The Value of Flexible Biogas Plant Operation: A Real Options Perspective

Gordon Briest [a,*], Lars-Peter Lauven [b], Stefan Kupfer [a], Elmar Lukas [a]

[a] Faculty of Economics and Management, Otto-von-Guericke University Magdeburg, Germany

[b] Department of Energy Management and Power System Operation, University of Kassel, Germany

Abstract:

The increasing share of intermittent renewable power generation leads to an increased demand for flexibility to balance power supply and demand. Flexible biogas plants, which can actively be committed to supply power in a time interval, can supply some of the required flexibility subject to sufficient biogas storage capacity and other technical restrictions. To reflect this, an optimization model with technical constraints is used to derive time series of maximum revenues that the biogas plant can exploit in a flexible operation. These time series are then used to determine and parametrize the stochastic evolution of the state variable for a real options model to investigate if and when it would be beneficial for plant operators to switch from constant to flexible operation. Further, the proposed real options model is used to study the special situation of biogas plants in Germany.

Keywords: Finite Technology Life, Operation Type Switching, Subsidy Policies, Biogas Case Study

* Corresponding author, Faculty of Economics and Management, Chair in Financial Management and Innovation Finance, Otto-von-Guericke-University Magdeburg, Universitätsplatz 2, D-39106 Magdeburg, Tel: +49 (0) 391 67 - 58113; Fax: +49 (0) 391 67 - 180 07, e-mail address: gordon.briest@ovgu.de

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The increasing share of intermittent renewable power generation leads to an increased demand for flexibility to balance power supply and demand. Flexible biogas plants, which can actively be committed to supply power in a time interval, can supply some of the required flexibility subject to sufficient biogas storage capacity and other technical restrictions. To reflect this, an optimization model with technical constraints is used to derive time series of maximum revenues that the biogas plant can exploit in a flexible operation. These time series are then used to determine and parametrize the stochastic evolution of the state variable for a real options model to investigate if and when it would be beneficial for plant operators to switch from constant to flexible operation. Further, the proposed real options model is used to study the special situation of biogas plants in Germany.

1. Introduction

In Germany, the increasing share of intermittent renewable power generation leads to increased requirements for flexibility to balance power supply and demand to address concerns with regard to the stability of the German electricity system. Such flexibility is required, as supply and demand of power must be balanced at all times (Papaefthymiou & Dragoon, 2016). Flexible biogas plants, which can actively be committed to supply power in a time interval, are suitable to supply some of the required flexibility subject to sufficient biogas storage capacity and other technical restrictions (Hochloff & Braun, 2014).

The adaptation from constant to flexible operation results in investment-related (CAPEX) and operation-related (OPEX) expenditures (Hochloff & Braun, 2014). While previous studies from several countries have shown that the additional revenues from flexible operation due to higher market prices is usually insufficient to earn these costs, the case for switching to flexible operation is different in Germany. The country's laws governing subsidies for renewable power generation include subsidies and premiums for direct marketing and flexibility, which offer additional benefits to abandon constant operation and the associated guaranteed feed-in tariffs in favor of flexible operation (Pablo-Romero et al., 2017). However, many biogas plants were put into operation before 2014, and hence enjoy a guaranteed profit for their electricity production from the German renewable support scheme (RSS), EEG, until around 2030 (Lauer et al., 2020). While decision support considering uncertain revenues has already been investigated using optimization models (e.g. Fichtner & Meyr (2019)), we demonstrate that combining an operational optimization model with a real options model not only supports the findings of previous studies, but also gives new insights in general and in particular for the German case when it comes to the valuation of the flexible operation of biogas plants.

2. Literature Review

In the following subsections, we first review literature on the role of biogas plants in the German market for flexibility in the power sector, before moving on to show the potential role of real option analysis to support flexibilization decisions. We emphasize the role of the German government subsidy regime for biogas and other renewable energy, as is has been found to have a major impact on such decisions.

2.1 Flexibility Marketing in Power Markets

Flexibility to balance the supply and demand of power is located in several parts of the power system. While some flexibility exists in the operation of the power grid itself, the three most significant groups of flexibility options (FOs) are flexible power generators, flexible power consumers and storage systems. As the value of flexibility rises with the more challenging balancing of power supply and demand, new business models and operational strategies can be derived for each of these groups (Helms et al., 2016). While flexible producers can exert market power by acting in both the day-ahead and intraday markets for power (Rintamäki et al., n.d.), the economics of operating biogas plants flexibly are often not by themselves sufficiently attractive to motivate operators to invest in flexibilization (Lauven et al., 2019).

In order to extend the number of flexible power generators at the expense of subsidized generators in constant operation, the renewable support schemes in the German EEG 2012 has been designed to incentivize a flexible operation of biogas plants (Gawel & Purkus, 2013). One the one hand, direct marketing, e.g. on the European Power Exchange (EPEX), is encouraged in Germany by market and management premiums, which are designed to ensure that plant operation in accordance with market needs results in higher income than the previous fixed feed-in tariffs. On the other hand, a flexibility premium was introduced to help recover the cost of installing greater electrical generators to supply power when

prices are high, while interrupting power production when prices are low (Pablo-Romero et al., 2017).
The relatively slow adaptation of flexible operation for the eligible biogas plants raises the question of how to properly assess the economic benefit of switching from constant to flexible operation. Valuing such flexibility has not been a focus in economic theory so far, but play a major role in energy systems with large and increasing intermittent renewable capacities (Goutte & Vassilopoulos, 2019). In the following, we discuss whether real options theory could offer suitable methods to do so.

2.2 Real Options

The real options approach has been applied with increasing frequency since the mid-1980s, when seminal works such as Brennan & Schwartz (1985) and McDonald & Siegel (1986) set the cornerstone for a broad development in the following decades. Beside many others, one particular field of research with regard to real options emerged around energy-related topics. Earlier works, such as Pindyck (1993), Frayer & Uludere (2001), Tseng & Barz (2002), Thompson et al. (2004), Näsäkkälä & Fleten (2005), Tseng & Lin (2007) and Wickart & Madlener (2007), focused on applying real options analysis to the valuation of traditional thermal power plants, i.e. nuclear plants, coal-fired plants and gas-fired plants. However, with the increasing importance of renewables, decentralized power generation units such as wind turbines, photovoltaic cells, smaller hydropower plants and biogas plants moved into the literature's focus.[1] Here, real option analysis is applied for decision support regarding project valuation, R&D appraisal and environmental economic policy (Kozlova, 2017).
Caporal & Brandão (2008) study the option to change markets for a hydroelectric plant, i.e. a firm's option to decide whether to sell its generated power at a fixed price in the long-term or at the stochastic spot market price. They find that such flexibility components cannot be captured with a traditional DCF method. Hence, they propose a real options analysis for that kind of problem. Bøckman et al. (2008) study the investment decision for small hydropower plants. By valuing the option to invest, they find an investment rule in the form a single optimal price threshold and, accompanying over the specific size-dependent functional form of the investment, they simultaneously find the optimal capacity of the plant. In a similar fashion, Boomsma et al. (2012) apply real options analysis to analyze the

[1] The literature's focus is not limited to the mentioned isolated types of renewables. In fact, it is also applied in related fields. To name a few, e.g. Bakke et al. (2016) apply real option analysis to study the sparsely investigated topic of transmission asset investment. Lukas & Welling (2014) investigate the investment decision for making the supply chain more economically friendly under uncertain CO_2 allowance prices.

investment and sizing decision of renewable projects. However, the analysis is conducted behind the background of various common support schemes, i.e. feed-in tariffs and renewable energy certificate trading. In the case of wind turbines, the optimal investment rule and capacity choice is studied by Fleten et al. (2007) and Kitzing et al. (2017). Also in the field of photovoltaic plants, real option analysis is widely used. Zhang et al. (2016) use the real options framework to assess investment opportunities into photovoltaic plants, or Torani et al. (2016) study the optimal investment behavior of consumers and derive policy implications in order to stimulate the consumers timing to adopt photovoltaic plants. Welling (2016) studies the impact of the flexibility regarding sizing and timing and applies his findings for German photovoltaic projects. For renewable energy projects in general, Bigerna et al. (2019) determine optimal subsidy levels for uncertain market demands.

While the real option analysis is quite often applied for wind, solar and hydro plants, it is only sparsely pronounced with regard to biogas plants (see Kozlova (2017)). One of the few exceptions is a study by Di Corato & Moretto (2011). They investigate the investment decision regarding a biogas plant, where the inputs are substitutable to a certain degree. They derive the value from the ability to restrictedly switch inputs to calculate an extended NPV. Unlike Di Corato & Moretto (2011), Siegert (2014) focuses on the shutdown option for a typical 500 kW biogas plant in Germany. Based on expected, inflation driven, increases in the price of biomass and the fix feed-in tariff structure for biogas plants in Germany, he finds the shutdown option as not negligible value component of the investment value.

The proposed model adds to the described literature in several ways. We study the investment decision into flexibility measures of an already (under RSS) operating biogas plant. Until the RSS expires, the plant operator faces a switching option, i.e. switching form a RSS-operation to a market-oriented operation. However, after RSS expiration, the whole decision problem is reduced to a simple option to invest. Based on this background, we derive the optimal investment policy for a whole range of RSS expiration times and derive implications for plant operators and policy makers. Furthermore, we do not consider the real options model in isolation. In fact, we combine the real options model with a unit commitment optimization model. The latter optimization model is used to derive time series of maximized revenues that the biogas plant can earn in flexible operation. These time series are then used to determine and parametrize the stochastic evolution of the state variable for the described real options model.

3. A Real Options Model for Flexible Biogas Plant Operation

In order to evaluate switching from an RSS-based operation to a market-based operation of the biogas plant, the plant operator first needs to estimate market revenues for market-based operation. Therefore, we perform a technical optimization based on historical electricity prices in subsection 3.1 by aiming to maximize revenues. Then, given the historical development of revenues for the flexible operation biogas plant, we use these to estimate a stochastic process which functions as state variable for the real option model to switch operation modes of the plant in subsection 3.2.

3.1 Modeling a flexible Biogas Plant

In order to evaluate the economics of retrofitting existing biogas plants to provide renewable power flexibly, we use an algorithm to approximate the market revenue potential of flexible biogas plants in specific energy markets based on past price data sets. Using the MILP unit commitment model from Lauven et al. (2019), we determine aggregated weekly revenues for a 500 kW biogas plant with an extended power capacity of 2 MW for flexible generation. We use the same objective function to maximize the revenues from power sales on the spot market:

$$\max_{x_i}\left(\sum_{i}^{I}(p_i P_{inst} x_i)\right)$$

where p_i is the power price in time slot i and P_{inst} is the capacity of power generation.

In order to represent technical limits of flexible power generation, the following constraints ensure for each time slot (hours in the current day-ahead markets) that sufficient biogas is available, while avoiding overloading the biogas storage at any time during the day. The considered time interval j, which initially only covers the first time step, is expanded steadily in each consecutive constraint until it covers all 24 hours of the considered day:

$$cap_j = cap_0 + P_{BGP} \cdot j - P_{inst} \cdot \sum_{i=0}^{j} x_i \qquad j = 1, \ldots, 24$$

$$cap_{min} \leq \ cap_j \leq cap_{max} \qquad \forall \text{ j} \in [1;24].$$

Here, p_{BGP} is the capacity of the biogas production, cap_0 and cap_j denote the biogas storage levels before the first considered hour and in time slot j, respectively, while cap_{min} and cap_{max} set the minimum and maximum feasible level of biogas storage.

The optimization problem is solved with the CPLEX solver in GAMS. Utilizing a python-GAMS API, the last storage level of each day is stored and then used as the first storage level for the following day's optimization problem.

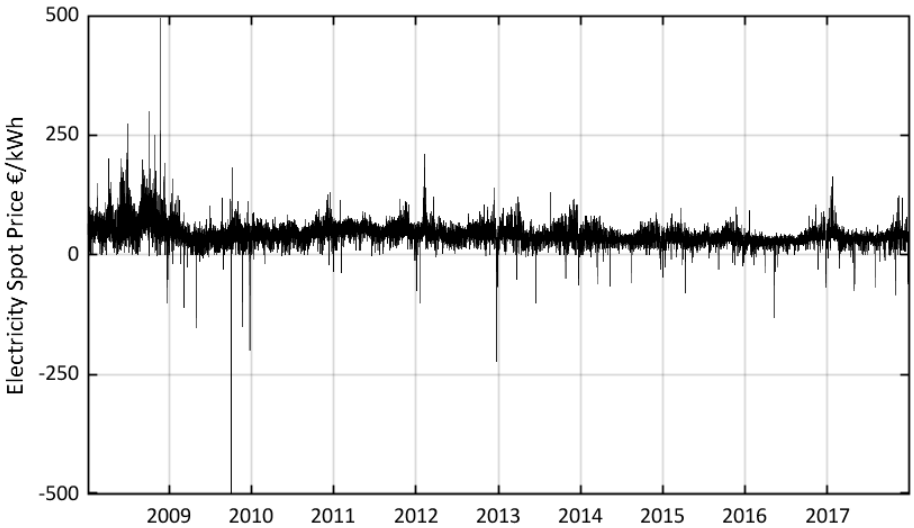

Figure 1: Hourly historical spot electricity prices (EPEX Base Load, 07.01.2008 - 31.12.2017).

We apply this optimization approach to derive weekly revenue values for hourly German electricity spot prices from 2008 to 2017 (see Figure 1), which leads to optimized weekly market revenues depicted in Figure 2.

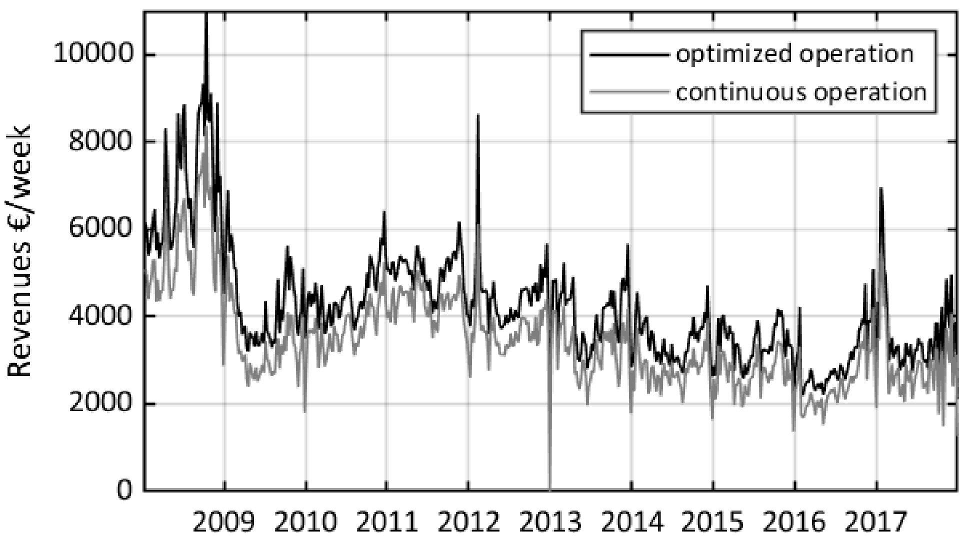

Figure 2: Estimated market revenues for flexible and continuous operation, with a 2 MW_{el} and $500kW_{el}$ generator respectively, for a 500 kW (rated power) biogas plant based on historical spot electricity data (EPEX Base Load, 07.01.2008 - 31.12.2017).

3.2 The General Real Option Model

In this subsection, we study the investment decision of a well-situated risk-neutral plant operator who has the option to switch from an RSS-oriented to market-oriented operation. For this purpose, we divide the investment problem into two parts. The first part refers to the investment decision after the expiration of the fixed RSS compensation, i.e. feed-in tariff. Here, we assume that the plant operator still possesses a perpetual option to invest in the flexibility measures[2]. This general problem is well studied by the real options literature and is straightforward to solve. The second part, however, refers to the situation where switching is not only associated with irreversible costs for the flexibility measure, but also with an additional cost of giving up the guaranteed RSS payment that could have been capitalized until RSS expiration. Hence, the option involved is finite, and the investment decision becomes more complex.
Before we start analyzing the investment problems in detail, we first focus on the stochastic evolution of the state variable that drives both problems, i.e. the optimized weekly revenues in a market-based operation (see Figure 2). To determine the underlying stochastic process we invoke a simple graphical argument provided in Figure 3 (see also Marathe & Ryan (2005)).

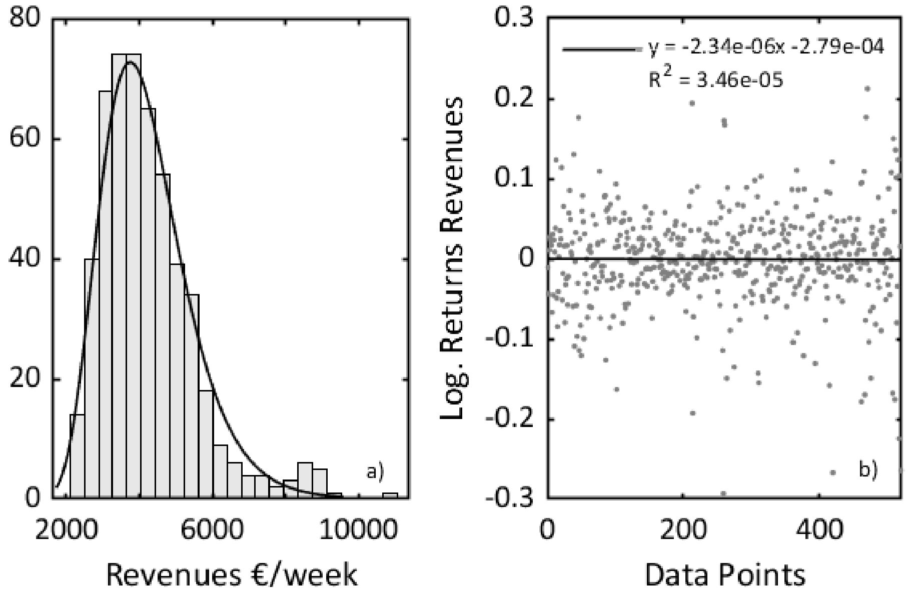

Figure 3: a) Histogram of weekly revenues with corresponding fit to probability density function of a lognormal distribution. b) Scatter plot of log-returns for the weekly revenues with linear regression.

At a glance, the shape of the histogram reminds of a lognormal distribution, however, with a deviation around 8000-9000 €/week. Further, we do not observe any pattern in the scatter plot. This indicates independent increments in the log-returns of the revenues. Also, the assumption of constant mean and standard deviation seems plausible with regard to the scatter plot. Hence, we assume that

[2] We also assume that the plant keeps its working condition such as under the RSS-based operation. Hence, we do not consider deterioration in the idle plant.

the revenues are lognormaly distributed and their stochastic evolution obeys a geometric Brownian motion

$$dx_t = \alpha x_t dt + \sigma x_t dz_t \tag{1}$$

with drift rate α, volatility σ and Wiener increment dz_t.
For the first part of the investment problem, i.e. finding the optimal point to exercise the perpetual option $F(x)$, we refer to standard real options literature such as Dixit & Pindyck (1994, pp. 182), where $F(x)$ has to satisfy

$$\frac{1}{2}\sigma^2 x^2 \frac{\partial^2 F(x)}{\partial x^2} + \alpha x \frac{\partial F(x)}{\partial x} - rF(x) = 0. \tag{2}$$

By exercising the option, the plant operator switches his plant from an idle[3] state to a market-oriented operating state by paying the sunk costs for the flexibility measures I. In return, he receives the expected project value under market-oriented operation

$$\begin{aligned} V_m(x) = \ & E\left[\int_0^{\tau} (x_t - c_1)e^{-rs} ds \mid x_0 = x\right] \\ & = \frac{x}{r-\alpha}\left(1 - e^{-(r-\alpha)\tau}\right) - \frac{c_1}{r}(1 - e^{-r\tau}), \end{aligned} \tag{3}$$

where r denotes the riskless interest rate, c_1 are the operating costs during the market-oriented operation and τ is the remaining lifetime of the plant after a complete RSS operating period . To ensure optimality of the investment rule, i.e. exercising the option, Eq. (2) is solved via value matching and smooth pasting conditions, respectively

$$F(x^*) = V_m(x^*) - I \tag{4}$$

$$\left.\frac{\partial F(x)}{\partial x}\right|_{x=x^*} = \left.\frac{\partial V_m(x)}{\partial x}\right|_{x=x^*}. \tag{5}$$

Applying the initial function $F(x) = Ax^{\beta_1}$ for this well studied problem, we finally find the optimal exercise point x^* and the coefficient A, respectively, determined as

$$x^* = (r-\alpha)\frac{\beta_1}{\beta_1 - 1}\left(\frac{c_1}{r}(1 - e^{-r\tau}) + I\right)\left(1 - e^{-(r-\alpha)\tau}\right)^{-1} \tag{6}$$

[3] Assuming that continuous operation after RSS with the old biogas plant is infeasible.

$$A = (\beta_1 - 1)^{\beta_1 - 1}\left(\frac{c_1}{r}(1 - e^{-r\tau}) + I\right)^{-(\beta_1 - 1)} \left((r-\alpha)\beta_1(1 - e^{-(r-\alpha)\tau})\right)^{-\beta_1}, \tag{7}$$

with $\beta_1 > 1$ as positive root of the fundamental quadratic with the form

$$\beta_1 = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}. \tag{8}$$

For the second part of the investment problem we need to find the optimal exercise points $x^*(t)$ for the finite option $F(x,t)$. Therefore, Eq. (2) is extended with a time derivative. Valid on $t \in [0,T]$ with T as initial RSS expiration time, $F(x,t)$ has to satisfy

$$\frac{1}{2}\sigma^2 x^2 \frac{\partial^2 F(x,t)}{\partial x^2} + \alpha x \frac{\partial F(x,t)}{\partial x} - rF(x,t) + \frac{\partial F(x,t)}{\partial t} = 0. \tag{9}$$

Here, we cannot find any analytical solution. Hence, we apply the Crank-Nicolson finite differences method. Since part one and part two of the investment problem equal at $t = T$, we use the analytical solution from the first part as terminal condition

$$F(x, t = T) = \begin{cases} Ax^{\beta_1}, & x < x^* \\ \frac{x}{r-\alpha}\left(1 - e^{-(r-\alpha)\tau}\right) - \frac{c_1}{r}(1 - e^{-r\tau}) - I, & x^* \le x. \end{cases} \tag{10}$$

For the lower bound of the problem we set

$$F(0,t) = 0. \tag{11}$$

For the upper bound, we first consider the additional cost that comes from giving up the remaining value of a RSS-based operation at an exercise time t

$$V_{RSS}(t) = \int_t^T (x_{RSS} - c_0)e^{-rs}ds = \frac{x_{RSS} - c_0}{r}(e^{-rt} - e^{-rT}), \tag{12}$$

with x_{RSS} as revenues from a RSS-based operation and c_0 as corresponding operating costs. By combining Eq. (12) with an adjusted version of Eq. (3) which accounts for the complete remaining lifetime of the plant and the cost of the flexibility measure I, we set the upper bound to

$$F(x_{max}, t) = \frac{x_{max}}{r-\alpha}\left(1 - e^{-(r-\alpha)(T-t+\tau)}\right) - \frac{c_1}{r}\left(1 - e^{-r(T-t+\tau)}\right) - I \\ - \frac{x_{RSS} - c_0}{r}\left(e^{-rt} - e^{-rT}\right). \tag{13}$$

4. Numerical Study

For the numerical study we use weekly base case values similar to the case study in section 5. Therefore, we estimate $\alpha =$ -8.8979*10^{-4}% (≙ -4.63% p.a.) and $\sigma =$ 5.98% (≙ 43.12% p.a.) based on the historical (optimized) weekly revenues (see Figure 2). For the interest rate we use a low value of $r =$ 0.0769% (≙ 4% p.a.) as compared to the real options literature. The feed-in tariff x_{RSS} =15,372€ is based on the German RSS EEG 2012. The operational cost consists of substrate costs and utilities, personnel and maintenance costs. The former is chosen form Kost et al. (2018) and the latter three are based on Balussou et al. (2018). Hence, we set the operational cost $c_0 = c_1$ =7,206€. The cost of the flexibility measure is extracted from cogeneration plant characteristics provided by ASUE (2011). Since an average 500 kW can quadruple its power output to 2000 kW with associated costs of 400€/kW, by still keeping its rated power of 500 kW, the investment in the resulting flexibility measure is set to $I =$ 600,000€. The maximum time for the RSS is set to T =1040 (Pablo-Romero et al., 2017). The remaining lifetime of the plant is chosen as $\tau =$ 520 (EEG 2012). For more details about computing the used values, we refer to the appendix.

First, we study the impact of uncertainty measured by σ on the optimal investment threshold $x^*(t)$ in Figure 4. The higher the uncertainty the higher is $x^*(t)$ and vice versa. This result is common in the real options literature and can be attributed to a generally higher value of the option to switch when uncertainty increases. Hence, at higher levels of σ the observed revenues need to satisfy higher requirements to justify investment. Further, the threshold decreases the greater the part of the RSS that has already expired. This effect is due to the smaller opportunity costs the plant operator needs to accept for switching from RSS-based operation to a market-based operation. However, the decrease in the opportunity cost along with remaining RSS time has a more pronounced effect for higher levels of uncertainty. Beside those general effects, we notice that with the used base case values the level of $x^*(t)$ is generally too high to attract investment at all (see Figure 2). Thus, switching into a market-oriented operation is probably never undertaken by plant operators under the studied conditions, i.e. without any further support payments by the government.

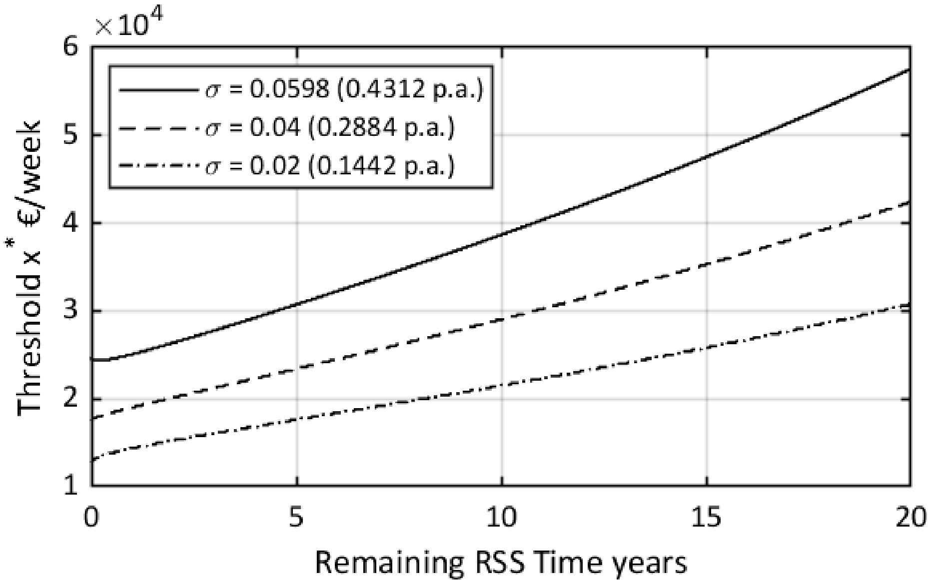

Figure 4: Effect of uncertainty on the optimal investment threshold $\boldsymbol{x}^{*}$ for remaining RSS expiration times.

Next, we study the impact of the fix feed-in tariff x_{RSS} in Figure 5. We observe a strong decrease in the investment threshold with lower x_{RSS}. This can be explained with the decrease in the value of the remaining RSS-based operation as x_{RSS} reduces and hence with lower opportunity costs. As soon as x_{RSS} reaches the operative costs c_0 the RSS-based operation is practically without value, since the plant solely works at break-even. Here, we observe a u-shape around 0-7 years of remaining RSS time. To work this effect out, we isolate the case for $x_{RSS} = c_0$ in Figure 6 and vary the remaining project life τ (black curves). For $\tau \to \infty$ the threshold $x^{*}(t)$ equals the canonical threshold x^{*} (see Eqn. (3) and (6)). However, the curve lies above the threshold curve for τ=10 years. This has two reasons. First,

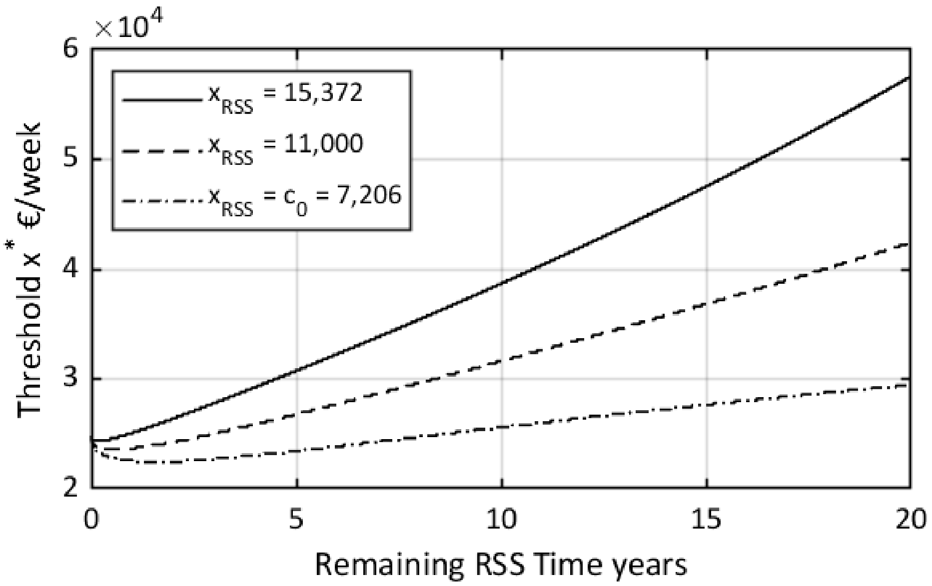

Figure 5: Effect of feed-in tariff $\boldsymbol{x}_{RSS}$ on the optimal investment threshold $\boldsymbol{x}^{*}$ for remaining RSS expiration times.

as τ approaches infinity, the market-oriented project to switch to gets infinitely lived. Hence, operating but not generating any cash flow (since $x_{RSS} = c_0$) by the RSS-based project for T years, does not influence the market-oriented project value anymore. This in turn reduces the whole problem, to finding the optimal exercise point of an option to invest. Second, since $\alpha < 0$ an increase in τ leads to a proportionally stronger increase in the value component related to operating costs c_1 as in the value component related to the revenues x (see Eq. (13)). Hence, the threshold curve for $\tau \rightarrow \infty$ needs to be above $x^*(t)$ for τ = 10 years at least at $x^*(t = T)$. To explain the u-shape we refer to the grey curve where $\tau = 10$ and the costs in the market-oriented operation $c_1 = 0$. Since the operating costs are zero, there is no intermezzo regarding discounting between x and c_1 related terms anymore (see Eq. (13)). Hence, the threshold course is straight forward again. However, by considering operating costs as for the black curve with τ = 10 years, those induce differing degrees of discounting. The latter is more or less pronounced for different levels of α and σ.

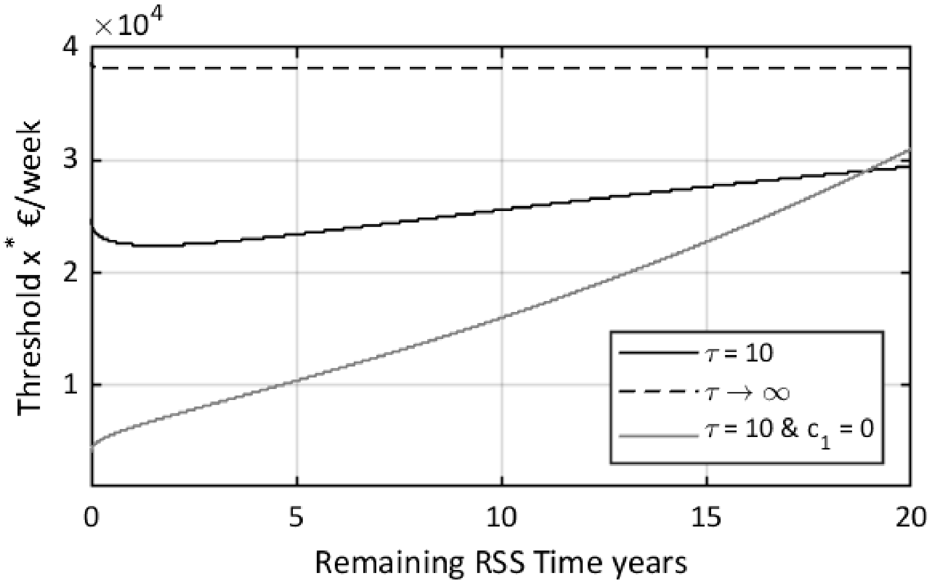

Figure 6: Effect of remaining project life τ on the optimal investment threshold $\boldsymbol{x}^*(t)$ for remaining RSS expiration times and $x_{RSS} = c_0$.

5. Case Study: Modeling Flexible Biogas Plant Operation in Germany

For the case study, we focus on a commonly sized German biogas plant with a rated power of 500 kW. Since the German regulatory framework gives special incentives, we extend the more general model as proposed in subsection 3.2. The German state gives incentives for biogas plant operators to switch to flexible operation through two premiums: A combined market and management

premium, which expires together with granted feed-in tariff from RSS, and a flexibility premium, that is payed for ten years as soon as the operator switches from RSS-based operation to a market-based operation.
To account for these incentives, we need to update Eqn. (6) and (7), i.e. the optimal timing x^* and the coefficient of the option to invest A, first. Respectively, they change to

$$x^* = (r-\alpha)\frac{\beta_1}{\beta_1-1}\Big(\frac{c_1}{r}(1-e^{-r\tau}) - \frac{p_{flex}}{r}(1-e^{-r\tau_{flex}}) + I\Big)\big(1-e^{-(r-\alpha)\tau}\big)^{-1} \tag{14}$$

$$A = (\beta_1-1)^{\beta_1-1}\Big(\frac{c_1}{r}(1-e^{-r\tau}) - \frac{p_{flex}}{r}(1-e^{-r\tau_{flex}}) + I\Big)^{-(\beta_1-1)} \Big((r-\alpha)\beta_1(1-e^{-(r-\alpha)\tau})\Big)^{-\beta_1}, \tag{15}$$

where τ_{flex} denotes the timespan for the guaranteed flexibility premium p_{flex}. Here, we implicitly assume $\tau_{flex} \leq \tau$. Second, during the RSS we need to modify the terminal condition Eq. (10) as well as lower and upper boundaries Eqn. (11) and (13), respectively to

$$F(x,t=T) = \begin{cases} Ax^{\beta_1}, & x < x^* \\ \frac{x}{r-\alpha}\big(1-e^{-(r-\alpha)\tau}\big) + \frac{p_{flex}}{r}(1-e^{-r\tau_{flex}}) - \frac{c_1}{r}(1-e^{-r\tau}) - I, & x^* \leq x \end{cases} \tag{16}$$

and

$$F(0,t) = \max\Big(\frac{p_{flex}}{r}(1-e^{-r\tau_{flex}}) + \frac{p_m}{r}\big(1-e^{-r(T-t)}\big) - \frac{c_1}{r}\big(1-e^{-r(T-t+\tau)}\big) - I - \frac{x_{RSS}-c_0}{r}(e^{-rt}-e^{-rT}), 0\Big) \tag{17}$$

$$F(x_{max},t) = \frac{x_{max}}{r-\alpha}\big(1-e^{-(r-\alpha)(T-t+\tau)}\big) + \frac{p_{flex}}{r}(1-e^{-r\tau_{flex}}) + \frac{p_m}{r}\big(1-e^{-r(T-t)}\big) - \frac{c_1}{r}\big(1-e^{-r(T-t+\tau)}\big) - I - \frac{x_{RSS}-c_0}{r}(e^{-rt}-e^{-rT}). \tag{18}$$

Here, p_m is the combined market and management premium. In Eq. (17) we need to additionally account for the possibility that the option is already in the money even when the revenues are zero.
For the case study, we use the same values as in the numerical study in section 4. We further add, based on Pablo-Romero et al. (2017) and Hochloff & Braun (2014), the weekly values: $p_{flex} = 2500$€, $p_m = 12{,}180$€ and $\tau_{flex} = 520$.

The basic effect of the provided incentives by the German government is depicted in Figure 7. First, resulting from high remaining expiration times, the investment threshold strongly decreases and reaches a minimum at around 7.5 years of remaining RSS with a level of 7,000 €/week. Here, three effects play a role. With a lot of time left to expiration, the RSS operation is relatively valuable. However, the more time under RSS has already expired, the stronger the impact of the governmental incentives p_{flex} and p_m. Since p_{flex} is payed for ten years fix and p_m has the same maturity as the RSS, they proportionally clear against the x_{RSS}. Here, also the value of the option to switch is reduced. However, as the threshold reaches its minimum, the option to switch once again gains value, in fact faster, then p_{flex} reduces its value. Hence, the threshold increases again. However, compared to the depicted base case in Figure 4 the threshold level is in general lower, which shows the effect of the governmental incentives.

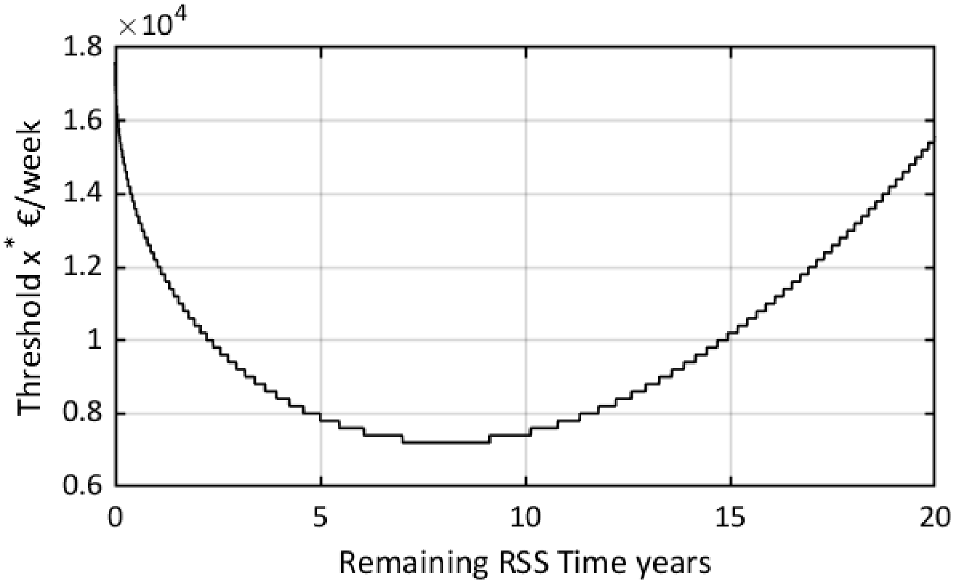

Figure 7: Combined effect of flexibility premium $\boldsymbol{p_{flex}}$ as well as the market and management premium $\boldsymbol{p_m}$ on the optimal investment threshold $\boldsymbol{x}^*$ for remaining RSS expiration times.

Figure 7 further shows why the immediate switch from RSS-based to market-oriented operation failed to materialize as expected by the German government, especially for the targeted biogas plants that were put into operation around 2009-2012. In 2012, those plants still had up to 20 years of RSS-oriented operation ahead, which places them towards higher revenue requirements in order to give up the certain feed-in tariff under the RSS, as compared to the minimum level of 7,000 €/week at around 7.5 years. However, due to different risk-preferences as compared to our assumption of risk-neutrality, it is imaginable, that some of the biogas plants switched their operational mode earlier.

6. Conclusion and Outlook

The results appear to help understand why a) Germany is an exception when it comes to flexible biogas plants, and b) the German flexibility premium has not immediately been a resounding success, but was only gradually adapted. So far, this has mainly been attributed to the complexity of compensation rules and necessary investment (Gawel & Purkus, 2013).

In the numerical study, it becomes apparent that investors outside the German RSS regime are very unlikely to invest in flexibilization since the general level of threshold values appears significantly higher than the hitherto observed values for weekly market revenues.

Regarding the case study including the German premiums, the results indicate that the general level of RSS premiums are sufficient to encourage flexibilization. But even in this case, the level required to choose the option is not negligible - values below 8,000 € of weekly revenues only suffice if between 4 and 12 years of guaranteed RSS payments remain. This reflects the fact that to some extent, certain RSS payments are waived in favor of uncertain market revenues.

7. References

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Appendix

Selected Base case values:

- $r = \frac{0.04\ p.a.}{52} = 0.0769\ \%\ p.w.$
- $x_{RSS} = 18.3 \frac{ct}{kWh}\ 168 \frac{h}{week}\ 500\ kW = 15{,}372 \frac{€}{week}$
- $p_{market} + p_{management} = 18.3 \frac{ct}{kWh} - Ø\ market\ value + 0.2 \frac{ct}{kWh} = 18.3 \frac{ct}{kWh} - 4 \frac{ct}{kWh} + 0.2 \frac{ct}{kWh} = 14.5 \frac{ct}{kWh}$
- $p_m = 14.5 \frac{ct}{kWh} 42 \frac{h}{week}\ 2\ MW = 12{,}180 \frac{€}{week}$
- $p_{flex} = 2{,}500 \frac{€}{week}$

- $c_0 = c_1 = 3.03 \frac{ct}{kWh_{th}} \frac{1}{0{,}4\frac{kWh_{el}}{kWh_{th}}} 168 \frac{h}{week}\ 500\ kW_{el} + 843\ €/week = 7206\ €/week$
- $I = 400 \frac{€}{kW} 1500\ kW = 600{,}000\ €$