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Wind Power Investment under Uncertainty and Simultaneous Electricity and Green Certificate Equilibrium

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Oppstartsdato **15. jan 2014**	Innleveringsfrist **11. jun 2014**
Oppgavens (foreløpige) tittel **Wind Power Investment under Uncertainty and Simultaneous Electricity and Green Certificate Equilibrium**	
Oppgavetekst/Problembeskrivelse We study how a green certificate scheme affects investment behavior for a potential wind farm. The investor is assumed to take into account the micro-structural properties of supply and demand through explicitly considering a simultaneous equilibrium in the green certificate market and the electricity market. There is uncertainty in the investment cost which is assumed to be dominated by the considerable fluctuations in the construction material costs, predominantly steel. This uncertainty is portrayed through expressing the input price as a mean reverting process. Regarding future cash flows as deterministic and the investment cost as a one-time expense at exercise, the investor derives a real options-based rule for the optimal investment timing. The resulting renewable power development rates is compared to the case where there is no subsidies, as well as the case of a feed-in tariff system.	
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29.04.2014

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

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Wind Power Investment under Uncertainty and Simultaneous Electricity and Green Certificate Equilibrium

Ingvild Mogensen and Hanne Eline Erdal Heggheim

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Abstract

This paper introduces the combination of an equilibrium model for electricity- and certificate supply and demand of and real options valuation theory for evaluating the effectiveness of support schemes applied in the electricity market. We study how a green certificate scheme affects investment behavior for a potential wind farm. The investor is assumed to take into account the micro-structural properties of supply and demand through explicitly considering a simultaneous equilibrium in the green certificate market and the electricity market. The source of uncertainty in the model lies in the investment cost, which is described as a mean reverting process. At any time the investor possesses an option to develop the wind farm or postpone the decision. Regarding future revenues as deterministic and the investment cost as a one-time expense at exercise, we derive a real options-based rule for the optimal investment timing. Using the Swedish/Norwegian green certificate market as foundation for calibration and focusing on support scheme efficiency, the resulting renewable power development rates are compared to the case where there are no subsidies, as well as the case of a feed-in tariff system. We highlight policy insights from investment aspects that interact with the simultaneous equilibrium in the electricity and green certificate markets. We conclude that for the specific goal of boosting investment in production capacity for renewable energy, and within the framework constructed by the assumptions made in this model, the feed-in tariff will perform better than the green certificate scheme.

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Sammendrag

Denne artikkelen introduserer en kombinasjon av en likevektsmodell for tilbud og etterspørsel av elektrisitet sertifikater og en realopsjonsmodell for å vurdere effektiviteten av støtteordninger som benyttes i kraftmarkedet. Vi studerer hvordan en ordning med grønne sertifikater påvirker investeringsatferd i en potensiell vindpark. Investoren antas å ta hensyn til mikrostrukturelle egenskaper i tilbud og etterspørsel gjennom eksplisitt å vurdere en samtidig likevekt i sertifikat- og kraftmarkedet. Usikkerhetskilden i modellen ligger i investeringskostnaden og er beskrevet som en middelreverserende prosess. Til enhver tid besitter investoren en opsjon om å utvikle vindparken eller utsette investeringen. Ved å anse fremtidige inntekter som deterministiske og investeringskostnaden som en engangskostnad, utarbeider vi en realopsjonsbasert regel for optimalisering av investeringstidspunktet. Modellen kalibreres mot det svensk/norske sertifikatmarkedet og ved å fokusere på støtteordningens effektivitet, sammenlignes resultatene for utviklingsraten for fornybar kraft med markedet hvor det ikke er noen subsidieordning, og et "feed-in tariff" system. Vi fremhever de systemegenskaper som fra et investeringsaspekt påvirkes av en samtidig likevekt i elektrisitet- og sertifikatmarkedet. Vi konkluderer med at for det konkrete mål om å øke investeringer i produksjonskapasitet for fornybare energikilder, og innenfor de rammer definert i oppgaven, vil feed-in tariff prestere bedre enn ordningen med grønne sertifikater.

1 Introduction

During the past decades there have been introduced numerous long- and short-term targets associated with energy production and the reduction of related greenhouse-gas emissions. Ambitious goals have been set on both national and global levels and the optimal path to their fulfillment is a topic of high political priority. The legislative methods applied in order to meet the objectives vary greatly among nations, but are in terms of energy economics defined as either price- or quantity-based mechanisms. These tools apply different philosophies in order to cause behavioral change in the market. The price-based mechanism uses price changes to induce investment and research in production technology for renewable energy sources. The dominating alternative in this group is the feed-in tariff scheme, in which the price of renewable energy is exogenously set by the government, securing the producers' revenue. Conversely, the quantity-based mechanisms incentivises investment by introducing requirements to the production quantity. The most representative approach of this group is the green certificate trading (GC) scheme, which by imposing a set ratio of the electricity sold to originate from renewable energy sources sets the ratio of renewable supply relative to the total electricity production.

The renewable certificate- and feed-in tariff schemes are similar with respect to having the goal of achieving increased investment and research within renewable energy production technology by minimizing the risk of the investor. However, their approaches to achieve this goal are quite different. Through a feed-in tariff, the government offers a long term contract and a guaranteed per unit price to the renewable energy producer to diminish their price risk[1]. The GC scheme is one of the newer policies applied in the energy market and has been adopted by several nations, among them USA, Norway, Sweden and UK. These countries however represent very different configurations. The common denominator is the awarding of a tradable certificate to the producer of renewable energy for one preset unit of electricity. Demand for these certificates is constructed through a penalty to be paid by the distributor per certificate they fail to procure according to a governmentally set required quota. The sale of these certificates hence removes some of the risk of investing in environmentally friendly production facilities by securing a second source of income.

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[1] There are several different price contracts in use, where the most widely used category is defined as the "fixed-feed-in tariff". In this configuration, the government fixes the level of per kWh compensation the renewable producer is to receive.

This paper aims to contribute to the existing literature on the choice and design of a support policy by using our equilibrium-real options-framework to compare the GC scheme to its closest alternatives. Focus will be placed on the comparison of the systems' abilities of leading to successful accomplishment of the environmental goals. An example of an article presenting a scheme comparison is Morthorst (2003), which states that a system with GCs alone will not be effective in reaching the goals for reducing greenhouse-gas emissions, but if GCs are combined with emission penalties this could have satisfying results. Huisman *et al.* (2013) argues that the risk-minimizing nature of the feed-in tariff scheme makes it lucrative for the investor, as most of the price risk is diminished by the fixed per kWh-price set by the government. However, it is also suggested that the risk of the government abandoning the scheme due to cost issues rises as it is more successful. This paradox is the topic of study for several articles, among them Amundsen & Mortensen (2001), Jensen & Skytte (2002), and Fischer (2006). These works present proof that the power price will go down as a result of increasing market share for renewable energy in a price competitive market due to the low marginal cost. Hence, the price risk that the investor avoids through the government's price guarantee is replaced with the risk of the government abandoning the scheme or substituting it with another. This policy uncertainty is naturally present in all schemes and hence thoroughly discussed in the literature. Boomsma & Linnerud (2013) aim to shed light on how uncertainty connected to the support scheme can affect the rate at which investment is undertaken by dividing the risk into two parts; market uncertainty and policy uncertainty. Market uncertainty will vary according to the scheme's specifications[2]. Policy uncertainty affects all schemes by reflecting the government's ability to change the market environment by either terminating the support scheme, make revisions in its regulatory conditions or switch among the schemes. Similarly, Fagiani & Hakvoort (2014) studies the role of regulatory changes on price volatility using a case study based on the Swedish market. It presents results showing that regulatory changes following the planning of the implementation of Norway into the Swedish system generated a regime of higher volatility in the market between 2010 and 2011.

In terms of scheme success and efficiency, this article looks at dynamic efficiency as a measure of attractiveness. del Río (2012) defines dynamic efficiency as *"the capacity of an instrument (or a design element) to induce a continuous incentive for technological improvements and cost reductions in the existing renewable energy technologies, facilitate that emerging technology's advance along the technological*

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[2] A fixed feed-in tariff scheme is connected with no, or very little, market risk as the government has imposed a fixed unit price. A certificate trading scheme implicates risks connected to both electricity and certificate price levels.

change process and promote renewable energy technologies with different maturity levels". The author further argues that the use of dynamic efficiency is a valuable tool in the evaluation of support policies and their design and shows how dynamic efficiency dimensions can be used to assess design elements. Finon & Menanteau (2003) compares the price-based feed-in tariff and the quantity-based certificate scheme and shows that price-based approaches has a better track-record for increasing installed capacity than the quantity-based[3]. This is explained by the possibility of the tariffs being set higher than the renewable producer's income in the quantity-based scheme, and that the feed-in tariff gives stronger incentives for investment through the guaranteed prices. According to the authors the price guarantee makes the feed-in system more stable and hence more attractive to investors. It is however also pointed out that the lacking control of production quantity can make this an expensive solution for society. Verbruggen & Lauber (2012) evaluates the two schemes according to four criterias; efficacy, efficiency, equity and, institutional feasibility and concludes that well-designed feed-in tariff schemes perform better than well-designed certificate schemes in every respect.

We present a simultaneous equilibrium model for electricity- and certificate price- and quantity dynamics. Research on the field of price development in financial instruments can be dated back as far as to Montgomery (1972), investigating the existence of a market equilibrium price in emission licenses as a result of joint cost minimization. Subsequent studies on this topic have turned in two main directions, the first of which uses stochastic descriptions of the price. This perspective points out the existence of a martingale property in the price formation, as stated in Seifert *et al.* (2008). Similar results are confirmed by Carmona *et al.* (2010) who argues that the price at compliance must equal either the penalty or 0, and hence that the price at any point in time must equal the discounted expected value of the price at compliance. The statement that the certificate price depends on the probability of a certain future outcome is also addressed by Chesney & Taschini (2011). They consider the price dynamics of the emission certificates due to asymmetric information where they prove the existence of a martingale condition in the discounted price. Other studies supporting this approach are among others Coulon *et al.* (2013).

The second direction of studies in the context of modelling price dynamics is in close continuation with Montgomery's work in describing the price formation as an equilibrium formed through supply and demand. In electricity markets the equilibrium mechanism is especially important, as electricity is difficult to store

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[3] The authors however emphasize that conclusions were drawn based on limited data on the GC market.

and supply failure might be costly, indicating the existence of a market equilibrium price. We utilize this in our description of the electricity price formation, continuing on the path trodden by amongst others Bye (2003). A price model is developed from the supply and demand of both electricity and GCs, defining the price movements by differentiating between electricity from traditional and renewable technology. Other models based on the market equilibrium assumption can be seen in Bessembinder & Lemmon (2002) and Borenstein & Bushnell (1999) among others. Rubin (1996) extends Montgomery's thoughts into a setting which allows banking and borrowing of emission allowances. The author analyses the inter-temporal effects of these opportunities and shows how they allow the firms to control and adjust their stream of emissions through time. A central assumption stated in this study is that the price of an emission allowance should equal the marginal abatement cost of reducing emissions. A similar stand is taken by Morthorst (2003) with respect to the GC market. Here it is concluded that the sum of the electricity spot price and the GC price should equal the long run marginal cost of investing in new renewable capacity[4]. This assumption is later used in the development of our own model. Lemming (2003) presents the equilibrium pricing mechanism for a consumer-based GC market as a tool for analysing a market where wind turbines is the only renewable energy production technology available. Amundsen & Mortensen (2001) investigates the relationship between green certificates and CO_2 emission permits under the existence of price bounds on the GCs through a static equilibrium model accounting for both instruments. They find that stricter CO_2 constraints as well as increased import wholesale price may lead to reduced capacity for renewable energy production. They also find the effects of increasing the GC quota to be inconclusive, however that the ratio of renewable electricity relative to the total production will increase.

As we have shown, the illustration of the green certificate market in terms of an equilibrium model, as known from basic microeconomics, is an already well explored field of study. However, the use of this method in combination with real options theory is undocumented and is an interesting path to examine, both for use in energy economics and in other areas. We use price data obtained from the equilibrium model to describe an investment threshold for the stochastic investment cost through a real options framework. Dixit & Pindyck (1994) highlights the value of real options theory in the valuation of projects and the opportunity to invest and delay investment. In the examples presented in this work, the authors

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[4] The basic principle from these results is consistent with the belief that a higher price would incentivize companies with lower marginal abatement- or investment cost to exploit the price difference. In general this way of describing the price dynamics simplifies the investment decision as the investment will be favorable only if the marginal investment cost is below the long run marginal cost and hence below the price.

focus on the energy industry and the value of the option to delay investment. They argue that for an irreversible investment, where the future returns are uncertain, the optimal investment rule corresponds to when the expected value of postponing the investment equals the expected value of investing now. The authors present the real options approach as an alternative to the net present value (NPV) valuation technique which is widely used, and how the introduction of irreversibility introduces the need for modifying this approach. They argue that irreversibility introduces an opportunity cost to investing comprising of the potential value of delaying the option to await further information about the market, that is, a value of flexibility. The NPV valuation approach simply evaluates the sum of all the discounted expected future cash flows less the investment cost, and hence do not account for this value, which can lead the investor to make erroneous decisions.

Boomsma *et al.* (2012) compares the investment behavior following the certificate and feed-in tariff schemes by considering several sources of uncertainty including the probabilities of a change of support system. The findings show that the investor's requirement for investing in terms of revenues is lower in the feed-in tariff market than in the green certificate system, but also that the potential investment capacity is larger in favor of green certificates. Abadie & Chamorro (2005) aims to derive the value of investment and the optimal investment rule for a natural gas-driven power plant where there exists an option to postpone investment. Kumbaroğlu *et al.* (2008) argues that *the value of waiting* becomes particularly important in the case of assessing investment opportunities in renewable technologies, because of their modular properties, relatively short investment times, and steep learning curves. According to the authors, the non-standard characteristics of the electricity market[5] calls for customizing of the applied theory and models.

When considering an investment opportunity in renewable energy technology through the lenses of real options theory, the most explored factors of uncertainty are those connected to the producer's revenue, especially electricity prices and subsidy payments. Boomsma *et al.* (2012) consider these factors, but also looks at the option value as a function of investment cost by considering steel prices as a stochastic part of the total investment cost. It shows that uncertainty connected to costs can be a major factor, a finding which is also illustrated in our paper where we define a stochastically modelled investment cost as the source of uncertainty. Several papers have pointed out the increased risk according to uncertainty in cost factors and how this affects the optimal investment rule. Pindyck (1993) studies the effect investment cost uncertainty has on irreversible investments. It considers two types

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[5] Kumbaroğlu *et al.* (2008) highlights among others time-variant price elasticities for energy demand, non-linear cost structures and changes in construction lead times.

of uncertainty over the cost of completion; technical- and price uncertainty. The results show that both of these factors affect the decision rule remarkably, however one positively and the other negatively[6]. Another paper considering the impact of the cost uncertainty is Sarkar (2003). The scope of the author is to detect the consequences of choosing GBM versus mean reversion as the stochastic process in a real option investment analysis. By comparing the two different processes both when the underlying is the investment's revenue as well as when it is the costs, he shows how the incentives for choosing the one over the other changes as the underlying changes. His results confirm the importance of awareness of the source of the investment's uncertainty and the choice of the stochastic process this is assumed to follow.

Sceptics to the green certificate scheme have argued that it causes increased volatility in the electricity price, as the prices of certificates, and hence also of electricity, relies on volatile production volumes. Amundsen *et al.* (2006) points out that the introduction of banking will reduce this volatility as well as contribute to an increase in the social surplus[7]. The authors look at the sensitivity to shocks in supply and demand in the GC market and state that banking indeed can counteract some of the price- and volume effects. Inspired by this we attempt to evaluate the volatility-effects of the GC and feed-in tariff schemes, as well as the market without a support scheme. This is done by evaluating the sensitivity of supply and demand "shocks" on the electricity- and certificate prices and on production volumes. Lemming (2003) studies the effects that a consumer-based certificate system will have on the financial risk taken by the investor of a wind-turbine. He presents variations in the total supply due to the stochastic nature of wind to be one of the main factors influencing the market equilibrium. The paper argues that the revenue of the individual turbine-owner is a product of the negatively correlated, and stochastic, production volume and certificate prices and points out that this indicates that wind fluctuations will tend to decrease the short-term financial risks. From this he draws the conclusion that certificate price fluctuations can in fact be a desirable phenomenon.

As mentioned, the contribution of this paper is to introduce a framework for evaluating an investment opportunity under investment cost-uncertainty given a simultaneous equilibrium in the electricity and green certificate markets. We evaluate

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[6] Technical uncertainty is defined as uncertainty in amount of time, material and effort needed to complete the project, which makes investing more attractive. Conversely, price uncertainty represents the uncertainty in prices of needed material and labor in order to complete the investment, and increases the value of delaying to get more information.

[7] However, the article also argues that banking would decrease the average price, which is not necessarily a positive development for the renewable energy producer.

a wind power investment opportunity under a green certificate support scheme where the investor holds a perpetual option to invest. In order to develop the optimal investment strategy, the value of the investment opportunity is hence derived by combining market equilibrium- and real option theory. We find that the green certificate scheme does indeed positively influence the ratio of renewable energy relative to the total electricity supply. However, we also find that for reasonable levels of the quota, this increase in renewable energy production capacity comes at a price of an increased total energy consumption. When comparing the GC scheme to its closest alternative, the feed in tariff, we find that the tariff induces a larger increase in renewable production capacity, but also that GCs lead to a larger reduction in the supply of non-renewable energy.

Further the paper is organized as follows; section 2 explains and presents the mathematical equilibrium model, followed by the general model for the valuation of the wind power investment. Section 3 presents results from the initial study of the certificate model and a sensitivity analysis performed using these results. In section 4 the GC system is compared to other market configurations, including an analysis of the price, volume and volatility effects. Section 5 summarizes and concludes.

2 Equilibrium and Real Option Investment Valuation

One of the main strengths of the GC scheme is that its financial instrument's price is constructed to follow the market mechanisms. Considering this property we propose a simultaneous equilibrium model which takes into account both the electricity- and the GC supply and demand. Combining this with a real options model considering the wind park investment opportunity, we derive a model where the market mechanisms are included in the investment decision. Compared to the most commonly performed real option valuations the stochastic process is in our case reversed as we assume the investment cost to be stochastic instead of the project income.

The following expressions have been obtained based on a few general simplifications. Firstly, we regard the support scheme to be a permanent solution. In an economic perspective permanent subsidy schemes are unfavorable, as the market is more efficient when it is not controlled. Nevertheless, it is conceivable that a successful implementation of such a system in one country might lead to more nations joining in on the same system, inducing changes in the initial setup leading to extensions of the original timeframe. This was observed in the Swedish GC system where the timeframe was extended as a result of Norway joining the scheme. Considering the possibility of a chain of such events over time we choose to model the scheme as infinitely lived.

Secondly, the investment decision will be based on the assumption that all input factors except the investment cost remain constant. The producers' income from the sale of electricity and GCs are, as stated above, assumed to be deterministic, and the optimal investment rule is derived considering today's price and income level.

We also generally state that the investment can be delayed infinitely and without cost, hence we ignore any possible expenses connected to expiration of concessions or potential technology development negatively affecting the investment value. However, we highlight the opportunity cost incurred by postponing the investment which comprises the cash flows the investor could have gained by immediate investment[8]. Lastly we define the investment to be irreversible and we do not consider shut-down or restart of the production plant as viable. In option theory terms the investor holds a perpetual put option where he receives the strike, comprising the sum of all future cash flows, by giving away the underlying, the investment cost. When the option is not exercised, that is, when not investing, the investor will pay a dividend by losing potential income, the opportunity cost.

The equilibrium expressions for both electricity and GCs are developed using the Cobb-Douglas approach, and the model is later calibrated with respect to relevant price data. Further we propose a real option modelling approach inspired by Dixit & Pindyck (1994) where we consider the value of an investment opportunity in a wind turbine park. The essential factors considered in this valuation are the possible project incomes from sold electricity and GCs and the investment cost of the project.

2.1 Equilibrium price models for electricity and certificates

The dynamics of the prices of both electricity and green certificates are described by introducing an equilibrium market price model in line with the methodology of Bye (2003). The price movements are assumed to follow the supply and demand relationship directly, excluding the impact of any outside factors. For simplicity

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[8] These opportunity costs are usually mainly comprised by lost potential income from product sales less the variable production cost of said product.

the market structure is assumed to consist of one representative producer and one representative distributor where the producer sells electricity and GCs while the distributor buys. The supply from the producer thus includes the supply from both renewable and non-renewable technology, which introduces the need for separating the supplied electricity into two groups[9]. We define electricity produced by non-renewable technology as Q_t^N, and electricity produced by renewable technology by Q_t^R. As the producer only receives certificates for renewable energy production, the supply of GCs will equal the amount of electricity produced from renewable technology[10]. The possibility of expansion in capacity is assumed to be unlimited for both technologies. The renewable production technology is further assumed to have a higher expansion cost per additional capacity than the non-renewable. Since the main idea of the GC scheme is to induce investment where it is most economically favorable, hence has the lowest investment cost per unit capacity increased, we assume the investment cost for additional capacity to increase with Q_t^R. Further we also assume the sum of the electricity price and the GC price to be high enough to make the production from renewable technology profitable. Electricity is a homogeneous product, hence the consumer is indifferent to how it is produced[11], and pays the same price, p_t^E, regardless of whether it stems from a renewable or non-renewable source. A system where both technologies are paid equally for the electricity would however make an investment in renewable technology unfavorable as this is more expensive. In order to successfully incentivise investment in renewable technology the combined price of electricity and certificate should cover the extra cost of expanding sufficient capacity to increase the electricity production by one unit. Due to governmental restrictions the distributor must purchase GCs according to a percentage, α, of the total consumption of electricity at a unit cost of p_t^{GC}. This results in a final purchaser price, p_t^D;

$$p_t^D = p_t^E + \alpha p_t^{GC}$$

A natural intuition is that this price will decrease as the share of renewable energy, α, in the total supply increases due to lower operational costs in renewable technology.

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[9] In the following these two groups can be seen as individual producers of energy from renewable and non-renewable sources respectively operating within the same firm. The firm, who at any time possesses complete market supply information, will maximize its total profit, hence the choice of production technology will not be influenced by speculation among the parties. In the analyses presented in later sections, they will be referred to as the "renewable producer" and the "non-renewable producer" respectively.

[10] The producer receives one GC for each MWh electricity produced from renewable technology.

[11] We ignore any additional value purchasing only "green" energy might give the consumer.

Electricity equilibrium As previously stated, the total amount of energy supplied by the producer is composed of both renewable and non-renewable electricity, hence the total supply of electricity is;

$$Q_t^S = Q_t^R + Q_t^N$$

On the demand side, the distributor seeks to maximize utility less the cost of purchasing electricity;

$$max\ \ U(Q_t^D) - p_t^D Q_t^D$$

These supply and demand functions result in the following initial equilibrium expression;

$$Q_t^R + Q_t^N = Q_t^D$$

Naturally, the demand of energy distributor will rely on the purchaser price, hence we write;

$$Q_t^D = f(p_t^D) = f(p_t^E + \alpha p_t^{GC})$$

Certificate equilibrium When not considering the subject of banking of certificates for future use, the total supply of certificates, S^{GC}, equals the total supply of energy from renewable energy sources[12];

$$S^{GC} = Q_t^R$$

The demand for certificates is strongly linked to the total amount of demanded electricity through the governmentally controlled quota;

$$D^{GC} = \alpha Q_t^D$$

Hence, the equilibrium for green certificates can be presented as;

$$Q_t^R = \alpha Q_t^D$$

Developing expressions using Cobb-Douglas The Cobb-Douglas specification is used for deriving the functions of the supply and demand. We define the expression for electricity demand as

$$Q_t^D = C^D(p_t^E + \alpha p_t^{GC})^{\varepsilon}$$

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[12] Assuming all electricity characterized as "renewable" is engaged in the certificate scheme.

Where C^D is a calibration coefficient securing the caption of the individual market's demand behavior and ε represents the demand elasticity. The electricity supply is composed of separate specifications for the renewable and non-renewable production;

$$Q_t^S = C^N(p_t^E)^{\kappa_N} + C^R(p_t^E + p_t^{GC})^{\kappa_R} - \xi$$

Where C^N and C^R are the calibration coefficients of the supply side components. κ_N and κ_R are the elasticities of renewable and non-renewable supply respectively, and ξ is the intercept for the renewable energy technology. This intercept represents the total market supply at the renewable producer's zero supply point, indicating the production quantity at which the equilibrium price sufficiently high to renewable production profitable. It is a result of the high market entry barrier for renewable technology, mainly explained by the substantial fixed costs. Since the supply of renewable energy is perfectly correlated in a 1:1 relationship with the supply of GCs the expressions for renewable energy supply and certificates are interchangeable. In the following we refer to the renewable elasticity and calibration coefficient as κ^{GC} and C^{GC} in order the ease the intuitive understanding of the parameters. With this notation the expression for the electricity supply becomes;

$$Q_t^S = C^N(p_t^E)^{\kappa_N} + C^{GC}(p_t^E + p_t^{GC})^{\kappa_{GC}} - \xi$$

This results in an equilibrium equation for electricity equal to;

$$C^N(p_t^E)^{\kappa_N} + C^{GC}(p_t^E + p_t^{GC})^{\kappa_{GC}} - \xi = C^D(p_t^E + \alpha p_t^{GC})^{\varepsilon} \tag{1}$$

Since the demand for GCs is governmentally regulated through the required quota, which is a fraction of the electricity demand, the GC demand will also be a fraction of the electricity demand;

$$Q_t^{GC} = \alpha Q_t^D = \alpha C^D(p_t^E + \alpha p_t^{GC})^{\varepsilon}$$

The supply of GCs is as explained given by the supply of renewable energy;

$$Q_t^{GC} = C^{GC}(p_t^E + p_t^{GC})^{\kappa_{GC}}$$

As this will serve a share equal to α of the total market demand, the rest, $1-\alpha$, will be supplied by the nonrenewable producer. This results in the following market equilibrium equations;

$$C^{GC}(p_t^E + p_t^{GC})^{\kappa_{GC}} - \xi = \alpha C^D(p_t^E + \alpha p_t^{GC})^{\varepsilon} \tag{2}$$

$$C^N(p_t^E)^{\kappa_N} = (1-\alpha)C^D(p_t^E + \alpha p_t^{GC})^{\varepsilon} \tag{3}$$

2.2 Stochastic processes – Mean Reversion

As mentioned, we model the construction costs as being the source of uncertainty. When investing in a wind turbine park the majority of the costs are related to the actual construction of the wind turbines. Modern turbines are mainly constructed from steel which indicates that changes in the investment cost are predominantly a product of fluctuations in the steel price[13]. Describing the appropriate process for modelling the price development in commodity prices have been the scope of several studies. One of the pioneering analyses on this topic is done by Schwartz (1997), where three different models are developed with the intention of verifying the mean reverting tendencies in commodity prices. This article makes out some of the foundation for our choice of modelling the steel price as a mean reverting process. Additionally, a more recent study; Ozorio *et al.* (2012) finds that as well as being led by a mean reverting component, the steel prices might have a rising drift component. We assume the steel price to be following a simple Ornstein-Uhlenbeck mean reverting process;

$$dX_t = \eta(\bar{X} - X_t)X_t dt + \sigma X_t dz \tag{4}$$

Here X_t is the steel price at time t, η is the speed of reversion, $\bar{X}$ is the level to which X tends to revert and σ is the short-term volatility.

2.3 Valuation

In order to define the optimal investment timing the investment opportunity is evaluated using real options theory. As explained above the investment cost represents the stochastic factor while the potential income is determined by the equilibrium model. We start by defining the value of the investment opportunity based on the investment cost, and then combining this with the equilibrium model in a value matching constraint to obtain the optimal investment rule deciding the investor's behavior as a function of the investment cost.

At any time, the value of the investment opportunity is constructed by the choice between two alternatives; investing today or delaying the investment for an additional period. This value will be denoted $F(X)$ and the objective is to find an investment rule which maximizes this value. The stochastic process is in our case reversed compared to the most commonly performed real option valuation as we assume the investment cost to be stochastic instead of the project income.

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[13] We here abstract from any cost due to acquisitions of land and subsequently required adjustment for further use.

The mean-reverting process has a non-constant growth rate leading to a non-constant risk-adjusted discount rate, μ. We therefore choose to utilize the contingent claims approach, as opposed to dynamic programming, as this allows us to use market principles to define the discount rate rather than specifying it as a fixed constant.

Contingent claims requires the existence of assets which individually or combined can perfectly span the stochastic changes in X through a replicating portfolio. Assuming that spanning holds, the replicating portfolio is constructed by;

1. Holding the option to invest with value $F(X)$
2. Shorting $n = F'(X)$[14] units of the asset which is perfectly correlated with X
3. The short position demands an obligation of paying the shorted asset's dividend, $\delta F'(X)X$, to the owner

The total value of this portfolio over the time period dt is;

$$dF - F'(X)dX - \delta X F'(X)dt \tag{5}$$

Since $F(X)$ is a function of X which is assumed to follow a stochastic mean-reverting process, we can apply Ito's Lemma to obtain an expression for dF;

$$dF = F'(X)dX + \frac{1}{2}F''(X)(dX)^2$$

From equation (4) we can derive the expression for $(dX)^2$ and by eliminating any higher degrees of dt, as these approaches zero faster than dt, we get;

$$(dX)^2 = \sigma^2 X^2 dt$$

Inserting the expressions for dF and $(dX)^2$ in equation (5) we get that the total value of the portfolio can be expressed as;

$$\frac{1}{2}F''(X)\sigma^2 X^2 dt - \delta X F'(X)dt$$

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[14] This exact amount is chosen in order to make the portfolio risk free.

From the expression in equation (4) we see that the expected rate of growth of X, $\alpha = \eta(\bar{X} - X_t)$, is not constant, but rather a function of X. This leads to a dividend rate which is also dependent on X[15]:

$$\delta(X_t) = \mu - \alpha = \mu - \eta(\bar{X} - X_t)$$

Inserting this expression for δ, the final expression for the portfolio's return is;

$$\frac{1}{2}\sigma^2 X^2 F''(X)dt - \left[\mu - \eta(\bar{X} - X)\right] XF'(X)dt$$

Since this is a risk-free portfolio it should earn the risk-free interest rate on the amount invested;

$$\frac{1}{2}\sigma^2 X^2 F''(X)dt - \left[\mu - \eta(\bar{X} - X)\right] XF'(X)dt = r[F - F'(X)X]dt$$

Dividing by dt and rearranging;

$$\frac{1}{2}\sigma^2 X^2 F''(X) + \left[r - \mu + \eta(\bar{X} - X)\right] XF'(X) - rF = 0 \tag{6}$$

Which is a differential stochastic equation of second order.

Boundary Conditions In order to find the investment cost which makes it optimal to exercise the option, here noted X^*, we need boundary conditions related to the stochastic differential equation. We start by stating that if the investment cost, X, is very large then the probability for it to drop to a level where we would invest is very small, resulting in the condition;

$$\lim_{x \to \infty} F(X) = 0 \tag{7}$$

Further we establish the value matching relationship stating that at the optimal investment time the value of the option and the net value obtained by exercising it[16] should be equal. The future cash flow is determined by the equilibrium model explained above and the stochastic investment cost by the mean reverting process. The present value of the total future revenue, V, is computed as the sum of the discounted future cash flows of electricity produced[17]. The risk adjusted discount rates of the electricity and the GC price are represented by μ^E and μ^{GC} respectively.

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[15] For a thorough explanation see Dixit & Pindyck (1994).

[16] The value at exercise is defined as the NPV of the future income less the investment cost.

[17] Assuming that all produced electricity and GCs are sold.

Further we assume no operating cost for the wind turbine. This gives the expression for the value matching condition;

$$F(X^*) = V(p^E, p^{GC}) - cX^* = \frac{p^E}{\mu^E} + \frac{p^{GC}}{\mu^{GC}} - cX^* \tag{8}$$

Here c is the amount of steel necessary to produce one unit of electricity yearly. As equation (8) depends on the optimal investment cost, X^*, which is an uncertain value, we need another condition in order to solve the second order differential equation. We utilize the smooth pasting condition which defines the investment cost to be continuous in the optimal value, X^*. Hence we require the property;

$$F'(X^*) = -c \tag{9}$$

Optimal Solution Due to the nature of the differential equation we need to introduce another function, $h(X)$, in order to find an appropriate solution;

$$F(X) = AX^\theta h(X) \tag{10}$$

Here A and θ are constants to be defined for $F(X)$ to satisfy the differential equation. Inserting equation (10) into equation (6) and rearranging we get;

$$\begin{aligned} &X^\theta h(X)\left[\frac{1}{2}\sigma^2\theta(\theta-1) + \left(r - \mu + \eta\bar{X}\right)\theta - r\right] \\ &\quad + X^{\theta+1}\left[\frac{1}{2}\sigma^2 X h''(X) + \left(\sigma^2\theta + r - \mu + \eta\bar{X} - \eta X\right)h'(X) - \eta\theta h(X)\right] = 0 \end{aligned} \tag{11}$$

In order for this equation to hold both the bracketed terms must equal zero. For the first bracket this implies;

$$\frac{1}{2}\sigma^2\theta(\theta-1) + \left(r - \mu + \eta\bar{X}\right)\theta - r = 0$$

This equation has two solutions, but to fulfill the boundary condition in equation (7) only the negative solution can be feasible:

$$\theta = \frac{1}{2} + \left(\mu - r - \eta\bar{X}\right)/\sigma^2 - \sqrt{\left[\left(r - \mu + \eta\bar{X}\right)/\sigma^2 - \frac{1}{2}\right]^2 + 2r/\sigma^2} \tag{12}$$

Letting the second bracketed term equal zero;

$$\frac{1}{2}\sigma^2 X h''(X) + \left(\sigma^2\theta + r - \mu + \eta\bar{X} - \eta X\right) h'(X) - \eta\theta h(X) = 0 \tag{13}$$

Performing the substitution $z = 2\eta X/\sigma^2$ equation (13) can be transformed to a standard form where we further can let $h(X) = g(z)$ so that $h'(X) = (2\eta/\sigma^2)g'(z)$ and $h''(X) = (2\eta/\sigma^2)g''(z)$. This allows equation (13) to be written as;

$$zg''(z) + (b - z)g'(z) - \theta g(z) = 0 \tag{14}$$

where

$$b = 2\theta + 2(r - \mu + \eta\bar{X})/\sigma^2$$

This is known as the Kummer's Equation which has two confluent hypergeometric functions, $H(z;\theta,b)$ and $U(z;\theta,b)$[18], as its solutions. The first solution, $H(z;\theta,b)$ can be represented by the following series;

$$H(z;\theta,b) = 1 + \frac{\theta}{b}z + \frac{\theta(\theta+1)}{b(b+1)}\frac{z^2}{2!} + \frac{\theta(\theta+1)(\theta+2)}{b(b+1)(b+2)}\frac{z^3}{3!} + ... \tag{15}$$

The second solution $U(z;\theta,b)$ takes the form;

$$U(z;\theta,b) = \frac{\Gamma(1-b)}{\Gamma(\theta-b+1)}H(z;\theta,b) + \frac{\Gamma(b-1)}{\Gamma(\theta)}z^{1-b}H(z;\theta-b+1,2-\theta) \tag{16}$$

This verifies that the solution of equation (6) has the form of equation (10) and can be redefined to either;

$$F(X) = AX^{\theta}H\left(\frac{2\eta}{\sigma^2}X;\theta,b\right) \tag{17}$$

or

$$F(X) = AX^{\theta}U\left(\frac{2\eta}{\sigma^2}X;\theta,b\right) \tag{18}$$

where A and the critical value of X, X^*, can be determined from the remaining boundary conditions (8) and (9). Since the solution consists of a confluent hypergeometric function which is an infinite series, A and X^* have to be found

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[18] $H(z;\theta,b)$ is known as the Kummer's function of first kind, whereas $U(z;\theta,b)$ is known as the Kummer's function of second kind or the Tricomi function.

numerically. We find that the first kind of Kummer's function does not satisfy the boundary condition in equation (7). The second kind of Kummer's function on the other hand is found to comply all the boundary conditions and possesses the appropriate properties, hence the final solution equals equation (18).

2.4 Equilibrium expressions adjusted for other policy systems

In order to gain more information about the GC policy efficiency we want to compare the GC results with a feed-in tariff system and a market without any subsidies. Deriving expressions for these policies requires some minor adjustments in the model's calculations of the future total revenue.

Feed-in tariff Huisman *et al.* (2013) describes a feed-in tariff system where the government guarantees a per kWh electricity price for the renewable producer and compensates for the difference should the prevailing electricity price be below this level. Hence, the firm's income per unit sold is fixed through a long term contract. We adjust our GC model to fit with this arrangement. As it in this case exists only one tradable commodity we operate with a single equilibrium equation. Taking this into account, we define the electricity supply function as;

$$Q_t^S = C^N(p_t^E)^{\kappa_N} + C^{GC}(L)^{\kappa_{GC}} - \xi$$

where L is the guaranteed price and hence is comprised by the electricity price, p^E and the amount compensated by the government, $l = L - p^E$. Since the distributor only have to pay for the electricity, not both electricity and GC, the electricity demand only depends on the electricity price, p_t^E. Hence the electricity demand can be expressed by;

$$Q_t^D = C^D(p_t^E)^{\varepsilon}$$

This gives the final equilibrium for the feed-in tariff market;

$$C^N(p_t^E)^{\kappa_N} + C^{GC}(L)^{\kappa_{GC}} - \xi = C^D(p_t^E)^{\varepsilon} \tag{19}$$

Market without applied subsidies In a market without financial support schemes the possible future cash flow for a wind park investor consists solely of the revenue from the sold electricity. This price is defined by the electricity supply and demand equilibrium in equation (1) where $p_t^{GC} = 0$. Hence we have

$$C^N(p_t^E)^{\kappa_N} + C^{GC}(p_t^E)^{\kappa_{GC}} - \xi = C^D(p_t^E)^{\varepsilon} \tag{20}$$

3 Results from the Green Certificate Model

We perform a case study of the Swedish/Norwegian market, and make use of sample data from this market for the calibration[19]. The calibration procedure and resulting coefficients can be seen in Appendix A. After illustrating the effects of varying the market's sensitivity to changes in the price, a set of final properties seen as the most likely and representative for this specific market is defined as a base-case providing the foundation for further analysis.

Through setting the quota the government has a tool for controlling the demand of renewable electricity. As the level chosen also decides the allocation of the market revenues, α is seen as one of the most crucial factors affecting the GC scheme's efficiency. This value is assumed to remain constant once set when regarding the optimal investment decision. However, its effect on the equilibrium prices of electricity and green certificates makes its influence on the outcome of the real option analysis quite substantial. For this reason, we highlight the effects of a change in the quota. Bye (2003) presents a series of analyses used to display the effects of changes in α on the equilibrium prices of a hypothetical market. More than a decade later we apply actual data from the Swedish/Norwegian market to perform similar calculations and further evaluate the subject.

3.1 Price and quantity effects of varying elasticities and quota

To display the effects of the choice of market properties on the results, we investigate a selection of hypothetical configurations of the market features, seen in table 1. The cases are comprised of different combinations of supply- and demand elasticities, and are evaluated for varying levels of α to display the changing price dynamics.

As can be seen in the table, the demand elasticity has in all cases been set to a quite small and negative value. The demand is prone to decline as the purchaser price increases, as a result of increasing electricity- or certificate price, making a negative elasticity value a natural assumption. Electricity is a quite fundamental good in today's society, hence a valid assumption is that the average consumption remains quite stable even when the prices change[20]. For this reason, most of the

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[19] We use monthly data from NordPool and NECS on the Swedish market on electricity- and GC prices dating from 2004–2013. As data on the Norwegian market is still highly limited, we used the Swedish data as representative for the Swedish/Norwegian market.

[20] Even if the purchaser price of energy increases drastically society relies on electricity to

cases evaluates a demand elasticity as low as 0.1, however we also explore the price reactions to higher and lower values[21]. It can be argued that this value is too low, as the model does not account for the possibility of import and export of energy to external markets. The Swedish/Norwegian market evaluated in our analysis is completely self-sufficient, that is, all energy supplied during a period is purchased and used within this market. The model also assumes instantaneous equilibrium at all times, no storage of either electricity or certificates is incorporated. In the real world, the possibility of both international trading and banking of certificates lowers the occasional gap, mostly due to seasonal variations, between supply and demand. As for the supply elasticities, several combinations are examined. Based on the same reasoning as for the demand elasticity, quite low supply elasticities are expected to best represent reality. We have also included scenarios showing more extreme values for both κ_{GC} and κ_N.

Table 1: Alternative combinations of elasticities for the demand and supply under the GC scheme

Alternatives	Supply elasticity		Demand elasticity
	κ_{GC}	κ_N	ε
02–02–01	0.2	0.2	–0.1
02–08–01	0.2	0.8	–0.1
09–01–01	0.9	0.1	–0.1
02–02–03	0.2	0.2	–0.3
02–02–005	0.2	0.2	–0.05

Based on the discussion above and also highlighting the limited availability of substitutes for electricity, which argues for low demand elasticity, we choose the first case, (02–02–01), combined with a quota-level of 0.07 as the normal level which will be used as the GC market base-case. This configuration is considered the most realistic scenario, and will later be used in the comparison of the GC scheme with other alternative support schemes and in the analysis of the optimal investment rule.

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function and will keep using electricity practically regardless of cost. As prices decrease, the consumption might slightly rise, however the average consumption is assumed quite stable also in this case.

[21] Bye (2003) presents articles, e.g. Johnsen (2001), in which this value has been estimated to lie close to 0.1 in reality. In an analysis of the Norwegian market from 1996–2010 Holstad & Pettersen (2011) even suggest electricity demand elasticities as low as –0.05.

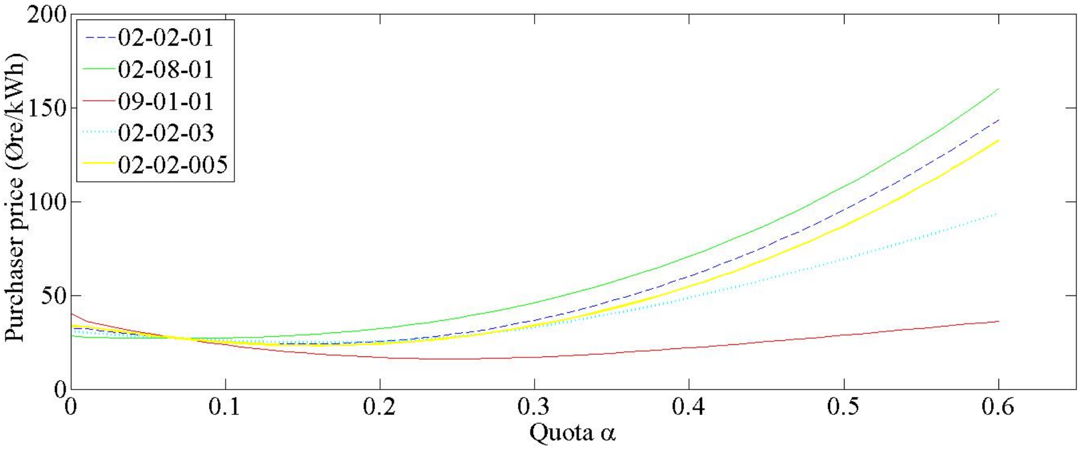

Figure 1: Total purchaser price for the different combinations of elasticities as a function of increasing α

Equilibrium price variations according to varying α Figure 1 shows the total purchaser price, p_t^D, as seen by the distributor as a function of varying quota, α, for each of the discussed elasticity scenarios. The figure indicates that varying α causes similar changes in the total purchaser price in all of the evaluated cases. A growing α results in replacing nonrenewable production with renewable. As long as the set α is below a certain level, increasing it has a negative effect on the purchaser price, whereas for an α above, the effect is positive[22]. This is a result of the electricity price, p^E, decreasing more rapidly than the expenses following the purchase of GCs, αp^{GC}, increases. Conversely, for αs greater than this level, αp^{GC} increases more rapidly than the p^E decrease, hence we see an increasing purchaser price.

Both in the (02–02–03) and the (09–01–01) cases, that is, the high ε- and κ_R-cases, the purchaser price follows a less steep slope than in the other cases. With a higher demand elasticity, this is a result of the purchaser's unwillingness to pay higher prices which restricts the increase in the price level. For the high κ_{GC} case we see that as α increases the renewable producer's revenue as the buyers are obligated to purchase more GCs. Because of the renewable supply's high price responsiveness, the renewable supply increases sharply as the price increases, inducing a decrease in the purchaser price. An interesting observation can be seen in case (02–08–01), where the nonrenewable elasticity is high. As α increases this case starts developing paralell to the lower κ_N case. The effect of the high κ_N hence diminishes as the share of non-renewable energy supply is dominated by the renewable share.

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[22] The purchaser-price-minimizing α varies among the elasticity-configurations.

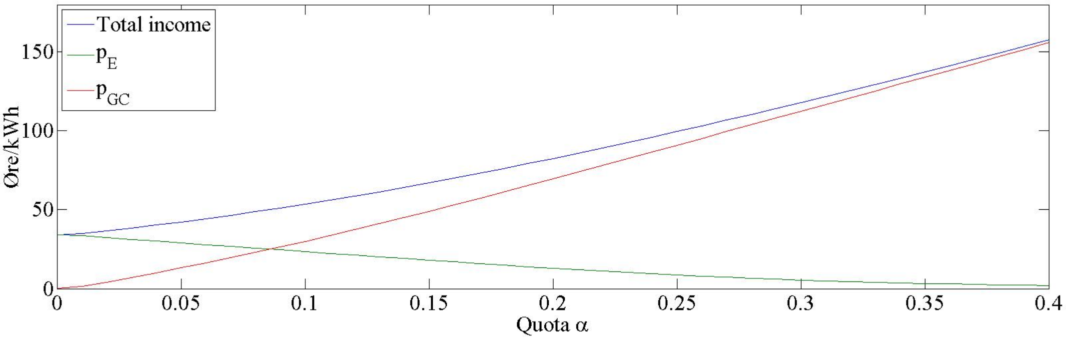
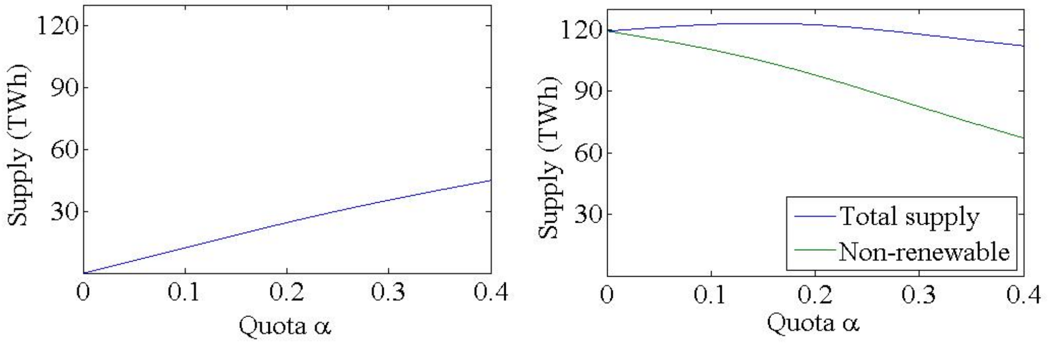


Figure 2: Total producer income as the sum of electricity and certificate price for varying the quota, α

Figure 2 illustrates the development in the income of the producer from renewable sources and its individual components, p^E and p^{GC}. As can be expected, the total income increases as the quota increases, as well as p^{GC}. Another confirmation of the model's ability to correctly describe the market dynamics is the decreasing electricity price. A reason for this reaction in p_E is the increased total supply combined with the decreasing demand for nonrenewable energy. The nonrenewable producer this way contributes in the financing of the renewable production.

Supply variations according to changing α The fact that the purchaser price declines until a certain level of α, is in line with the findings of Bye (2003), who also argues that this indeed will lead to a higher share of renewable energy in the market. However, it is also suggested that the slope of the decreasing price faced by the consumer will lead to a higher total consumption of electricity. This result can in fact be seen in figure 3b where the total supply increases as long as the quota is held below 0.2. Jensen & Skytte (2002) points out that managing the GC scheme might be difficult if its introduction has both the target of increasing renewable supply as well as reducing total electricity consumption. In our case, the only way to satisfy both targets, would be to set the quota substantially higher than 0.2. The goal of reducing total consumption is mainly grounded in that increased consumption will increase emission. This will however not apply in this specific situation concerning the Swedish/Norwegian market as most of the production plants which are not qualified for receiving GCs are older hydropower plants which do not produce emissions.



(a) Green energy supply for varying α (b) Total electricity supply for varying α

Figure 3: Supply in the GC scheme when the required quota increases

Variation in optimal investment rule according to varying α Though the effect α has on the purchaser price is limited as long as the α is maintained at a lower level, it still has a crucial role in allocating the revenues between renewable and non-renewable electricity producers. We want to investigate how the level of the quota influences the optimal investment timing in the wind park and the probability of this investment taking place within the next two years. Studying the combinations of base-case elasticity values and αs of 0.02, 0.07 and 0.15, which are valid values for the Swedish/Norwegian system, we find the optimal investment cost by solving equation (18) for X constrained by the boundary conditions in equations (8) and (9). The average level to which the investment cost is assumed to revert, $\bar{X}$, is set equal to 2. Further the amount of steel necessary to produce one unit of electricity, c, is set equal to 1.5^{23}. Not surprisingly, it is optimal to invest sooner as the quota, and hence the future cash flow, rises. The probability of exercising the option to invest within the next two years can be seen in table 2. The probabilities are calculated using the method described in AppendixB.

Table 2: The probability of investing within the next two years for different required quotas, α, for GC base-case elasticity values

Level Quota	$\alpha = 0.02$	$\alpha = 0.07$	$\alpha = 0.15$
$Pr(X < X^*)$	10.26%	17.60%	37.13%

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[23] Since the main purpose is to demonstrate the effect on X^* when α changes rather than the actual cost when investment is optimal, the value of $\bar{X}$ and c are set to make a realistic ratio between the revenues and the cost.

In figure 4 the optimal investment rule is demonstrated in terms of the option value versus the intrinsic value of investing today. Here the optimal investment is defined by the investment cost being at the level where the option value equals the intrinsic value, hence where the value of postponing the investment is the same as the value of investing in the wind park today. Remembering that we are considering a put option, the results from figure 4 shows that when $\alpha = 0.15$ the investor would exercise when the investment cost lies just below the average level, $\bar{X}$. We see that as α decreases, the level at which the cost must fall to for the investor to exercise decreases. Hence he invests sooner at high αs than when α is lower, as displayed by the probabilities in table 2. This confirms our natural intuition and the GC scheme fulfills its purpose; the higher the α, the higher are the investor's incentives to invest in renewable technology.

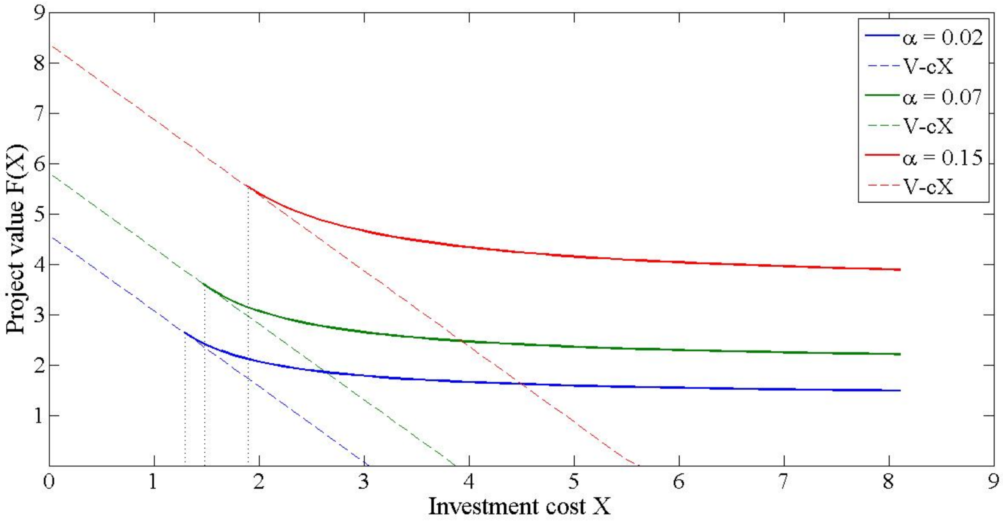

Figure 4: Option value for varying quota versus the intrinsic value, $V - cX$, in each case

3.2 Supply and demand equilibrium – GC base case

In an equilibrium model, changing one factor has consequences for the other variables. In the equilibrium model explained above both the electricity and the GC price are variables and the purchaser price is a function of these two and the set level of the quota. In order to find the equilibrium values for the prices and the quantity of sold electricity, the base-case properties in table 3 are used when solving the equations for the electricity demand and total supply for varying p_t^E and p_t^{GC}. The result can be seen in figure 5. Here it can be observed that the quantity of electricity in the equilibrium will remain stable while the prices vary.

This implies that the purchaser price remains practically constant as a result of p_E and αp_{GC} being negatively correlated. In the price combinations where both prices approaches zero the demand increases strongly, whereas it remains stable for increasing prices. This result is caused by the electricity being considered a fundamental good in today's society, hence that consumers are willing to pay almost any price for electricity.

Table 3: Base-case properties for the Swedish/Norwegian GC market

Market Property	κ_{GC}	κ_N	ε	ξ	α
	0.2	0.2	-0.1	122.5	0.07

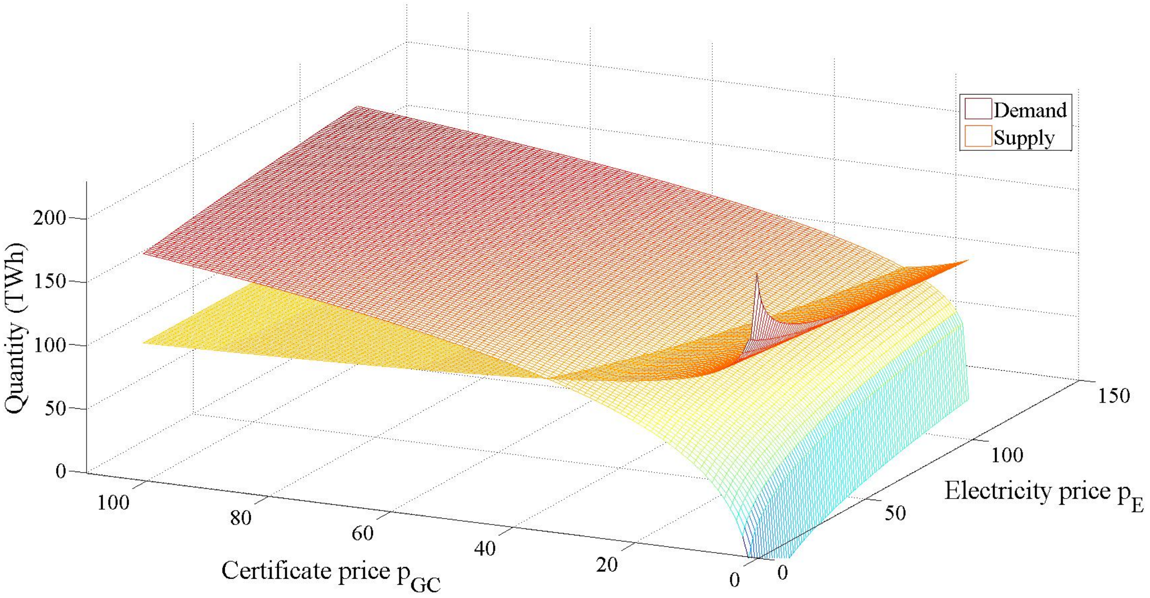

Figure 5: Base-case electricity supply and demand with varying electricity and GC prices. The equilibrium demonstrates an approximately constant traded quantity

If we optimize the equilibrium equations (2) and (3) with respect to the input price data we find the prices to be as shown in table 4. With these prices the renewable supply can be calculated to be 8.5175 TWh, as shown in table 5, and also confirmed in figure 3a. Table 5 also presents the renewable-to-total supply ratio, which in a green certificate market should be equal to the quota. This theory does indeed correspond to our findings.

Table 4: Electricity and certificate prices in GC scheme base-case

Price	p^E	p^{GC}
[øre/kWh]	26.7971	19.6934

Table 5: Production allocation for market applying the green certificate scheme

Production	Total Supply	Non-renewable	Renewable	Renewable Ratio
[TWh]	121.6791	113.1616	8.5175	0.0700

4 Policy Comparison

The green certificate scheme is only one of a broad selection of regulatory tools authorities can apply to stimulate investment in renewable energy facilities. As mentioned above policy choice and design is an already thoroughly discussed topic with highly divergent conclusions. The alternative which in design bears the closest resemblance to the certificate scheme can be said to be the feed-in tariff system. For this reason it has been chosen as the best benchmark in order to illustrate the properties of the green certificate scheme with respect to efficiency and ability to successfully induce investment. We also compare our results to the case of no applied support scheme in order to better demonstrate the general effects of such a scheme.

Considering the investment opportunity under these different systems, the most influential factor is the possible revenue of the investor, comprising the income from sale of electricity, as a function of p^E, and from the potential support scheme. We present an analysis on how the different systems and hence the change in future revenue affects the investor's behavior and the optimal investment rule. As there are infinitely many configurations to be chosen for the feed-in tariff, we have, as with the GC scheme, chosen a single representative base case for its market properties as the basis of comparison. The representative configuration chosen for the GC-system has already been presented as the (02–02–01) case with an α of 0.07 and has been thoroughly described above. The main focus is set on the development of the supply of renewable energy and the reduction of non-renewable energy production. We evaluate the dynamics of the electricity price and producer revenues and also consider specific scenarios introducing shocks in supply and demand. The potential consequences in the shape of changes in the market's price-responsiveness are studied and compared. It is important to note that variables considered being market properties are held identical when describing the base-cases of each system. This is done to secure the comparison to be performed based on the same core conditions for all schemes considered. Hence, the supply and demand price-elasticities, κ_R, κ_N and ε, the calibration constants, C_N, C_{GC} and C_D, as well as the intercept, ξ, are kept the same in all schemes[24]. Most of the input parameters in the base-case of the feed-in tariff are therefore identical to the GC scheme, with the exception of α, which is replaced by a compensation level, L, to be described below. For the case of no support scheme the only difference from the GC scheme is the absence of p_{GC} and α.

4.1 Feed-in tariff comparison

Under the feed-in tariff scheme the producer of energy from renewable sources receives a fixed compensation, L, per unit of electricity, through long term contracts[25]. This guaranteed revenue relieves the renewable producer from any price risk, and the level of production from renewable energy sources is hence inelastic to changes in the electricity market price. This dynamic is displayed by replacing the equilibrium equation in the original model with equation (19) as explained above.

In the same way as the output from the green certificate expressions is assumed to be, to a significant extent, defined by the quota, the most influential factor for the outcome of the feed-in equilibrium equations is assumed to be the compensation level. In order to set L to a relevant and comparable level relative to the GC scheme, we utilize a price-based approach[26] for obtaining the optimal comparison basis. The fixed compensation in the feed in base-case is here set to equal the average level of total revenues for the renewable producer in the GC scheme. To achieve this we use the GC model's input price data and set L equal to the average sum of the electricity and the GC price. This results in a $L = 52.59$ øre/kWh.

An interesting feature of comparison against the GC-scheme is the level of supply from renewable energy sources and the rate at which it changes according to defining factors like the level of L. As can be seen from figure 6b and table 6, the level of supply is higher for the feed-in tariff base-case with a value of 11.79 TWh, than for the GC system, which gives a production of 8.52 TWh. This can be seen as a result of the systems' fundamental differences; where feed-in controls the price, the GC scheme controls the desired renewable supply. This indicates that the compensation level set in the feed-in scheme provides financing for more expensive renewable technology than what the efficient market in the GC scheme

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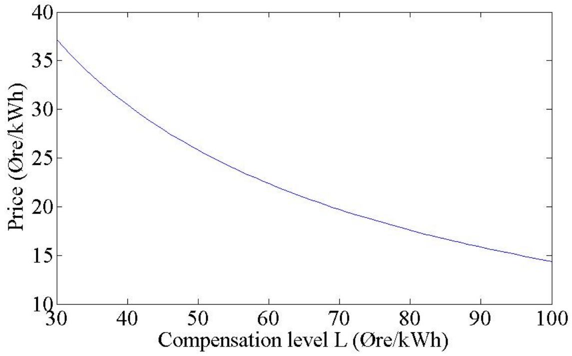
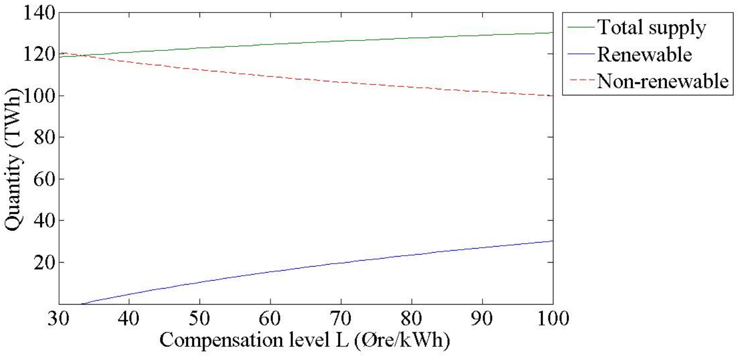
[24] The coefficients are presented in Appendix A.

[25] In the following derivations these contracts will be seen as perpetual.

[26] As opposed to a quantity-based approach which aims to force equal production quantities in both systems. This would require choosing a compensation level in the feed-in tariff system which provides the same amount of renewable supply as the chosen α provides in the GC scheme.



(a) Development in the equilibrium electricity price as the renewable producer's guaranteed price, L, increases



(b) Equilibrium supply of total, renewable and nonrenewable electricity as a function of increasing compensation level, L

Figure 6: Equilibrium electricity price and supply for feed-in tariff for varying compensation level, L

is willing to pay for. As a consequence, the total electricity supply in the feed-in tariff system is substantially higher than in the GC system with 123.23 TWh versus 121.68 TWh.

Another interesting comparison is the different schemes' efficiency in reducing emission by making production from nonrenewable technology less attractive. The defining factor of the profitability for the nonrenewable producer is the electricity price. Figure 6a shows the negative development in the market electricity price for increasing compensation levels. We stress that this market electricity price does not include any financing of the fixed subsidy paid to the renewable producer, as this is externally compensated by the government. Comparing figure 6b showing the supply development for increasing L to figure 3b, we see that the feed-in performs poorly compared to the GC in terms of reducing non-renewable supply.

Table 6: Supply allocation for market applying the feed-in tariff scheme.

Production	Total Supply	Non-renewable	Renewable	Renewable Ratio
[TWh]	123.23	111.44	11.79	0.096

For an $\alpha = 0.15$, which is a highly plausible scenario, the GC system reduces non-renewable supply by around 17%. For the feed-in tariff to result in the same reduction in non-renewable supply, the government would need to impose a fixed price of around 100 øre/kWh, which is an unlikely level to ever approach.

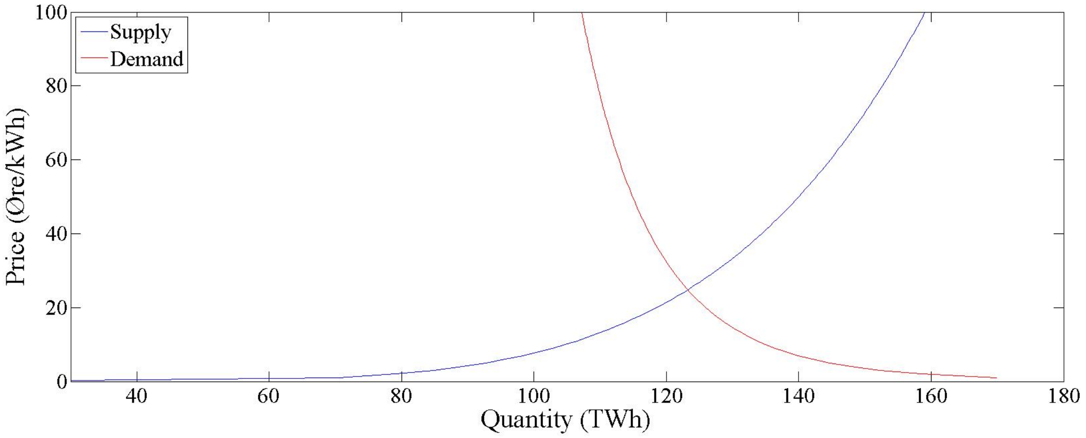


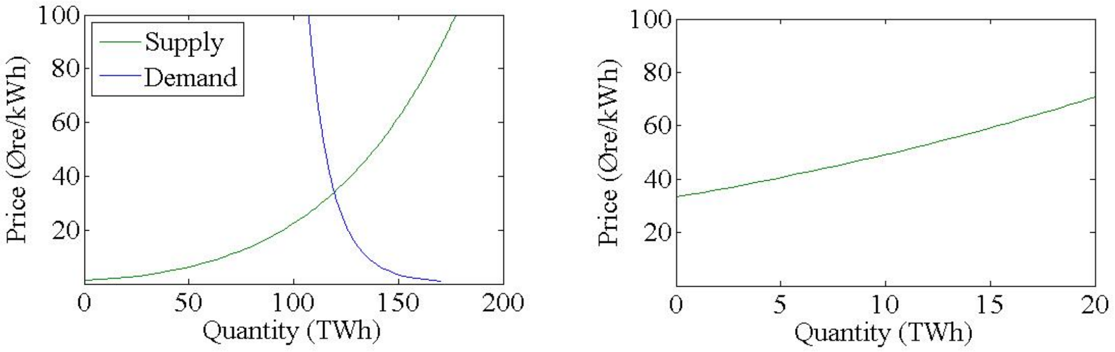
Figure 7: Supply and demand equilibrium in the feed-in tariff scheme for $L = 52.59$ øre/kWh

From the seen results the feed-in tariff system with a base-case compensation level of 52.59 øre/kWh is more effective in increasing the share of renewable supply than the GC base-case scenario. This is in compliance with the findings of Finon & Menanteau (2003) who argue that the feed-in tariff is more efficient in inducing investment. In terms of reducing emissions the GC scheme however redeems itself slightly by showing higher efficiency, especially when α is set at a slightly higher level than in our base-case. To remove the ambiguity of the results, the social cost of the support scheme should be assessed in order to make a balanced statement on the schemes' efficiency. The GC system is constructed in such a way that the subsidies assigned to the renewable producer are dynamically controlled by the market. This results in an economically efficient financing instrument where the subsidies just cover the marginal costs, leaving the producer with little or no surplus. In the feed-in tariff system the price received by the renewable producer is a fixed amount, while the subsidy paid by the government varies with p^E. As

L is normally set to a higher level than the producer's marginal cost, the total cost of the feed-in scheme is higher than for the GC. On the other hand, Finon & Menanteau (2003) claims that this gap allows for more R&D activity.

4.2 No support scheme

We also consider the investment opportunity under a scheme with no subsidies. Given this setting, we replace equation (1) with equation (20) in the equilibrium model.



(a) Supply- and demand-curves for no scheme applied

(b) Renewable supply-curve for no scheme applied

Figure 8: Market equilibrium and renewable production development in a no-support market

The solution of the no support base-case[27] gives a supply-demand equilibrium where the traded quantity is 119.38 TWh, as can be seen in table 7, and the electricity price is 34.1 øre/kWh, as displyed in figure 8a. According to Finon & Menanteau (2003) the low renewable supply is a result of the technology not being mature enough to compete on profitability with the nonrenewable sources. An investment in these sources is less expensive while also contributing with a more stable supply flow. We also note that, as expected, the ratio of renewable supply is significantly lower when no support is applied, as the investor chooses the cheaper non-renewable technologies.

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[27] As mentioned the no scheme base-case operates with the same elasticities and coefficients as the GC scheme.

Table 7: Production allocation for a market without support scheme

Production	Total Supply	Non-renewable	Renewable	Renewable Ratio
[TWh]	119.38	118.74	0.64	0.0053

4.3 Investment decision under different schemes

As already stated, the main purpose of green certificates is to induce investment in renewable technology with the objective of increasing the total renewable energy supply. We are therefore interested in comparing the GC system's ability to boost the investment rate in renewable technology compared to the alternative schemes[28]. We consider the wind turbine investment opportunity described earlier. By using the output prices from the supply-demand equilibrium equations we compare the GC scheme with the feed-in tariff and no support scheme through the real option model from section 2.3.

Table 8: The probability of investing within the next two years for the different support scheme base-cases

Support Scheme	GC	Feed-In Tariff	No Support
$Pr(X < X^{*})$	17.60%	22.99%	8.62%

All input parameters in the real option model are held constant except the investment's possible income according to the individual scheme[29]. We solve the real option model for the optimal investment cost, X^{*}, in each alternative and calculate the probability of investment within the next two years, as displayed in table 8. These results are demonstrated graphically in figure 9 where the project value under each scheme is drawn against its intrinsic value. The results show, as expected, that the investor will wait the longest with investing in a market with no active support system. In the feed-in base-case the investor would exercise his investment option sooner than under the GC scheme base-case. This is in compliance with the results presented in Boomsma *et al.* (2012). A valid explanation to this is that the feed-in tariff scheme allocates the benefit entirely to the producer, and hence to the investor, whereas in the GC scheme this benefit is assigned the

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[28] We hence look at the schemes efficiency in leading to higher probabilities of investment at any given level of X_0.

[29] One could argue that the required rate of return and hence the discount factors for each scheme should be differentiated according to the schemes' varying risk profiles. A valid assumption might be that an investor under the feed-in tariff system would require a lower rate of return as the guaranteed price eliminates some of the investment's risk. This is an interesting perspective, but it falls beyond the scope of this paper.

consumer[30]. Summarized the results imply that, between the alternatives, the feed-in scheme induces investment earlier than the GC scheme.

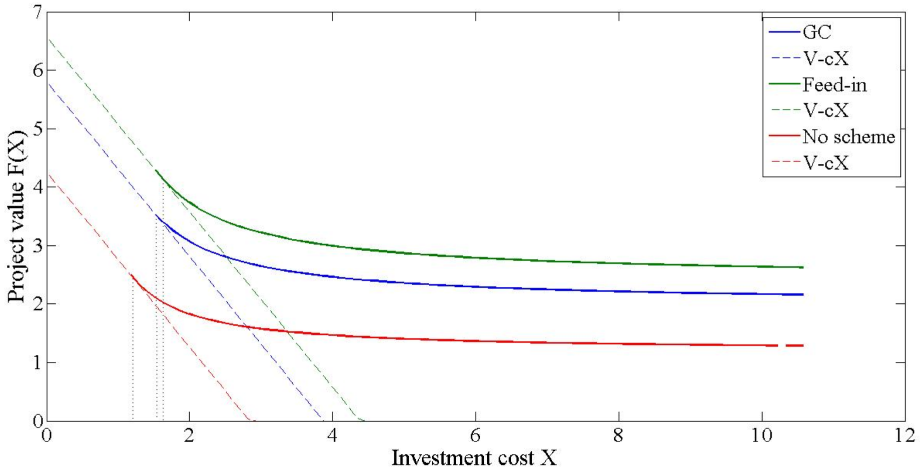

Figure 9: Base-case option value in the different support schemes versus the intrinsic value, $V - cX$, in each case

4.4 Uncertainty in renewable energy production

An important aspect to consider when evaluating the efficiency and potential contribution of a support scheme, is the risk taken by the individual market actors and the vulnerability of their revenues to unstable production levels. Renewable technology is especially exposed to this kind of uncertainty as its energy source mainly depends on uncontrollable weather conditions. This risk does not only apply to the renewable energy producers, but also to the market as a whole depending on its sensitivity to changes in supply. Considering a sudden change in the production conditions for the renewable energy sources, we investigate the effect this kind of "shock" has on the market for each evaluated support scheme. We consider the sensitivity in the different schemes to the changes in renewable production in the market and investigate the consequences this has for a potential wind park investor.

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[30] As the purchaser price decreases in the relevant range of quotas, as shown in figure 1.

Supply shock We start by assuming that the total amount of renewable supply in the market originates from wind turbines. Further the number of yearly effective production hours is assumed to be 3000 per year. We evaluate the effects of increasing or decreasing this by 10 hours, or 0.33%, representing positive and negative "shocks" in the renewable supply. These are very modest changes, but as is shown in table 9 it results in substantial changes in both price and supply.

Table 9: Relative changes in electricity price p^E, certificate price p^{GC}, purchaser price p^D and total electricity production Q_{total} for a 10 hour increase and decrease in effective production time for the renewable energy technology

Positive shock	GC	Feed-In Tariff	No Support
$\Delta_{p^{GC}}$	– 99.7%	–	–
Δ_{p^E}	+ 1.68%	– 0.11%	– 0.006%
$\Delta_{Q_{total}}$	+ 0.29%	– 0.05%	– 0.003%
Δ_{p^D}	– 3.3%	–	–
Negative shock			
$\Delta_{p^{GC}}$	+ 102.1%	–	–
Δ_{p^E}	– 1.66%	+ 0.11%	+ 0.006%
$\Delta_{Q_{total}}$	– 0.34%	– 0.011%	– 0.0006%
Δ_{p^D}	+ 3.4%	–	–

As can be seen, the market's reactions to positive and negative supply shocks are almost perfectly negatively correlated. We therefore only evaluate the results from the positive "shock". The effects are by far the most significant in the GC scheme, where the price of certificates plummets while the electricity price rises slightly. This results in a negative development in the purchaser price, which in turn increases total demand and hence total supply. Quite surprisingly, we observe an increase both in p^E and nonrenewable supply[31]. This is a consequence of the demand not facing the same price as the nonrenewable producer receives. Hence the demand responds to the decrease in the purchaser price while the nonrenewable producer responds to the increase in the electricity price. The other schemes, on the other hand, show limited sensitivity to the changes imposed. These results highlight the difference in risk allocation, especially to the producer and investor in renewable energy production. The income of the renewable producer in the GC scheme is extremely sensitive to shocks on the supply side and small changes in effective production time can make production unprofitable. In the feed-in tariff

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[31] Normally one would expect to find a negative correlation between electricity price and supply.

scheme, the renewable producers income per energy unit sold is unaffected by supply changes and the increased amount of production leads to an increase in total revenues. A 10 hour increase in production time hardly affects a market without support scheme, but illustrates the signs of changes in price and quantity expected to follow larger changes.

Assuming the sudden "shock" has a long-term effect, we are interested in how this will affect the decision of the potential wind park investor. Based on the p^E and p^{GC} found after implementing the positive supply shock and a slightly reduced investment cost per yearly added MWh, c in the model[32], the changes in the probability of an investment taking place within the next two years are as displayed in table 10. Under the feed-in tariff the investor's decision is only affected by the supply shock through its effect on yearly effective production hours as the fixed guaranteed price remains constant. In a market without support system the investor's probability of investing has a slightly positive development, indicating that by augmenting the total supply from renewable sources the investor is more prone to invest. Not surprisingly, the GC price's extreme sensitivity to changes in the renewable supply has a major effect on the investor's decision. From table 10 we see that the probability of investing drops by 70.89%. This indicates a probability of investing within the next two years of 5.12%, meaning that the GC scheme performs even poorer than the no scheme case. For a negative supply "shock" we would see relative changes of similar magnitude, though having the opposite signs.

Table 10: The relative change in the probability of investing within the next two years after a positive supply "shock" in the different support schemes

Support Scheme	GC	Feed-In Tariff	No Support
$\Delta_{Pr(X<X^*)}$	–70.89%	0.73%	0.81%

The GC scheme's high sensitivity to renewable energy production volume can be explained by the low demand elasticity, which restricts the increase in electricity demand in response to the rising supply. This naturally also applies to certificates, and a small increase in certificate issuance can hence result in an over-supply and the price rapidly approaching zero[33]. In the real world the results would however have a less extreme nature as the opportunity to store, or bank, certificates is opened. In real life the demand of GCs is based on the yearly consumed electricity, a fraction of which must be submitted within a fixed date the following

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[32] Due to the increased number of effective production hours.

[33] In accordance with the martingale condition.

year[34]. Because of this lag in the demand of GCs the renewable suppliers have the possibility of banking GCs for future sale if they observe over-supply one year[35]. Amundsen *et al.* (2006) argues that in a market including banking, speculators will buy the commodity for storage in periods of abundance, when prices would sink in a no-banking scenario. Hence prices are driven up to the point of next period's expected price less depreciation. In scarcity the spiked demand will increase prices to the point where storage is unprofitable, leading to a "stock-out" and spiking prices. With this flexibility the GC scheme is not as sensitive to oversupply as we observe in our model, though results from the market show a stable over-supply in the market and an increasing level of the accumulated level of banked GCs.

Demand shock As with changes in the supply conditions, a "shock" on the demand side will cause changes in the purchaser price and its composition as well as in the ratio between renewable and non-renewable energy supply. Table 11 shows the changes resulting from a 1% increase and 1% decrease in total demand respectively giving a positive and a negative demand shock.

Table 11: Changes in electricity price p^E, certificate price p^{GC}, purchaser price p^D and renewable and non-renewable electricity production Q_{GC} and Q_N for a 1% demand increase and 1% decrease in electricity demand

Positive shock	GC	Feed-In Tariff	No Support
$\Delta_{p^{GC}}$	– 6.17%	–	–
Δ_{p^E}	+ 5.10%	+ 5.56%	+ 2.49%
$\Delta_{Q_{GC}}$	+ 1.0%	0.0	+ 95.4%
Δ_{p^D}	+ 4.5%	–	–
Negative shock			
$\Delta_{p^{GC}}$	+ 5.9%	–	–
Δ_{p^E}	– 4.9%	– 5.4%	– 2.4%
$\Delta_{Q_{GC}}$	– 1.0%	0.0	– 95.4%
Δ_{p^D}	– 4.4%	–	–

The results from the demand shocks show that the market is as sensitive for positive as it is for negative shocks. We therefore, as was done under the supply shock, analyse the two scenarios under one. Considering the positive demand shock it is

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[34] In the Swedish/Norwegian market this date is set to 1. April.

[35] In the Norwegian system banked certificates are valid for submittance, and can hence be banked, throughout the lifetime of the scheme.

natural to expect to observe an increase in the supply to satisfy the augmented demand. We see that all the schemes experience an increase in the electricity price when demand goes up which hence indeed does induce a higher supply. Regarding the renewable supply, this increases both in the GC system and the no support system, where especially the relative change under the latter is noteworthy. This extreme growth is a result of the electricity price surpassing the range where the profitability of renewable technology increases rapidly. In the feed-in tariff the renewable supply remains constant as the renewable producer is not affected by the changes in demand. An interesting observation is the dynamics of the GC price, both according to the change in renewable supply and to the increasing demand. Although the GC price decreases, the renewable producer has incentives to increase renewable supply. This is a result of the increase in the electricity price being higher than the drop in the GC price, and hence the investor's total revenues increases.

As with the supply shock, we are also interested in how the demand changes will affect the investor's willingness to invest under the different schemes. Table 12 shows the relative changes in the investment probabilities for a positive demand "shock". The feed-in tariff investor is unaffected as the fixed price stays constant. In the GC scheme we observe that the demand shock only induces a minor change in the investor's behavior, in contrast to the major influence of the supply shock. The development is slightly positive in the terms of increasing the probability of investing as a result of growth in the potential total revenue. The investor operating in a market with no support scheme shows the highest sensitivity to changes in demand, where the positive demand shock has a rising effect on the investment probability.

Table 12: The relative change in the probability of investing within the next two years after a positive demand "shock" in the different support schemes

Support Scheme	GC	Feed-In Tariff	No Support
$\Delta_{Pr(X<X^*)}$	0.74%	0.00%	6.01%

An overall conclusion from evaluating both supply and demand shocks is that regarding the renewable supply the feed-in tariff scheme is, not surprisingly, the least sensitive to any changes as the renewable producer is not subject to this risk. Further we see that the no support system has the lowest sensitivity to the relative changes brought by the shock. Finally we note that the sensitivity according to supply changes is far more substantial than to demand changes. This can have its reasoning in the supply and demand elasticities where the supply is slightly more sensitive than the demand.

5 Conclusion

Many different market funding- and penalty schemes and other governmental tools exists to evoke investment in production technology for renewable energy sources. Although in varying configurations, the green certificate scheme and the feed-in tariff have become the dominating alternatives among the support scheme. This paper places its initial focus on the green certificate scheme and introduces the combination of an equilibrium model for simultaneously describing supply and demand of electricity and green certificates, and real options valuation theory. The investment decision is analysed by defining future cash flows as deterministic through the equilibrium expressions and placing the uncertainty in the investment cost.

We have presented an initial analysis of the green certificate market focusing on the influence of the set market properties and the quota level on the price seen by the distributor, the income of the producers and on the quantity of electricity produced. We find that the model does present the expected results of an increasing supply of energy from renewable sources with increasing quota and a slightly convex curve for development in the purchaser price. Through the real options framework we also discuss the effects of varying the quota on an investor's decision as this factor possesses an essential position in allocating the market revenues. This analysis shows that increasing α leads to the investor being less sensitive to cost and hence a higher probability of investment.

Further we performed a general comparison of the results to those of a system using the feed-in tariff scheme and one without any applied support arrangement. The results showed that the tested support schemes indeed have the wanted effect on the supply of renewable energy compared to the no support scheme scenario. Within a valid range of quotas, we however find that the increase in the renewable share resulting from the GC scheme also brings an increase in the total consumption of electricity, which in most markets is an unfortunate development. However, in the Swedish/Norwegian electricity market a great majority of the production capacity not connected to the certificate scheme, which in this article hence is defined as non-renewable, is hydro power, which minimizes this issue.

Using representative configurations for the market properties of both alternatives, the feed-in tariff performs better in respect of inducing investment in renewable sources, hence contributes to a larger increase in renewable production capacity. On the other hand, the GC scheme does prove to be more efficient in reducing the supply from nonrenewable sources. Hence the feed-in tariff leads to a higher ratio of renewable energy in the market. We also present arguments for the feed-in tariff paying the renewable producer in excess of what is needed to cover the marginal costs and hence being a better facilitator of initiative within R&D. Our findings also state that the GC scheme shows a substantially higher sensitivity to quantity "shocks", especially in supply, than the other schemes. Our overall results hence indicates that, within the limitations set in this paper, the feed-in tariff is the best choice for reaching the specific goal of increased investment in production technology for energy from renewable sources. When also regarding a target of reducing overall energy consumption, stabilize the market's reactions to sudden changes in the supply or demand while also minimizing the social cost of the scheme, the answer however becomes more ambiguous.

Appendices

A Derivation of calibration coefficients C^D, C^R and C^N

As explained above, all comparative analyses on the respective market base-cases are performed using the same supply- and demand elasticities, intercept, and calibration coefficients. The elasticities and intercept have been exogenously set on the basis of observations and intuitions about the market described in section 3. Equations (2) and (3) describe the equilibrium conditions under which the investment decision is made in the market adopting the green certificate scheme, as does equations (19) and (20) for the feed-in tariff market and the market without support scheme respectively. In order to find global values for C^D, C^R and C^N, we perform three calibrations, one for each market in question, and set the global level to the average of the three respective solutions. The calibration is performed using monthly sample data for the Swedish/Norwegian market from NordPool and certificate price data from NECS dating from 2004 to 2013.

The algorithm is based on an iterative approach using a least squares method to set the optimal coefficients. In each iteration, C-values are set and inserted into the equilibrium equation(s) for the respective market, which are solved for the unknown(s) p^E (and p^{GC})[36]. The resulting prices are presented in the [1x1] ([1x2]) vector P. This is used to calculate the sum of the squared differences between the price suggested by the model, P, and each of the observed prices in the input-data. By iteratively changing the C-values, the algorithm works towards the optimal Cs by minimizing the sum of squared differences, and hence finds the C^D, C^R and C^N which results in the price(s) best fitting the price data. The global C-values used in the comparative analyses, are as mentioned found by calculating the average C^D, C^R and C^N from the results of the three individual market configurations.

Table 13: Alternative combinations of elasticities with resulting calibration coefficients

Alternatives	C_D	C_R	C_N
Green Certificates	169.93	61.72,98	59.39
Feed-in	169.20	59.51	56.34
No scheme	170.58	61.14	60.15
Average	169.90	60.79	58.62

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[36] In this procedure we use the average values of the prices in the dataset as our initial guess.

B Probability distribution of the mean reverting process

We want to derive the probability of investing in the wind park within a future time t. Considering the Ornstein-Uhlenbeck mean reverting process in equation 4, which is a Gaussian process, the expected value at time t and its variance can be derived using the Kolmogorov forward equation and applying the moment-generating function for the variable, as can be seen in Dixit & Pindyck (1994). If the current value of X is X_0 then the process of X_t is normally distributed[37] with expected future value at time t equal to

$$E[X_t] = \bar{X} + (X_0 - \bar{X})e^{-\eta t} \tag{21}$$

where η is the speed at which X revert against $\bar{X}$. Further the variation of $(X_t - \bar{X})$ is

$$Var[X_t - \bar{X}] = \frac{\sigma^2}{2\eta}\left(1 - e^{-2\eta t}\right) \tag{22}$$

The probability of investing within time t where the time steps are measured monthly, $\Delta t = \frac{1}{12}$, is derived by converting the normal random variable, X, to normal standard, z;

$$z = \frac{X - E[X_t]}{\sqrt{Var[X_t - \bar{X}]}}$$

Inserting the relevant values for the parameters which are used in the real option model; $\eta = 0.05$, $\sigma = 0.2$ and $\bar{X} = 2$ and setting the current level of X, X_0, to 2.1 we find the expected future value when $t = 24$ to be $E[X_t] = 2.03$ and the $Var = 0.3637$ and $\sqrt{Var} = 0.60308$. The investor will invest when X reaches the optimal investment value X^* derived from the real options model for each scenario. To find the likelihood of investing in the next two years we find the probability of $X < X^*$ when $t = 24$ using

$$Pr(X < X^*) = Pr\left(\frac{X - E[X_t]}{\sqrt{Var}} < \frac{X^* - E[X_t]}{\sqrt{Var}}\right) = N\left(\frac{X^* - E[X_t]}{\sqrt{Var}}\right) \tag{23}$$

Applying this to the different cases with their related investment rules, X^*, from the real option analysis we get the following probabilities for investment within the next two year period:

And similar the results for the different schemes case:

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[37] As explained in Franco (2003).

Table 14: The optimal investment rule for different values of the required quota and the respective probabilities of investing in the wind park within the next two years

Level Quota	$\alpha = 0.02$	$\alpha = 0.07$	$\alpha = 0.15$
X^*	1.26	1.47	1.83
$Pr(X < X^*)$	10.26%	17.60%	37.13%

Table 15: The optimal investment rule for the different support schemes and the respective probabilities of investing in the wind park in each scheme within the next two years

Support Scheme	GC	Feed-In Tariff	No Support
X^*	1.47	1.58	1.21
$Pr(X < X^*)$	17.60%	22.99%	8.62%

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