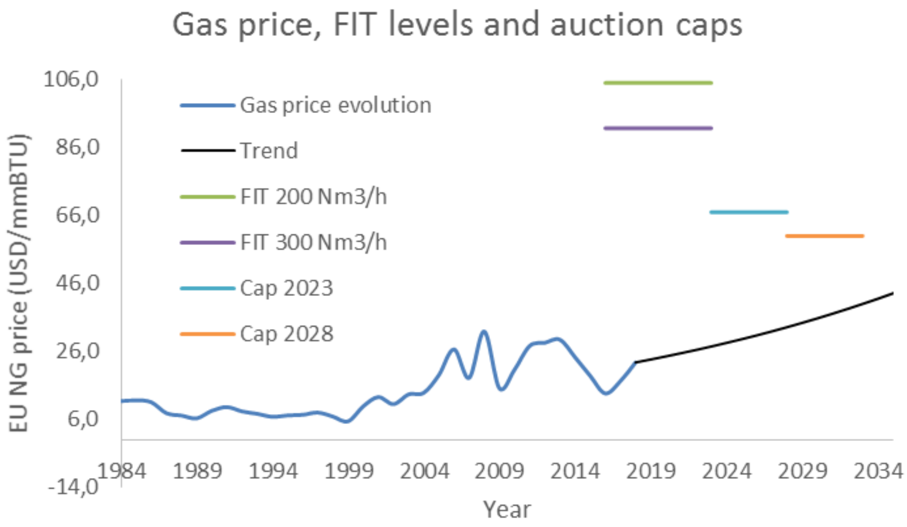

*Figure 5 : Evolution of natural gas prices in Europe since 1984 in euro/MWh. Illustration of market premium. Trend with 66% confidence interval*

Based on the data from BP's statistical review reports the annual growth rate and volatility of the natural gas price is determined. Since conversion rates between dollars and euros are assumed constants the growth rate μ and volatility σ are identical:

- The growth rate follows from the trend line shown in Figure 5: μ = 3,8%
- The volatility σ is calculated as follows: $\sigma = \sqrt{\frac{\sum_i^N (\bar{x}-x_i)^2}{N-1}}$ = 38%

This volatility is consistent with those found in reports like (ACER / CREER, 2018, page 29).

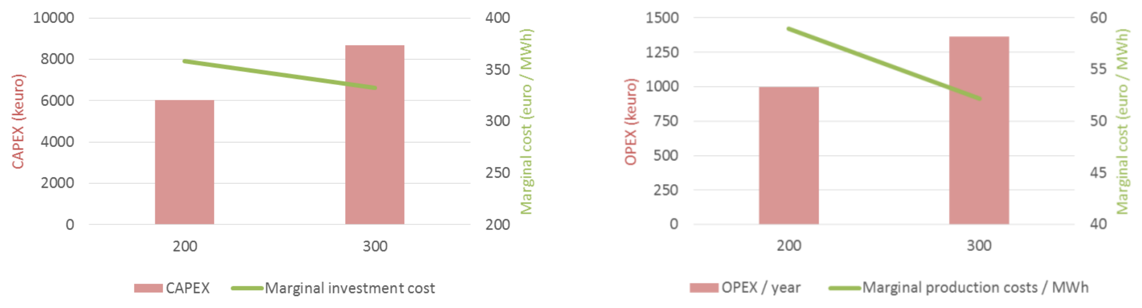



### A3: Costs and learning

We computed actual CAPEX and OPEX value for two anonymous biomethane injection projects. The following figure shows the absolute CAPEX and OPEX values as well as the marginal costs. There is a clear scale effect of lower marginal costs with increasing production capacity. From a pure investment strategy point of view without a feed-in tariff it is more interesting to invest in a big scale biomethane installation than a small one.

| |
|---|
| Installed capacity of 200 $Nm^3/h$: Annual production is 16 872 MWh : LCOE = 92 euro / MWh |
| Installed capacity of 300 $Nm^3/h$: Annual production is 26 127 MWh: LCOE = 83 euro / MWh |




*(a)* *(b)*

*Figure 6 : CAPEX (a), OPEX (b) and marginal costs of two anonymous biomethane installations*

The LCOE is the unit present value cost of energy. It is the discounted total cost (CAPEX and OPEX) over the project lifetime divided by the discounted energy production over the project lifetime. The LCOE's for the two projects are 92 and 83 € / MWh, similar to those calculated by ENEA who found 94 and 85 € / MWh for respectively 200 and 300 Nm3/h.

### A.4: Optimal solution

Until the adoption time the option to switch has no return, so the only return from having the option is the expected value $E[dF(P_t)]$ which according to Bellman principle, must equate the expected return on exercising the option. For a detailed description see (Dixit, Pindyck, 1994).

$$rF(P_t)dt = E[dF(P_t)] \quad \text{(A.1)}$$

With $P_t$ being the price of natural gas that follows a Geometric Brownian Motion:

$$dP_t = \mu P_t dt + \sigma P_t dz \quad \text{(A.2)}$$

Replacing A.2 in equation A.1 and applying Ito's Lemma for the right hand side we can write:

$$rF(P_t) = \frac{E[dF(P_t)]}{dt} = \mu P_t F'(P_t) + \frac{1}{2}\sigma^2 (P_t)^2 F''(P_t) \qquad \text{(A.3)}$$

The following differential equation, which is satisfied by the option value, is derived from Bellman principle:

$$\mu P_t F'(P_t) + \frac{1}{2}\sigma^2 (P_t)^2 F''(P_t) - rF(P_t) = 0 \qquad \text{(A.4)}$$

Equation A.4 has the general associated solution:

$$F(P_t) = A(P_t)^{\beta} + B(P_t)^{\varepsilon} \qquad \text{(A.5)}$$

Where $\beta > 1$ and $\varepsilon < 0$ are solutions of the quadratic equation:

$$\frac{1}{2}\sigma^2 \beta(\beta - 1) + \mu\beta - r = 0 \qquad \text{(A.6)}$$

$$\beta = \frac{\left[-\left(\mu - \frac{1}{2}\sigma^2\right) + \sqrt{\left(\mu - \frac{1}{2}\sigma^2\right)^2 + 2\sigma^2 r}\right]}{\sigma^2} > 1 \qquad \text{(A.7)}$$

The second part (A.5) goes to infinity for very small P, since $\beta_2 < 0$. However, when P is very small it is unlikely that it rises to the optimal price and thus the option value should be negligible (Dixit, Pindyck, 1994). We therefor ignore the second part. This leaves us with only the first part of the right hand side of (A.5). *Proposition 1* in section **Erreur ! Source du renvoi introuvable.** can then be written as (with $\delta = r - \mu$):

$$V(P,\gamma) = \begin{cases} AP_t^{\beta} & P_t < P^* \\ \left(\frac{P_t}{\delta}\left(1 - e^{-\delta T}\right) + \frac{S-C_e}{r}\left(1 - e^{-rT}\right) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right)\right) Q - K \times Q, & P_t \geq P^* \end{cases}$$

(A.8)= (7)

By applying value matching and smooth pasting we can find A and the optimal price $P^*$. Value matching gives:

$$AP^{*\beta} = \left(\frac{P^*}{\delta}\left(1 - e^{-\delta T}\right) + \frac{S-C_e}{r}\left(1 - e^{-rT}\right) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right)\right) Q - K \times Q \qquad \text{(A.9)}$$

And smooth pasting gives:

$$\beta A P^{*\beta - 1} = Q\left(1 - e^{-\delta T}\right)\frac{1}{\delta} \qquad \text{(A.10)}$$

$$A = \frac{Q\left(1 - e^{-\delta T}\right)}{\delta \beta} P^{*1-\beta} \qquad \text{(A.11)}$$

Putting (A.11) in (A.9) and solving for $P_t$ gives:

$$P^* = \frac{\beta}{\beta - 1}\left(\frac{C}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) + \frac{C_e - S}{r}\left(1 - e^{-rT}\right) + K\right)(\delta) \qquad \text{(A.12) = (8)}$$

Replacing $P_t$ in (A.11) with (A.12) and putting (A.12) in (A.5) we can write for the option value:

$$F = \frac{Q\left(1 - e^{-\delta T}\right)}{\delta \beta}\left(\frac{\beta}{\beta - 1}\left(\frac{C}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) + \frac{C_e - S}{r}\left(1 - e^{-rT}\right) + K\right)(\delta)\right)^{1-\beta} P_t^{\beta} \qquad \text{(A.13) = (9)}$$

The time of waiting for investment is derived as follows.

### A.5 Outcome of bidding strategy

Two methods have been evaluated.

*Method 1:*

$$MaxE[H(P^{**},\lambda,N)] = \left(\frac{1-F(P^{**})}{1-F(P)}\right)^N \left[\left(\left(\frac{P^{**}}{\delta}\left(1 - e^{-\delta T}\right) + \frac{S-C_e}{r}\left(1 - e^{-rT}\right) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right)\right) Q - K \times Q\right) \times \left(\frac{P}{P^{**}}\right)^{\beta}\right] + \left(1 - \left(\frac{1-F(P^{**})}{1-F(P)}\right)^N\right) \times 0, \quad (12)$$

Where $F(P^{**})$ is the cumulative distribution probability of losing i.e. probability that the bid $P^{**}$ is greater than the market clearing price.

$$\left(\frac{1-F(P^{**})}{1-F(P)}\right)^N \times \frac{\partial V(P^{**})}{\partial P^{**}} - \frac{N f(P^{**})\left(1 - F(P^{**})\right)^{N-1}}{\left(1 - F(P)\right)^N}\left[\left(\left(\frac{P^{**}}{\delta}\left(1 - e^{-\delta T}\right) + \frac{S - C_e}{r}\left(1 - e^{-rT}\right) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right)\right) Q - K \times Q\right) \times \left(\frac{P}{P^{**}}\right)^{\beta}\right] = 0$$

Dividing by $\left(\frac{1-F(P)}{1-F(P^{**})}\right)^N$, we obtain:

$$\left(\frac{Q}{\delta}\left(1-e^{-\delta T}\right)\right)\times\left(\frac{P}{P^{**}}\right)^{\beta}-\frac{\beta}{P^{**}}\left(\frac{P}{P^{**}}\right)^{\beta}\left(\left(\frac{P^{**}}{\delta}\left(1-e^{-\delta T}\right)+\frac{S-C_e}{r}\left(1-e^{-rT}\right)-\frac{c_t}{\gamma Q+r}\left(1-e^{-(\gamma Q+r)T}\right)\right)Q-K\times Q\right)-\frac{Nf(P^{**})}{1-F(P^{**})}\left[\left(\left(\frac{P^{**}}{\delta}\left(1-e^{-\delta T}\right)+\frac{S-C_e}{r}\left(1-e^{-rT}\right)-\frac{c_t}{\gamma Q+r}\left(1-e^{-(\gamma Q+r)T}\right)\right)Q-K\times Q\right)\times\left(\frac{P}{P^{**}}\right)^{\beta}\right]=0$$

Simplifying and rearranging, the first order condition can be rewritten as:

$$\frac{P^{**}Q}{\delta}\left(1-e^{-\delta T}\right)-\beta\left(\left(\frac{P^{**}}{\delta}\left(1-e^{-\delta T}\right)+\frac{S-C_e}{r}\left(1-e^{-rT}\right)-\frac{c_t}{\gamma Q+r}\left(1-e^{-(\gamma Q+r)T}\right)\right)Q-K\times Q\right)-\frac{P^{**}Nf(P^{**})}{1-F(P^{**})}\left[\left(\left(\frac{P^{**}}{\delta}\left(1-e^{-\delta T}\right)+\frac{S-C_e}{r}\left(1-e^{-rT}\right)-\frac{c_t}{\gamma Q+r}\left(1-e^{-(\gamma Q+r)T}\right)\right)Q-K\times Q\right)\right]=0$$

We denote with $\Lambda=\frac{Nf(P^{**})}{1-F(P^{**})}$ the hazard rate and considering an exponential distribution function we have:

$$CDF=1-e^{-\lambda P^{**}},\ \ Prob(P^{**}\geq P_t) \qquad \Lambda=\frac{Nf(P^{**})}{1-F(P^{**})}=\ \mathrm{N}\lambda$$

$$\frac{P^{**}Q}{\delta}\left(1-e^{-\delta T}\right)-\beta\left(\left(\frac{P^{**}}{\delta}\left(1-e^{-\delta T}\right)+\frac{S-C_e}{r}\left(1-e^{-rT}\right)-\frac{c_t}{\gamma Q+r}\left(1-e^{-(\gamma Q+r)T}\right)\right)Q-K\times Q\right)-\Lambda P^{**}\left[\left(\left(\frac{P^{**}}{\delta}\left(1-e^{-\delta T}\right)+\frac{S-C_e}{r}\left(1-e^{-rT}\right)-\frac{c_t}{\gamma Q+r}\left(1-e^{-(\gamma Q+r)T}\right)\right)Q-K\times Q\right)\right]=0$$

$$P^{**} = \frac{(\beta + \Lambda P^{**})\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - \beta - \Lambda P^{**})(1 - e^{-\delta T})}$$

With an exponential distribution function we have:

$$CDF = 1 - e^{-\lambda P^{**}},\ \ Prob(P^{**} \geq P_t) \qquad (13)$$

$$P^{**} = \frac{(\beta + \mathrm{N}\lambda P^{**})\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - \beta - \mathrm{N}\lambda P^{**})(1 - e^{-\delta T})}$$

Thus, the optimal threshold under competition can be obtained as the positive root of the following equation:

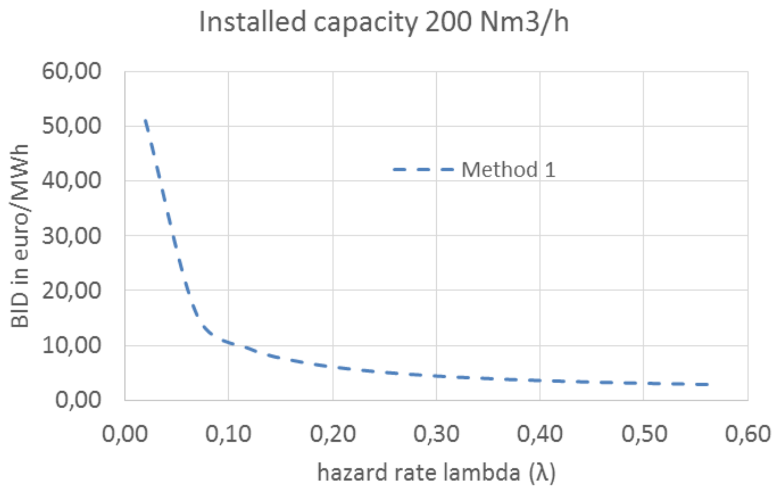
$$\begin{aligned} P^{**}(1-\beta) - \mathrm{N}\lambda P^{**2} &= \beta \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})} \\ &+ \mathrm{N}\lambda P^{**} \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})} \end{aligned}$$

$$\begin{aligned} -\mathrm{N}\lambda P^{**2} + \left(1 - \beta - \mathrm{N}\lambda \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})}\right) P^{**} \\ - \beta \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})} = 0 \end{aligned}$$

$$\begin{aligned} \Delta = \left(1 - \beta - \mathrm{N}\lambda \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})}\right)^2 \\ - 4\mathrm{N}\lambda\beta \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})} \end{aligned}$$

$$\begin{aligned} P^{**} = -\frac{1}{2\,N\lambda}\Bigg( -\left(1 - \beta - N\lambda \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})}\right) \\ + \sqrt{\left(1 - \beta - N\lambda \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})}\right)^2 - 4N\lambda\beta \frac{\left(\frac{S - C_e}{r}(1 - e^{-rT}) - \frac{c_t}{\gamma Q + r}\left(1 - e^{-(\gamma Q + r)T}\right) - K\right)\delta}{(1 - e^{-\delta T})}}\Bigg) \end{aligned}$$

The graph below shows the outcome of the bidding strategy for different hazard rates λ:




*Method 2:*

This method is derived from the approach described in the book *Auction Theory* (Vijay Krishna, 2002). In a standard first price auction (bid as high as possible) the payoff is given by:

$$\pi_i = \begin{cases} v_i - \varepsilon_i, & if\ \varepsilon_i > min_{i \neq j}\ \varepsilon_j \\ 0, & if\ \varepsilon_i < min_{i \neq j}\ \varepsilon_j \end{cases}$$

Given the established value $v$ of the object, the bidding strategy $\varepsilon$. The first-price auction description is adapted for reverse auctions. The minimum value $v$ of the object $v$ is replaced with $P_m^i$ and $\varepsilon$ with $P^{*i}$. The immediate pay-off of the reverse auction is the difference between the optimal bid price $P^*$ of and the minimum established value of the object which we call $P_m$We then get:

$$\pi_i = \begin{cases} P^{*i} - P_m^i, & if\ P^{*i} < min_{i \neq j}\ P^{*j} \\ 0, & if\ P^{*i} > min_{i \neq j}\ P^{*j} \end{cases}$$

The bidding strategy in the case of biogas reverse auction is:

$$P_a^* = P_m + \int_{P_m}^{\infty} \frac{1-CDF(p)}{1-CDF(P_m)} dp = P_m + \frac{1}{\lambda} \text{ (16)}$$

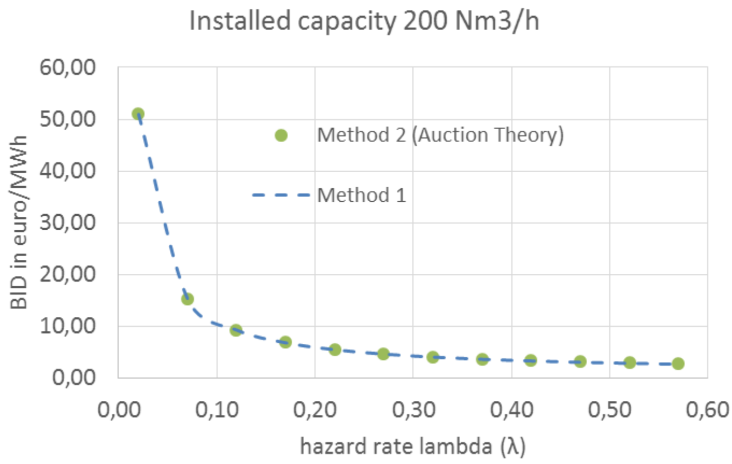
Using insights from auctions theory, the equivalent optimal price under price uncertainty and market competition can be obtained as follows, where the first term inside the integral represents the uncertainty factor from the GBM of natural gas prices.

$$P^{**} = P_m + \int_{P_m}^{\infty} \left(\frac{P_m}{p}\right)^{\beta} \left(\frac{(e^{-\lambda * p})}{(e^{-\lambda * P_m)})}\right)^N dp$$

Setting $\beta = 0, i.e. r = 0$ we obtain the traditional optimal price within an auction framework:

$$P_a^* = P_m + \int_{P_m}^{\infty} \left(\frac{(e^{-\lambda * p})}{(e^{-\lambda * P_m)})}\right)^N dp$$

Thus, we find that method 1 equals method 2 when $\beta = 0$



Installed capacity 200 Nm3/h
60,00
50,00
40,00
30,00
20,00
10,00
0,00
BID in euro/MWh
Method 2 (Auction Theory)
Method 1
0,00
0,10
0,20
0,30
0,40
0,50
0,60
hazard rate lambda (λ)