Identifying investor behaviour in small hydropower projects using duration analysis

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Preface

This thesis is a part of the Financial Engineering Master's specialization at the Industrial Economics and Technology Management program at the Norwegian University of Science and Technology (NTNU).

The authors would like to thank professor Stein-Erik Fleten for his invaluable guidance. We would also like to thank Kristin Linnerud for valuable insight regarding the topic at hand, and Johannes Mauritzen for methodological help. Further, Rune Skjevdal deserves a special thanks for his contributions by providing key insight from a professional investor's point of view.

Abstract

In this thesis, we use duration analysis to study empirical data for 184 licences to build small hydropower plants in Norway, granted in the period from 2001-2008. We argue that investors based on their characteristics can be divided into two groups; non-professional and professional. To determine the theoretically optimal time of investment for each project, we develop models describing a real options and a now-or-never approach to the investment decision, including different expectations for subsidies. By comparing the observed data to the theoretical models using a Cox regression, we try to identify the investors' expectations to future subsidy schemes, and explain to which degree the investor groups tend to value the option to wait for new information.

We conclude that the non-professional investors only to a limited degree expect revenue from hydropower subsidy schemes. We also find that they tend to view the investment decision on a now-or-never basis. This aligns with earlier research on the behavior of investors in renewable energy. For the professional investors, we see signs that they had expectations of revenues from subsidy schemes upon investing, and that they tend to act in accordance with theory of investment under uncertainty, taking into account the value of waiting to receive new information.

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1 Introduction

1.1 Contemporary developments in the field of renewable energy

Throughout the last 30 years, two trends have dominated the development of the power industry. Restructuring of power markets, starting with the Chilean market in 1982, profoundly changed the market structures. In addition, focus on climate change has propelled the political drive for a change in the energy mix in favor of renewable sources.

The Renewable Energy Directive commits the EU 28 and members of the EEA to change their energy mix and introduce an increased amount of renewable energy by 2020 (Council of European Union 2009). Norway is also committed to national goals through the EAA agreement. When it comes to developing additional renewable generation capacity, Norway and Sweden has a common goal of developing an additional 28.4 TWh by 2020 (Ministry of Petroleum and Energy 2009). The amount of hydropower in EU has been more or less constant since the early 2000s, whilst the generation capacity from wind, solar and biomass has more than doubled (European Commission 2017). In Norway, the growth in generator capacity almost came to a halt in the 1980s due to a growing concern with environmental consequences of regulating major watercourses, and fewer major projects was initiated from the 90s onward (Bye & Hope 2005). However, the political support for development of small hydropower remains consistently high. The access to watercourses that can support major generating facilities is very limited because the most promising projects are either developed or subjected to conservation regulations. This leaves small hydropower and wind power as the most promising technologies for additional renewable energy generation (NVE 2010a).

In 1999 the Norwegian government published Report No.29 of 1999 to the Parliament on long-term strategic management of Norwegian energy resources. The conclusion regarding small hydropower plants was that the interest from investors in the late 90s was sufficient without policies to incentivize for new investments (The Bondevik I Government 1999). This view changed over the course of the next years, and in 2003 a strategy for increased investments in small hydropower was presented. Among the adjustments suggested to incentivize investments was reduced formal requirements for license applications and adjusted taxation for the smallest projects. In addition, they signaled less complicated processes to get grid access and that future subsidy schemes would be retroactive for projects initiated after January 1st of 2004 (Ministry of Petroleum and Energy 2003). Thereafter, the political process with regards to investments in small hydropower has for the most part been concerned with the question of support schemes. The effect of uncertainty induced by a prolonged political discussion about support schemes and taxation is thoroughly researched, among others by Boomsma et al. (2012), Linnerud et al. (2014), Linnerud & Holden (2015) and Linnerud & Simonsen (2017). The effect of uncertainty regarding the implementation of subsidies is not studied in this paper, but investor expectations to subsidies are analyzed.

1.2 The investment problem from an investor's perspective

To alter watercourses in Norway, one generally needs a license granted by The Norwegian Water Resources and Energy Directorate (NVE)[1]. NVE has published a guide for the development of watercourses for power production, where the process is divided into five steps; planning, application, investment decision, building and production, summarized in Table 1.1 (NVE 2010*b*).

Table 1.1: Stages in developing a small hydropower plant

Stage	Explanation
Planning	Map the production and capacity potential, access to the power grid, environmental consequences and cost of development and construction
Application	Measure water level in watercourse, hire required consultants[2] and write and submit license application in accordance with the requirements
Investment decision	If the license is granted, the development plan can be updated to comply with the license and the investment decision can be made
Building	Build the power plant in accordance with the license and connect the hydropower plant to the grid
Production	The plant is operational and produces electricity to the wholesale market

A large share of the Norwegian land is in private ownership. As a consequence, the right to utilize a watercourse for power production, generally belongs to local landowners. Some landowners choose to consult external parties, often experienced players in the small hydropower market, to help develop the project, assist in the license application, and in some cases operate the power plant. In practice, these external parties own the power plant and compensate the landowner for utilizing the watercourse through a negotiated agreement, up until some point in time where the power plant is offered to be sold back to the landowner (Idsø 2012). Ultimately, this leads to a distinction between non-professional investors who invest in a hydropower plant on their own land and professional investors who develop and own hydropower plants without legal ownership of the land where the watercourse is located. This also means that when a separate entity is founded to produce power from a watercourse, the owner of the watercourse is usually compensated for the utilization of the head in the watercourse through a rent. This rent is often set through negotiations between landowners and developers on basis of the profitability of the project. Due to taxation, both professional investors and non-professional investors will choose to organize the power plant as a limited liability company and pay rent on the

[1]Some projects do not need a license, mainly projects with an applied capacity below 1 MW that do not affect the public interests negatively (NVE 2015).

[2]Parts of the license application must be done by third parties, for example assessments of the ecological impact of the development.

utilization of the water course[3]. Due to this, one can assume that the operational costs of small hydropower plants on average are the same independent of the investor backing the project.

Establishing a small hydropower plant is capital intensive, with large capital expenditures early in the development phase. An operational power plant generates revenue from the sale of produced power and from applicable support schemes. The main costs of an operational power plant are the operational and maintenance costs, as well as any grid connection costs and potential expenditures for compensating to the landowner.

1.3 Literature review

A well researched topic within the field of renewable energy is how investments are affected by the introduction of support schemes (Boomsma et al. 2012, Linnerud & Holden 2015, Linnerud & Simonsen 2017). An overview of the articles taking a real options perspective on renewable energy investments published prior to 2015 can be found in Kozlova (2017).

A common way of comparing costs for renewable energy investments is to compare levelized costs of energy (LCOE) (Awerbuch 2003). This way of analyzing the economy of a renewable energy investment has been subjected to broad criticism. Kahn (1996) points out how financing affects profitability of wind power projects and Donovan & Nuñez (2012) underscore that the costs of risk and uncertainty also need to be taken into consideration. Söderholm et al. (2007) shed light upon the risk added to renewable energy projects by policy uncertainty. Another obvious weakness of LCOE analysis is that it does not consider income (Bergek et al. 2013). In this thesis, LCOE analysis provides a good foundation for comparison of development costs, as only one technology is considered. The criticism of LCOE mainly concerns variable renewable technologies such as wind and photovoltaic (Ueckerdt et al. 2013). For our purposes, the established practice of using LCOE for economic comparison poses some challenges. For economic comparison of projects owned by non-professional investors, the LCOE approach will work reasonably well. However, the professional investor will have to compensate the landowner for utilization of the watercourse. This should be addressed, because it impacts profitability, but through a mechanism that is masked if LCOE is used in profitability calculations. This challenge is discussed more thoroughly in Section 3.1.

An important focus within the research of renewable power investments has been towards identifying the investor. Bergek et al. (2013) suggest that renewable energy investors are a diverse group with different motives and driving forces. The four main traits that should be used to categorize the investors are motives, background, resources and personal characteristics. The diversity among investors in renewable energy is also confirmed by Heiskanena et al. (2017). Bergek & Mignon (2017) showed that there are clear differences in the motives for investing in renewable power for different investor types. There are also differences in motivation based on which technology the investor is engaged in. Independent power producers are generally more focused on the economic aspects, whereas individuals are more concerned about environmental benefits and energy savings. This is

[3]The understanding of how and why the hydropower plants are organized this way is based on interviews with hydropower professionals.

an interesting finding, which indicates that studies assuming rational economic behavior from the investor part might be disregarding important factors when determining investor behavior in their analysis. As non-economic motivations are not studied in this paper, some of the factors explaining investor behavior might be missing from the analysis.

From an investment point of view, special interest is given the issue of differences between the investment behavior of professional and non-professional investors (Linnerud et al. 2014). The distinction is of increased importance with the emergence of decentralized generating units owned by investors who traditionally have no ties to utilities (Bergek et al. 2013, Linnerud et al. 2014, Heiskanena et al. 2017). This is a tendency that is especially relevant when considering photovoltaic sources of generation in Germany, where citizen ownership of renewable energy is incorporated in the Renewable Energy Law from 2014. From 2017, this policy is further strengthened by incorporating special support for citizen-owned wind power production sites (Bundesministerium für Wirtschaft und Energie 2017).

The relevance of the distinction between professional and non-professional investors in Norway might arguably be diminishing over time. This is due to the fact that available watercourses for development is limited by geography and environmental regulations, and are hence a scarce resource. The most profitable projects are likely to be developed before more costly and complex projects. As time passes this leads to a skew in the choice of possible projects towards the more complex and expensive ones for all investors. This may in turn limit the possibility of developments conducted by non-professional investors as the required competence and ability to carry financial risk will increase. This hypothesis will be further addressed in the sections to follow, as it, if true, affects our data, the applicability of methods and thereby the results. The potential for such a skew is less likely to be found for non-professional investors in small scale photovoltaics in Europe.

To study various aspects of investor behavior in relation to renewable energy, the theory of irreversible investment under uncertainty has been used, among others by Fleten & Ringen (2006), Bøckman et al. (2008), Boomsma et al. (2012), Linnerud et al. (2014) and Fleten et al. (2016). By using such a real options approach, the investors awareness of the value of waiting, given uncertainty can be assessed (Linnerud et al. 2014, Fleten et al. 2016).

Linnerud et al. (2014) propose that professional investors are less optimistic with respect to the economy of an investment project than non-professional investors. The professional investor tend to adhere to real options theory, valuing the option to wait once the license to invest is granted, whilst the investment behavior of non-professional investors seem to be in accordance with net present value theory. Linnerud et al. (2014) also suggest that the investment decision of non-professional investors might be influenced by other, non-economic factors not caught by the analysis. However, the research so far has utilized linear or logistic regression to identify whether real option or net present value is most describing for the observed investment behavior. The use of linear or logistic regression has no way of taking into account that during the observation period, for some data points no investment decision is made, or the license is cancelled (Columbia University Mailman School of Public Health 2015). This will cause biased results, as those events are treated as either an investment or no investment by the regression, or removed from the data set. For a more thorough discussion of the usage of regression techniques and survival analysis we refer to Harrell Jr (2015). We argue that data describing the investor behavior in connection to the usage of hydropower licenses has characteristics lending to the use of duration analysis, discussed further in Section 2.1.

Duration analysis is widely used within econometrics, for example in analyzing bankruptcy in various fields (Taylor 1999, Gross & Souleles 2002, DeYoung 2003). However, the method presents a series of methodical challenges, discussed thoroughly in Heckman & Singer (1984). Technology adaption within agriculture is an area that bears several resemblances to investment in small hydropower, where duration analysis has been applied. More specifically, Dadi et al. (2004) use duration analysis to investigate which factors determine the adaption time of fertilizer and herbicide among farmers in Ethiopia. Li (2008) uses duration analysis to test whether a real option perspective can explain the investment behavior in venture capital staging. Mauritzen (2014) uses duration analysis to analyze how subsidy schemes influence the scrapping of old wind turbines. Favero et al. (1994) use duration analysis to study if theory of irreversible investment under uncertainty can explain the lag between the discovery and the development of oil fields on the UK continental shelf. In the same paper, a Cox regression is used to study which investor behavior has the most explanatory power, and controls for heterogeneity in the data set by introducing covariates describing physical aspects of the different oil fields.

1.4 The contributions of our study and the structure of the paper

The goal in this thesis is to gain insight into how different investors think when faced with the option to invest in a licensed hydropower project. We will employ duration analysis to compare our empirical data to data for optimal investment constructed from theoretical investment rules. In particular, we establish three sets of investors' expectations to future subsidies, and consider two theoretical investment rules for each set of expectations, generating a total of six theoretical scenarios for investor behavior. We use duration analysis to construct empirical duration curves for professional and non-professional investors, assumed to reflect the true survival functions of these investor types[4]. For all combinations of expectations and decision rules, we use the theoretical models to find the optimal year of investment by comparing the investment threshold to observed prices. Then, we use this data to construct theoretical duration curves; one curve corresponding to each scenario. Finally, we compare these curves to the observed empirical duration curve, and use a Cox regression to assess how well the predictions fit observed investor behavior. In this way we will be able to study which investment rule most appropriately describes the observed behavior, and explore which expectations regarding subsidies the investors held. By including several non-economic, project-specific traits into the Cox regression, we hope to gain insight into whether other factors than economic considerations are determining the time from a license is granted until an investment decision is made. By doing this, we can assess whether the assumption about the investment as a purely financial decision, made in earlier research about renewable energy investments, is valid. To our knowledge, the use of duration analysis to investigate investment behavior within renewable energy is new.

[4]Given that we have data for almost all licenses given in Norway in the period from 2001-2008, this assumption is fair.

In line with earlier research, we expect the professional investors to acknowledge the value of waiting to a larger extent than the non-professionals. For subsidies, we expect that both groups expected additional revenue.

The thesis is structured as follows: Section 2 introduces duration analysis and the real options models that we will use in our analysis. Thereafter, in Section 3 we present the empirical data. In Section 4 our results are presented, before we discuss our findings in Section 5 and conclude in Section 6.

2 Methodology

2.1 Duration analysis

Duration analysis studies the time to the occurrence of an event and assesses the influence of covariates, i.e. predictive parameters, on duration (Fox & Weisberg 2011).

To conduct a duration analysis, three concepts need to be unambiguously defined: 1) The subject of study, 2) the event and 3) the time of origin (Kalbfleisch & Prentice 2002). In addition, the observation period needs to be defined, which is the period when occurring events will be recorded. In our case, the observation period runs from 2001 until 2017. The duration analysis characteristics specific to this thesis are summarized in Table 2.1.

Table 2.1: Definition of terms related to duration analysis

Term	Definition
Subject:	A licence to build a hydropower plant
Time of origin:	Time to event is measured relative to the time of approval of a specific licence
Event:	An investor deciding to invest in a licensed hydropower plant

The survival function[1] $S(t)$ is defined by the probability that the time T until an event exceeds a value t. Figure 2.1 illustrates the estimation of the true survival function for a population. The hazard function $h(t)$ is closely related, defined as the event rate at time t, conditional on no event occurring before time t. These functions are important for understanding the duration curves and Cox regression models in Section 4. Readers unfamiliar with the concepts of duration analysis are directed to Appendix A.

2.1.1 The Kaplan-Meier estimator and the Cox model

The Kaplan-Meier estimator estimates the survival function that maximizes the likelihood of observing the events as in the sample (Kalbfleisch & Prentice 2002). This estimator allows for stratification of the data set, and by conducting a log-rank test, we can test the null hypothesis that the duration curves for two strata of the data set are equal.

The Cox model is semi-parametric and aims to model the relationship between the duration distribution and specific covariates (Fox & Weisberg 2011). The Cox model is specified as follows

$$h_i(t) = h_0(t)e^{\beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik}} = h_0(t)e^{\beta \mathbf{x}'} \tag{2.1}$$

The exponential term describes the relationship between the value of the covariates and the hazard, through the value of the coefficients β. The model is semi-parametric because the baseline hazard $h_0(t)$ is unspecified, meaning that we make no assumptions about

[1] The terms duration analysis and survival analysis are used interchangeably. In this thesis, we follow the convention in the literature of naming equation A.1 in Appendix A *the survival function*, even though we use *duration analysis* to describe the statistical method.

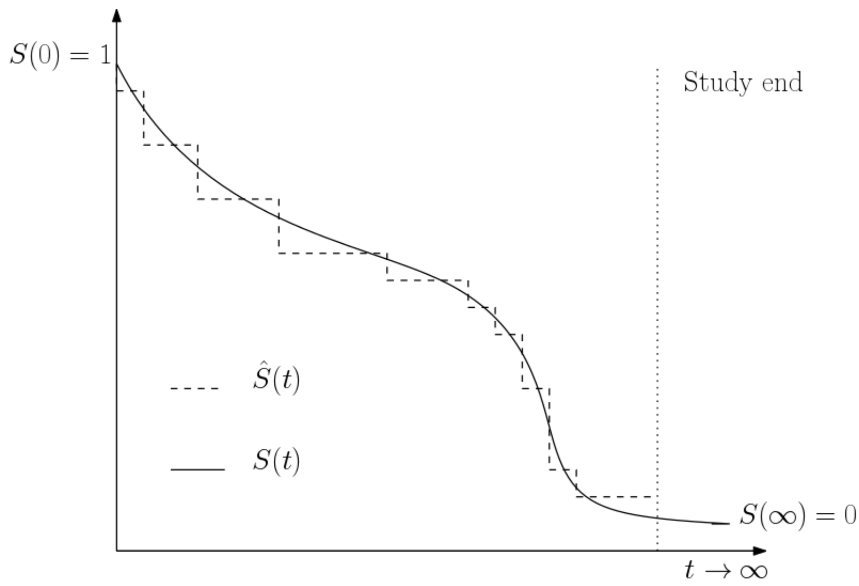

Figure 2.1: Illustration of theoretical and estimated duration curves for a hypothetical data set.

its shape. There is no evident reason in the nature of hydropower licenses suggesting that the survival function for such licenses (or other comparable types of licenses) should follow a named distribution. Hence, the semi-parametric Cox model is appropriate for our analysis.

We use a time-dependent version of the Cox model, to be able to properly account for covariates that are not constant over time for a project. Covariates describing the development of the electricity price and theoretical decision indicators must be allowed to vary with time.

2.2 Real options modelling of the investment decision

Earlier research on the topic, such as Linnerud & Holden (2015) and Fleten et al. (2016), attempt to assess whether investors in small hydropower plants consider the added value from postponing the investment when timing the investment decision. Through interviews, we can infer that very few investors explicitly adhere to real options valuation when making the investment decision. This is also consistent with earlier research conducted by Fleten et al. (2016). Although, without explicitly applying the valuation approach in the decision process, the investors still may recognize the value of waiting and exert investment behavior that is better explained by a real options (RO) approach than by the traditional net present value (NPV) approach.

After interviewing several investors, it became clear that the main concern of the investors was the costs related to developing the power plant. This is understandable, as the investment costs are thoroughly estimated, whereas the revenues from sale of electricity and potential subsidies are stochastic. The investors' projections for the development of the electricity price is crucial for estimating the profitability of the project. A lower LCOE will make the individual project profitable at a lower electricity price. This also holds for the development of potential support scheme revenue sources. The operational and maintenance cost per yearly produced unit of electricity has a minimal impact on the profitability of the project compared to the impact of sources of revenue and the investment cost. Modelling future developments of the revenue sources is complex, even taking into account the ability to use financial contracts to lock in a more stable source of revenues than the spot electricity price[2]. In general, there is limited liquidity in financial contracts with the electricity price as underlying with a maturity of more than three years. In addition, the electricity price is volatile compared to other commodities as it cannot be stored conveniently for later use. This can explain the focus towards investment cost for the individual investors.

As outlined earlier, in the period prior to the introduction of the support scheme for el-certificates in Norway in 2012, there was uncertainty related to the revenue potential for new hydropower plants. Therefore, we have chosen to consider an exhaustive set of potential investor expectations to subsidy introduction. The scenarios reflect the political discussion during our period of observation. These expectations form the foundation for modelling the investment decision in the RO and NPV approach. In the period prior to 2012, an investor could have had expectations related to future revenue potential as shown in Table 2.2.

Table 2.2: Overview of possible investor expectations and decision rules

	Expectation set	Decision rule based on	
A	Revenue from sale of electricity	I II	RO NPV
B	Revenue both from sale of electricity and el-certificates from a certain year with a certain probability of introduction	I II	RO NPV
C	Revenue from both sale of electricity and el-certificates. The scheme is introduced retroactively	I II	RO NPV

Investors with expectation set A represents investors that plan their power plants without revenue from support schemes, effectively indicating that they do not expect or dare to rely on future subsidies. An investor with expectation set B believes that there is some probability of a support scheme being implemented in a certain future year, providing an additional source of revenue. Investors with expectation set C plan their power plant with revenue from both sale of electricity and the certain implementation of a support scheme with retroactive effect. For a more detailed discussion of the political process preceding the decision to grant subsidies, see Fleten et al. (2016).

For each of these sets of expectations, we will develop two economic decision rules, one based on a real options approach and one on net present value calculations. This results in a total of six models. For each of these, we obtain the theoretically optimal year of

[2]We have used forward contracts with maturity three years into the future in our analysis instead of the spot price because the investors are thought to have a long-term perspective for the operation of their power plant.

investment given the observed electricity and el-certificate[3] prices during our observation period. In the following sections, we will explain the real options approach that is used to model the investment problem, for the different expectations regarding the introduction of a support scheme. Developing a real options model requires the present value of the underlying project to be known. The real option value is the maximum of the continuation value of holding the option to invest in the project and the net present value of the underlying project. Therefore, it is possible to obtain the net present value investment threshold (effectively the break-even price) for each power plant from the real options model. See Appendix B for a more thorough description of the three models. For simplicity we have not included taxes in our models. The hydropower industry is subject to heavy taxation in Norway, and it is important to keep in mind any effect that taxes might introduce in our models. However, taxation policies are ideally designed not to affect investments in profitable projects.

2.2.1 Expectation set A: One-factor stochastic model without subsidies

Incorporating expectation set A is done by developing a one-factor stochastic model similar to what is done in Dixit & Pindyck (1994, Chap. 6, Section 1). We assume that the electricity price follows a Geometric Brownian Motion (GBM)[4], but our model differs in the way that operational costs are included in the investment cost and that the cash flows only last for the operational period of the plant. From the model, we obtain an investment threshold for the electricity price. Whenever the observed price is above this threshold, investment is optimal. The expressions for the value of the project, the optimal investment threshold and the option value are given below. Note that the value P is not the spot price of electricity, but rather the electricity price determined by three-year forward contracts, as this is the best available proxy for the long-term electricity prices. For the el-certificate price S, we used the spot prices, as there was no data available on forward contracts for el-certificates for the full period.

$$V(P) = r_p P \tag{2.2}$$

$$P^* = \frac{\beta_1}{\beta_1 - 1}\frac{I}{r_p} \tag{2.3}$$

$$F(P) = \begin{cases} AP^{\beta_1}, & \text{if } P \leq P^* \\ V(P) - I, & \text{otherwise} \end{cases} \tag{2.4}$$

Here $I = I_0 + r_c C_0$ is the investment cost including the discounted value of the operational cost, β_1 is the positive root of the characteristic equation determined by parameters of the stochastic GBM price process, A_1 is a constant and r_p is the discount factor for the cash flow from electricity sale over the lifetime of the power plant.

[3]Sweden introduced el-certificates in 2003. We use the Swedish prices, as they would have been the investors best proxy for what subsidy levels one could expect in Norway. For years 2001-2002, we have used the price in 2003 as a proxy.

[4]An assumption in line with earlier research, among others Fleten & Ringen (2006), Fleten et al. (2011), Boomsma et al. (2012), Linnerud et al. (2014) and Fleten et al. (2016).

2.2.2 Expectation set B: One-factor stochastic model with contributions from subsidy scheme

Modelling expectation set B is done by using the approach of Linnerud et al. (2014), where the revenue stream from the potential el-certificates is viewed as a constant value, scaled down by a factor of $\rho_{t,c}$, where $\rho_{t,c}$ denotes the investors'[5] beliefs in year t of el-certificates being introduced[6]. To allow for different expectations for different project sizes, we use the same approach as Linnerud et al. (2014):

$$\rho_{t,c} = \gamma_{N_t}\theta_{t,c} \tag{2.5}$$

where γ_{N_t} is the probability of an el-certificate scheme being retroactively introduced in year N_t, and $\theta_{t,c}$ is the probability of a power plant of capacity c being eligible for certificates. Under these assumptions, the investors' uncertainty regarding the introduction of the el-certificate scheme will be captured. Unfortunately, the simple way of modelling the el-certificate prices fails to capture any uncertainty regarding future price levels. However, the subsidies' impact on the option value is more dependent on the introduction of the scheme itself, than on the correct specification of the price process used for the el-certificates. The estimated probabilities $\rho_{t,c}$ for each year, as well as the price expectancy of certificates for each year are given in Table B.1 in Appendix B (Linnerud et al. 2014). As before, the value of the project, the electricity price threshold for optimal investment and option value for a given project are given below:

$$V(P, N_t, S_t) = r_p P + r_s \rho_{t,c} S_t \tag{2.6}$$

$$P^* = \frac{\beta_1}{\beta_1 - 1}(\frac{I - \bar{S}}{r_p}) \tag{2.7}$$

$$F(P, N_t, S_t) = \begin{cases} AP^{\beta_1}, & \text{if } P \leq P^* \\ V(P, N_t, S_t) - I, & \text{otherwise} \end{cases} \tag{2.8}$$

where

$$\bar{S} = r_s \rho_{t,c} S_t \tag{2.9}$$

Here r_p is the discount factor for the cash flow from electricity sales over the 40-year life time expectancy of the power plant, r_s is the discount rate for el-certificate, running 15 years from year N_t, and S_t is the expected level of subsidies if introduces in year N_t.

2.2.3 Expectation set C: Two-factor stochastic model

When modelling expectation set C, we have used the same approach as Fleten et al. (2016). This approach uses two GBM price processes, one for the electricity price and one for the el-certificate price.

$$dP_t = \alpha_P P_t dt + \sigma_P P_t dz_P \tag{2.10}$$

$$dS_t = \alpha_S S_t dt + \sigma_S S_t dz_S \tag{2.11}$$

[5]We assume that all investors in a given year and for our given range of capacity $[1MW, 10MW]$ has homogeneous expectations as to whether the certificates are introduced or not.

[6]We make the simplifying assumption that all investors believe that the el-certificates will be introduced retroactively.

This is a more comprehensive model, which allows for modelling both of the stochastic price processes separately. From the Bellman equation we get a partial differential equation instead of an ordinary differential equation obtained in the two other models. This leads to a two-dimensional boundary of optimal investment through a pair of threshold prices, P^* and S^*. Støre et al. (2017) show that an analytical solution for the option value outside the investment boundary is obtainable, but for simplicity we only evaluate the solution at the investment boundary. This approach gives a subsidy price investment threshold and the corresponding option value at the investment boundary given an electricity price $P_t = P$, as described below. Further details on the derivation of these expressions are provided in Appendix B.3.

$$S^*(P) = \frac{\beta_P \eta(P) + 1}{\beta_P[\eta(P) + 1]} \frac{I}{r_S} \tag{2.12}$$

$$F(P^*, S^*) = r_p^{\beta_p} r_s^{(1-\beta_p)} \beta_p^{-\beta_p} \beta_s^{(\beta_p-1)} S^{*(1-\beta_p)} P^{*\beta_p} \tag{2.13}$$

2.2.4 Explaining the approach through an example

From the three theoretical models, we obtain optimal investment thresholds for specific hydropower projects, which in turn can be compared to observed prices to find the theoretically optimal year of investment. Figures 2.2, 2.3 and 2.4 illustrate the resulting investment thresholds and investment boundaries for Nordlandselva, a hydropower plant in our data set. In Figures 2.2 and 2.3 the vertical dashed lines represent the price investment thresholds for corresponding investment decision rules.

In cases where the observed price in a year is above investment threshold, the theoretical models signal investment. An example is the red colored line in Figure 2.3, which indicates that the optimal year of investment for the RO approach under expectation set B is 2008, because this is the first year that the observed electricity price is above the investment threshold. The green line represents the observed year of investment. We use the same color convention for Figure 2.4. Thus, the investment boundary for the RO approach and NPV approach are uniquely specified in red and blue color respectively. Using these three graphs, we can infer time-dependent binary variables indicating whether investment is optimal for each year the investor is holding a license to invest in Nordlandselva hydropower plant[7]. We refer to Appendix B.4 for a more detailed description of this example.

[7] Some observed prices are omitted from the graphs for illustrative purposes.

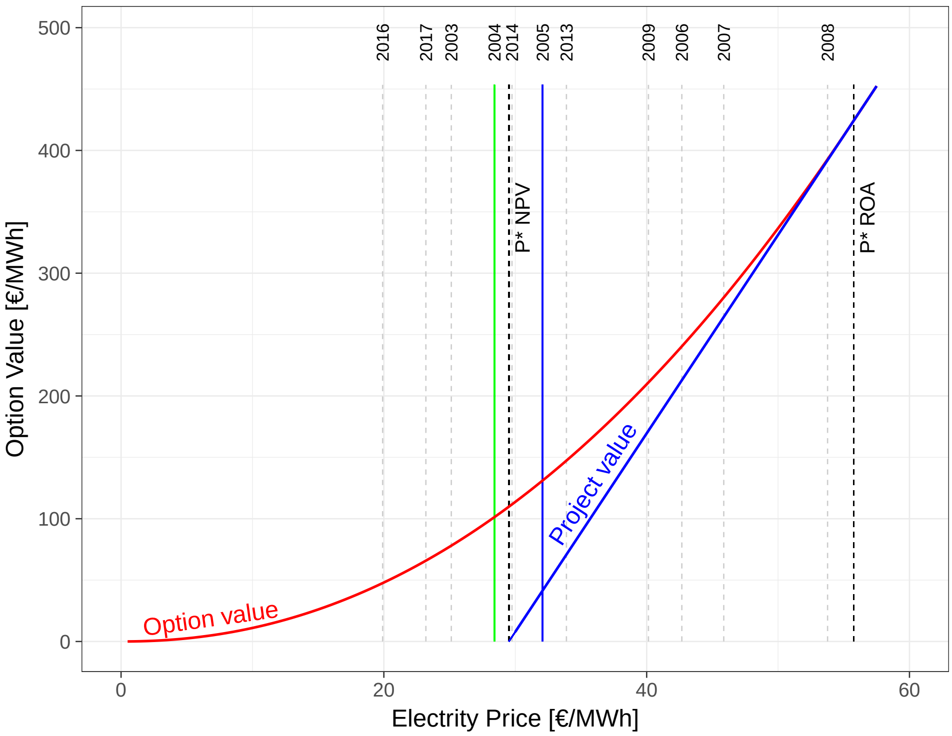

Figure 2.2: Modelling expectation set A for Nordlandselva hydropower plant

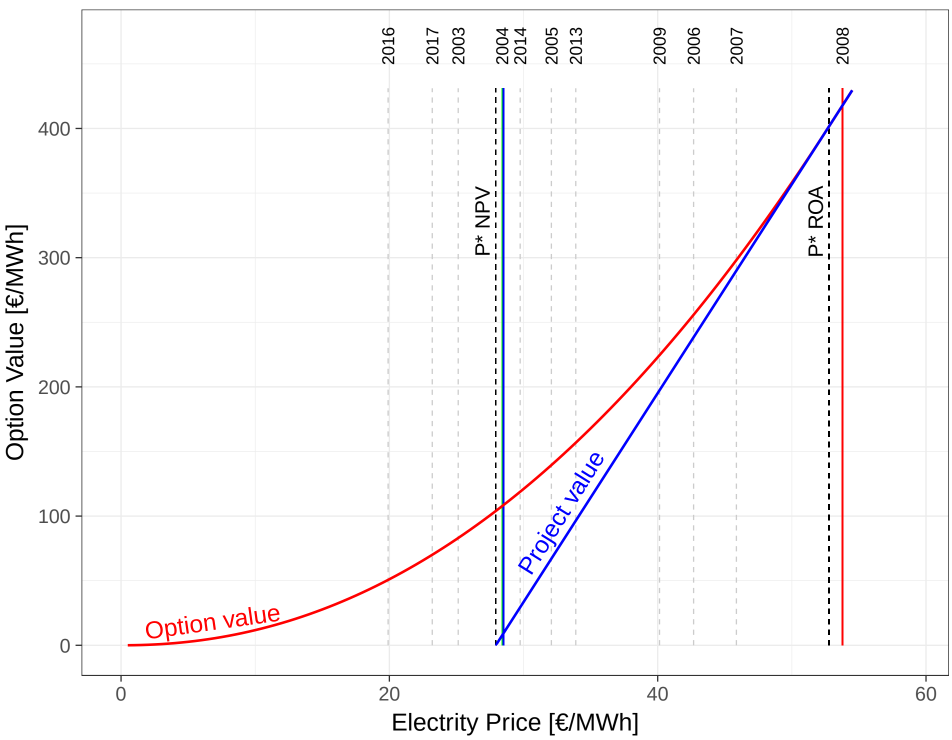

Figure 2.3: Modelling expectation set B for Nordlandselva hydropower plant

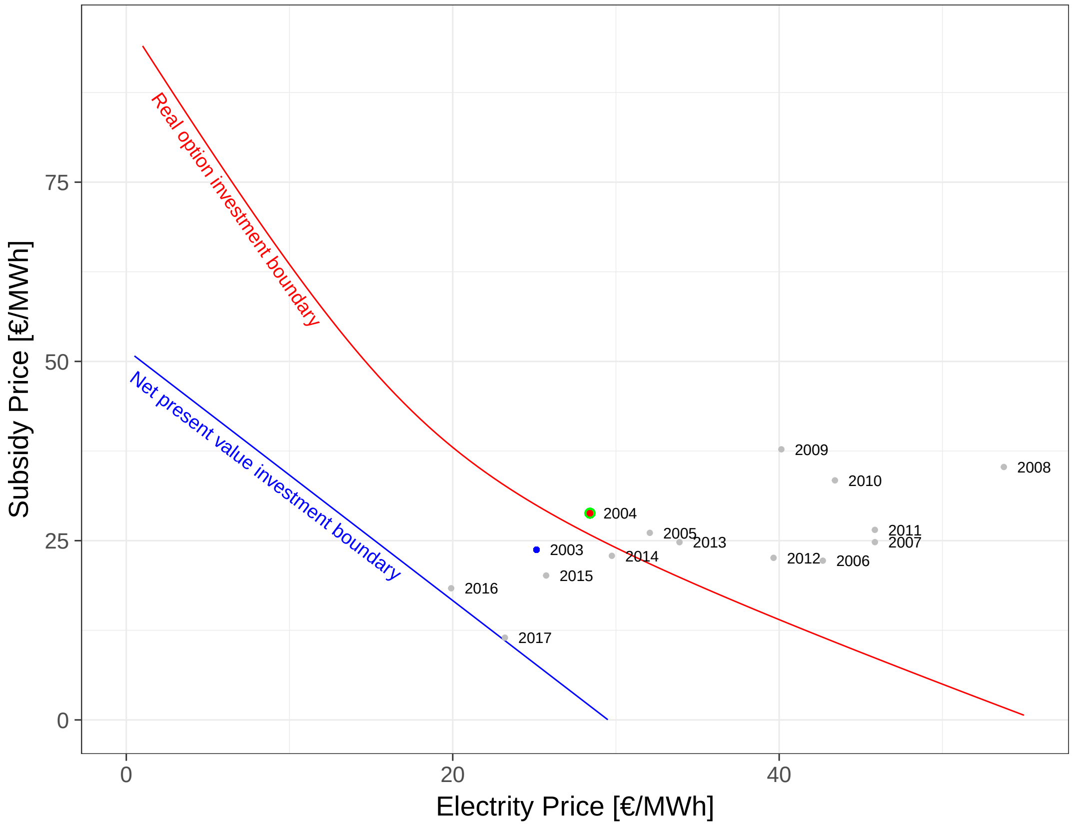

Figure 2.4: Modelling expectation set C for Nordlandselva hydropower plant

3 Data

3.1 Description of the data set

The study is based on licenses granted by the Norwegian Water Resources and Energy Directorate (NVE) for new hydropower installations with an installed nominal capacity below 10 MW from 2001 until the end of 2008. The majority of this data was originally gathered by Ane Marte Heggedal and later updated by Maria Tandberg Nygård. The data set used by Nygård was updated through interviews with the licence holders, reaching a response rate of 98.6 %. As the data set had not been updated since the spring of 2013, the state of several projects needed to be updated.

In the original data set containing 214 licenses, 35 of these licenses were still pending a committing investment decision in the spring of 2013. As the database of licences and hydropower plants available at NVE's homepage is not continuously updated, we contacted the investors in question to get an updated status for these projects. All replied, giving a response rate of 100 % for the data set as a whole. The last update of the data set was done on the 26th of October 2017, at which point 95.3 % of the granted licenses had been utilized.

The investors were primarily contacted by telephone, supplemented with e-mails when needed. We used the original questionnaire from Nygård (2013) to ensure that we got data on the same format as previously gathered. The original questionnaire is found in Appendix C. The data set contained information regarding investment year, annual energy production, installed capacity and investment cost. However, as the Cox model allows us to study the effect of other covariates, we extended the data set with data from NVE about whether the projects were planned with reservoirs or not, to capture production flexibility. When gathering the data for reservoirs, we were not able to capture the differences in projects that were planned with reservoirs that allows for regulation of the flow to the power station, and simpler reservoirs that do not provide this kind of production flexibility. Therefore, the share of projects with reservoir regulation is assumed to be lower than what is expressed in Table 3.1.

Generally, the investors were generous in sharing their insight in regard to individual projects. Understandably, the non-professional investors [1], had detailed information about their project more readily available than the professionals. We got the needed information about investment timing, development and operation of the plants where an investment decision had been made since 2013. For the cases where a decision was still pending, we could update the rationale for not investing. Although different methods were used to gather the required information, we believe that the data is consistent as the same questionnaire was guiding in the correspondence, independent of which method was used for gathering the data.

[1] Defined as owning only one license.

3.2 Discussion of the data set

Of the 214 licenses in the original data set, 25 are micro and mini hydropower plants[2]. In our analysis, we choose to exclude these projects based on the following reasoning: First, for these licenses, the investment decision had either been made immediately (or in some cases even before the licence was given), or the decision was not yet made by the end of the observation period. This substantiates our impression from the interviews that the investors owning the smallest projects might have other incentives to invest than economical ones, as discussed by Bergek et al. (2013). This might be a personal interest in the hydropower technology, ensuring sufficient supply of electricity to the farmers' own production, or utilizing existing penstock used for irrigation purposes in power production[3]. Second, the small scale of these projects favors non-professional investors (farmers) that probably can do much of the groundwork themselves[4]. Third, hydropower plants with less than 1 MW capacity only need a license if the development negatively influences the public interests (NVE 2015). Therefore, the data set may be incomplete for mini and micro hydropower plants. Under these conditions, the comparability to bigger projects will suffer. After excluding mini and micro hydropower plants from our data, we are left with 184 small hydropower plants.

In total, the licenses amount to an installed capacity of 648 MW and an average annual production of 2358.3 GWh, costing estimated 814.5 million €^{a}. This corresponds to about 2.04 % of the total installed capacity and 1.77 % of the annual production of power in Norway according to NVE (2017). The average hydropower plant in the data set has an installed capacity of 3.52 MW and produces 12.82 GWh annually, with a LCOE of 352 €$/MWh$ ^{a}.

Table 3.1: Descriptive statistics for hydropower plants included in the analysis

-	Value	Unit
Share of professional investors	51.6 %	–
Share with reservoir	66.3 %	–
Avg. installed capacity	3.52	MW
Total installed capacity	648	MW
Avg. annual production	12.82	GWh
Total annual production	2358.3	GWh
Levelized Cost of Energy	352.2	€$/MWh^a$
Total Investment cost	814.5	million €^{a}
Average time from licensing to investment decision	1.91	years

a: 2008 cost base.

Figure 3.1 gives a graphical representation of when individual licences were granted and when the corresponding investment decisions were made. The numbers above the bars for

[2]Hydropower plants with nominal installed capacity of less than 1 MW are defined as mini power plants, under 0.1MW as micro power plants, whereas power plants between 1 and 10 MW are defined as small hydropower (NVE 2015).

[3]An example of this can be found in the license application for Kjønås Kraft AS, `http://kraftverk.hoystad.net/wp-content/uploads/2017/01/Kjonnas-Konsesjonssoknad-endelig.pdf`.

[4]Accounting for the opportunity costs of the farmers' time spent working on the project go beyond the scope of this thesis.

each year represents the number of licenses granted in that year and the numbers inside the bars represent the number of investment decisions made in the specific year. For the purpose of illustration, the number 42 above the bar at year 2008 indicates that 42 licenses were granted in 2008, which corresponds to the sum of the numbers inside the blue bars. The blue bars at years 2008 and 2009 indicate that for the licenses granted in 2008, there was an investment decision recorded for nine and eleven licenses in the respective years. NI on the horizontal axis means that no investment has been recorded in the observation period.

Figure 3.2 and Figure 3.3 follow the same principle, but the data set is divided by investor type. We clearly see that the non-professional investors make investment decisions sooner after the license is granted than what is observed for the professional investors. This suggests that the non-professional investors may be taking the approach of a now-or-never investment, while the professional investor seem to be more likely to postpone the investment decision longer. This is interpreted in the direction of non-professional investors behaving according to the NPV investment rule, whereas the professional investors behave more in line with the RO approach. This is consistent with findings by Linnerud et al. (2014).

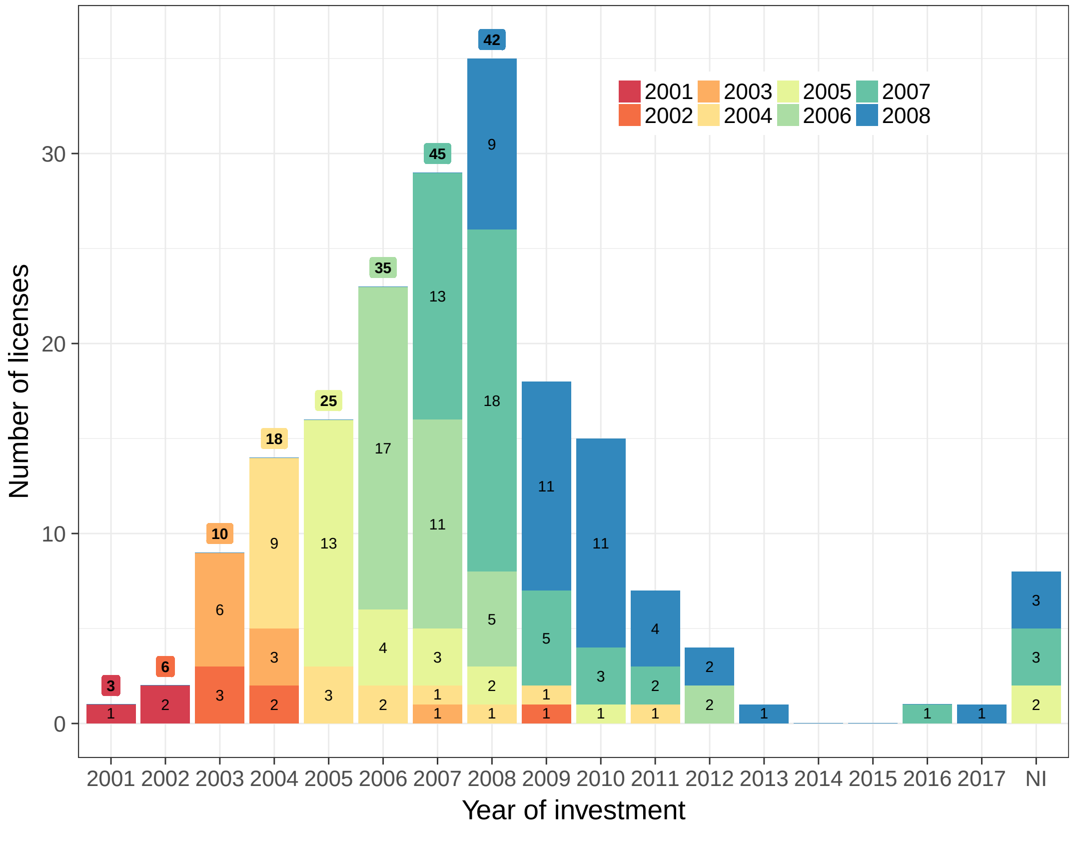

Figure 3.1: Timing of investment relative to time of licensing for all investors

During our observation period, we see a steady increase in the percentage of licenses granted to professional investors. This lends credibility to the hypothesis raised in Section 1.3 that the most profitable projects are developed first, and as time passes, the available projects become increasingly inaccessible to non-professionals due to lack of competence and capital. This will probably also favor large investors in the professional group, as

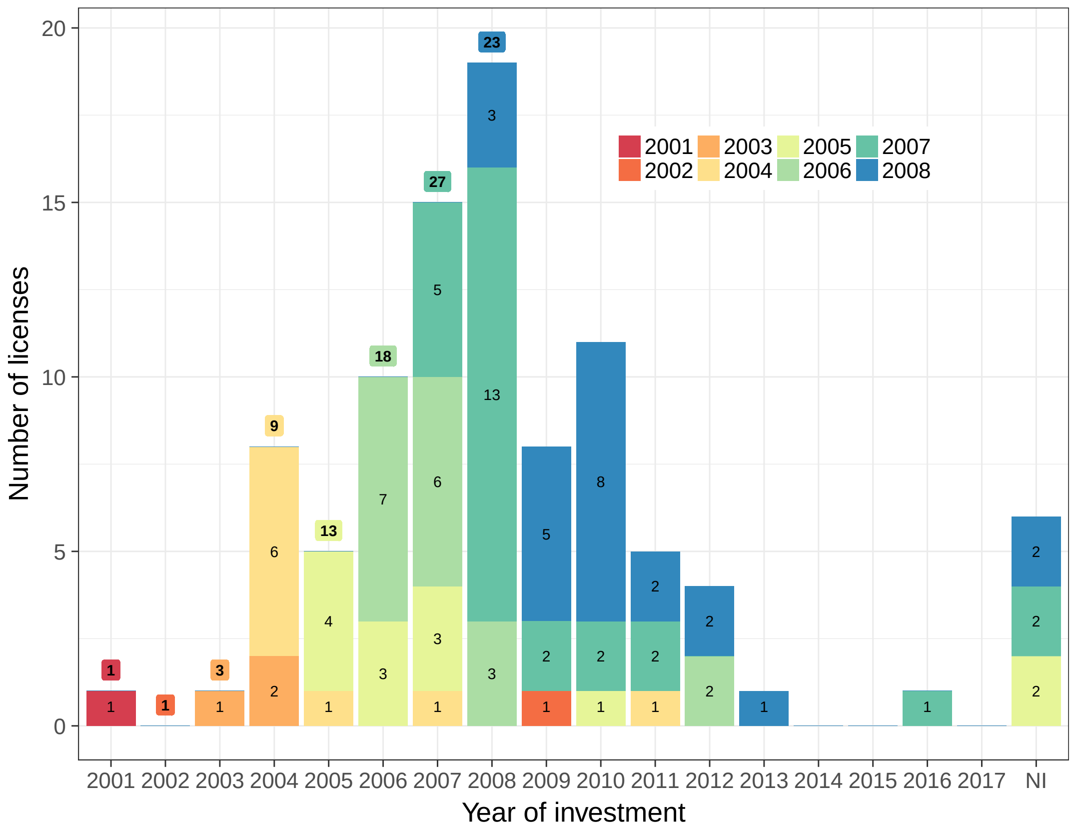

Figure 3.2: Timing of investment relative to time of licensing for professional investors

there are considerable differences between individual professional investors when it comes to competence on developing projects, according to Rune Skjevdal[5].

According to a digital mapping of the remaining feasible hydropower potential in Norway done by NVE, the remaining potential is 23.2 TWh when an investment threshold of 1250 €$/MWh$ is used, and 5.7 TWh with a threshold of 625 €$/MWh$ (The Solberg Government 2016). These numbers are estimates made after the period where licenses were granted in our data. However they clearly show that the potential for new hydropower is diminishing, and that the potential for less expensive projects is limited. The tendency of professionalization of the investors is accompanied by increasing average LCOE of the projects, as shown in Figures 3.4 and 3.5. This leads to higher investment cost on average for the licenses owned by professional investors. In addition, less complicated projects might favor non-professionals as they can do much of the groundwork themselves[6]. These effects will probably mask some of the real costs of developing the projects owned by non-professionals, and further contribute to the differences in LCOE between the investor groups, clearly shown in figure 3.5.

In total, this introduces a time-dependent heterogeneity in our data set that raises questions about whether the data can be treated without compensating for this development. The main consequence of this is that differences between professional and non-professional investors might be caused by the skew in the data and not characteristics of the investor

[5]Hydropower professional, CEO of NGK Utbygging AS.

[6]Most non-professionals are farmers or groups of farmers with access to equipment and knowledge about less complicated construction work.

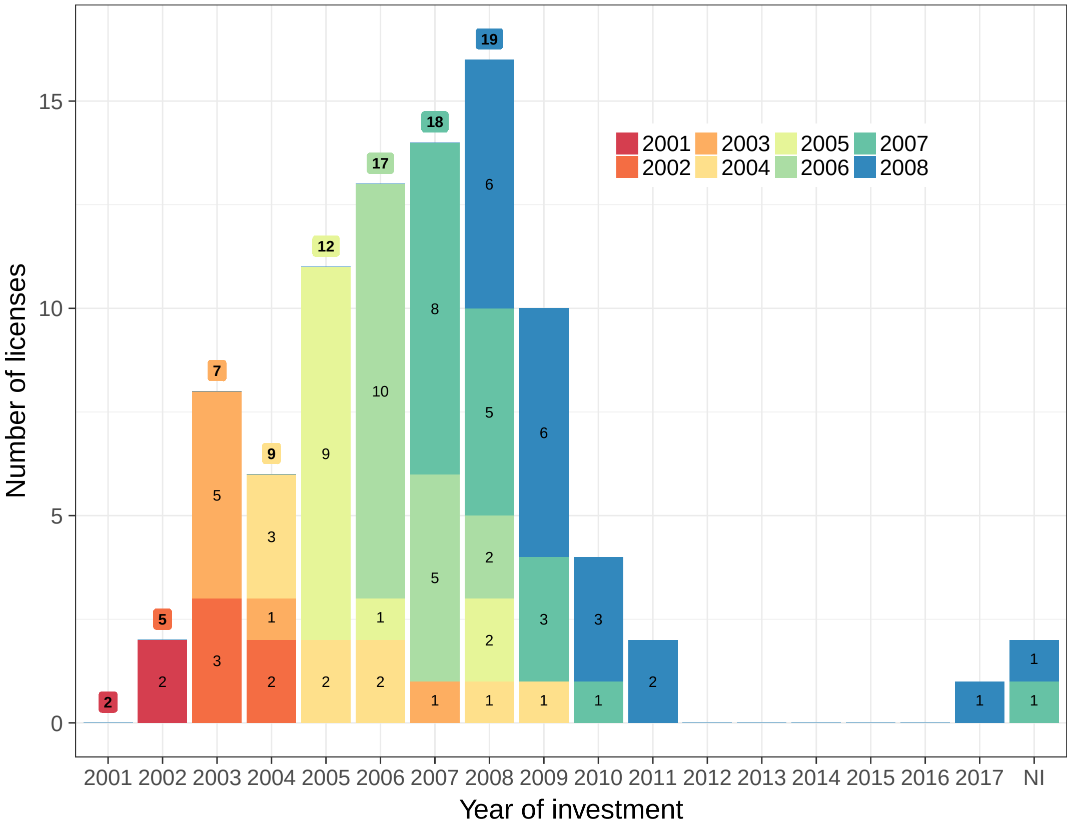

Figure 3.3: Timing of investment relative to time of licensing for non-professional investors

types per se. In turn, this will weaken findings pointing in the direction of differences in economic rationale between the investor groups, because the investor behavior is determined by circumstance, not choice. This is also applies for earlier research making the distinction between professional and non-professional investors, such as Linnerud et al. (2014). Further research on investor behavior should consider the possibility of addressing the time-dependent development in the accessibility of projects.

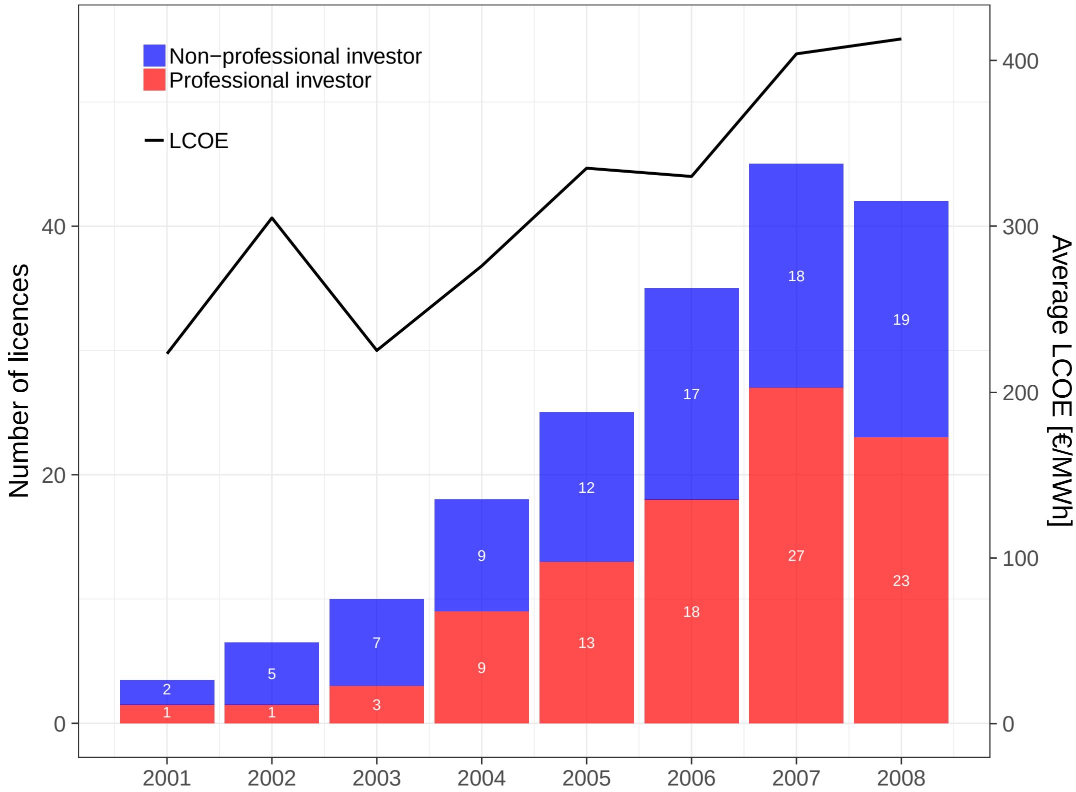

Figure 3.4: Licenses granted by investor type compared to LCOE development

3.3 Explanatory variables

In addition to gaining insight related to investor behavior, we want to analyze how different characteristics of a project affect the duration of the licenses. This analysis will aid in identifying the most likely investment rule pursued by professional and non-professional investors by running a Cox regression. Including other project-specific information, we hope to explain any discrepancy between the theoretical and empirical duration curves. Covariates are chosen to reflect the heterogeneity in the data set by characteristics of the individual projects, that are not incorporated in the theoretical models describing the investment rules. This follows the logic of Favero et al. (1994) for choosing covariates. Table 3.2 summarizes the variables used in our models. Some of the variables deserve a short explanation about how we believe that they affect the duration of licenses. These are presented below.

capacity : Higher installed capacity will be more expensive, but adds flexibility to the production[7]. We expect the added complexity that follows higher installed capacity to outweigh the benefits of added flexibility, and thus delaying the investment.

prod : Annual energy production is a good measure of the future cash flows the investor can expect the hydropower plant to generate[8]. The annual average production is also expected to capture various geographic factors determining the access to water for production.

[7]Norwegian hydropower production is highly seasonal and dependent on precipitation (Fanelli et al. 2015).

[8]The Nordic power market is an energy only market (Botterud & Doorman 2008).

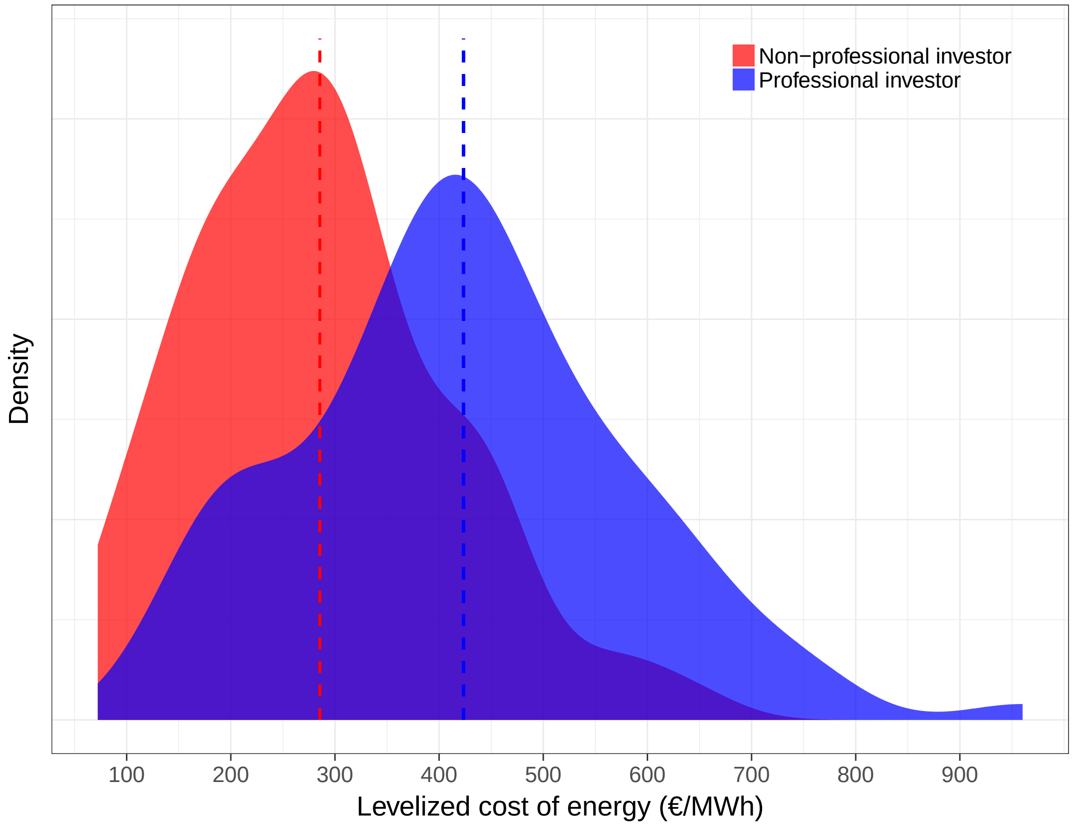

Figure 3.5: Distribution of LCOE by investor type

We expect projects with high production to be developed before projects with lower production.

runtime : The time spent producing divided by the power output measures the number of hours in a year the generator is running, if assuming that it always runs at full speed. High runtime[9] indicates that the generator can produce electricity at times when generators with lower runtime do not run. Therefore, increased runtime increase the profitability, and is expected to advance the investment decision.

dam : Some reservoirs allows for water storage and production planning, thus increasing production flexibility. Projects with higher production flexibility are more attractive and we expect them to be developed sooner.

We have chosen not to include variables for investment cost in the regressions, as this information is already captured by the time-dependent dummy variables for whether investment is optimal or not, conditional on the investor behaving according to a given investment rule. These are described in Table 3.2.

[9]Flow duration is the more commonly used term for this measure, but we use runtime to avoid confusion with the statistical method.

Table 3.2: An overview of variables used in the regressions

Variable name	Describes	Variable type	Explanation	Unit
capacity	Project size	Continuous	Rated capacity of installed (planned) generators	MW
prod	Project size	Continuous	Estimated annual production of power plant	MWh
runtime	Project utilization	Continuous	Annual energy production divided by installed capacity, hours running at max capacity	$hours$
dam	Production flexibility[a]	Binary	1 if project is planned with reservoir, 0 otherwise	-
$D\_A\_ROA_t$	Investment behaviour	Binary[b]	1 if investor should invest at time t according to RO theory and expectation set A, 0 otherwise	-
$D\_A\_NPV_t$	Investment behaviour	Binary[b]	1 if investor should invest at time t according to NPV theory and expectation set A, 0 otherwise	-
$D\_B\_ROA_t$	Investment behaviour	Binary[b]	1 if investor should invest at time t according to RO theory and expectation set B, 0 otherwise	-
$D\_B\_NPV_t$	Investment behaviour	Binary[b]	1 if investor should invest at year t according to NPV theory and expectation set B, 0 otherwise	-
$D\_C\_ROA_t$	Investment behaviour	Binary[b]	1 if investor should invest at time t according to RO theory and expectation set C, 0 otherwise	-
$D\_C\_NPV_t$	Investment behaviour	Binary[b]	1 if investor should invest at time t according to NPV theory and expectation set C, 0 otherwise	-
el_t	Revenue potential	Continuous[b]	Observed electricity price at time t	€$/MWh$
$cert_t$	Revenue potential	Continuous[b]	Observed certificate price at time t	€$/MWh$

a: See discussion regarding this variable in section 3.1.
b: Time-dependent variables.

4 Results

4.1 Duration curves for empirical data

Figure 4.1 shows the duration curve for the complete data set, based on the Kaplan-Meier estimator described in Section 2.1.1. It shows that approximately 40% of the license holders make the decision to invest within the first year after the license is granted. The number at risk[1], is rapidly decreasing the first few years, and after two years the duration curve flattens out. Six years after license approval the number at risk is only 7.7% of the initial license holders, and after twelve years more than 98 % of the licenses has either expired without an investment decision, or more commonly, the decision to develop the project is made.

We stratify the data by investors type to assess the validity of our assumption that the non-professional investors owning only one license behave differently than the professional investors owning more than one license. This is shown in Figure 4.2.

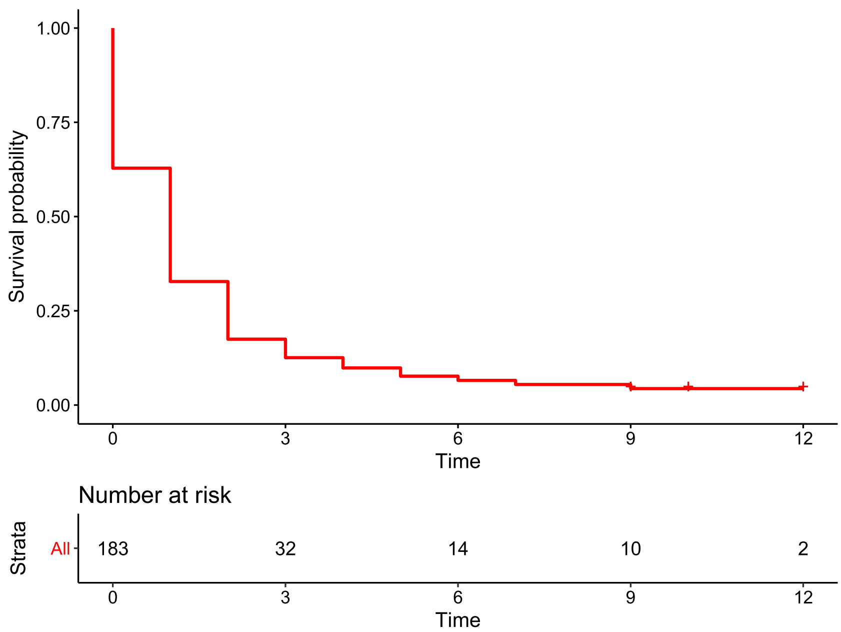

Figure 4.1: Kaplan-Meier duration curve for all licences granted from 2001 to 2008. Time in years from license approval.

Based on the log-rank test, we can conclude that H_0 of the duration curves being equal can be rejected on a highly significant level ($\alpha = 1\%$) for the binary variable describing investor type. In line with the results from Linnerud et al. (2014), there is reason to believe that one can observe differences in investment behavior based on investor type. This result justifies our division of investor types into professional and non-professional investors based on how many licenses they possess, and we will in the following conduct separate analysis on the two investor types.

[1]The number of licenses that has not been used.

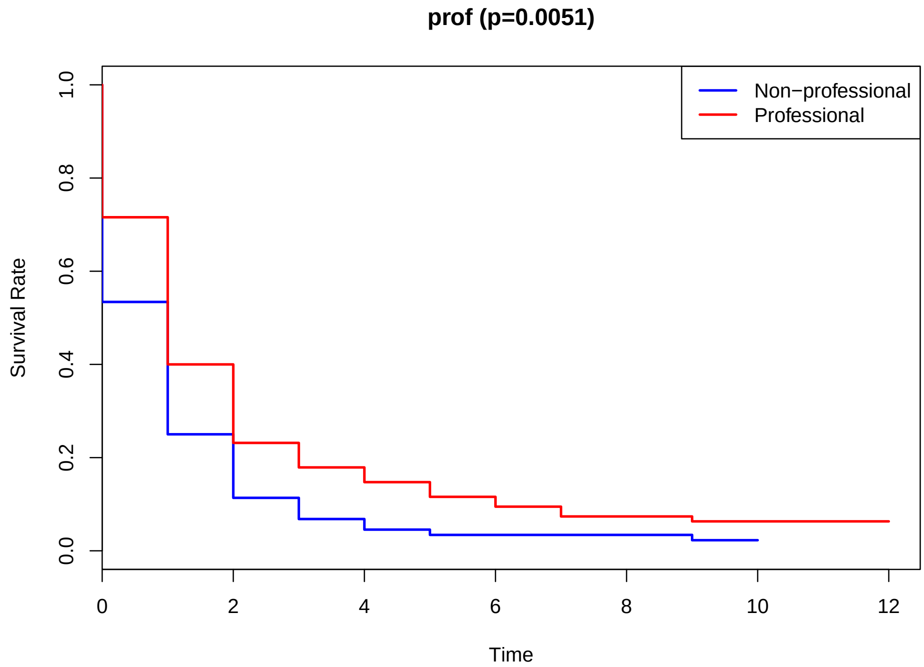

Figure 4.2: Kaplan-Meier estimators stratified by investor type

4.2 A visual interpretation of the Kaplan-Meier curves

Figure 4.3 and 4.4 compare the observed duration curve in our data set to the constructed duration curves from the optimal year of investment as predicted by the six theoretical models defined in Table 2.2, for non-professional and professional investors, respectively.

We look for curves of similar shape to the empirical duration curves, since vertical shifts in the constructed duration curves can be explained by effects not captured in our models, as investment cost is the only project-specific characteristic that is included. By visual inspection of the curves, we can conclude that some of the scenarios do not seem to be good representations of the observed investment behavior.

In particular, for the non-professional investors in Figure 4.3, the two-factor model combined with expectation set C seems to imply investment at a stage much earlier than what was observed. The results for expectation sets A and B are similar, but the duration curves of expectation set A is being offset in the direction of later investments. This intuitively makes sense, since investors following expectation set A do not expect revenue from el-certificates. The revenue potential is lower, leading to a less profitable project, and in turn the duration curves will flatten out sooner. The NPV decision rule seems to lead to many investments being undertaken too early for expectation sets A and B to match the empirical data. Real options theory can help in explaining this tendency to wait longer than the NPV curves predict, and it seems that non-professional investors expect some level of subsidies in the future.

For the professional investors in Figure 4.4, we see a different pattern. Here, the one-factor models in expectation set A and B give investment thresholds so high that investment is

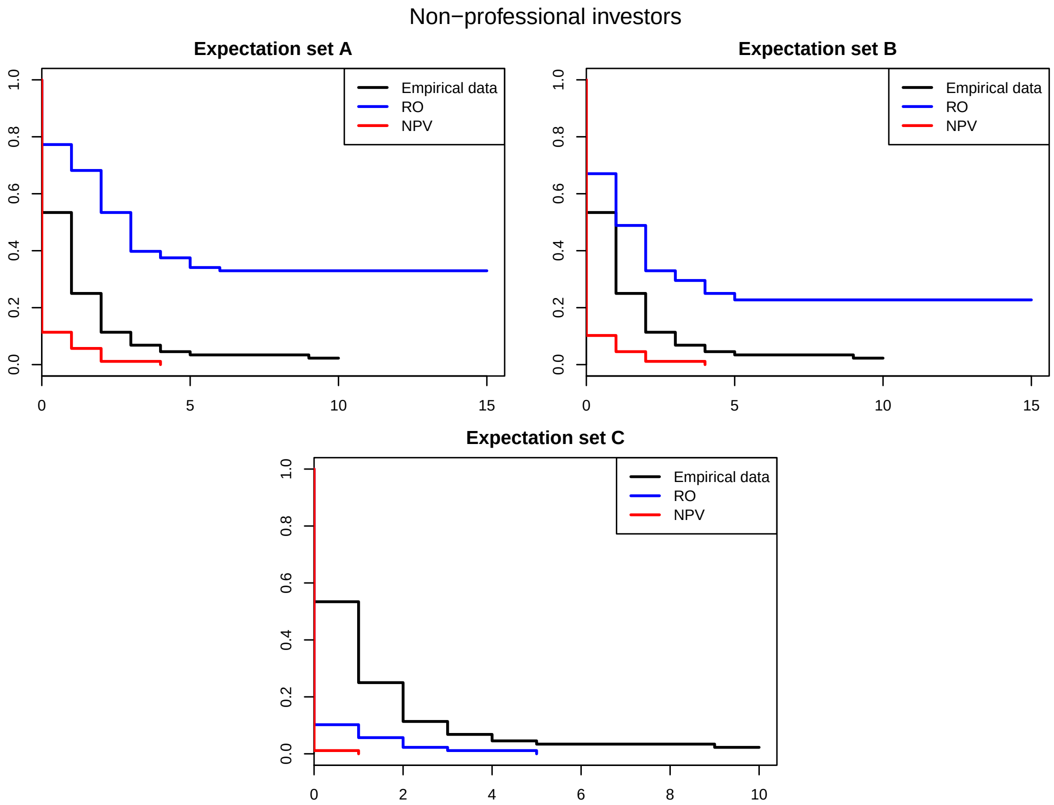

Figure 4.3: Kaplan-Meier duration curves for three sets of investor expectations and two different investment rules, for non-professional investors. X-axis is time in years from license approval, y-axis is survival probability

never optimal for a large share of these investors under the RO approach. However, we must keep in mind that the option to invest is modelled as a perpetual option. Under this assumption, the investor does not have to take into account that the license eventually will expire. A more realistic assumption regarding the expiration of licenses would reduce the value of waiting, making the RO curves more similar in shape to the NPV curves. We see the effect of introducing expectations of a future subsidy scheme in expectation set B as a downward shift compared to the curves in expectation set A. Also for the professional investors, the NPV rule seems to lead to a large share of early investments, for all sets of expectations. Expectation set C, where investors expect subsidy revenues from the first year, seems to give decent results when the investment decision is made according to RO theory. Expectation set B and C represent rather conservative and very enthusiastic expectations to subsidy revenues, respectively, and the true investor expectations for professional investors are likely to be somewhere in between.

These first results point in the direction that professional investors follow an approach most in line with RO theory. For the non-professional investors, there is some ambiguity about which decision rule most appropriately fits the observed behavior, but we conclude that they do not invest according to expectation set C. We also suggest that there are different expectations between investor types regarding how the subsidy scheme will be designed, if introduced, with the professional investors being the more optimistic.

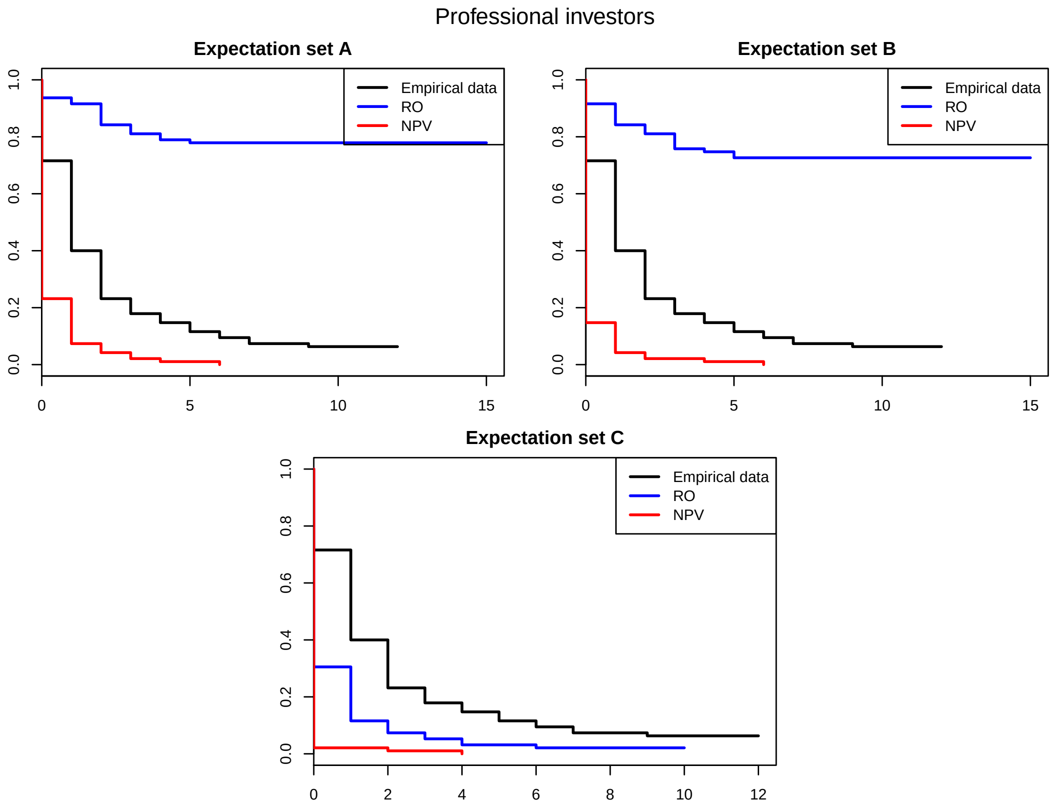

Figure 4.4: Kaplan-Meier duration curves for three sets of investor expectations and two different investment rules, for professional investors. X-axis is time in years from license approval, y-axis is survival probability

4.3 Results from Multivariate Cox Regressions

Tables 4.1 and 4.2 show the results of running Cox regressions on the observed investment decisions using variables outlined in Table 3.3. These regressions help to quantify our preliminary findings from Section 4.2, as well as providing additional insight. When interpreting the data it is useful to keep equation 2.1 in mind, as the coefficients in the regression appear as the β vector in this equation. Thus, a negative coefficient will indicate a reduction in the hazard rate, and hence an increased duration, and a positive coefficient will have the opposite effect. A zero coefficient will not have any impact on the hazard. The binary decision variables deserve special attention. If the investor acts according to the decision variable in question, we would expect to see a rapid increase in hazard[2] at this point in time[3], and thus a corresponding steep section in the duration curve. Such rapid increases in the hazard are equivalent to large positive values of the coefficients.

4.3.1 Non-professional investors

In our discussion of the Kaplan-Meier curves in Figure 4.3, we suggested that the non-professional investors tend to exhibit a limited belief in the introduction of a subsidy scheme through their investment behavior. Overall, they invest at a later stage than what was optimal according to expectation set C from Table 2.2. However, it was harder

[2]The event rate of the investment decision to be made in the next infinitesimal time step.
[3]We emphasize that this is time relative to the defined time of origin, not calendar time.

Table 4.1: Cox regression output for non-professional investors

	Dependent variable:		
	hazardNonProfessional		
	(1)	(2)	(3)
capacity		0.188	0.236
		(0.460)	(0.455)
prod		-0.046	-0.029
		(0.116)	(0.114)
runtime		0.0001	0.0001
		(0.0004)	(0.0004)
dam		0.141	0.139
		(0.281)	(0.270)
$D\_A\_ROA_t$	0.548	0.851**	
	(0.395)	(0.419)	
$D\_A\_NPV_t$	-1.463*	-0.805	
	(0.755)	(0.779)	
$D\_B\_ROA_t$	0.430	0.622*	
	(0.350)	(0.364)	
$D\_B\_NPV_t$	3.012***	3.052***	
	(1.038)	(1.040)	
$D\_C\_ROA_t$	0.450		1.359**
	(0.617)		(0.559)
$D\_C\_NPV_t$	13.100		14.770
	(2,640.220)		(3,926.906)
el_t		-0.045**	-0.008
		(0.018)	(0.014)
$cert_t$		0.002	-0.015
		(0.025)	(0.023)
Observations	190	190	190
R^2	0.150	0.187	0.072
Max. Possible R^2	0.961	0.961	0.961
Log Likelihood	-293.024	-288.819	-301.376
Wald Test	23.980*** (df = 6)	32.040*** (df = 10)	9.710 (df = 8)
LR Test	30.895*** (df = 6)	39.305*** (df = 10)	14.189* (df = 8)
Score (Logrank) Test	29.977*** (df = 6)	38.606*** (df = 10)	11.489 (df = 8)
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 4.2: Cox regression output for professional investors

	Dependent variable:		
	hazardProfessional		
	(1)	(2)	(3)
capacity		0.262	0.312
		(0.274)	(0.269)
prod		-0.074	-0.078
		(0.071)	(0.069)
runtime		0.0003	0.0003
		(0.0003)	(0.0003)
dam		0.232	0.236
		(0.253)	(0.250)
$D\_A\_ROA_t$	0.388	0.418	
	(0.723)	(0.720)	
$D\_A\_NPV_t$	0.436		1.069**
	(0.556)		(0.533)
$D\_B\_ROA_t$	0.713	0.679	
	(0.608)	(0.607)	
$D\_B\_NPV_t$	0.058		0.039
	(0.623)		(0.620)
$D\_C\_ROA_t$	0.336	1.030***	
	(0.380)	(0.315)	
$D\_C\_NPV_t$	1.784		2.152*
	(1.191)		(1.197)
el_t		-0.029*	-0.043**
		(0.017)	(0.018)
$cert_t$		-0.028	-0.016
		(0.021)	(0.021)
Observations	293	293	293
R^2	0.068	0.076	0.078
Max. Possible R^2	0.895	0.895	0.895
Log Likelihood	-320.263	-319.060	-318.678
Wald Test	18.530*** (df = 6)	23.740*** (df = 9)	19.890** (df = 9)
LR Test	20.671*** (df = 6)	23.077*** (df = 9)	23.840*** (df = 9)
Score (Logrank) Test	21.151*** (df = 6)	25.938*** (df = 9)	21.599** (df = 9)
Note:			*p<0.1; **p<0.05; ***p<0.01

to interpret which of the investment decision rules provide the most explanatory power among the likely set of expectations (A and B). In model (2), we therefore included the binary decision variables from expectation set A and B to gain further insight. In model (3), we tested the decision variables from the less plausible expectation set C. In models (2) and (3), we included project-specific variables whose effects is not captured in the construction of the theoretical duration curves, as well as variables for observed prices. We also ran a regression with all the possible decision variables in model (1) to check if the results from this regression is consistent with our discussion in the previous section.

The output from the Cox regression for the non-professional investors in Table 4.1, show that there is a highly significant relationship between the electricity price el_t and the duration of licenses. The negative sign of the coefficient means that it will cause a reduction in hazard, which implies a flattening of the duration curve as the price increases. This is contradicting our intuition that a rational investor will invest sooner in periods with higher prices. The coefficient is however fairly close to zero, so the impact on hazard is limited. This is also the case for the el-certificate price $cert_t$, but this coefficient is not significant. None of the non-economic, project-specific covariates *capacity*, *prod*, *runtime* or *dam* are significant. *runtime* and *prod* have coefficients close to zero, which further confirms that they do not influence duration. We get significant effects from the investment decision variables, apart from the NPV rule for expectation set A. The highest impact on the reduction in duration is found for the NPV rule in combination with expectation set B. This is also the coefficient with the highest significance. The negative coefficient for $D\_A\_NPV_t$ does not make sense, since this implies a lower hazard in periods where investment under this investment rule is optimal, implying that investors act counter-optimally.

When testing the decision variables from expectation set C in model (3), we get significant results for the RO variable, but insignificant results for the NPV variable. We note that the Wald test[4] score for model (2) is substantially higher than for model (3). In total, this leads us to the conclusion that non-professional investors to a limited degree expect revenue from el-certificates in their project, as expressed in expectation set B, and that they tend to follow an NPV approach when making the investment decision, in line with our expectations from the preliminary investigations of the data set. The results also align well with previous research, such as Linnerud et al. (2014), but challenges the underlying assumption of homogeneous subsidy expectations for all investors in Fleten et al. (2016).

4.3.2 Professional investors

In Section 4.2, we arrived at the conclusion that the professional investors showed signs of behaving in accordance with real options theory. We follow a similar approach as for the non-professional investors when choosing the variables in the regression. We included the RO decision variables from all the expectation sets in regression model (2), and the NPV decision variables in model (3). These models also include the project-specific characteristics, as well as the price variables. Model (1) is once again used to investigate our belief that professional investors indeed follow an RO approach.

The results from this regression are shown in Table 4.2. For all three regressions, we see that also for professional investors, el_t has a significant impact on duration. The sign is

[4]A commonly used measure for goodness of fit in duration analysis.

negative, indicating that a higher electricity price increases duration, however with low impact because of a coefficient close to zero. The output from model (1) is somewhat more ambiguous than the corresponding model for the non-professional investors in table 4.1, giving no significant estimates for the decision variables. The results from model (2) indicate that the professional investors' behavior is most consistent with the RO approach under expectation set C. The positive coefficient suggests that the hazard is rapidly increasing at points in time where the real option decision indicator under expectation set C suggests that investment is optimal. Model (3) gives significant results for both expectation sets A and C, and expectation set A exhibits the highest significance levels among the net present value indicator variables.

Overall, we conclude that model (2) is the model that most appropriately describes the empirical data, however less clearly than the results for non-professional investors. This implies that professional investors expected the introduction of a subsidy scheme and that they exhibit investment behavior best described by real options theory. This aligns well with earlier research by Linnerud et al. (2014) and Fleten et al. (2016) and our discussion in Section 4.2, as well as our findings in Section 3.2. The regression models have lower goodness of fit for the professional investors than for the non-professional investors, strongly indicating that there are factors not included in the analysis that influence the investment timing for professional investors. These findings are further discussed in Section 5.

RO theory emphasize the value added from postponing investment and obtaining new information. This is the theoretical foundation for our argumentation above. However, there might be other reasons for investors choosing to postpone their investment than the added value of waiting. Linnerud et al. (2014) emphasized that investors in small hydropower projects also have to deal with non-economical factors that might cause them to postpone their investment decision. Such factors include complaints filed by investors or stakeholders, grid access issues, or problems regarding project funding. These effects are not explicitly captured in our analysis, and might help explain the discrepancy between theoretical and empirical curves.

5 Discussion of the results

Our findings suggest that the investment behavior of professional and non-professional investors differ, and hence confirms findings by Linnerud et al. (2014). However, Linnerud et al. (2014) fail to address the effect of the rent for utilizing the watercourse.. This rent affects the comparability of the profits of professional and non-professional investors. Therefore, their conclusion is drawn without recognizing that the results for the professional investors are biased, indicating better profitability than is really the case.

The relationship between profitability and utilization rent introduces an endogeneity in our analysis. The profitability of a project depends on the utilization rent required by the landowner. More profitable projects will likely be subject to higher utilization rents, since we assume the landowner to be informed about the high profitability of the project, thus possessing bargaining power when facing professional investors. This will in turn make the project comparatively less profitable for a professional investor, and we have a simultaneous causality between project profitability and utilization rent.

However, we believe that we have limited the possible effects of this endogeneity by separating the professional and the non-professional investors in our analysis, since the biased results for the professionals are not compared to the results for the non-professionals. Nevertheless, for professional investors, it is still a fact that some projects will require the investor to pay a higher utilization rent than others, effectively introducing an endogeneous relationship between project profitability and utilization rent. Future research should consider methods for mitigating the effects of this endogeneity, for example by including data on utilization rent.

To our knowledge, duration analysis has not previously been used to compare investor behavior for renewable energy projects. By controlling for project-specific factors in the Cox regression, we confirm that the decision to build a hydropower plant is purely financial, where the economic characteristics of the project captures the decision-relevant information. Therefore, we believe that the conclusions made in earlier research are not affected by the exclusion of such factors.

We conclude that the professional investors behave in a way most accurately described by the theory of investment under uncertainty, whereas the non-professional investors' behavior aligns better with the view of the investment opportunity as now-or-newer. An explanation can be that professional investors are better informed about the value of waiting, whereas the non-professionals lacks the experience to recognize how uncertainty favor waiting.

In our data, projects held by professional investors on average have higher LCOE than those of the non-professional investors. Projects with low LCOE allow for a higher degree of debt financing, making non-professionals able to develop the projects without involving professionals. There are examples of projects being financed solely by debt-financing (Watle & Sontum 2004)[1]. As discussed earlier, there is reason to believe that non-professionals do some groundwork themselves, and thereby mask some of the development costs. Also, better competence and financial backing make professionals able to take on more complex projects.

[1] Also confirmed by Rune Skjevdal.

The prolonged time between the licensing and investment decision for professional investors might simply be caused by the fact that the projects are less favorable to invest in. Hence, the licence will be kept alive for a longer period of time, waiting for circumstances to improve. If this is the case, it weakens the conclusion that professional investors to a larger extent considers the value of waiting than non-professionals. This skew in costs between investor types is not taken into account by Linnerud et al. (2014) and Fleten et al. (2016).

Another consideration worth noting is that there are factors influencing the decision to invest, that are neither economic nor related directly to the project characteristics as pointed out by Bergek et al. (2013) and Linnerud et al. (2014). The existence of such barriers to investment are confirmed in interviews with investors during this study. The significantly lower explanatory power in the results for professional investors suggest the presence of such external factors not captured in our data set. One such factor might be a portfolio effect[2], which arises when a professional investor has multiple licenses available for development. In this case, they will choose to develop the less costly projects first, and other projects will be postponed due to capacity restrictions. This might cause other profitable projects in the investors portfolio to be put on hold, even though investment is optimal when considered in isolation. Future research should consider extending the data set to capture such factors that could influence the timing of the investment decision.

We find clear indications of different expectations to support schemes. The professional investors seem to have expected retroactive subsidies, as signaled by the government in 2004. The non-professional seem to have had more modest expectations towards the introduction of subsidies. One explanation can be that the professional investors were more informed about the political discussion about support schemes, and therefore had more realistic assumptions. Our findings can also help nuance the conclusions drawn by Fleten et al. (2016) regarding investor rationality and expectations to future subsidies, as no distinction between investor groups was made in their paper. Our results indicate that many investors make their decision based on political signals of retroactive subsidies. However, when subsidies were introduced, small hydropower received subsidies only if the power plant was built after 2009. Even though outside the scope of this paper, this is an interesting example of how politically induced uncertainty influences investor behavior.

We have assumed that the options to invest in the hydropower projects are perpetual options. In the real world, these options expire after ten years[3]. Thus, waiting might be less favorable for the investor as the expiration date approaches. We justified our assumption of perpetuity by highlighting that the right to utilize the watercourse will still belong to the landowner, which in theory can reapply for the same license at later point in time. This assumption holds better for non-professional investors than for professional investors, who might face competition from other professional investors in the case where a landowner once more finds the development of the watercourse interesting. If we had modelled the real option using a binomial model, we would observe earlier optimal investments for professional investors as the real option value approaches net present value when time approaches expiration. Some of the discrepancy between the empirical duration curve and the theoretically constructed duration curves could thereby be explained.

[2]Confirmed in interviews with Rune Skjevdal, CEO NGK Utbygging AS.

[3]The license to invest expires after five years, but it can be renewed for five new years without much effort.

We encourage future studies to explore the possibilities for a more nuanced approach to the expiration of the real options in their models.

6 Conclusion

This study utilizes duration analysis to analyze investor behavior when faced with the option to invest in a small hydropower plant. We make the distinction between professional and non-professional investors, as a contemporary trend in energy markets is the emergence of non-professional actors as investors in generation capacity. For each group, we find the optimal investment time for a NPV and RO approach, given the observed electricity prices and subsidies as observed in a related market. Then, through Cox regression, we assess which decision rule provides most explanatory power by comparing the theoretically optimal year of investment to the observed investment decisions for 184 hydropower licenses granted in Norway between 2001 and 2008. This method allows for control of other project-specific characteristics such as installed capacity and annual energy production for each power plant. By controlling for project-specific characteristics, we confirm that an approach only considering economic theory captures the decision-relevant aspects of the investment problem, not gaining further insight by including project-specific attributes beyond cost data.

Our empirical analysis shows that professional investors tend to act in accordance with the theory of investment under uncertainty, taking into account the value of waiting, whereas the non-professionals seemingly view the investment opportunity as now-or-never. We also uncover clear differences in the expectations to future subsidy schemes between the groups. The professional investors seem to have expected retroactive subsidies in line with the Swedish price levels, whereas the non-professionals had far more conservative expectations to subsidies.

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A Duration analysis

A.I The survival and hazard functions

Duration analysis aims to estimate the true survival function for the population from which the studied sample is drawn. In the following, assume that T is the non-negative random variable representing the time until an event happens for a subject from a homogeneous population. Kalbfleisch & Prentice (2002) state that the survival function is defined for discrete and continuous distributions by the probability that T exceeds a value t in its range, so that

$$S(t) = Pr\{T \geq t\} = 1 - F(t) = \int_t^{\infty} f(x)dx \tag{A.1}$$

Where $F(t)$ is the cumulative distribution function. In our case, the survival function at time t represents the probability that a license is unused at time t, meaning that the investor holding the license has not made an investment decision yet.

Closely related to the survival function is the hazard function. Generally, the hazard function is specified as follows

$$h(t) = \lim_{dt \to 0+} \frac{P(t \leq T < t + dt | T \geq t)}{dt} = \frac{f(t)}{S(t)} \tag{A.2}$$

The hazard function specifies the instantaneous rate at which events occur for subjects that are surviving at time t. Specific to our data set, this constitutes the rate at which licenses are being utilized at a time t, given that they have not been utilized up until time t.

A.II Modeling the duration curve

One can model duration data using parametric, semi-parametric and non-parametric duration models. The table below illustrates how the assumptions of the models differ. The

Table A.1: Comparing different duration models (Srivastava 2015)

Type of model	Baseline hazard	f(covariates)
Non-Parametric	No distribution assumed	No distribution assumed
Semi-Parametric	No distribution assumed	Some distribution assumed
Parametric	Some distribution assumed	Some distribution assumed

true duration curve of a population may be well represented by some known distribution, such as a Weibull distribution or an exponential distribution. This distribution is known as the baseline hazard. If the duration of the population can be assumed to follow a known distribution, a parametric model will be most appropriate. However, in most real life examples, the true survival and hazard functions are complex, and specifying the baseline parametric distribution may be challenging or impossible. This kind of complexity is present in our study. There is no evident reason in the nature of hydropower licenses suggesting that the survival function for such licenses (or other comparable types of licenses) should follow a named distribution.

Therefore, we employ the non-parametric Kaplan-Meier method, and the semi-parametric Cox model to analyze the time from license approval to a potential investment decision. These methods allow us to analyze the duration of the licenses without having to specify any distribution for the baseline hazard function (Cox 1972).

A.III The Kaplan-Meier Estimator

The Kaplan-Meier estimator is given by

$$\hat{P}(t) = \prod_{i:t_i \leq t} \left(1 - \frac{d_i}{n_i}\right) \tag{A.3}$$

where d_i is the number of deaths before time t_i, and n_i is the total number of subjects. This expression can be interpreted as the function that maximizes the likelihood of observing the sample data. The Kaplan-Meier estimator allows for stratification of the data set. Stratification means dividing the original data set into subsets based on certain characteristics and plotting the duration curve estimates for the individual subsets. By dividing the duration data into different strata, we are able to study how these characteristics influence the timing of the event. As an example we divide the data into two groups based on whether the investor is professional, illustrated in Figure 4.2 in Section 4.1.

A log-rank test is used to check the likelihood of obtaining different empirical duration curve estimates which originate from the same population. If the result from the log-rank test is significant, we reject the null hypothesis of equal duration curves and the Kaplan-Meier estimation for the different subsets can be viewed as a starting point for further analysis. The Kaplan-Meier estimation is only appropriate for assessing the effect of a limited number of covariates at once. To assessing the effect of several covariates simultaneously, a Cox regression models is more appropriate.

A.IV The Cox Model

We have the Cox model:

$$h_i(t) = h_0(t)e^{\beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik}} = h_0(t)e^{\beta \mathbf{x}'} \tag{A.4}$$

The model is semi-parametric because the baseline hazard $h_0(t)$ is unspecified, meaning that we make no assumptions about its shape. In some cases, using a semi-parametric model instead of a correctly specified parametric model will yield worse results. However, as discussed above, to correctly specify a baseline hazard one needs to assume a distribution of the data.

A hazard ratio describes how a unit change in a covariate influences the duration of a subject, keeping the other covariates constant.

A.V Censored data

Censored data has not experienced an event during the observation period. In the data set analyzed in this thesis roughly 5 % of the data is right-censored[1]. In our study, there are two causes for censoring of data:

1. No event has occurred by the end of the period in which the subjects are studied. In our case, this means that a license remains unused as of 26.10.2017.
2. A subject cannot be a part of the study for the entire period. Licenses may expire or be withdrawn for other reasons during the period of study.

A fictitious example to illustrate censoring of data Imagine that we are to analyze the effect of a new drug on the expected remaining lifetime of patients diagnosed with a certain type of fatal cancer[2]. Let us assume that 200 patients are part of the study lasting for a time period of three years. By the end of the study, 50 patients have died, whereas 140 patients are still alive. The remaining ten patients have not been possible to follow for the entire duration of the study, due to matters related to external factors making it impossible for them to complete the study. For the 150 patients that did not die in the observation period of the study, we do not know when death will occur, only that is did not occur during the time the subjects were a part of the study. When analyzing the data from this study using linear or logistic regression, the 150 patients who are still alive by the end of the study are hard to handle because we do not know the exact time when death occurred. Excluding these patients would underestimate the time until death as we only consider those patients who dies during the study. Interpreting these patients as cured would overestimate the time until death because some of the patients are likely to die during the time after the end of the study. Analogous to our analysis, using duration analysis is appropriate because it allows us to handle the licenses where no investment decision has been made before the end of the study, and include the licenses that have expired (loss of follow-up) as these subjects brings valuable information to the study.

[1]Right-censoring occurs when an object leaves the study without experiencing an event up until the time it it leaves the study. The concept of censoring is further discussed in Kalbfleisch & Prentice (2002).

[2]Duration analysis is widely used in medicine. A real example studying the effects of adjuvant chemotherapy for postmenopausal patients with early breast cancer can be found in Goldhirsch et al. (1989).

B Real options models

B.I Model A: One-factor stochastic model without subsidies

This model is thoroughly explained in Dixit & Pindyck (1994, p. 185), with two minor deviations. In our model, operating costs are taken as a part of the investment costs I, further discussed in Section B.2. Also, we do not have perpetual revenue streams from the project, so that the discount factor for the revenue becomes:

$$r_p = \left(\frac{1 - e^{-(r-\alpha_P)T_P}}{r - \alpha_P}\right) \tag{B.1}$$

B.II Model B: One-factor stochastic model with contributions from subsidy scheme

The price process is modelled as a Geometric Brownian Motion:

$$dP_t = \alpha P_t dt + \sigma P_t dz \tag{B.2}$$

where dz is a standard Wiener process, and α and σ is the drift rate and the volatility of the electricity price process, respectively.

We model the revenue stream from the potential el-certificate sales as a constant value, scaled down by a factor of $\rho_{t,c}$, where $\rho_{t,c}$ denotes the investors'[1] belief in year t of el-certificates to be introduced[2]. To allow for different expectations for different project sizes, we use the same approach as Linnerud et al. (2014):

$$\rho_{t,c} = \gamma_{N_t}\theta_{t,c} \tag{B.3}$$

where γ_{N_t} is the probability of an el-certificate scheme being retroactively introduced in year N_t, and $\theta_{t,c}$ is the probability of the scheme being applicable for a project with capacity c. Under these assumptions, the investors uncertainty regarding the introduction of the el-certificate scheme will be captured. Unfortunately, the simple way of modelling the el-certificate prices fails to capture any uncertainty regarding the future level of the el-certificate prices. However, the magnitude of impact on the option value depends more heavily on the introduction of the scheme itself, rather than the correct specification of the price process for the el-certificates. The estimated probabilities $\rho_{t,c}$ for each year, as well as the price at which the certificates were believed to be introduced at this year, are given in table B.1. We can express the current value of the investment as a function of the electricity price and the expected el-certificate level as:

$$V(P, n_t, S_t) = r_p P + r_s \rho_{t,c} S_t \tag{B.4}$$

[1] We assume that all investors in a given year and for our given range of capacity ($[1MW, 10MW]$) has homogeneous expectations as to whether the certificates are introduced or not.

[2] We make the simplifying assumption that all investors believe that the el-certificates will be introduced retroactively.

where

$$r_s = \Big(\frac{e^{-(r-i)T_{S_1}} - e^{-(r-i)T_{S_2}}}{r-i}\Big) \tag{B.5}$$

$$r_p = \Big(\frac{1 - e^{-(r-\alpha_P)T_P}}{r-\alpha_P}\Big) \tag{B.6}$$

We add the operational and maintenance costs of the power plant to the investment cost, following the reasoning of Fleten et al. (2016) we have:

$$I = I_0 + c_o r_c \tag{B.7}$$

where

$$r_c = \Big(\frac{1 - e^{-(r-i)T_p}}{r-i}\Big) \tag{B.8}$$

Following the dynamic programming approach of Dixit & Pindyck (1994), we set up the Bellman equation for the value of the investment opportunity and simplify it to get the ordinary differential equation (ODE):

$$\frac{1}{2}\sigma^2 P^2 F''(P) + \alpha P F'(P) - rF(P) = 0 \tag{B.9}$$

which has the solution

$$F(P) = AP^{\beta_p} \tag{B.10}$$

where β_p is the positive root of the fundamental quadratic equation

$$\frac{1}{2}\sigma^2 \beta(\beta - 1) + \alpha\beta - r = 0 \tag{B.11}$$

Applying standard value matching and smooth pasting conditions, we get

$$A = \frac{(\frac{\beta}{\beta-1} - 1)(I - \bar{S})}{\left[\frac{\beta}{\beta-1}\Big(\frac{I-\bar{S}}{r_p}\Big)\right]^{\beta}} \tag{B.12}$$

$$P^* = \frac{\beta}{\beta - 1}\Big(\frac{I - \bar{S}}{r_p}\Big) \tag{B.13}$$

where

$$\bar{S} = r_s \rho_{t,c} S_t \tag{B.14}$$

Table B.1 shows the assumptions made in the model, regarding expected subsidy level S_t, year of subsidy scheme introduction N_t, and the probabilities of the subsidy scheme to be introduced; on a global level (γ_{N_t}) and for projects of different levels of installed capacity ($\theta_{t,N_t,c}$) conditional on the scheme being introduced.

Table B.1: Subsidy probability, level of support and year of introduction, under expectation set B. Based on Linnerud et al. (2014)

	2001	2002	2003	2004	2005	2006	2007	2008
$S_t[€/MWh]$	22	22	22	21	24	24	5	23
γ_{N_t}	25 %	25 %	25 %	25 %	75 %	25 %	75 %	25 %
$\theta_{t,N_t,[1-3MW]}$	50 %	50 %	50 %	50 %	50 %	50 %	100 %	50 %
$\theta_{t,N_t,[3-10MW]}$	50 %	50 %	50 %	50 %	50 %	50 %	0 %	50 %
N_t	2004	2004	2004	2006	2007	2008	2008	2012

B.III Model C: Two-factor stochastic model

We refer to Fleten et al. (2016) for the details in this model, and restate the main characteristics. Both price of electricity P and price of el-certificates S are modelled as GBMs:

$$dP_t = \alpha_P P_t dt + \sigma_P P_t dz_P \quad \text{(B.15)}$$

$$dS_t = \alpha_S S_t dt + \sigma_S S_t dz_S \quad \text{(B.16)}$$

The value of the project will be a function of the prices P and S, the required rate of return r and the drift rates of the price processes α_S and α_S:

$$V(P,S) = r_S P + r_S S \quad \text{(B.17)}$$

where

$$r_S = \Big(\frac{e^{-(r-\alpha_S)T_{S_1}} - e^{-(r-\alpha_S)T_{S_2}}}{r-\alpha_S}\Big) \quad \text{(B.18)}$$

$$r_P = \Big(\frac{1 - e^{-(r-\alpha_P)T_P}}{r-\alpha_P}\Big) \quad \text{(B.19)}$$

T_P is the expected lifetime of the project (40 years), and T_{S1} and T_{S2} is the start-up and ending date of the revenue streams from the subsidy scheme, respectively. Also for this model, we include the variable costs c in the investment cost I of the project, by discounting the annual investment costs c_t to the present value using the inflation rate i. Thus,

$$C = c_0 r_C \quad \text{(B.20)}$$

where

$$r_C = \Big(\frac{1 - e^{-(r-i)T_P}}{r-i}\Big) \quad \text{(B.21)}$$

To value the real option, we find the maximum of the value of immediate investment, and the continuation value, represented by the Bellman equation:

$$F(P,S) = \max\Big\{V(P,S) - I, \frac{1}{1+rdt}E[F(P+dP, S+dS|P,S]\Big\} \quad \text{(B.22)}$$

Expanding by Itô's Lemma and simplifying, we get the partial differential equation

$$\frac{1}{2}\Big(\sigma_P^2 P^2 \frac{\partial^2 F}{\partial S^2} + \sigma_S^2 S^2 \frac{\partial^2 F}{\partial S^2} + 2\sigma_P\sigma_S\rho_{P,S} PS \frac{\partial^2 F}{\partial P \partial S}\Big) + \alpha_P P \frac{\partial F}{\partial P} + \alpha_S S \frac{\partial F}{\partial S} - rF = 0 \quad \text{(B.23)}$$

where $\rho_{P,S}$ is the correlation between the price processes. This equation is a second order homogeneous equation. For the technical details of the solution to this equation, we once again refer to Fleten et al. (2016), and simply state that the solution is on the form

$$F(P,S) = AP^{\beta_P}S^{\beta_S} \tag{B.24}$$

where β_P and β_S are the positive solutions to the fundamental quadratic equation for the PDE in equation B.23. The boundary to the region where investment is optimal is defined by the trigger values P^* and S^*, and the option value at this boundary is $F(P^*, S^*)$.

By applying the value matching and smooth pasting conditions,

$$F(V(0,0)) = 0 \tag{B.25}$$
$$A(P^*)^{\beta}_{P}(S^*)^{\beta}_{S} = r_P P + r_P S^* - I \tag{B.26}$$
$$A\beta_P(P^*)^{\beta_P-1}(S^*)^{\beta}_{S} = r_P \tag{B.27}$$
$$A\beta_P(P^*)^{\beta}_{P}(S^*)^{\beta_S-1} = r_S \tag{B.28}$$

it can be shown that:

$$P^* = \frac{\beta_S}{\beta_P + \beta_S - 1}\frac{I}{r_P} \tag{B.29}$$
$$S^* = \frac{\beta_S}{\beta_P + \beta_S - 1}\frac{I}{r_S} \tag{B.30}$$

At this point, we have five unknowns $(A, P^*, S^*, \beta_P, \beta_S)$, and only the four equations B.25 - B.28. For a given $P_t = P$, we introduce a new variable $\eta(P)$ and the following relationship between β_P and β_S

$$\eta(P) = \frac{I - r_p P}{r_P P} \tag{B.31}$$
$$\beta_S = \beta_P \eta(P) + 1 \tag{B.32}$$

The β's are dependent on each other, implying that the investment boundaries depend on each other. As a result, we end up with the following expression for the investment threshold for the subsidy price after specifying an electricity price $P_t = P$. Included below are also the resulting expression for the option value at the investment boundary.

$$S^*(P) = \frac{\beta_P \eta(P) + 1}{\beta_P[\eta(P) + 1]}\frac{I}{r_S} \tag{B.33}$$

$$F(P^*, S^*) = r_P^{\beta_P} r_S^{(1-\beta_P)} \beta_P^{-\beta_P} \beta_S^{(\beta_P-1)} S^{*(1-\beta_P)} P^{*\beta_P} \tag{B.34}$$

For the details leading up to the equations B.33 and B.34, we direct interested readers to Fleten et al. (2016).

The values of S^* for different values of P^* is given for our example hydropower plant in table B.6. The corresponding values for the NPV rule are also given.

B.IV Approach illustrated using Nordlandselva hydropower plant as an example

We suggest reading this part of the Appendix with Figures 2.2, 2.3 and 2.4 in mind. For each of these figures, there is a corresponding theoretical model; model A, B and C, respectively. The tables below specify the parameters specific to the theoretical models, as well as project-specific characteristics for Nordlandselva hydropower plant.

Table B.2: Parameters used in the theoretical models

Model	Parameter and symbol	Value	Unit
All models	Drift rate for electricity price (α_P)	2.5^a	%
	Volatility of electricity price (σ_P)	15	%
	Required rate of return (r)	8	%
	Lifetime power plant (T_P)	40	years
B	Probability of introduction of el-certificate scheme (γ_{Nt})	$[25, 75]^b$	%
	Probability of scheme covering plant of size c ($\theta_{t,c}$)	$[0, 100]^b$	%
	Expected subsidy level ($\bar{S}_t$)	$[5, 24]^b$	$€/MWh$
	Lifetime support scheme (T_S)	15	years
C	Drift rate for subsidy price (α_S)	2.5^a	%
	Volatility of subsidy price (σ_S)	15	%
	Correlation between electricity and subsidy price (ρ)	-0.5	-

a: Based on the exogenously defined rate of return as used in the Dynamic Programming approach by Dixit & Pindyck (1994).
b: These values are time-dependent. See Table B.1 in Appendix B.2.

Table B.3: Characteristics related to Nordlandselva hydropower plant

Characteristic	Value	Unit
Year of license approval	2003	-
Year of observed investment decision	2004	-
Total investment cost	3237500	€
Levelized Cost of Energy	340.79	$€/MWh$
Operational and maintenance cost	9	$€/MWh$
Annual production	9.5	GWh
Installed capacity	2	MW
Professional investor	True	-

The two one-factor models give investment thresholds for the electricity price. In Figures 2.2 and 2.3, the investment thresholds corresponding to a RO approach and the NPV approach are indicated by the black dashed lines denoted P^*ROA and P^*NPV respectively. We can proceed to find the optimal year of investment by comparing this investment threshold to the observed electricity prices in the years following the license approval. The optimal year of investment is the first year in which the observed price is above the investment threshold. In each model, we have indicated the theoretically optimal year of investment according to the RO approach and the NPV approach in red and blue lines, respectively. We have also included the year in which the investment decision was observed for this power plant, indicated by the green line. Expectation set B includes expectations of a subsidy scheme. Therefore, we observe a slightly lower investment threshold compared to expectation set A, which only takes into account the revenue from the sale of electricity. This makes intuitive sense, as the revenue potential is larger if the investor expects the subsidy scheme to be implemented. Figure 2.3 tells us that an investor with expectation set B with a behavior consistent with real options theory should invest in year 2008, since this is the first year in which the electricity price is above the investment threshold. There is no corresponding optimal year of investment in Figure 2.2 because the investment threshold lies above all observed electricity prices in the period from 2003 to 2017, indicating that an investor following real option theory should postpone the investment decision. If the investment decision rationale of the investor is consistent with net present value, the optimal year of investment corresponding to expectation set B is year 2004, which coincides with the observed investment decision for this power plant.

The two-factor model describes the electricity and subsidy price as separate stochastic processes. This model produces an investment boundary in a two-dimensional space, uniquely specified by the combination of an electricity price threshold and a subsidy price threshold, illustrated in Figure 2.4. Analogously to the one-factor models, if the observed combination of electricity and subsidy price lies above the investment boundary, this indicates that the investor should invest in the project. Using the same color conventions as earlier, we see that an investor with a investment decision rationale in line with the NPV approach should invest in year 2003. An investor whose investment decision rationale is in line with real options theory should invest in year 2004, which matches the observed year of investment.

As this example illustrates, the observed year of investment is predicted correctly by the net present value decision rule for model B and the real options value for model C. Repeating this for all of the power plants in our data set enables us to create theoretical duration curves for each expectation set and investment decision rule, and provides a way of assessing which investment decision rule is most consistent with the empirically observed data.

Table B.5 shows the calculated investment thresholds corresponding to expectation set A and B, whereas Table B.6 lists the investment boundary corresponding to expectation set C. To produce the theoretically optimal year of investment these values are compared to the observed prices, given in Table B.4.

Table B.4: Observed prices in the period 2003-2017

Year	Electricity price €/MWh	El-certificate price €/MWh
2003	25.13	23.74
2004	28.41	28.83
2005	32.08	26.09
2006	42.68	22.21
2007	45.87	24.79
2008	53.77	35.28
2009	40.14	37.74
2010	43.42	33.41
2011	43.86	26.50
2012	39.66	22.60
2013	33.89	24.79
2014	29.75	22.89
2015	25.72	20.14
2016	19.91	18.36
2017	23.20	11.47

Table B.5: Theoretical investment thresholds for Nordlandselva hydropower plant

Expectation Set	P^*_{ROA} €/MWh	P^*_{NPV} €/MWh
A	55.76	29.52
B	52.77	27.93
C^b	-	-

b: See Table B.6 in Appendix B for investment boundary.

Table B.6: Theoretical investment boundary for Nordlandselva hydropower plant

P^*	S^*_{RO}	S^*_{NPV}
1	154.65	82.00
2	151.11	80.25
3	147.58	78.50
4	144.07	76.75
5	140.57	75.00
6	137.09	73.25
7	133.62	71.50
8	130.18	69.75
9	126.77	68.00
10	123.37	66.25
11	120.01	64.50
12	116.68	62.75
13	113.38	61.00
14	110.11	59.25
15	106.89	57.50
16	103.72	55.75
17	100.59	54.00
18	97.51	52.25
19	94.50	50.51
20	91.54	48.76
21	88.66	47.01
22	85.84	45.26
23	83.11	43.51
24	80.46	41.76
⋮	⋮	⋮
25	77.89	40.01
26	75.41	38.26
27	73.02	36.51
28	70.73	34.76
29	68.53	33.01
30	66.42	31.26
31	64.40	29.51
32	62.46	27.76
33	60.61	26.01
34	58.84	24.26
35	57.14	22.51
36	55.51	20.76
37	53.94	19.01
38	52.43	17.26
39	50.98	15.51
40	49.57	13.77
41	48.21	12.02
42	46.90	10.27
43	45.62	8.52
44	44.37	6.77
45	43.16	5.02
46	41.97	3.27
47	40.81	1.52
48	39.68	-0.23

C Questionnaire

Questionnaire

1. Contact info	
Name:	
Telephone:	
Email:	
2. What is the status of your project today (February 2013)?	
a. Developed	
b. Under construction	
c. Detail planning	
d. Waiting – Uncertain profitability	
e. Waiting – Problem: Grid access	
f. Waiting – New application sent or is being considered	
g. Waiting – Problem: Neighbors or family	
h. Waiting – Other reason	
Comment:	
3. If 2.a) or 2.b): When was the decision to invest made? For example, when was the deal with the contractor signed?	
Month:	
Year:	
Comment:	
4. Have there been any delays? For example: filed complaint, problems with grid access or neighbors	
Comment:	
5. What was the estimated investment cost when the decision was made? Include cost of equipment and cost of grid connection	
[NOK/kWh]	

6. What is the installed capacity?	
[MW]	
7. What is the expected annual production?	
[GWh]	
8. When was/is production start?	
Month:	
Year:	
Comment:	
9. What is the expected annual maintenance cost of running the plant?	
[NOK/kWh]	
10. What is the expected economic life time of the power plant?	
Years:	
11. What taxes is your plant eligible to pay? For example: profit tax, property tax, natural resource tax (>5.5 MVA), tax on economic rent	
Comment:	
12. How did you create an image of the profitability of the project? For example: Net Present Value (NPV)	
Comment:	
13. Have you included income from green certificates in your calculations throughout the decision process?	
Comment:	