NTNU
Norwegian University of
Science and Technology

Real Options in Small Hydropower Investments: An Empirical Study from Norway

Guro Gravdehaug
Ragnhild Remmen

Industrial Economics and Technology Management
Submission date: June 2011
Supervisor: Stein-Erik Fleten, IØT

Norwegian University of Science and Technology
Department of Industrial Economics and Technology Management

NTNU
Det skapende universitet

MASTERKONTRAKT

- uttak av masteroppgave

1. Studentens personalia

Etternavn, fornavn **Gravdehaug, Guro**	Fødselsdato **08. okt 1987**
E-post **gurogravdehaug@gmail.com**	Telefon **47663011**

2. Studieopplysninger

Fakultet **Fakultet for Samfunnsvitenskap og teknologiledelse**	
Institutt **Institutt for industriell økonomi og teknologiledelse**	
Studieprogram **Industriell økonomi og teknologiledelse**	Hovedprofil **Investering, finans og økonomistyring**
E-post **gurogravdehaug@gmail.com**	Telefon **47663011**

3. Masteroppgave

Oppstartsdato **17. jan 2011**	Innleveringsfrist **13. jun 2011**
Oppgavens (foreløpige) tittel **Real Options in Small Hydro Power Investments**	
Oppgavetekst/Problembeskrivelse Many land owners have the option to build a small hydro power plant. Among these, not everyone exercise this option even though the project has a positive estimated net present value. To explain the behaviour we perform an empirical analysis which examine whether investors behave according to real option theory. 1. Identify, model and analyse the decision problem when investing in small hydro power. The analysis will be based on real option theory, with empricial data. 2. Analyse future electricity prices and possibly other sources of uncertainty.	
Hovedveileder ved institutt **Professor Fleten Stein-Erik**	Biveileder(e) ved institutt
Merknader **1 uke ekstra p.g.a påske.**	

4. Underskrift

Student: Jeg erklærer herved at jeg har satt meg inn i gjeldende bestemmelser for mastergradsstudiet og at jeg oppfyller kravene for adgang til å påbegynne oppgaven, herunder eventuelle praksiskrav.

Partene er gjort kjent med avtalens vilkår, samt kapitlene i studiehåndboken om generelle regler og aktuell studieplan for masterstudiet.

Trondheim 10/1-2011
Sted og dato

Gun Gravdehaug
Student

Stein-Erik Fleten
Hovedveileder

Originalen oppbevares på fakultetet. Kopi av avtalen sendes til instituttet og studenten.

NTNU
Det skapende universitet

MASTERKONTRAKT

- uttak av masteroppgave

1. Studentens personalia

Etternavn, fornavn **Remmen, Ragnhild**	Fødselsdato **14. apr 1986**
E-post **ragre86@hotmail.com**	Telefon **97427357**

2. Studieopplysninger

Fakultet **Fakultet for Samfunnsvitenskap og teknologiledelse**	
Institutt **Institutt for industriell økonomi og teknologiledelse**	
Studieprogram **Industriell økonomi og teknologiledelse**	Hovedprofil **Investering, finans og økonomistyring**
E-post **ragre86@hotmail.com**	Telefon **97427357**

3. Masteroppgave

Oppstartsdato **17. jan 2011**	Innleveringsfrist **13. jun 2011**
Oppgavens (foreløpige) tittel **Real Options in Small Hydro Power Investments**	
Oppgavetekst/Problembeskrivelse Many land owners have the option to build a small hydro power plant. Among these, not everyone exercise this option even though the project has a positive estimated net present value. To explain the behaviour we perform an empirical analysis which examine whether investors behave according to real option theory. 1. Identify, model and analyse the decision problem when investing in small hydro power. The analysis will be based on real option theory, with empricial data. 2. Analyse future electricity prices and possibly other sources of uncertainty.	
Hovedveileder ved institutt **Professor Fleten Stein-Erik**	Biveileder(e) ved institutt
Merknader **1 uke ekstra p.g.a påske.**	

4. Underskrift

Student: Jeg erklærer herved at jeg har satt meg inn i gjeldende bestemmelser for mastergradsstudiet og at jeg oppfyller kravene for adgang til å påbegynne oppgaven, herunder eventuelle praksiskrav.

Partene er gjort kjent med avtalens vilkår, samt kapitlene i studiehåndboken om generelle regler og aktuell studieplan for masterstudiet.

Trondheim 10/1-2011
Sted og dato

Ragnhild Remmen
Student

Stein Erik Fleten
Hovedveileder

Originalen oppbevares på fakultetet. Kopi av avtalen sendes til instituttet og studenten.

NTNU
Det skapende universitet

SAMARBEIDSKONTRAKT

1. Studenter i samarbeidsgruppen

Etternavn, fornavn **Gravdehaug, Guro**	Fødselsdato **08. okt 1987**
Etternavn, fornavn **Remmen, Ragnhild**	Fødselsdato **14. apr 1986**

2. Hovedveileder

Etternavn, fornavn **Stein-Erik, Fleten**	Institutt **Institutt for industriell økonomi og teknologiledelse**

3. Masteroppgave

Oppgavens (foreløpige) tittel **Real Options in Small Hydro Power Investments**

4. Bedømmelse

Kandidatene skal ha *individuell* bedømmelse ☐
Kandidatene skal ha *felles* bedømmelse ☒

Trondheim, 10.1.2011
Sted og dato

Guro Gravdehaug
Guro Gravdehaug

Stein-Erik Fleten
Hovedveileder

Ragnhild Remmen
Ragnhild Remmen

Originalen oppbevares på instituttet.

Real Options in Small Hydropower Investments: An Empirical Study from Norway

Guro Gravdehaug Ragnhild Remmen

June 8, 2011

Abstract

This empirical study examines investment behavior in small hydropower investments under uncertain electricity prices and revenues from selling so-called green certificates. We assess 73 small hydropower projects granted a license to build from the Norwegian authorities. The license is considered an American call option with infinite lifetime. To examine the investment behavior, we conduct a survey to recreate the available information on the date of investment decision. We apply a net present value approach and a real options value approach to the small hydropower projects by using two scenarios; with and without green certificates. Our data does not support that a real options approach explains investor behavior better than a net present value approach.

1 Introduction

In 2001, the European Commission launched a directive promoting electricity produced from renewable energy sources. The directive required Member States to take appropriate actions to encourage a greater development of electricity production from renewable energy sources. Each Member State was given an indicative target (European Commission, 2001), and in 2003, Sweden introduced a green certificate (GC) market as a support scheme to achieve their renewable target. The objective was to increase the production of electricity from renewable energy sources by 10 TWh within 2010, relative to the corresponding production in 2002. A decision by Parliament in June 2006 raised the targets for electricity production from renewable energy sources to 17 TWh in 2016. The latest change to the system was done in June 2009, when the target was raised to 25 TWh in 2020. Since some Member States, like Sweden, already had a large share of renewable energy production, we refer to the required renewable energy in the target as *new renewable energy*.

After the introduction of the Swedish GC market, Norway invited Sweden to discuss a future common GC market. The motivation for a Norwegian-Swedish market, instead of two separate markets, was to achieve a more cost-efficient development through higher liquidity, lower price volatility and lower political risk. After several years of negotiations, an agreement on the final principles for a common GC system was signed in December 2010. The market is expected to be introduced in January 2012. The Renewable Directive requires the share of electricity produced from renewable energy sources in the European Union to increase from 8.5 % of the total energy consumption in 2005, to 20 % in 2020. Norway will comply with the Renewable Directive (European Commission, 2009) under the agreement with Sweden.

The potential of new renewable energy sources in Norway is extensive. Wind conditions in Norway are of the best in Europe. A report published in 2005 by the Norwegian Water Resources and Energy Directorate (NVE) estimated an economic potential of wind power to 250 TWh. Despite this, the annual electricity production from wind power in Norway was less than one TWh in 2008. The annual average production of electricity from hydropower in Norway is 124 TWh. The overall technical and economical potential of new renewable energy from hydropower is estimated to 34 TWh. The majority of this potential is hydropower plants with installed capacity below 10 MW, so-called small hydropower (SHP) (NVE, 2010).

This paper is an empirical study of investments in SHP projects in Norway. Our main objective is to recreate the investor's decision problem, in order to describe investor behavior under uncertainty with respect to electricity prices and climate policy. The parameters and premises describing the investor's decision problem are numerous; electricity prices, GC prices, annual production volume, investment costs, taxes, operational costs, interest rate, lifetime and construction lag. To reflect available information the investor had when making the decision, a survey is conducted.

A license to build a SHP plant gives an opportunity to invest, and there are different ways of evaluating the investment opportunity. The most common approach is the net present value (NPV) decision rule, which is a discounted cash flow method. The neoclassical application of this decision rule is to invest if expected $NPV \geq 0$. An investment in a SHP plant can be considered as an irreversible investment with uncertainty. McDonald and Siegel (1986) and Dixit and Pindyck (1994) point out that the real option value (ROV) approach includes uncertainty. The uncertainties considered, when applying the ROV approach in this paper, are future electricity and GC prices. These uncertainties are directly influencing the profitability of the investment since they are factors affecting the future generated cash flows. When applying the ROV approach we find a threshold price where it is optimal to invest. This paper questions whether investor behavior is better described by the ROV approach compared to the NPV approach. To assess this, we apply empirical data to both a NPV approach and a ROV approach, to complete an empirical analysis. The main result from the empirical analysis is that our data does not support that a ROV approach explains investor behavior better than a NPV approach. We observe that the NPV decision rule to some extent explains projects invested in, while the ROV decision rule explains investors sitting on the fence due to economic reasons.

Empirical research on real options include Paddock et al. (1988), who value offshore petroleum leases as a function of the oil price by applying an option-based method. Similar to our approach, were we examine investment decisions as a function of electricity prices and GC prices, Quigg (1996) empirically tests whether an option-pricing model can explain asset prices. She finds empirical support for a model incorporating the option to wait. Newer empirical research is Moel and Tufano (2002) who look into the decision to closing and re-opening a mine. This is a switching-option, while our approach only evaluates one decision. However, we can relate our work to their results. For instance, volatility of the gold price has a negative effect on the decisions. In our case, evaluating the effects of volatility in the electricity price on investment decisions is interesting. Case studies on real options in electricity markets have been conducted in the Nordic Electricity market. Bøckman et al. (2008) and Fleten et al. (2007) consider investment timing and optimal choice of capacity. These papers consider uncertainty in the electricity price, while we also include uncertainty in GC prices. Fleten and Ringen (2009) derive the potential of new renewable capacity in Norway when introducing GCs, and model the GC prices. Our paper reflects the common Norwegian-Swedish market to be introduced in 2012. The price processes have an extended approach to how the GC price is affected by the electricity price. We find a lack of research which empirically tests the application of ROV models in investments. Heggedal et al. (2011) consider climate policy under uncertainty in SHP projects. Our contribution to this field of study is new empirical data and a different approach to model electricity and GC prices.

This paper is organized as follows. Section 2 explains the idea of a common GC market for Norway and Sweden. Section 3 presents the investors in SHP plants in Norway, and in Section 4, the stochastic processes for the electricity price and the GC price are presented. In Section 5, the NPV and the ROV approach are introduced, while Section 6 describes the estimated parameters required for the empirical analysis. Section 7 presents the results from an empirical analysis of 73 SHP projects and an empirical testing of the results.

2 Green Certificates

This section presents the ideas of implementing a market for GCs. First, we give an introduction to what a GC is. Next, examples are given from the existing Swedish market and finally, the expectations to the Norwegian-Swedish GC market are presented.

2.1 What is a Green Certificate?

A GC is an electronic certificate the producer may obtain when producing one MWh of renewable electricity. The certificate is a financial asset to be sold in a market established for GCs. The producer of new renewable energy realizes an extra revenue from selling GCs received in the allocation period[1], in addition to revenues from selling electricity. The total price the producer receives for each MWh produced, equals the sum of the electricity price plus the GC price during the allocation period. Producers not eligible for GCs will have a price only consisting of the electricity price.

The supply side in a GC market consists of producers of electricity based on new renewable energy who sell GCs. To ensure the demand side, the government implements an obligation of GCs on certain consumer's electricity consumption. This obligation implies that consumers

---

[1] The allocation period is the number of years a new renewable energy project is entitled GCs.

subsidize the deployment of new renewable energy. The consumer price after introducing an obligated GC system, is the sum of the electricity price plus the GC price multiplied with the obligated quota settled by the government. The quota reflects the required annual growth of new renewable energy in order to achieve a renewable target.

2.2 The Swedish GC market

The Swedish GC market was introduced in May 2003. Within December 2008, around 640 plants producing electricity from new renewable energy sources were commissioned. The electricity production from new renewable energy amounted in the same year to 14.2 TWh. The contribution of electricity produced from these plants has become a significant part of the total share of renewable electricity production in Sweden. In Figure 1, we show how the historical GC price in Sweden has developed since 2005.

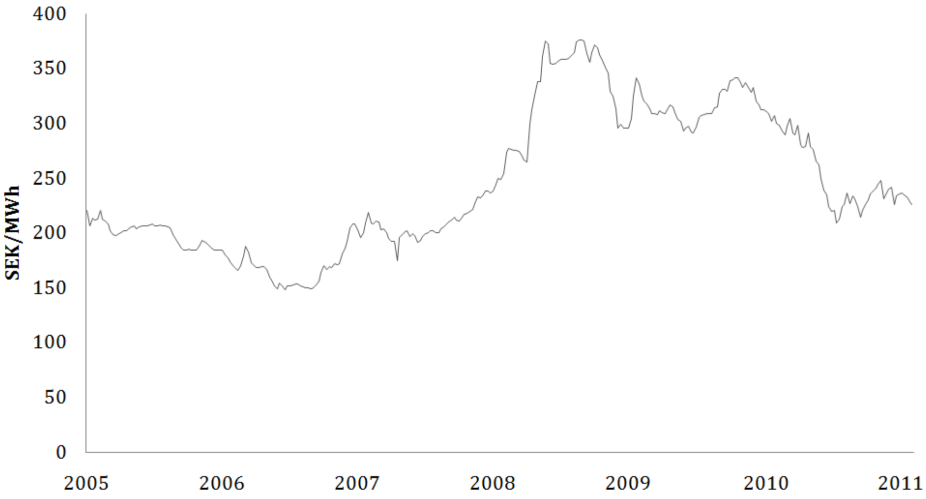


Figure 1: Historical GC prices in Sweden in SEK/MWh (Tricorona, 2010)

2.3 A Norwegian-Swedish GC market in 2012

The initiatives to establish a Norwegian-Swedish GC system is motivated by the targets of renewable energy development launched by the European Commission. A GC market with a regulated obligated quota will ensure achieving the politically planned targets. By using market forces, a GC system is expected to make it increasingly desirable to invest in new renewable energy sources, and make sure that these investments are made in the most effective technologies and locations (Jensen and Skytte, 2002).

A common GC market between Norway and Sweden is expected to be introduced in 2012, and to develop 26.4 TWh of new renewable electricity production within 2020 (Ministry of Petroleum and Energy, 2010c). The two countries have a burden share of 50 % to subsidize the renewable target. The new capacity to be commissioned is not required to be evenly divided between the countries. An example of the required annual growth of new renewable energy in

Norway, is presented in Figure 2. This growth is the consumer's annual obligated quota, which is expected to result in the annual deployment of new renewable energy. The figure shows how the system is expected to be regulated from the introduction in 2012 until the end of the system in 2035. The definition of which renewable energy sources to be eligible for GCs, is quite similar in both countries. Sweden has assigned GCs to hydropower, wind power, solar energy, wave energy, geothermal energy, bio fuels and peat[2] (Statens Energimyndighet, 2010). In Norway, hydropower, wind power, solar energy, oceanic energy, geothermal energy and bio fuels, are assigned GCs (Ministry of Petroleum and Energy, 2010c).

The allocation period of GCs is the same for all new renewable energy sources commissioned after 2012. Projects are entitled GCs for 15 years, or until the end of 2035. In Norway, plants commissioned before 2012 are entitled GCs due to a retroactive effect if the construction of the plant or upgrading of an existing plant is commenced after September 7th 2009. Hydropower plants with installed capacity less than one MW constructed after January 1st 2004, are also subject to the retroactive effect (Ministry of Petroleum and Energy, 2010c).

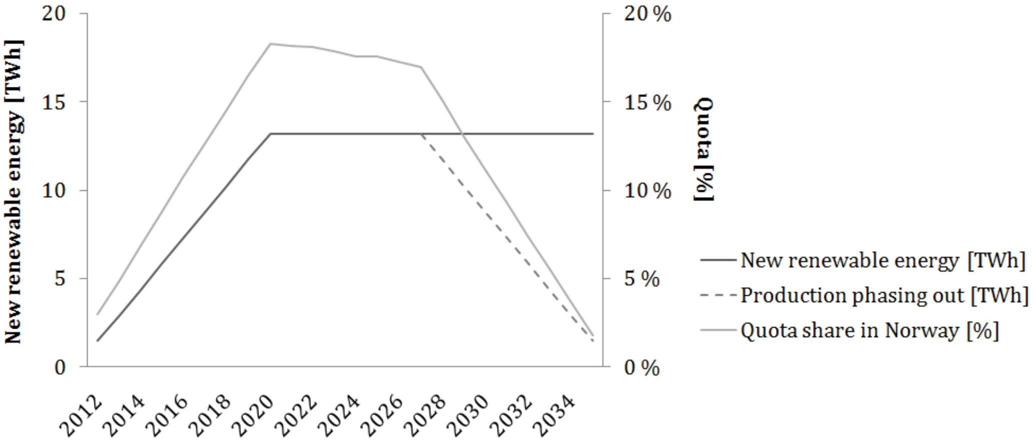


Figure 2: Quota share and new renewable energy in Norway from 2012 to 2035 (Ministry of Petroleum and Energy, 2010a)

2.4 Technologies to be developed under the GC system

The Norwegian-Swedish GC market has a renewable target of 26.4 TWh within 2020. If the annual growth of the new renewable energy is not accomplished, the GC price will increase due to the obligated quota, hence making it more profitable to invest in new renewable energy sources. Competition between the producers of new renewable energy in the GC market ensures that the supply of GCs reflects the actual cost required in order to ensure the renewable target (Jensen and Skytte, 2002).

Morthorst (2003) argues that the sum of the GC price and the electricity price must equal the marginal cost per unit of produced electricity over the lifetime of the plant. The new renewable

---

[2] Peat, when burnt in CHP plants.

energy sources with the lowest marginal costs are most likely to be developed under the GC system. We discuss which new renewable energy sources to be developed under the Norwegian-Swedish GC system by considering their long-run marginal cost (LRMC).

Table 1: LRMCs for renewable technologies in Norway and Sweden

Renewable energy sources	**Country**	**LRMC [€/MWh]**	**Potential energy [TWh]**
Hydropower[a]	NO	31-47	13
CHP - bio[b]	SE	52-60	3
Onshore wind power[c]	NO/SE	56-86	24
Offshore wind power[d]	NO	80-120	13.5

[a] Data according to NVE (2010) and Enova (2008)

[b] Data according to EIA (2010), APX-ENDEX (2011) and Statens Energimyndighet (2007)

[c] Data according to NVE (2010), Enova (2008) and Svensk Energi (2010)

[d] Data according to NVE (2010)

Table 1 presents the potential renewable energy sources with the lowest LRMCs in Norway and Sweden. In 2008, NVE and Enova[3] published a study on onshore wind power (Enova, 2008). The study estimates that approximately 30 TWh of new renewable energy in the year 2020 is achievable, of this 13 TWh is hydropower and 17 TWh is wind power. In contrast to Norway, Sweden has more bio energy and a significant part of the Swedish share will likely be covered by bio energy. The potential of new bio energy is mainly from reconstructing fossil fuelled Combined Heat and Power (CHP) plants. Wind power, hydropower and bio energy are expected to be the most important technologies in a common GC market, where wind power is assumed to account for the largest share of the renewable electricity production (Ministry of Petroleum and Energy, 2010c).

3 The Investor's Decision problem

In this empirical study of SHP investments, we examine investor behavior by recreating the parameters and premises the investor had when making the investment decision. This recreation is what we refer to as *the investor's decision problem*. A GC system is expected to trigger a number of investment decisions in SHP projects in Norway. Before the final agreement of a common GC market in 2010, there were years of negotiation between Norway and Sweden. Along with the negotiations, the Ministry of Petroleum and Energy launched several promises. Promises given to the SHP investors were regarding the different types of climate policy, introduction years and criteria of the retroactive effects. New promises every year created uncertainty whether SHP would be subsidized or not. This section presents the investor's decision problem, available information regarding climate policy, how we select the cases to be examined and the information we collect by conducting a survey.

---

[3] Enova SF is owned by the Ministry of Petroleum and Energy. It was established to take a leading role in promoting environmentally friendly restructuring of energy consumption and energy generation in Norway.

3.1 Defining the Investor's Decision problem

The investor in a SHP project is defined as the one deciding whether to invest or not, typically a landowner or a firm. The investor is also the holder of a license granted by NVE. Hence, the investor has an opportunity to invest. The license expires after a number of years, however, the investor can apply for extension and later apply for a new license. Therefore, we consider the license as an *option to invest*[4] with infinite lifetime. Hence, the decision problem in our approach is an investor who already is granted a license, and holds an option to invest.

We believe the investor makes the final decision after an extensive detail planning, performed after the license is granted. We have used data from NVE, containing the information from the license application of 318 SHP projects. Further, this dataset is referred to as the *original dataset*. Unfortunately, the original dataset does not reflect the information after the detail planning. Therefore, it is necessary to update the projects' information after detail planning. We also want to know the result of the decision; did the investor decide to invest or not? Other problems and obstacles the investors were confronted with is also interesting, especially uncertainty regarding climate policy. Based on the arguments above, we have conducted a survey for collecting the required information.

Table 2: Published information regarding climate policy from 2005 to 2011

Year	**Information published by the government**	**Introduction year**
2005	A common GC market	2007
2006	A common GC market is delayed one year. In the end of the year the negotiations break down.	2008
2007	A feed-in-tariff will replace the GC market. Hydropower will receive 5 €/MWh for production representing the first 3 MW of the installed capacity (Ministry of Petroleum and Energy, 2006).	2008
2008	The feed-in-tariff is canceled. New negotiations for a common GC market have started (Ministry of Petroleum and Energy, 2007).	2009
2009	The main principles for the common GC market are signed (Ministry of Petroleum and Energy, 2009a,b).	2012
2010	Waiting for a final agreement on the common GC market.	2012
2011	The final agreement for the common GC market are signed (Ministry of Petroleum and Energy, 2010b).	2012

The years of negotiations have led to climate policy uncertainty. During these years there has been uncertainty attached to the different types of climate policy, introduction years and criteria of the retroactive effects. Table 2 presents the information the investor had access to when deciding to invest in the years from 2005 to 2011. This is based on publicly available information. The year 2007 stands out due to discussions about feed-in-tariffs (FI).

---

[4] An option to invest is a right, but not an obligation to invest.

3.2 Selecting projects

The original dataset consists of 318 SHP projects, which have been granted a license between 1998 and 2009. From these we have extracted a selection of projects after the following procedure.

1. Eliminate projects applying for license to upgrading an already existing SHP plant.
2. Eliminate projects without information about the investor or investment costs.
3. We sort the projects after investment costs, and include the projects with the highest investment costs. This is to capture the projects depending on potential climate policy to achieve profit.
4. To capture the behavior of different independent investments, we select a maximum of four projects per investor or firm. For instance, the firm Småkraft AS has several SHP projects in their portfolio and can prioritize the most profitable alternatives.

3.3 Collecting data

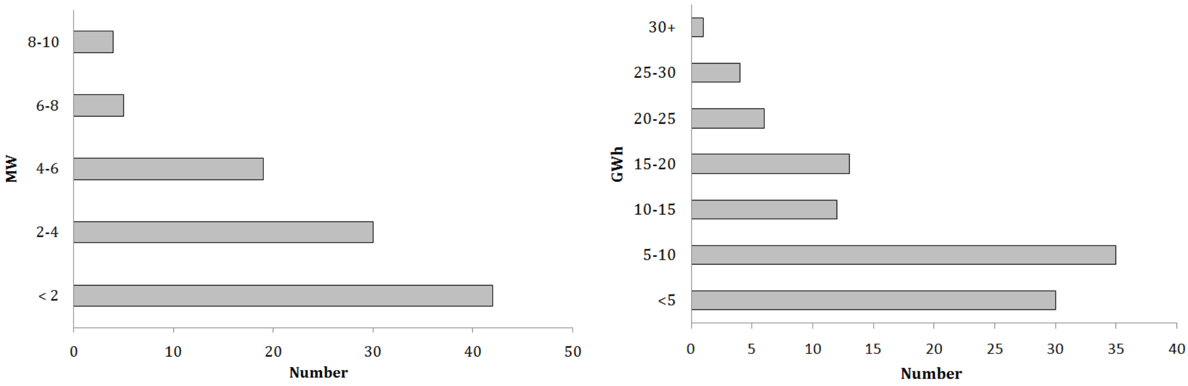
The purpose of the survey is to collect new and updated information. New information, described in this section, is the project's status and the date of the investment decision. Updated information incorporates installed capacity, annual production and investment costs. We also included questions on operational costs, taxes, economical lifetime, costs of applying for license and expectations to GCs. In order to collect quantitative and qualitative information, a methodology suitable for both these types of information is desirable. To provide the expectations and the behavior of the investor, qualitative information, interviews have been conducted (Kvale, 1996). The complete survey and the quantitative results can be found in Appendix A.1 and Appendix A.2.

To examine whether the investor has decided to invest or not, the *status of the project* is required. The status divides the projects into two groups; *invested* and *not invested*. The investors who have decided to invest are either currently constructing the plant or the plant is constructed. We separate investors who have not invested in two groups based on reasons for not investing; *uncertain profitability* and *non-economic reasons*. Investors who are uncertain about the profitability in the project might be waiting for better economic conditions, while the investors in the group non-economic reasons might wait due to problems with a third party. The third party can be NVE, grid companies, contractors, other landowners, or other factors that cannot be controlled by the investor.

To evaluate the investor's decision problem, it is valuable to know the date of decision together with the status of the project. *The date of investment decision* is defined as the date the investor signs a contract with a contractor or the date the board agrees to invest in the project. We will use the date of decision as input for determining the exact parameters and premises.

3.4 Main Observations

The survey resulted in a dataset of 98 SHP projects. In Figure 3, the distribution of installed capacity and annual production after the detail planning are presented. The majority of the projects are under 5 MW.



(a) Capacity

(b) Production

Figure 3: Distribution of installed capacity [MW] and annual production [GWh] of 98 SHP projects

Figure 4 presents the status of the SHP projects on February 1st 2011. Investors have invested in 64 % of the projects. The remaining investors are waiting due to uncertain profitability in 10 % of the projects and non-economic reasons in 26 % of the projects. In the further analysis of investor behavior, projects with non-economic reasons are eliminated. Moel and Tufano (2002) support this argument in their analysis where non-economic reasons for opening and closing mines are removed from their dataset. The remaining projects define a *final dataset* of 73 SHP projects.

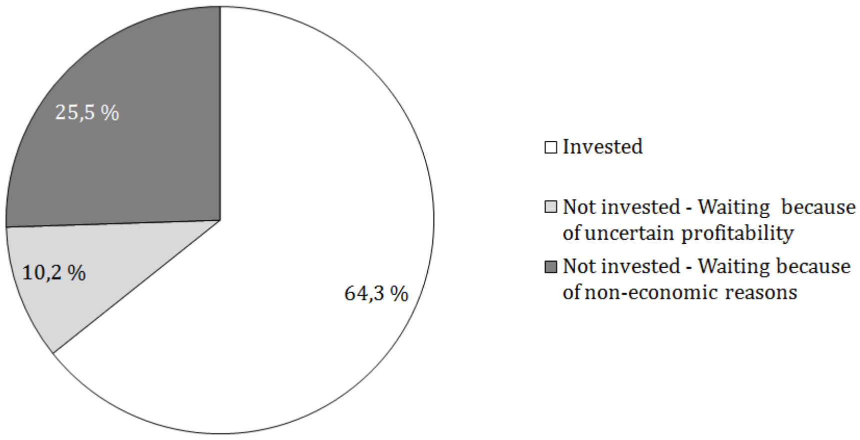


Figure 4: The status of 98 SHP projects on February 1st 2011

In Figure 5, we compare the expected investment costs from the original dataset with the actual investment costs after the detail planning, as deducted from the survey. In addition, two linear regression lines of expected and actual investment costs are drawn. It is worth noticing that actual investment costs increased twice as much as expected investment costs from 2005 to 2011. These results support the importance of updating the information.

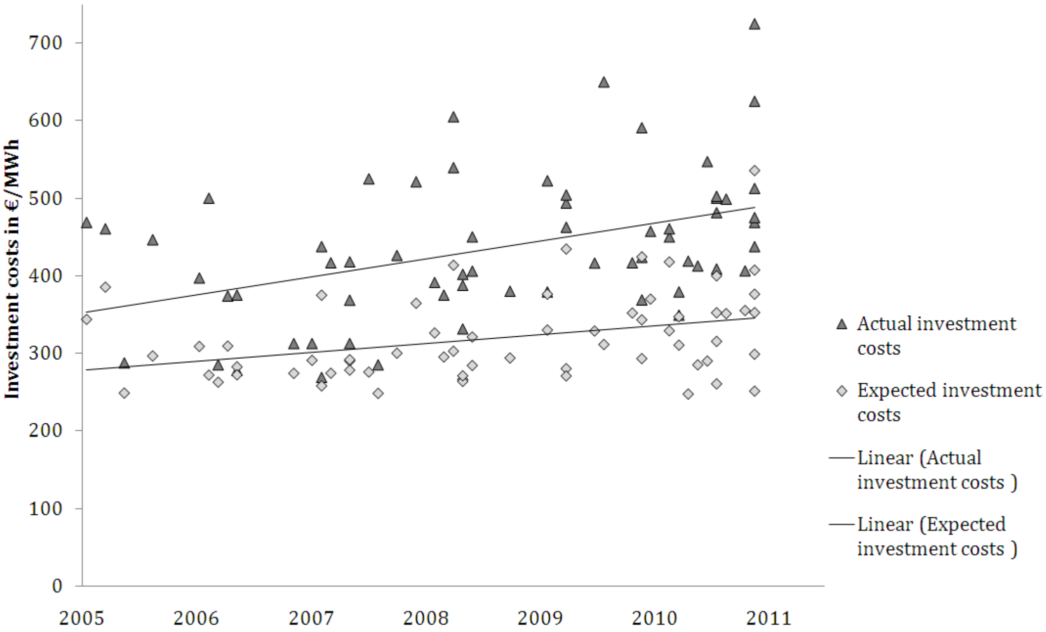


Figure 5: Expected investment costs compared to actual investment costs in €/MWh

The operational costs range from zero to 13 €/MWh. The explanation to the wide range is that investors estimate the operational costs differently. In several projects investors have not considered these costs. Either they avoid considering the necessity of maintaining a SHP plant, or they assume the required maintenance cost to be neglectable.

When evaluating an investment, the delay in operational revenues is necessary. We did not ask for this specific in the survey, but when performing the interviews, some investors informed us when the plant started to operate. Bar-Ilan and Strange (1996) discuss the effects of including investment lags for irreversible investments. An investment lag, also called a construction lag, is in our approach a delay of operational revenues caused by the time it takes to construct the SHP plant. Hence, the lag is the time from an investment decision is made to the plant starts to generate electricity. "...lags reduce the deterrent effect of uncertainty on investment and tend to lessen inertia" Bar-Ilan and Strange (1996). By comparing the date of decision to the start-up year, we find an average construction lag of two years.

The information from NVE contains the date the license was granted. From the survey we are given the date of the investment decision, for projects invested in. From these two dates we can estimate the decision lag, which describes the time the investor uses from receiving the license to investing. A decision lag less than one year is considered as investing immediately, since the decision procedure normally takes a number of months due to required meetings or board decisions. The results show that 66 % of the investors, who have decided to invest, took the decision immediately and 26 % waited between one to three years after the license was granted before making the decision.

As discussed, investor behavior depends on expectations regarding a potential GC system. These expectations are considered as qualitative information, which is important in the recreation of the investor's decision problem. The investors in the survey had different expectations regarding climate policy. Some investors had no expectations, while others had included revenues from selling GCs in their calculations. "Yes, we have estimated 120 NOK/MWh in support, and we rely on this!" said one investor, while another point of view was: "Green certificates? No, we do not believe in that, the politicians will never decide".

4 Price Processes

The operational revenues in a SHP project depends on production volume, electricity prices and potential income from selling GCs. The production volume is determined by hydrology and installed capacity, where the size of capacity is optimized due to turbine costs and expected inflow. According to the Norwegian Climate Centre, Norway can expect more extreme weather and increased inflow, but the increase will not be evenly distributed over the year (Norwegian Climate Centre, 2009). A SHP plant is usually run-of-river, hence, it has a limited ability to take advantage of variations in inflow. When estimating the future revenues the annual average production will be used, implying that we do not include uncertainty in hydrology. This is appropriate to assume when considering a long-term investment. Remaining uncertain factors for future income are electricity prices and potential GCs. We assume perfect competition in the electricity market, indicating that the production volume from a single investor has no effect on prices. In this section we first describe both electricity and GC prices as stochastic processes. Finally, we discuss the correlation between the electricity market and the GC market.

4.1 The Electricity price

The largest part of the revenues comes from selling the generated electricity at the Nordic Power Exchange, Nord Pool Spot.[5] Nord Pool Spot trades about 74 percent of the total consumption of all physical electricity in the Nordic countries. The spot electricity price is a market equilibrium price, determined by supply and demand.[6] The spot price forms the basis for financial contracts traded on NASDAQ OMX Commodities.[7]

When evaluating an option to invest, the investor considers the long-term electricity spot price. Despite the fact that electricity has a limited storability and transportability, we consider elec-

---

[5] Nord Pool Spot is the Nordic Power Exchange, established in 1993. Today it consists of a physical market (previously also a financial market).

[6] The spot electricity price is also called the system price. Due to bottlenecks in the transmission system, Nord Pool defines price areas. We assume the system price to be a good estimate for the area price the SHP plant obtains.

[7] Financial contracts previously traded on Nord Pool.

tricity as a *flow commodity*, according to Lucia and Schwartz (2002). Samuelson (1965) presents a proof stating that commodity prices follow a Random Walk (RW) with a drift. Schwartz and Smith (2000) consider short-term variations and long-term dynamics in commodity prices, arguing that short-term variations are influenced by for instance the weather, while long-term variations come from uncertainty in demand, regulations and the price of other substitutable energy sources. When considering long-term investments with construction lag and long productive lifetime, they argue that the long-term component is dominant. Schwartz (1998) argues that the long-term component is dominant when valuing a long-term investment project, for instance a SHP project. Hence, a one-factor model only considering the long-term development, can be a satisfactory model. He also introduces the shadow spot price, reflecting the long-term equilibrium price. The shadow spot price can be modeled by long-term forward contracts. Lucia and Schwartz (2002) discuss short-term and long-term effects in electricity price and power derivatives, and present different one- and two-factor models. Here, the short-term development is mean-reverting (MR) while the long-term development follows Brownian motions. They model the future and forward prices, and concludes that one-factor models based on the price explains the actual futures and forward prices better than models based on the log-price. Koekebakker and Ollmar (2005) investigate models with prices (additive) and log-prices (multiplicative). We note that their models explain about 70 % of the price development of the forward curve, but both the models fail the normality test.

The literature presented supports modeling the long-term electricity price as a Brownian motion, and further supports one-factor models based on price levels. This motivates the use of a Brownian motion with drift, also referred to as an arithmetic Brownian motion (ABM). On behalf of these arguments, we assume long-term electricity prices to follow an ABM. We find it interesting to implement an ABM for the electricity price in long-term investments, due to a lack of literature in this area. The process is stated in Equation 1, where α_{EL} is the annual price drift (in €/MWh) and σ_{EL} is the annual volatility (in €/MWh). The increment of a standard Wiener process is denoted by dz_{EL}, where ε_t is a normally distributed random variable with a mean of zero and a standard deviation of one. The expected value is given by $E[P_{EL}(t)] = P_{EL}(0) + \alpha\, t$.

$$dP_{EL} = \alpha_{EL}dt + \sigma_{EL}dz_{EL} \tag{1}$$

As suggested by Schwartz (1998), we estimate the prices using long-term forward contracts. Given a long-term investment, the forward contracts with the longest time to maturity is desirable to use. High liquidity is also preferable, hence we use the 3-years forward contracts. The time series for 3-years forward contracts traded in €/MWh on Nord Pool (NASDAX OMX) spans from March 28th 2001 to February 1st 2011. As we see in Figure 6, the spot price contains more volatility compared to the 3-years forward contract, and has more extreme spikes. The descriptive statistics of the 3-years forward contract and the spot price (Appendix A.3) shows that the price changes of neither the spot price nor the 3-years forward contract follow a normal distribution. This is caused by skewness and kurtosis, which implies asymmetric and fat-tailed returns. Despite that this result contradicts the assumption of an ABM, we choose to keep the stochastic process.

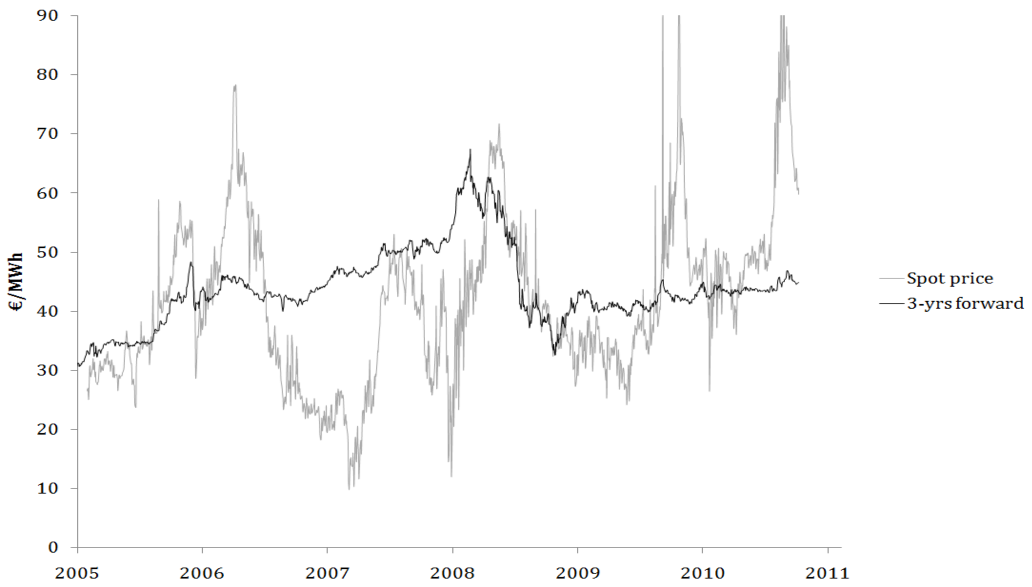


Figure 6: Historical data for the spot price and the 3-years forward contract (source: Reuters EcoWin, Nord Pool)

4.2 The Green Certificate price

A GC is a politically determined instrument for increasing the contribution of renewable energy sources in electricity production. In this paper we consider the common Norwegian-Swedish GC market, where GCs will be traded as financial assets. The government in both countries can regulate the market through obligated quotas. The assumptions regarding the GC prices are based on expectations to the political targets, and to a minor extent taking into consideration the experience from the Swedish GC market.

The principle of banking[8] is important when modeling the mechanisms for a GC market. The possibility of not selling the GCs immediately might have large consequences on the GC price. For instance, if the supply of GCs is larger than the demand, the producers may hold the GCs and sell them later with the purpose of receiving a higher return. The effect of banking GCs is discussed by Amundsen et al. (2006). They argue that an introduction of banking GCs may reduce price volatility considerably. Due to the banking principle, which gives storability, we consider a GC as a commodity. Inspired by Samuelson (1965), we let the GC price to follow a RW with drift. We further assume the GC price to follow an ABM, given by Equation 2. This is also motivated by the fact that we believe price levels matter, and because an ABM is a simple model. We also assume the electricity price to follow an ABM, hence can an ABM be argued for the GC price given that GCs are a by-product of electricity. As for the stochastic for the electricity price, α_{EL} is the annual price drift (in €/MWh) and σ_{EL} is an annual volatility (in €/MWh). We are aware that an ABM can return negative prices.

$$dP_{GC} = \alpha_{GC}dt + \sigma_{GC}dz_{GC} \tag{2}$$

---

[8] The principle of banking indicates the possibility of storing GCs and selling them at a later point in time.

We estimate the GC prices by applying the following assumption; an investor requires the long term electricity price and the expected GC price to cover the LRMCs in order to invest, $LRMC = P_{EL} + kP_{GC}$. The factor k adjusts for projects only receiving GCs in the allocation period of 15 years, while the economical lifetime in most cases is longer. To determine the renewable technologies and the amount of energy from each renewable technology to be commissioned under the GC system, we have derived a merit order for technologies entitled to receive GCs in Figure 7 (cf. Section 2).

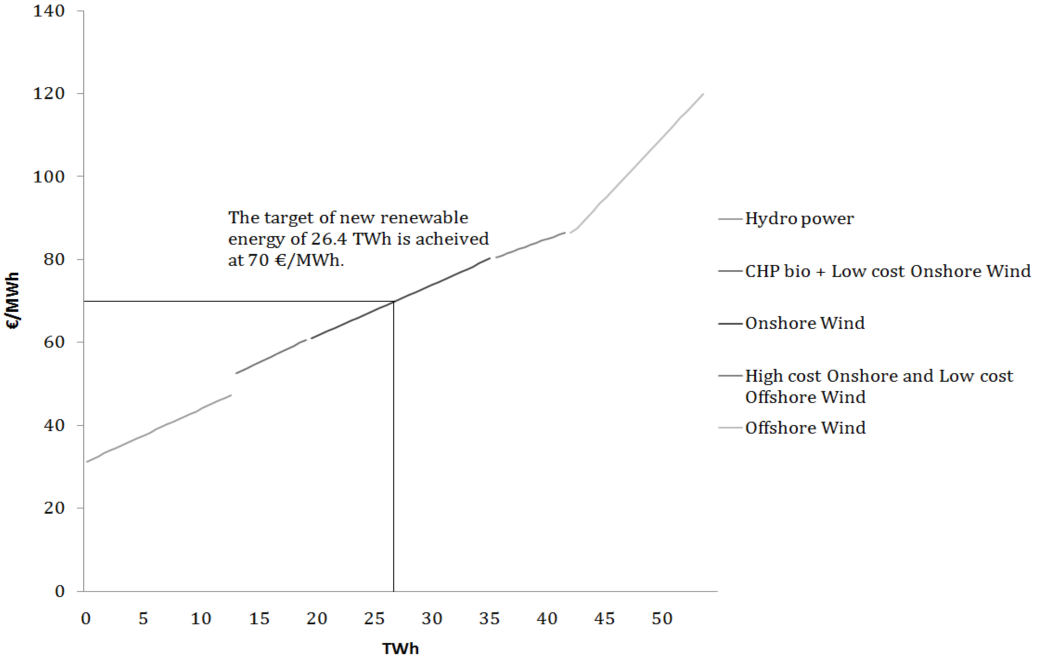


Figure 7: Merit order of LRMCs of new renewable technologies

As banking of GCs is allowed, the LRMC of the most expensive plant required to balance the demand over the lifetime of the GC system, is the price level clearing the market. This implies that it is not the technology that clears the market every year, but the technology that clears the entire GC market, which decides the GC price. With a target of 26.4 TWh, Figure 7 indicates that onshore wind is the technology to clear the common GC market. Since the government introduces an obligated quota, we assume the target to be achieved. This indicates that the GC market will deploy investments in hydropower, bio and onshore wind power. With onshore wind to be the technology to clear the market for GCs, we can determine the GC price to be introduced in 2012. The GC price can then be found by Equation 3.

$$P_{GC} = \frac{LRMC - P_{EL}}{k} \tag{3}$$

As a simplification, the factor k is assumed to equal one. Then, the GC price introduced in 2012 is expected to be the difference between the LRMC for onshore wind of 70 €/MWh and the electricity price, $P_{GC} = LRMC_{onshorewind} - P_{EL}$. An electricity price of 44 €/MWh, results in a GC price of 26 €/MWh in 2012. The assumption of bankable GCs implies that the expected GC price cannot have a drift that exceeds the growth of a risk-free instrument. If the expected drift exceeds the risk-free growth, producers would not have sold the GCs, and instead, banked the GCs for longer periods with an intention of receiving a greater return at a later stage. Our conclusion is that the GCs will have an introduction level determined by Equation 3, and the expected drift is less or equal to a risk-free instrument.

4.3 Correlation between the markets

Since a GC is a by-product of electricity, it is interesting to see if there are any interactions between these two markets. In the literature, Morthorst (2003) assumes that changes in the spot price are reflected immediately and totally in the GC price. Jensen and Skytte (2002) also argue that the GC prices can be explained by a linear relation to the electricity price. Both Morthorst (2003) and Jensen and Skytte (2002) do not take into account the banking principle. Figure 8, from Amundsen et al. (2006), shows the price effects of GCs with and without banking. The banking principle tightens the market, which results in more stable prices, lower volatility and correlation. Due to the linear relation, and the fact that GCs are a by-product of electricity, we believe electricity and GC prices are negatively correlated. However, the banking principle argues for a small correlation.

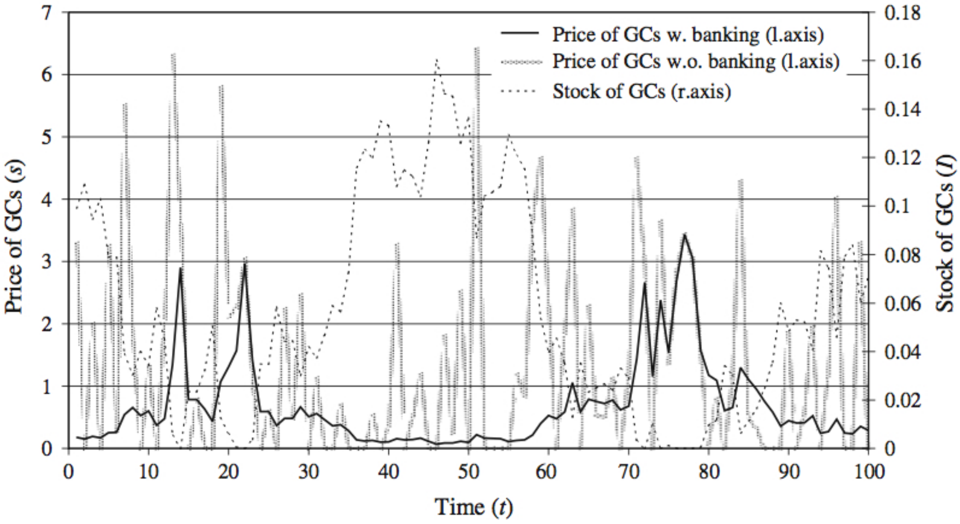


Figure 8: Simulated values of GC prices and stocks of GC (Amundsen et al., 2006)

5 Methodology

We examine investor behavior in SHP investments by using a ROV approach and a NPV approach. An investor holding a license has the right, but not the obligation, to invest in the project. This right is an option, which can be exercised by the investor as long as the license is valid. As discussed in the previous sections, the investors have faced uncertainty regarding the climate policy when making investment decisions. Investors in our survey tend to either expect GCs or not, hence we introduce two scenarios when applying the different approaches (cf. Section 3). Excluding GCs is referred to as *Scenario 1*, while *Scenario 2* includes GCs.

GCs are included in the methodology, but when we run the model for Scenario 1, GCs are excluded. This section first presents how each project is valued by calculating the NPV. Second, we present the ROV approach, which includes the value of waiting, in contrast to the static NPV. We assume that holding a license corresponds to an American style option[9] with infinite lifetime (cf. Section 3.1). Finally, a binary choice model is presented.

5.1 Valuing the Project

The NPV of each project equals the discounted sum of future cash flows over the project's lifetime. The future cash flows to be discounted, are derived from multiple factors. The expected NPV of project n can be found by Equation 4. We let $NPV_{n,t} = NPV_{n,t}(P_{EL,t}, P_{GC,t}, \tau_n, m_n, I_n, r, c_t)$.

$$NPV_{n,t} = m_n(1-\tau_n)\left[\sum_{j=t+l}^{L+t+l}\frac{P_{EL,i}}{(1+r)^j} + \sum_{j=t+l}^{A+t+l}\frac{P_{GC,j}}{(1+r)^j} - \sum_{j=t+l}^{L+t+l}\frac{c_j}{(1+r)^j}\right]\frac{1}{(1+r)^l} - I_n \tag{4}$$

$NPV_{n,t}$ is the expected NPV of the project n on the date of investment decision t. The expected electricity price $P_{EL,t}$ is the price the investor assumes to receive from selling the generated electricity at Nord Pool during the project's lifetime. The expected GC price $P_{GC,t}$ is the price received from selling GCs during the allocation period. Both prices are stochastic processes, cf. Section 4. The investment cost I_n is the total cost of project n where dams, tunnels, power station, pipelines and machine-oriented equipment are included. The expected annual production volume is denoted by m_n, and the tax parameter τ_n is calculated for each project.

Other factors are the risk-free interest rate r and the operational cost c. The project's lifetime and the allocation period of GCs are given by L and A. Finally, the constant l is the construction lag, which discounts the cash flows from the date of investment decision until the project starts operating. Under the assumption that the electricity price and the GC price follow ABMs, the summation is expressed in Equation 5 and Equation 6. These are sums of arithmetic-geometric series. To simplify the expression we re-write the discounting term; $R = \frac{1}{1+r}$.

$$\left[\sum_{j=t+l}^{L+t+l}\frac{P_{EL,j}}{(1+r)^j}\right]\frac{1}{(1+r)^l} = \left[\frac{P_{EL,t+l}(1-R^L)}{1-R} + \frac{R\alpha_{EL}(1-LR^{L-1}+(L-1)R^L)}{(1-R)^2}\right]R^{l+1} = k_1 + k_2 P_{EL,t+l} \tag{5}$$

$$\left[\sum_{j=t+l}^{A+t+l}\frac{P_{GC,j}}{(1+r)^j}\right]\frac{1}{(1+r)^l} = \left[\frac{P_{GC,t+l}(1-R^A)}{1-R} + \frac{R\alpha_{GC}(1-AR^{A-1}+(A-1)R^A)}{(1-R)^2}\right]R^{l+1} = k_1 + k_2 P_{GC,t+l} \tag{6}$$

The operational costs are assumed to increase by the inflation rate i. The total operational cost C over the project's lifetime is derived in Equation 7.

$$\left[\sum_{j=t+l}^{L+t+l}\frac{c_j}{(1+r)^j}\right]\frac{1}{(1+r)^l} = \frac{c_0}{r-i}\left[1-\left(\frac{1+i}{1+r}\right)^L\right] = C \tag{7}$$

SHP plants in Norway are subject to taxes; *corporate property tax, profit tax, tax on economic rent tax* and *natural resource tax*. Table 3 describes the different taxes in detail. In the valuation

---

[9] An American style option is an option which can be exercised at any time during the lifetime of the option.

Table 3: Taxes for SHP plants in Norway

Tax	Discription
Corporate property tax	Property tax reduces EBIT[a] by ≤ 0.7 % of the fiscal value (cf. Property Taxation Act §8)
Profit tax	After the property tax is subtracted, the profit tax reduces the profit by 28 %.
Tax on Economic rent	The tax on economic rent is 30 %, and compared to the calculation of the profit tax, "free-income" is tax deductible. The "free-income" is calculated as the average of the fiscal value the previous year multiplied with a norm-rent[b]. The tax is claimed for power plants of ≥ 5.5 MVA[c] (cf. Taxation Act §18-2 and §18-3)
Natural Resource Tax	The natural resource tax is 1.625 EUR/MWh multiplied by the average production the last seven years. The tax is claimed for power plants ≥ 5.5 MVA. This tax is coordinated with the profit tax, indicating that the sum of natural resource tax and profit tax never will exceed 28 % of operating income (cf. Taxation Act §18-2 and §18-3).

[a] Earnings before interest and taxes (EBIT) equals the general income subtracted by depreciation and amortization. Depreciations for hydropower: dams, tunnels, power station, pipelines (except tubes) should be depreciated by 1.5 % yearly over 67 years, while machine-oriented equipment should be linear depreciated by 2.5 % yearly over 40 years (Taxation Act §18-6). We have depreciated 60 % over 67 years and the remaining 40 % over 40 years (NVE, 2007).

[b] The norm rent is set by the Ministry of Finance (Skatteetaten, 2011).

[c] A power factor of 0.9 converts reactive power to active power.

of the project, taxes are estimated from expected prices and production volume. Equation 8 describes how the tax parameter presents corporate property tax τ_n^p, profit tax τ_n^s and tax on economic rent τ_n^r. Inputs required for the tax parameter are $P_{EL,t+l}, P_{GC,t+l}, m_n, C_n$ and I_n.

$$\tau_n(P_{EL,t+l}, P_{GC,t+l}, m_n, C_n, I_n) = \tau_n^p + \tau_n^s + \tau_n^r \tag{8}$$

The NPV is simplified in Equation 9a and Equation 9b. Further in the paper, this NPV approach will be referred to as the NPV model.

$$NPV_{n,t} = m_n(1-\tau_n)k_2\left[P_{EL,t+l} + \frac{d_2}{k_2}P_{GC,t+l}\right] - X_n \tag{9a}$$

$$X_n = I_n + m_n(1-\tau_n)(C - d_1 - k_1) \tag{9b}$$

5.2 Valuing the Real Option

The value of the option to investment depends on two stochastic processes. Both, the electricity price and the GC price are following an ABM. By applying the dynamic programming approach (Dixit and Pindyck, 1994), we find a partial differential equation (PDE) for the option value. By combining Itô's lemma (Equation 10) and the Bellman equation (Equation 11) we obtain the resulting PDE given in Equation 12.

$$dF = F_{EL}dP_{EL} + F_{GC}dP_{GC} + \frac{1}{2}F_{EL,EL}(dP_{EL})^2 + F_{EL,GC}dP_{EL}dP_{GC} + \frac{1}{2}F_{GC,GC}(dP_{GC})^2 \tag{10}$$

$$E[dF] = rFdt \tag{11}$$

$$\frac{1}{2}\sigma_{EL}^2 F_{EL,EL} + \rho\sigma_{EL}\sigma_{GC}F_{EL,GC} + \frac{1}{2}\sigma_{EL}^2 F_{EL,EL} + \alpha_{GC}F_{GC} + \alpha_{GC}F_{GC} - rF = 0 \tag{12}$$

Analytical solutions are rarely available for PDEs, and numerical solutions are mostly ad hoc. In the present case the natural homogeneity of the problem allows us to reduce the PDE to an ordinary differential equation (ODE). The optimal decision will be determined by the project's total price $p \equiv P_{EL} + \frac{d_2}{k_2}PGC$. We express the option value as a function of p, derive the different partial differentiations of the option value and apply these to the PDE. This results in an ODE, Equation 13, with the scalar independent variable p.

$$F(P_{EL}, P_{GC}) = f(P_{EL,t+l} + \frac{d_2}{k_2}P_{GC,t+l}) = f(p)$$

$$F_{EL} = f'(p) \quad , \quad F_{GC} = \frac{d_2}{k_2}f'(p)$$

$$F_{EL,EL} = f''(p) \quad , \quad F_{EL,GC} = \frac{d_2}{k_2}f''(p) \quad , \quad F_{GC,GC} = (\frac{d_2}{k_2})^2 f''(p)$$

$$\frac{1}{2}\left(\sigma_{EL}^2 + 2\frac{d_2}{k_2}\rho\sigma_{EL}\sigma_{GC} + (\frac{d_2}{k_2})^2\sigma_{GC}^2\right)f''(p) + (\alpha_{EL} + \frac{d_2}{k_2}\alpha_{GC})f'(p) - rf(p) = 0 \tag{13}$$

The general solution of this equation has the form $a_1e^{\beta_1 p} + a_2e^{\beta_2 p}$. The fundamental quadratic is then given by Equation 14.

$$Q = \frac{1}{2}\left(\sigma_{EL}^2 + 2\frac{d_2}{k_2}\rho\sigma_{EL}\sigma_{GC} + (\frac{d_2}{k_2})^2\sigma_{GC}^2\right)\beta^2 + (\alpha_{EL} + \frac{d_2}{k_2}\alpha_{GC})\beta - r = 0 \tag{14}$$

From the solution of the quadratic equation, we derive that $\beta_1 > 0$ and $\beta_1 < 0$. Given that $\lim_{t\to\infty}F(t) = 0$, the constant $a_2 = 0$. This results in an option value given by $f(p) = a_1e^{\beta_1 p}$. The positive unit root of β_1 is given by Equation 15.

$$\beta_1 = \frac{-\left(\alpha_{EL} + \frac{d_2}{k_2}\alpha_{GC}\right) + \sqrt{\left(\alpha_{EL} + \frac{d_2}{k_2}\alpha_{GC}\right)^2 + 2r\left(\sigma_{EL}^2 + 2\frac{d_2}{k_2}\rho\sigma_{EL}\sigma_{GC} + (\frac{d_2}{k_2})^2\sigma_{GC}^2\right)}}{\sigma_{EL}^2 + 2\frac{d_2}{k_2}\rho\sigma_{EL}\sigma_{GC} + (\frac{d_2}{k_2})^2\sigma_{GC}^2} \tag{15}$$

5.3 Optimal Investment Strategy

Before determining the optimal investment strategy the following arguments should be considered; investing now implies that the investor will start receiving revenues from the project, but then loses the opportunity to avoid losses if the electricity price should drop or the GCs are not introduced. Postponing the investment saves the interest of the investment cost. The optimal investment threshold p^* is the trigger level for investing in the project. To find the optimal investment strategy, we apply the value matching (VM) and smooth-pasting (SP) conditions (Dixit and Pindyck, 1994). VM states that the option value equals the NPV of the project in the threshold price, $f(p^*) = NPV(p^*)$. SP states that the expected NPV of the project is a tangent to the option value in the threshold price, $f'(p^*) = NPV'(p^*)$. By applying VM and SP we are left with two equations (Equation 16a and Equation 16b). From these equations, the threshold price p^* and the constant a_1 can be expressed (Equation 16c and Equation 16d).

$$VM: \quad a_1 e^{\beta_1 p^*} = m_n k_2 p^* (1-\tau_n) - X_n \tag{16a}$$

$$SP: \quad \beta_1 a_1 e^{\beta_1 p^*} = m_n k_2 (1-\tau_n) \tag{16b}$$

$$(P^*_{EL} + \frac{d_2}{k_2} P^*_{GC}) = p^* = \frac{X_n}{m_n k_2 (1-\tau_n)} + \frac{1}{\beta_1} \tag{16c}$$

$$a_1 = \frac{m_n k_2 (1-\tau_n)}{\beta_1 e^{\beta_1 p^*}} \tag{16d}$$

Finally, Equation 17 expresses the final value of the investment option. For $p > p^*$, the option value equals the NPV and the investor should invest right away. If $p \leq p^*$, the option has a higher value than the NPV, and the investor should wait. The NPV alone will recommend the investor to invest if the NPV is positive, but the ROV approach will recommend the investor to wait as long as $p \leq p^*$. Further in this paper, this model approach will be referred to as the ROV model.

$$f(p) = \begin{cases} \frac{m_n k_2 (1-\tau_n)}{\beta_1} e^{\beta_1 (p - p^*)} & \text{if} \quad p \leq p^* \\ m_n k_2 p (1-\tau_n) - X_n & \text{if} \quad p > p^* \end{cases} \tag{17}$$

5.4 Binary Choice model

For analyzing the investment decisions, we formulate a binary choice model where the investor has two choices; invest or wait. This section presents a binary choice model, where the *logit formulation* (Berkson, 1944) is applied.

The decision variable y is a binary variable, where investing equals one and waiting equals zero. Below we present the logit formulation with two explanatory variables, x_1 and x_2. The logit formulation is expressed in Equation 18a, and returns probabilities between zero and one. We let $G(z) = G(\beta_0 + x_1\beta_1 + x_2\beta_2)$, and the logit formulation includes the explanatory variables. The binary choice model returns the response probability, which is given in Equation 18b. The response probability returned is the probability of investing given the two explanatory variables.

$$G(z) = \frac{e^z}{1+e^z} \tag{18a}$$

$$P(y = 1 \mid x_1, x_2) = G(\beta_0 + x_1\beta_1 + x_2\beta_2) \tag{18b}$$

6 Parameter Estimation

This section presents how we estimate the required parameters for valuing the project and the real option. Since 2001, a financial market for electricity has been operated at Nord Pool (NASDAQ OMX). Under the assumption of an efficient market, we use electricity forward contracts to estimate parameters. On the other hand, the existing GC market in Sweden is not efficient. Because of small traded volumes, historical prices are not optimal in the parameter estimation for a Norwegian-Swedish GC market.

According to Section 4, we use the 3-years forward contracts at Nord Pool (NASDAX OMX) to describe the expected electricity price in each year from 2005 to 2011. In Table 4, we present annual expected electricity prices, GC prices and parameters required. The GC prices result from Equation 3 in Section 4.2, where the annual expected electricity price is applied. The drift in the electricity price is the observed growth in the market. We observe the growth by comparing the 2- and 4-years forward contract to the 3-years forward contract. Annual average prices for the contracts are found, and then the annual growth between the time series can be calculated. Finally, the average of the annual growth between the time series is assumed to be the annual drift. The volatility in the electricity price is estimated by historical volatility in 3-years forward contracts. Both observed drift and volatility in the electricity price are assumed to be constant over the project's lifetime.

Table 4: Expected annual prices and parameters

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Electricity price (€/MWh)	28.40	32.06	42.68	45.87	53.73	40.15	43.42
GC price (€/MWh)	21.25	21.25	5.00	21.88	16.27	31.15	29.18
Drift electricity price (€/MWh/year)	0.14	0.00	0.41	0.00	0.66	2.70	1.34
Drift GC price (€/MWh/year)	0.90	0.90	0.21	0.92	0.69	1.31	1.23
Volatility electricity price (€/MWh/year)	3.27	3.73	4.62	4.65	6.87	7.14	6.96
Volatility GC price (€/MWh/year)	2.50	2.50	-	2.50	2.50	2.50	2.50

As presented in Section 4.2, the drift in the GC price cannot exceed the risk-free rate due to the banking principle. We assume the inflation rate to reflect the growth. For applying the growth as the required drift in an ABM, we estimate a drift from an extrapolation of the price with the inflation and then find the annual average change. The lack of liquidity in the Swedish GC market causes higher historical volatility. We believe that the volatility in the common market will be smaller compared to the Swedish market. The volatility in a common GC market is assumed to be 2.5 €/MWh/year. In 2007, the volatility of the feed-in-tariff is zero because of no price uncertainty in the subsidy level.

The correlation between the electricity price and the GC price is discussed in Section 4.3 where we conclude that the prices cannot be perfectly negatively correlated, due to the banking principle. The correlation has to be smaller, and we therefore assume a correlation of -0.5. Exogenous parameters are listed in Table 5. The remaining parameters have been found in the survey and are project specific. These are annual production, installed capacity, investment costs and the date of investment decision.

Table 5: Exogenous parameters

Exogenous parameters	**Symbol**	**Value**	
Risk-free rate[a]	r	5 %	
Inflation rate[b]	i	2.5 %	
Economical lifetime of the project	L	40	years
Allocation period	A	15	years
Construction lag	l	2	years
Operational cost[c]	c	6	€/MWh

[a] The risk-neutral discounting rate is 5 % according to Bernhardsen and Gerdrup (2006) and Gjølberg and Johnsen (2007). This is a nominal risk-free rate based on a neutral real interest rate of 2.5-3.5 % and the expected inflation rate of 2.0-2.5 %.

[b] According to the Norwegian Central Bank.

[c] The operational cost c is derived from the survey results. By including the expected maintenance, transmission and sale costs we assume operating expenses of 6 €/MWh.

7 Empirical Analysis

In this section, an introduction to the optimal investment strategy is presented before the empirical results from the NPV and ROV models derived in Section 5. Next, we perform a logistic regression to empirically test whether the NPV or the ROV decision rule better explain actual investor behavior. Finally, a sensitivity analysis is conducted, in which the effects of changing the drift, volatility and interest rate will be discussed. The final dataset of 73 projects is applied in this empirical analysis. The parameters and premises were presented in Section 3 and the parameter estimation in Section 6. For each project, the information available on the decision date is applied as parameters in the modeling framework (cf. Table 4). Projects awaiting improved economic conditions are evaluated on February 1st 2011 (cf. Section 3.4).

7.1 Introducing Decision rules

The optimal investment threshold p^* is the price where the option value $f(p)$ equals the NPV, hence $f(p^*) = NPV(p^*)$. According to real options theory, the optimal investment strategy is to invest when the price level reaches the threshold price. In Figure 9, an example of how the option value and the NPV depend on the price level is presented. The option value reflects the opportunity to invest, hence the value is never negative. As the graph shows, the option value equals the NPV for price levels higher than the threshold price, which indicates that investing is the optimal action. Price levels below the threshold price indicate waiting as the optimal behavior. The standard NPV decision rule, on the other hand, is to invest when $NPV \geq 0$. Investors applying the ROV decision rule will therefore require a higher price level before investing, as shown in the graph.

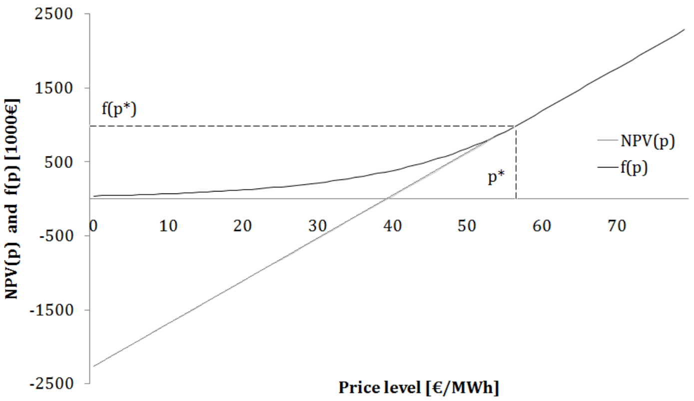


Figure 9: Option value and NPV of a SHP project

7.2 Results from the NPV and the ROV models

Since we include two scenarios, the results are twofold. Figure 10 and Figure 11 show the option value and the NPV for each of the projects and indicate the difference between the NPV and the option value by a line. For simplifying the comparison of small and large investment projects, both values are divided by the project's investment costs. The option values are denoted by *triangles* for projects invested in and *circles* for projects put on hold. Waiting investors claim they wait due to economical reasons.

Considering no GCs, Figure 10 shows that some projects were invested in, despite negative NPV. We therefore question whether these investors expected GCs or not. The waiting investors behave according to the ROV model. Overall, there are significant differences between the option value and the NPV of the projects. Marginal profitability and uncertainty in projects result in higher value of the opportunity to wait.

Figure 11 presents Scenario 2, with GCs included. Here, fewer projects are invested in with negative NPV, compared to Scenario 1, with no GCs. This supports our intuition saying that many investors have included GCs in their profitability calculations when considering investing. The option values, indicated by triangles and circles, increase due to higher drift and volatility when including GCs. The difference between the option value and the NPV, on the other hand, has decreased, indicating that the waiting investors (circles) are closer to invest.

In Figure 12 and Figure 13, the threshold prices on the SHP project's date of decision are plotted. In addition, we plot price level, drift and volatility to visualize that parameters used in the given years (cf. Table 4). Scenario 1, without GCs, is shown in Figure 12. The threshold price of each project is above the price level, indicating waiting as the optimal investment strategy. All the projects invested in (triangles) have pursuant to the ROV model invested to early. Contrary, the waiting projects (circles) behave according to the ROV decision rule. Without GCs, the ROV model indicates that the price level is too low to trigger investments for all the projects. Figure 13 presents the threshold prices in Scenario 2. The threshold prices are higher with GCs, due to higher drift and volatility. For some projects, the threshold prices are below the price level, indicating that investing is optimal due to no additional value of waiting. Projects invested in (triangles) with threshold prices below the price level, behave consistent to the ROV

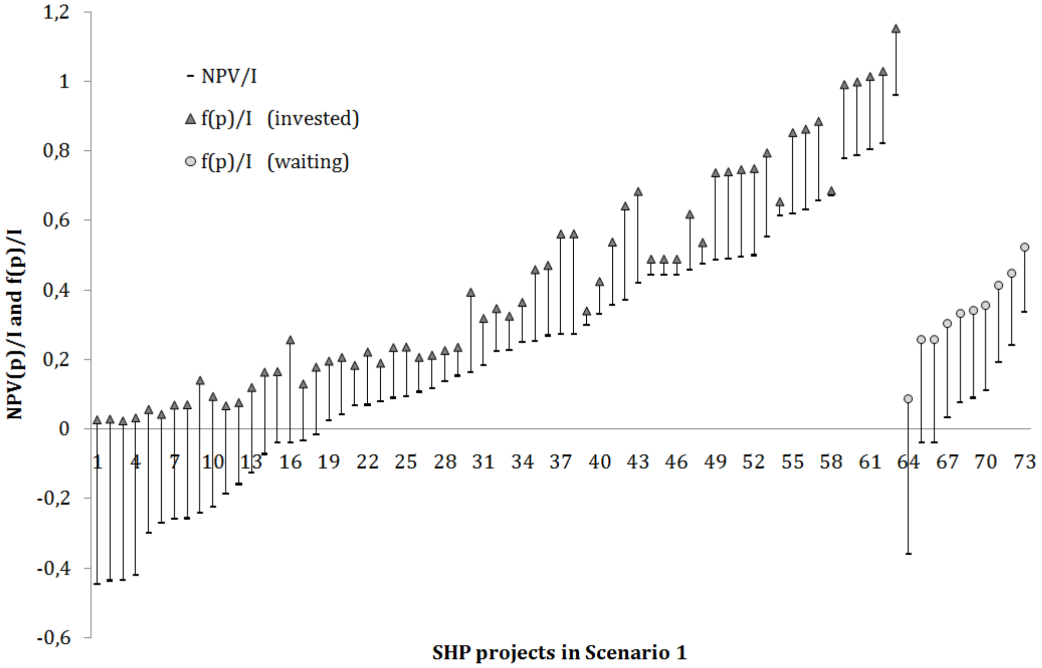


Figure 10: The NPV/Investment cost and f(p)/Investment cost for Scenario 1 for each SHP project

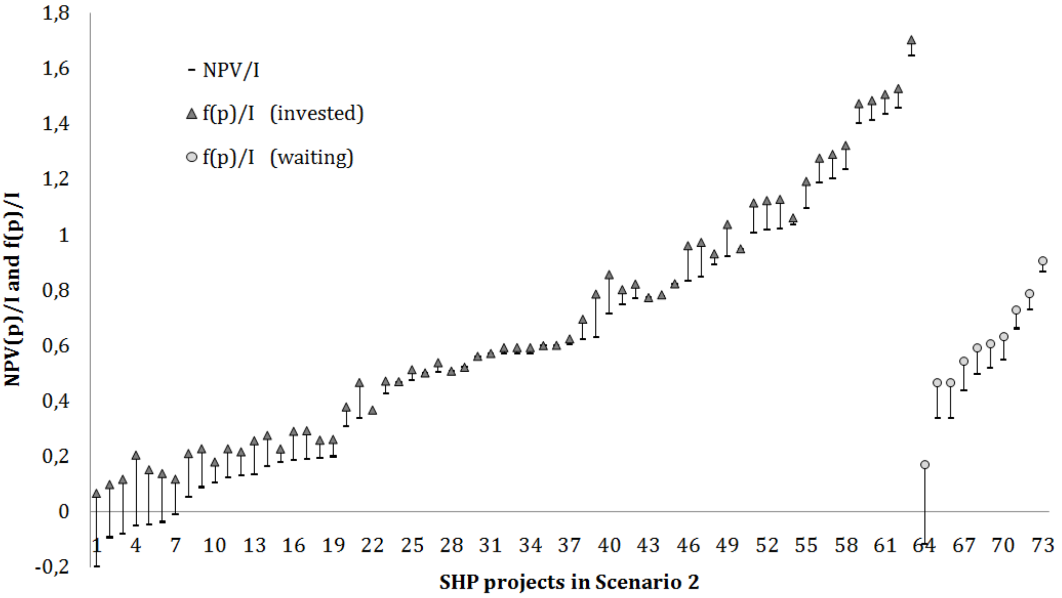


Figure 11: The NPV/Investment cost and f(p)/Investment cost for Scenario 2 for each SHP project

model in Scenario 2. All the projects on hold (circles) behave according to the ROV model. Compared to Scenario 1, the threshold prices, with GCs, are closer to the price level, indicating that these investors are closer to investing.

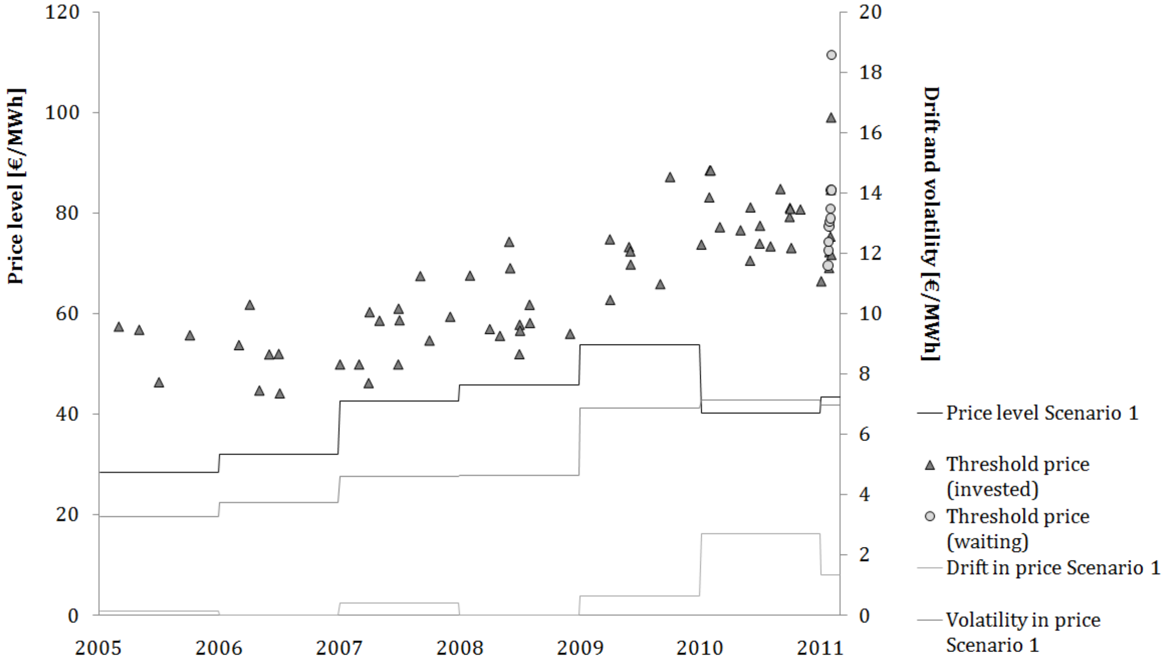


Figure 12: Price levels and threshold prices for each year and project for Scenario 1

The behavior of waiting investors (circles) can be explained by the ROV decision rule in both scenarios. The projects invested in (triangles) contradict the ROV decision rule in Scenario 1, while some investment decisions are pursuant to the ROV decision rule in Scenario 2. The NPV decision rule fails to explain a number of investment decisions in Scenario 1, while Scenario 2 gives more explanatory power. Given these indications, it is reasonable to believe that many investors expected GCs when making their investment decision.

The parameters used as input in this analysis change every year, since we try to recreate the investor's decision problem. The parameters changing significantly over the years are price level, drift and volatility as indicated in Figure 12 and Figure 13. In 2010, we find a cluster of investments. In both scenarios, these projects have invested too early according to the ROV decision rule. Given the fact that these investments have positive NPV, a possible explanation is that investors have accounted for lower volatility. The threshold prices are higher due to both a higher level of drift and volatility. Increased drift and volatility implies a higher value of waiting for more information. A ROV approach with no volatility corresponds to a NPV approach, but there is still a potential price growth giving an inner value of the investment option.

In 2007 and 2008, the expectations regarding climate policy changed from expecting a feed-in tariff to expecting a GC system (cf. Table 2). All threshold prices for these two years are above the price level in Scenario 1. When including GCs, some investments during this period are legitimate according to the ROV decision rule. Investors tend to expect GCs, and assume a lower uncertainty. This impression is strengthened by the following quote. "If you cannot

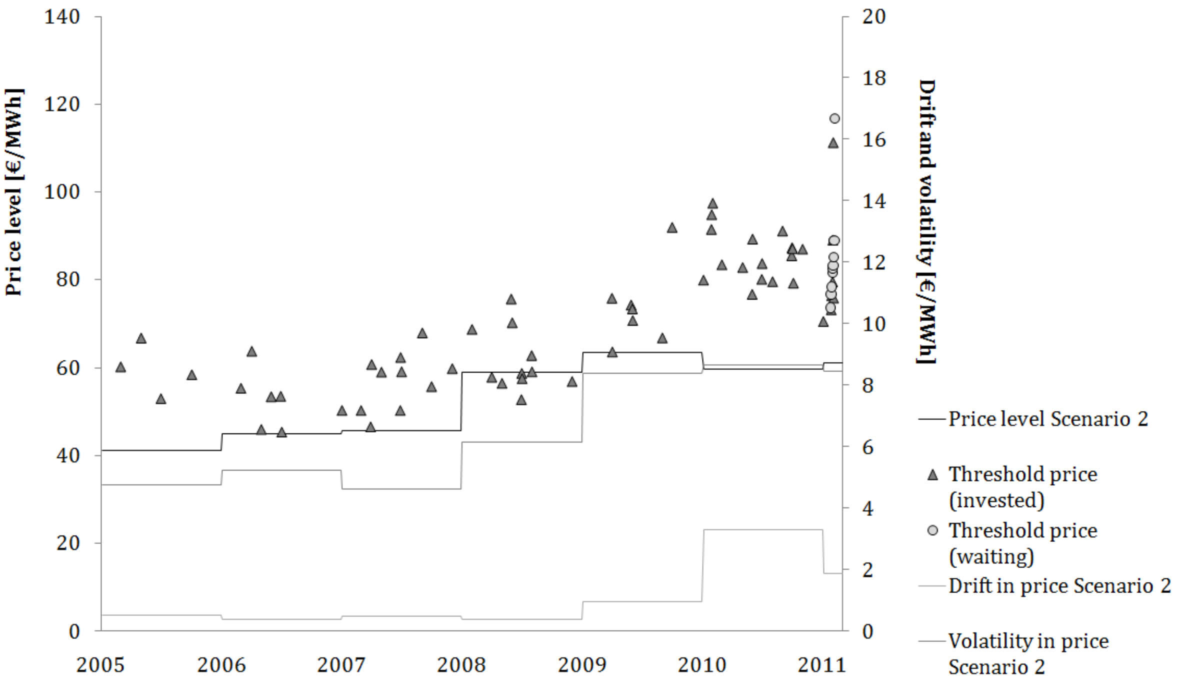


Figure 13: Price levels and threshold prices for each year and project for Scenario 2

believe the Minister of Energy, who should you then believe?", says a frustrated investor who has invested based on a GC market to be introduced in the near future.

The ROV decision rule can be considered as a guiding investment rule. Construction lag can cause inertia in the process of commissioning a SHP project, indicating that the investor may invest when the price level is close the threshold price, and not necessarily on the exact trigger level. This implies that investments made, with price levels close to the threshold price, are reasonable when evaluating the ROV decision rule. In Figure 13, multiple projects invested in have threshold prices close to the price level. When considering the ROV model as a guiding investment rule, more investment decisions are reasonable. Even though many threshold prices are close to the price level, neither the NPV model nor the ROV model succeeds in explaining all investor behavior.

7.3 Results from the Logistic regression

From the previous subsection, neither the NPV nor the ROV decision rules alone can explain all the investment decisions made. For further investigation, we empirically test the NPV and the ROV model by performing a logistic regression with the binary choice model presented in Section 5.4. Through the logistic regression, we aim to analyze investor behavior.

We have applied a number of different explanatory variables for describing investor behavior in the logistic regressions. Examples of variables are *NPV(p)*, *f(p)-NPV(p)*, *NPV(p)/Investment cost*, *(f(p)-NPV(p))/Investment cost*, *dummy variables* for *size, professional firms* and *decision rule.* The dummy variables for the NPV and ROV decision rule equal one for investors investing according the decision rule and zero otherwise. Unfortunately, when both the NPV and the ROV decision rules are included, the regression parameters are not significant. Table 6 shows the regression for *NPV(p)/Investment cost* and *(f(p)-NPV(p))/Investment cost* for Scenario 2, further referred to as the NPV and the value of waiting. More results are presented in Appendix A.4. The pseudo R^2 is below 0.1[10], implying that the regression does not fit the data very well. The lack of goodness of fit may originate from several reasons. First, the number of observations is low. Second, the difference between the results from the estimated regression and the actual results is high, causing a high standard deviation. The consequence of a high standard deviation is insignificant parameters. Finally, multi-collinearity occurs when the explanatory variables are correlated. The lack of significance when including variables for both decision rules, can be explained by the fact that the NPV and the ROV models are correlated. The correlation is a result of how the ROV model is derived (cf. Section 5.3).

Table 6: Results from the logistic regression for Scenario 2 with NPV/Investment cost and (f(p)-NPV)/Investment cost as explanatory variables

	Coefficient	**Std.Error**	**t-value**	**t-prob**
Constant	2.3958	0.9905	2.42	0.018
NPV(p)/Investment cost	0.0265	0.9215	0.03	0.977
(f(p)-NPV(p))/Investment cost	-6.1889	5.7330	-1.08	0.284
Log-likelihood	-28.3185			
Baseline log-likelihood	-29.1602			
No. of observations	73			
Pseudo R^2	0.041			

We fail to find a regression with significant variables when including both the NPV and ROV decision rules. Despite insignificant variables, we present the results from the regression of NPV, x_1, and value of waiting, x_2. The resulting regression is presented in Equation 19. The positive regression parameter indicates the probability of investing to be positively related to the NPV. If the option value is higher than the NPV, the optimal strategy is to wait, hence a difference between the option value and the NPV is negatively related to the probability of investing. Both these effects are reasonable and correspond to our expectations.

$$P(y = 1 \mid x_1, x_2) = 2.3958 + 0.0265x_1 - 6.1889x_2 \tag{19}$$

In the following figures, one variable is explained while the other variable is held constant (mean value). The plotted line in Figure 14 presents the regression by varying the explanatory variable for the NPV model. We notice that the probability of investing increases when the NPV increases, when the value of waiting is constant (8 %). The value of waiting from the option is presented in Figure 15. The probability of investing decreases when the value of waiting increases, when the NPV is constant (57 %). The figures also show the results from inserting actual projects (triangles) into the regression (Equation 19). Both figures show high probabaility of investing, with values ranging from 0.65 to 0.92. We notice again, that no conclusions can be derived from these results, due to insignificant variables.

---

[10] A pseudo R^2 measures the goodness of fit. We apply Nagelkerke/Cragg and Uhler's pseudo R^2_N, ranging from zero to one, where one is perfect fit.

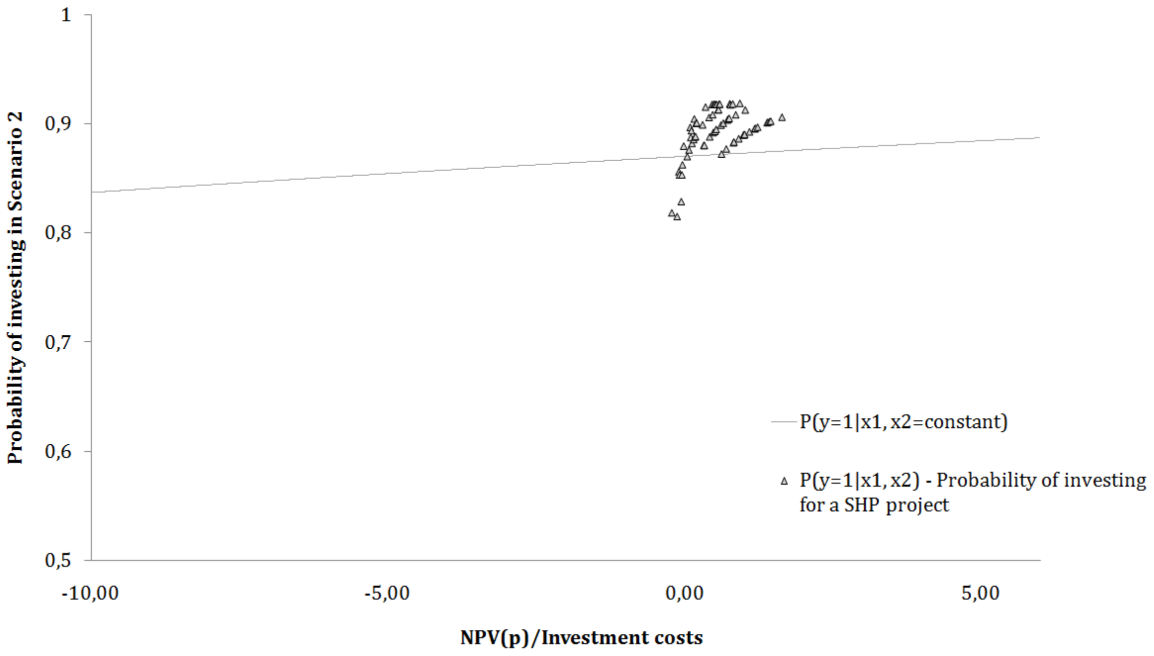


Figure 14: The probability of investing conditional on the NPV/Investment cost, while the (f(p)-NPV)/Investment cost is constant (8 %). The probability of investing for each project is plotted conditional on both variables (Scenario 2)

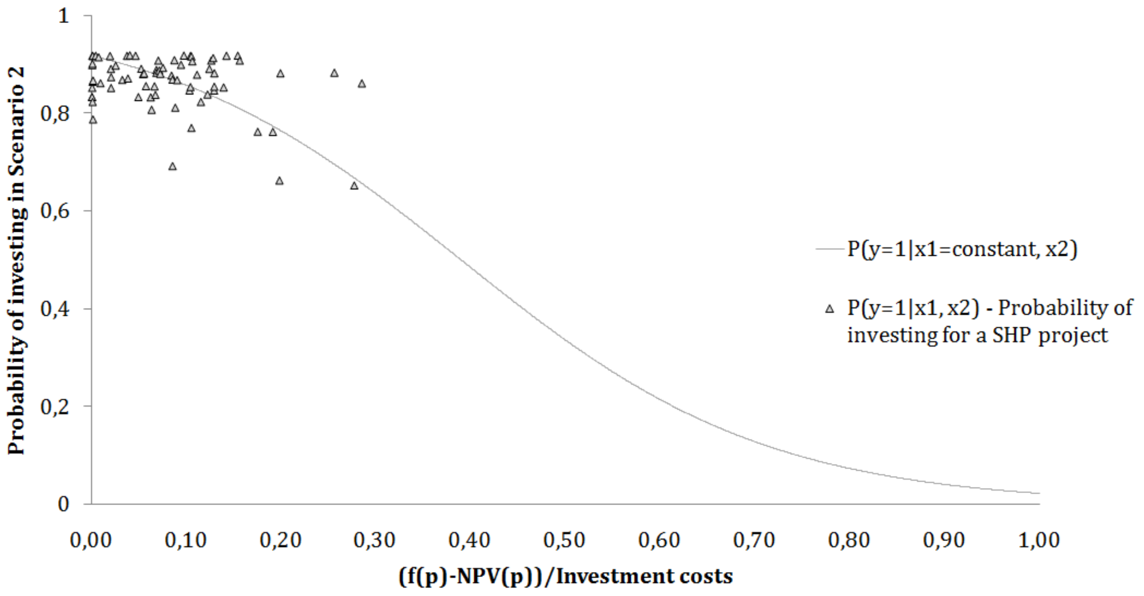


Figure 15: The probability of investing conditional on the (f(p)-NPV)/Investment, while the NPV/Investment cost is constant (57 %). The probability of investing for each project is plotted conditional on both variables (Scenario 2)

Including more relations and variables should improve the regression, but in our regression, problems occur when we include multiple variables. The dummy variables included either have problems with convergence or quasi-complete separation. This may be explained by correlation between the regressors, which prevents the Maximum Likelihood-optimization from identifying the partial effects. Due to convergence problems, we run the regression separately. Here, significant variables for the NPV decision rule in both scenarios are obtained, while the dummy variable for the ROV decision rule resulted in no convergence. We conclude that the NPV model alone can explain investor behavior, but we can neither exclude the ROV model nor say that the NPV model is better than the ROV model.

The logistic regression states that the NPV decision rule alone can explain investor behavior, but few observations make the binary choice model unsuited to evaluate the NPV model up against the ROV model. What we can say is that the ROV decision rule explains some behavior to a certain extent. We experience that the projects on hold due to low profitability or awaiting GCs are explained by the ROV model. The lack of significance can relate to the fact that some decisions are made irrationally. Given the variety of investors (landowners and firms), it cannot be assumed that they all behave equally under the same premises. When conducting the survey, we got the impression that some investors were behaving irrationally. An investor expressed: "If we are so lucky to get a license, we build!" Not all investors behave rationally, and in this case, the investment decision was taken before the license was granted. To divide the decision process in a stepwise process is left for future work.

7.4 Sensitivity analysis

The sensitivity analysis reflects the importance of the model parameters. Drift and volatility are interesting parameters, because they determine the development of the prices. Electricity prices and GC prices are vital profitability factors in SHP projects. Interest rate is an important parameter when valuing the project. Even though, parameters in reality rarely change independently from each other, we consider the effects from isolated changing drift, volatility and interest rate in Scenario 2. A sensitivity analysis on the results from the logistic regression, has not been performed. It could be interesting to see if changes in the parameters result in better regression results. This is left for future work.

Drift parameter
Both the electricity price and the GC price follow stochastic processes with drift. The drift parameter affects the expected revenues, hence the profitability of the project. Increasing the drift parameter results in higher threshold price and higher option value. When GCs are included, the total drift is higher than without GCs. This is one of the reasons for why the threshold prices are higher in Scenario 2 compared to Scenario 1. We find it necessary to comment that the drift parameter changes every year according to the model parameters presented in Table 4. The drift parameter varies from zero to 2.7 €/MWh/year. Despite the market estimate of zero drift in the electricity price, it is unlikely that investors assumed zero drift when considering investing. On the other hand, 2.7 €/MWh/year is a relatively high drift. Variations in the drift parameter effect the value of the project. Therefore, we conduct a sensitivity analysis on how the NPV changes

when the drift varies with 0.5 €/MWh/year.[11] Figure 16 shows how changes in drift affect the NPV. As the figure shows, some projects with negative NPV turn positive when a higher drift is implemented.

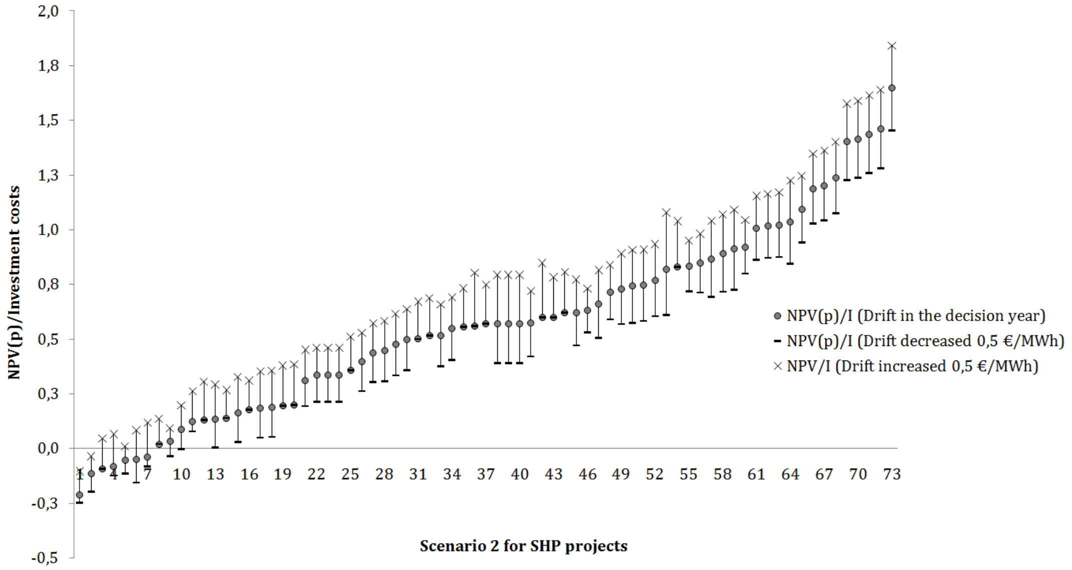


Figure 16: SHP projects presented by NPV/Investment costs where the electricity drift parameter changes for Scenario 2

Volatility parameter

The volatility in electricity and GC prices presents the uncertainty the investor is exposed to when investing in a SHP project. An increase in the volatility parameter results in a higher threshold price and a higher option value. In contrast to the NPV model, the ROV model takes the consequence of uncertainty into account when valuing the project. The effects of changing the volatility of the electricity price are presented in Figure 17. The option values increase (decrease) due to higher (lower) volatility. This corresponds to an increased value of waiting, when the volatility increases.

The volatility in Scenario 2 is determined by the volatility in electricity and GC prices, and the correlation between the prices. The correlation explains the relationship between the electricity and the GC markets. We have assumed the correlation to be -0.5, and the effects of changing the correlation to zero and minus one are tested. We experience that large changes in the correlation have a relatively small impact on the option value. A comment to this, is that a GC system is introduced in order to trigger investments in new renewable energy. With GCs, a SHP investor will receive a higher price level. Therefore, it can be reasonable for an investor to expect lower uncertainty in Scenario 2, hence a lower level of volatility. We believe, on the other hand, that an investor will face a higher volatility in Scenario 2. This is because the total price is the sum of two prices settled in two different markets. The uncertainty in the expected revenues relies on two markets, indicating a higher uncertainty.

---

[11] It is assumed that the minimum value of the drift is zero.

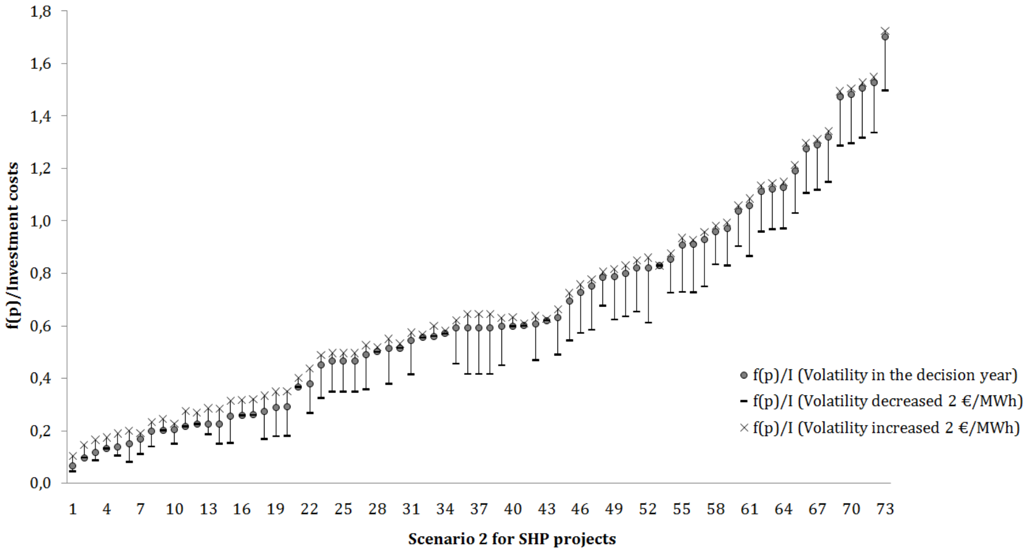


Figure 17: SHP projects presented by f(p)/Investment costs where the volatility of the electricity price changes for Scenario 2

Interest rate parameter

The risk-free interest rate is used as the discounting rate when valuing the projects. An increased interest rate results in a lower value of the project, hence a lower option value. Decreasing the interest rate parameter results in a higher option value. The effects of changing the interest rate are presented in Figure 18. The option values increase (decrease) due to lower (higher) interest rate. The interest rate causes large changes in the option value, hence the interest rate is a sensitive parameter.

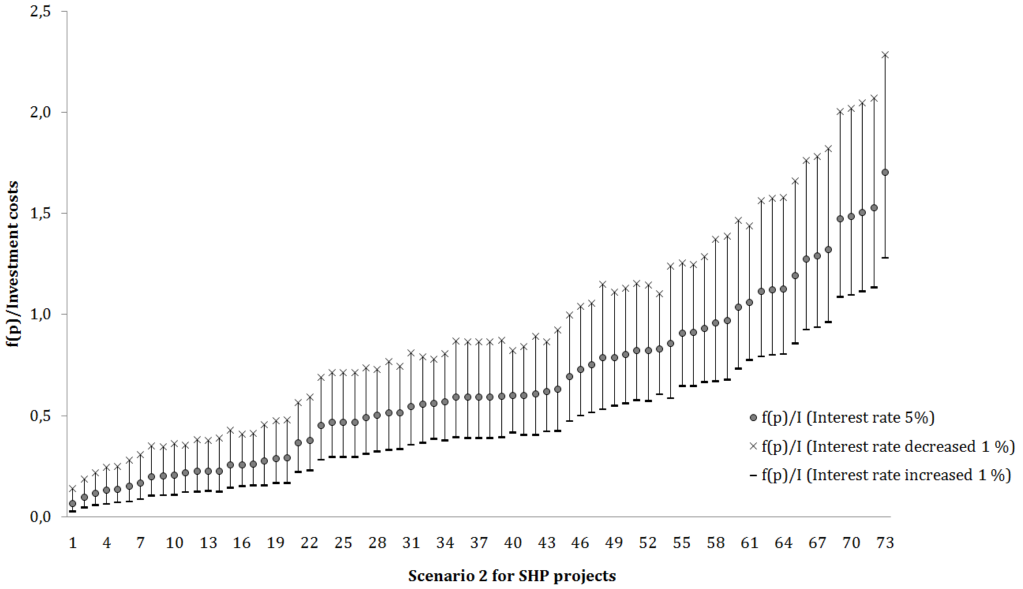


Figure 18: SHP projects presented by f(p)/Investment costs where the interest rate parameter changes for Scenario 2

We notice that isolated changes in the model parameters result in relatively large changes in NPVs and ROVs. This makes our analysis sensitive to the parameters, especially for projects with limited profitability.

8 Conclusion

In this empirical study, the investor behavior in 73 SHP projects has been examined. An extensive survey has been conducted to recreate the investor's decision problem (cf. Section 3). From the empirical analysis in Section 7.2 we observe that investors tend to expect revenues from GCs when making their investment decision. The empirical results from applying the NPV model and the ROV model imply that one decision rule does not explain investor behavior better than the other. The logistic regression in Section 7.3 does not achieve significant results when comparing the two decision rules, but the NPV decision rule alone has explanatory power.

The study does not support the ROV approach to better explain investor behavior than the NPV approach. We observe that the NPV decision rule to some extent explains projects invested in. The ROV decision rule explains projects on hold due to economic reasons. We also find a group of investors who, according to our NPV model, have invested despite a negative NPV. This behavior is not consistent with any of the decision rules presented.

Acknowledgments

We would like to thank our academic supervisor Professor Stein-Erik Fleten and PhD candidate Ane Marte Heggedal for support and constructive feedback. Additionally, we would like to thank the investors who helped us to provide useful information by participating in the survey.

References

Amundsen, E. S., Baldursson, F. M., Mortensen, J. B., 2006. Price volatility and banking in green certificate markets. Environmental and Resource Economics 35, 259–287.

APX-ENDEX, 2011. Industrial wood pellets pricing. `http://www.apxendex.com`.

Bar-Ilan, A., Strange, W. C., 1996. Investment lags. The American Economic Review 86 (3), 610–622.

Bøckman, T., Fleten, S.-E., Juliussen, E., Langhammer, H. J., Revdal, I., 2008. Investment timing and optimal capacity choice for small hydropower projects. European Journal of Operational Research 190 (1), 255–267.

Berkson, J., 1944. Application to the logistic function to bio-assay. Journal of the American Statistical Association 39 (227), 357–365.

Bernhardsen, T., Gerdrup, K., 2006. Den nøytrale realrenten. Penger og Kreditt 34 (4), 208–220.

Dixit, A. K., Pindyck, R. S., 1994. Investment under uncertainty. Princeton University Press.

EIA, 2010. Electricity market module. Report from the U.S. Energy Information Administration.

Enova, 2008. Mulighetsstudie for landbasert vindkraft 2015 og 2025. Report nr. 18, Enova SF.

European Commission, 2001. Directive 2001/77/ec.

European Commission, 2009. Directive 2009/28/ec.

Fleten, S.-E., Maribu, K. M., Wangensteen, I., 2007. Optimal investment strategies in decentralized renewable power generation under uncertainty. Energy 32 (5), 803–815.

Fleten, S.-E., Ringen, G., 2009. New renewable electricity capacity under uncertainty: The potential in Norway. Journal of Energy Markets 2 (1), 71–88.

Gjølberg, O., Johnsen, T., 2007. Investeringer i produksjon av fornybar energi: Hvilket avkastningskrav bør Enova SF legge til grunn? Report for Enova SF.

Heggedal, A. M., Linnerud, K., Fleten, S.-E., 2011. Uncertain climate policy decisions and investment timing: Evidence from small hydropower plants. Working Paper, Norwegian University of Science and Technology.

Jensen, S. G., Skytte, K., 2002. Interactions between the power and green certificate markets. Energy Policy 30 (5), 425–435.

Koekebakker, S., Ollmar, F., 2005. Forward curve dynamics in the nordic electricity market. Managerial Finance 31 (6), 73–94.

Kvale, S., 1996. Interviews: An introduction to qualitative research interviewing. Sage Publications.

Lucia, J. J., Schwartz, E. S., 2002. Electricity prices and power derivatives: Evidence from the nordic power exchange. Review of Derivatives Research 5 (1), 5–50.

McDonald, R., Siegel, D., November 1986. The value of waiting to invest. The Quarterly Journal of Economics 101 (4), 707–728.

Ministry of Petroleum and Energy, 2006. Støtteordningen for elektrisitetsproduksjon fra fornybare energikilder (press release no. 135/06, November 24th 2006).

Ministry of Petroleum and Energy, 2007. Nye samtaler med Sverige om grønne sertifikater til fornybar energi (press release no. 173/07, December 7th 2007).

Ministry of Petroleum and Energy, 2009a. Enige om prinsippene for et felles elsertifikatmarked (press release no. 135/09, September 7th 2009).

Ministry of Petroleum and Energy, 2009b. Overgangsordning for elsertifikatermarkedet på plass (press release no. 143, November 26th 2009).

Ministry of Petroleum and Energy, 2010a. Grunnlagsnotat - norske elsertifikatkvoter (news, December 8th 2010).

Ministry of Petroleum and Energy, 2010b. Norge og Sverige enige om et felles elsertifikatmarked (press release no. 117/10, December 8th 2010).

Ministry of Petroleum and Energy, 2010c. Protokoll for arbeidet om et felles svensk-norsk marked for elsertifikater (appendix to press release no. 117/10, December 8th 2010).

Moel, A., Tufano, P., 2002. When are real options exercised? An empirical study of mine closings. Review of Financial Studies 15 (1), 35–64.

Morthorst, P. E., 2003. A green certificate market combined with a liberalised power market. Energy Policy 31 (13), 1393–1402.

Norwegian Climate Centre, 2009. Klima i Norge 2100. Report.

NVE, 2007. Kostnader ved produksjon av kraft og varme. Report nr. 1-07, NVE.

NVE, 2010. Tilgangen til fornybar energi i Norge. Report nr. 2-10, NVE.

Paddock, J. L., Siegel, D. R., Smith, J. L., 1988. Option valuation of claims on real rssets: The case of offshore petroleum leases. The Quarterly Journal of Economics 103 (3), 479–508.

Quigg, L., 1996. Empirical testing of real options-pricing models. The Journal of Finance 48 (2), 621–640.

Samuelson, P. A., 1965. Proof that properly anticipated prices fluctuate randomly. Industrial Management Review 6 (2), 41–49.

Schwartz, E. S., 1998. Valuing long-term commodity assets. Financial Management 27 (1), 57–66.

Schwartz, E. S., Smith, J. E., 2000. Short-term variations and long-term dynamics in commodity prices. Management Science 46 (7), 893–911.

Skatteetaten, 2011. Normrente for beskatning av rimelige lån hos arbeidsgiver. Yearly norm rents published by the Internatl Revenue Service.

Statens Energimyndighet, 2007. Tillgång på förnybar energi. Report.

Statens Energimyndighet, 2010. Elcertifikatsystemet 2010. Report.

Svensk Energi, 2010. Vindkraft - en viktig del av framtidens kraftsystem. `http://www.svenskenergi.se/sv/Vi-arbetar-med/Elproduktion/Vindkraft/` (accessed June 4th 2011).

Tricorona, 2010. Svensk kraftmäkling el-certificate price history. `http://www.tricorona.se/priceinfo/history` (accessed June 4th 2011).

A Appendix

A.1 Survey

1. What status has your project today (February 2010)?	
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. Other reasons	
Comment:	

2. If answered 1a) or 1b): When was the decision to invest made? *For example, when was the deal with the contractor signed?*	
Month:	
Year:	
Comment:	

3. What type of model is used in the valuation of the project? *For example: Net Present Value*
Comment:

4. Person to contact:	
Name:	
Phone number:	
5. What is the installed capacity in [MW]?	
MW:	
6. What is the expected annual production in [GWh]?	
GWh:	
7. What is the expected economical life time of the power plant?	
Year:	

8. What is the investment cost of the power plant in [NOK/kWh]? *Include cost of equipment and cost of grid connection*	
NOK/kWh or %	
Comment:	

9. What is the expected annual maintenance cost in [NOK/kWh]?	
NOK/kWh	
Comment:	

10. What is the cost of applying for a license in [NOK]?	
NOK	
Comment:	

11. a. Is your project entitled to pay property tax? [%] **b. Does the economic rent affect the size of the turbine? (>5.5MVA)**

12. What are your expectations concerning green certificates?
Comment:

A.2 Responses from survey

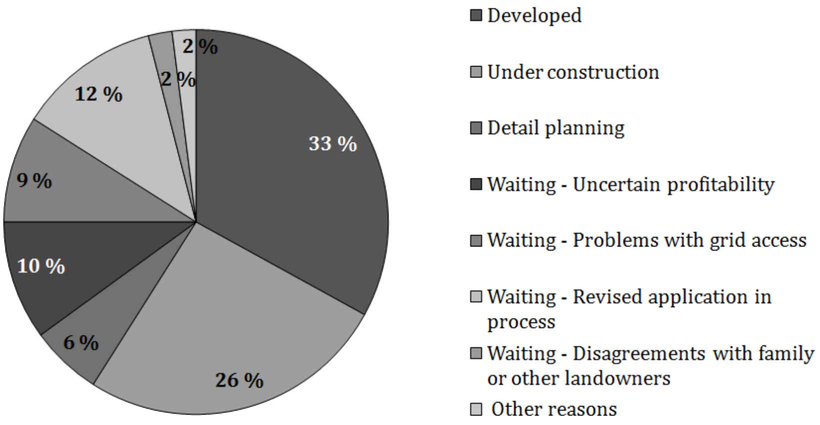


Figure 19: Status of SHP projects on February 1st 2011

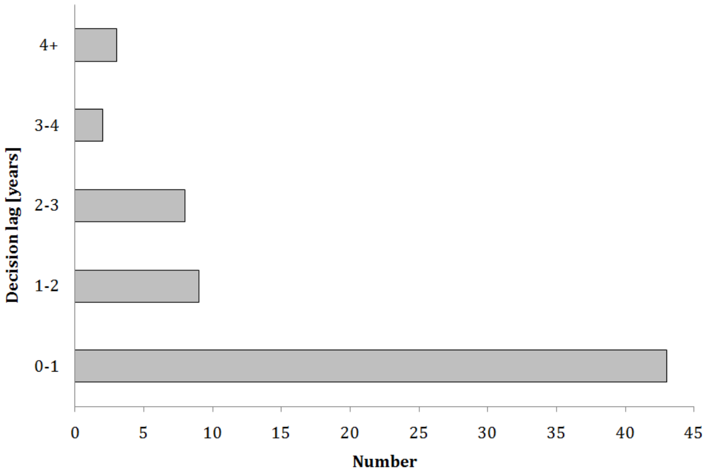


Figure 20: Decision lag

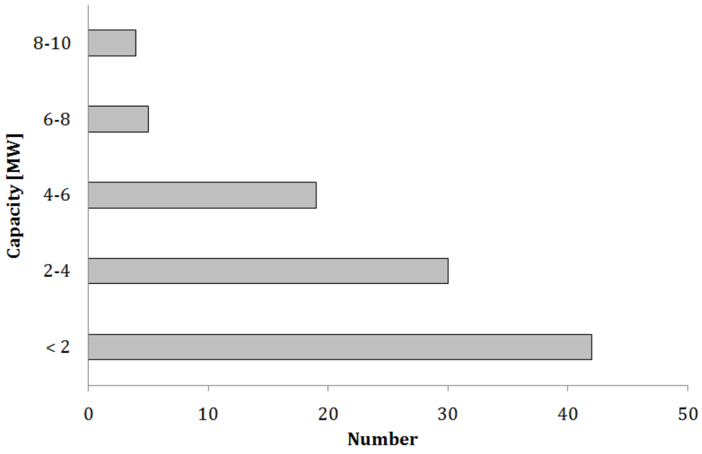


Figure 21: Distribution of capacity

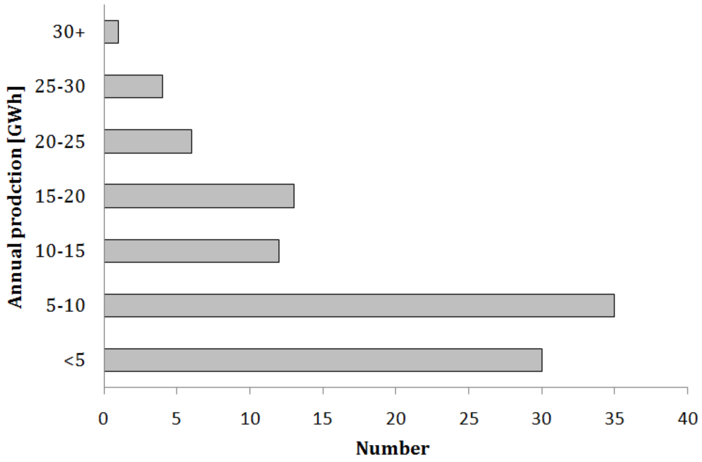


Figure 22: Distribution of production

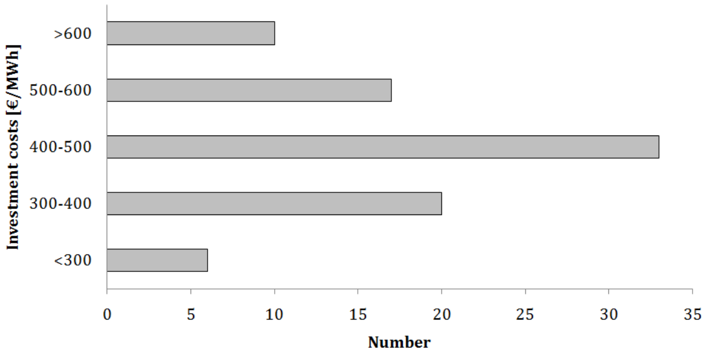


Figure 23: Distribution of Investment costs

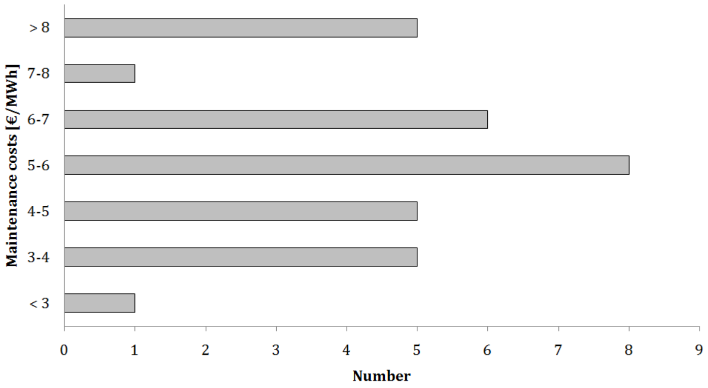


Figure 24: Distribution of Maintenance costs

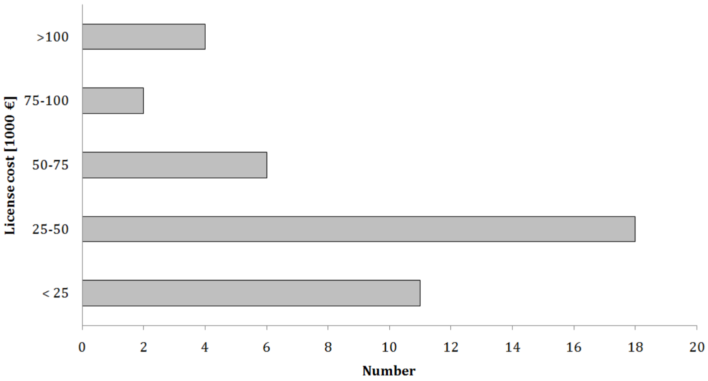


Figure 25: The cost of applying for license

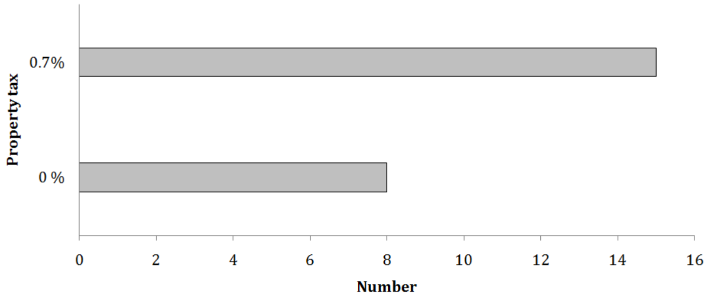


Figure 26: Distribution of Property tax

A.3 Descriptive statistics

Table 7: Descriptive statistics, spot prices and 3-years forward contracts (cf. Section 4, Reuters EcoWin (Nord Pool))

Descriptive statistics Price levels	**Spot Prices**	**3-years forwards**
Number of observations	1412	2472
Standard deviation [€/MWh]	3.96	6.94
Minimum	-47.57	-5.39
Maximum	38.36	3.69
95 % quantile (Value at Risk)	5.70	0.60
5 % quantile (Value at Risk)	-4.36	-0.60
Skewness	0.51	-0.53
Kurtosis	31.01	23.62
Autocorrelation lag 1	-0.21	0.06
Autocorrelation lag 2	-0.16	-0.02
Autocorrelation lag 3	-0.02	-0.02
Autocorrelation lag 4	-0.12	0.07
Autocorrelation lag 5	0.29	0.03
Mean [€/MWh]	0.02	0.01
Test statistic autocorrelation $\alpha = 5$ %	0.05	0.04
Q statistics(quadratic sum autocorrelations)	239.65	22.83
Critical value Q statistics, n=5 and $\alpha = 5$ %	11.07	11.07

A.4 Logistic regression results

Table 8: Results from binary choice model for Scenario 1 with NPV/Investment cost and (f(p)-NPV)/Investment cost as explanatory variables.

	Coefficient	**Std.Error**	**t-value**	**t-prob**
Constant	2.88767	1.210	2.39	0.020
NPV(p)/Investment cost	0.307921	1.312	0.235	0.815
(f(p)-NPV(p))/Investment cost	-4.65128	4.207	-1.11	0.273
Log-likelihood	-27.7103388			
Baseline log-likelihood	-29.1602			
No. of observations	73			
Pseudo R^2	0.071			

Table 9: Results from binary choice model for Scenario 1 with dummy for whether investment decision is according to the NPV decision rule.

	Coefficient	**Std.Error**	**t-value**	**t-prob**
Constant	0.944462	0.4454	2.12	0.037
Dummy NPV decision rule	1.76359	0.7443	2.37	0.021
Log-likelihood	-26.0458326			
Baseline log-likelihood	-29.1602			
No. of observations	73			
Pseudo R^2	0.149			

Table 10: Results from binary choice model for Scenario 2 with dummy for whether investment decision is according to the NPV decision rule.

	Coefficient	**Std.Error**	**t-value**	**t-prob**
Constant	-0.251314	0.5040	-0.499	0.620
Dummy NPV decision rule	4.27666	1.128	3.79	0.000
Log-likelihood	-15.9992549			
Baseline log-likelihood	-29.1602			
No. of observations	73			
Pseudo R^2	0.550			