

Bachelor's Programme in Economics

Effects of Introducing Green Energy Certificates to a Competitive Energy Market

Modelling the impact of introducing green energy certificates alongside a government mandated green energy quota to understand the subsequent price and consumption effects, as well as corresponding policy implications.

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**Bachelor's thesis
2024**

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Title of thesis Effects of Introducing Green Energy Certificates to a Competitive Energy Market

Programme Bachelor's programme in Economics

Major Economics

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Date 31.12.2024 **Number of pages** 30 **Language** English

Abstract

Climate change is a detrimental and worsening problem in today's world. An effective way to tackle climate change is to decarbonise the energy sector by transitioning from brown energy to green energy. This thesis examines the energy price and consumption effects of introducing green energy certificates alongside a government imposed green energy quota in competitive energy markets. Through theoretical modelling and empirical analysis, this thesis finds that implementing such a policy has both subsidy and tax-like effects on green and brown energy producers respectively. This is different to some of the other policy mechanisms in place today, such as the cap-and-trade system or carbon pricing, as not only is brown energy production being disincentivised, but green energy production is also further being incentivised. The price and consumption effects of this policy are ambiguous. However, modelling variations in the government mandated quota is useful in determining an optimal policy decision which balances both climate objectives and economic efficiency.

Keywords Energy markets; Green energy certificates; Renewable energy

“Climate change is a defining challenge for humanity. The economic consequences of inaction will be severe and irreversible.”

— Christine Lagarde, *President of the European Central Bank*

“We’re running out of time to deal with climate change. Every year that we delay, the cost of action goes up, and the risks of catastrophe increase.”

— Paul Krugman, *Winner of the Nobel Memorial Prize in Economic Sciences*

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Preface and Acknowledgements

I want to thank Professors Dr. Miri Stryjan and Dr. Matti Liski for their excellent advice and guidance.

I also want to thank my family for all their support.

Espoo, 31 December 2024
Yash Nagal

Symbols, Operators and Abbreviations

Symbols

N	net utility
U	utility function
δ, η, λ	parameters of utility function
π_b	profit function of brown energy producer
π_g	profit function of green energy producer
C_b	cost function of brown energy producer
$\alpha_b, \beta_b, \gamma_b$	parameters of cost function of brown energy producer
C_g	cost function of green energy producer
$\alpha_g, \beta_g, \gamma_g$	parameters of cost function of green energy producer
p_e	price of energy
p_c	price of green energy certificate
q^D	quantity of energy demanded
q_b^S	quantity of brown energy supplied
q_g^S	quantity of green energy supplied
K	government imposed green energy quota
M	slope of energy-certificate price relationship
L	affine part of energy-certificate price relationship
Z	relative price elasticity between consumer and green energy producer
X^D	Cobb-Douglas specification of demand function
X_b^S	Cobb-Douglas specification of brown supply function
X_g^S	Cobb-Douglas specification of green supply function
μ^D	calibration factor for energy demand
μ_b^S	calibration factor for green energy supply
μ_g^S	calibration factor for brown energy supply
ε	elasticity of demand
κ_b	supply elasticity for brown energy
κ_g	supply elasticity for green energy
ξ_g	intercept for green energy carrier

Operators

$\frac{\partial}{\partial x}$ derivative with respect to variable x

Abbreviations

EU	European Union
EAC	energy attribute certificate
GO	guarantees of origin
LCOE	levelized cost of electricity
kWh	kilowatt-hour
MWh	megawatt-hour
TWh	terawatt-hour

1 Introduction

Climate change is one of the most detrimental crises ongoing in our world today, with global surface temperatures increasing predominantly due to the anthropogenic emissions of greenhouse gases, such as carbon dioxide and methane (IPCC, 2023). The fact that climate change is a global problem makes it extremely difficult to address the negative externalities caused by these greenhouse gas emissions (Nordhaus, 2019). Despite the complexity of the problem, finding and implementing solutions to mitigate climate change is a challenge that must be addressed urgently.

An effective way to tackle climate change is to decarbonise the energy sector by producing energy renewably instead of using fossil fuels, as electricity generation accounts for approximately 25% of global greenhouse gas emissions, with more than two-thirds of this electricity consumed by commercial or industrial users (Brander et al., 2018). These greenhouse gases are emitted into the atmosphere as a result of burning fossil fuels, such as coal, petroleum, and natural gas (Verbruggen and Marchohi, 2010). On the other hand, renewable energy is derived from natural sources, such as the sun and wind, and do not emit harmful greenhouse gases (Güney, 2019). Note that in this thesis, all energy produced renewably will be referred to as “green energy”, and all energy produced non-renewably will be referred to as “brown energy”. Please also note that the terms “energy” and “electricity” are used interchangeably. Hence, by transitioning to green energy, it is possible to decarbonise the energy sector.

Despite the ecological benefits associated with producing energy renewably, many countries are still reliant on fossil fuels. India, for example, still relies heavily on coal, which accounts for about 72% of total electricity generation as of now (International Energy Agency, 2024). Even in the Nordic countries, which have transitioned away from fossil fuels relatively more, only 49% of gross energy consumption was derived from renewable sources in 2021

(Nordic Statistics, 2024). This is because the costs associated with producing energy renewably are typically higher compared to producing non-renewably (Ang et al., 2022). Furthermore, renewable-based technologies are intermittent, meaning that renewable energy production depends on various physical conditions which can change over time (Ferrasse et al., 2022). For example, solar energy can only be produced when there is a sufficient amount of sunlight. This makes it difficult to always match energy demand with renewable energy supply. These unattractive traits of renewable energy sources lower the incentive to invest and switch to green energy production (Ang et al., 2022).

To create a more substantial incentive, government intervention is a valid option. As can be seen in the real world, to address climate change, governments across the globe have established net-zero targets, and have implemented policies to achieve these targets as well. The EU, for example, aims to be climate-neutral by 2050. It is an objective at the heart of the European Green Deal and legally binding according to the European Climate Law (European Commission, 2019).

In order to comply with government regulations, as well as the sustainable demands of customers, an increasing number of companies, including Google and Microsoft, are finding solutions to reduce their own emissions (Microsoft, 2020, Google, 2024). However, now another problem arises. Electricity is a homogenous good (Truong and Hamasaki, 2021). This means that electricity produced renewably or electricity produced using fossil fuels cannot be distinguished from one another, and can be considered as perfect substitutes. This makes it important to establish some sort of tracking system to keep a tab of which energy was produced renewably. Many governments have thus implemented the use of green energy certificates as a mechanism to both incentivise and track green energy production. In Europe, these certificates are called GOs. The GO market interacts with electricity markets and affects prices, volumes, and thus market equilibriums.

The results of this thesis show how a careful implementation of green energy quotas alongside these certificates can help to increase the share of green energy production more quickly. However, imposing excessively high green energy quotas can risk unintended economic consequences, such as increased consumer prices and reduced energy supply. It is important to research more about such a policy to understand whether it is beneficial for countries to implement it or not. Furthermore, the results from this thesis can be used to further think about improving certificate systems in countries that have already adopted it. The fact that such a policy setup has both a subsidy and tax-like effect on green and brown energy producers respectively makes it very interesting to study further. While other policy mechanisms, such as the cap-and-trade system or carbon pricing, make brown energy production less favourable, the combination of green energy certificates with the government-imposed quota simultaneously further incentivises green energy production.

1.1 Aim

The aim of my thesis is to first properly understand both electricity and certificate markets and how they function in a competitive setting. On this knowledge basis, I seek to determine the price and consumption effects of introducing green energy certificates alongside a government imposed green energy quota in a competitive energy market. Furthermore, I would also like to delve into the relevant policy implications. Hence, my research question is *“What are the energy price and consumption effects, as well as the policy implications, of introducing green energy certificates alongside a government imposed green energy quota in a competitive energy market?”* This aim will be achieved by conducting a literature review on both theoretical models and empirical studies to get a holistic understanding of the topic.

1.2 Structure

I have structured this thesis as follows. Section 2 presents the theoretical background. Sections 3 covers the mathematical model by Jensen and Skytte,

and Section 4 covers the empirical model by Bye, which are both used to analyse the policy. Section 5 serves as the discussion part of the thesis, where I add a lot of my own analysis and ideas. Section 6 concludes. Sections 7 and 8 include the references and appendix respectively.

2 Theoretical Background

In this section, I explain the relevant theory to serve as a knowledge basis for the rest of the thesis. This includes elaborating on both theoretical economic concepts and real specific characteristics of energy and certificate markets.

2.1 Supply and Demand Model

A market, by definition, is a way that people exchange goods and services by means of directly reciprocated transfers, voluntarily entered into for mutual benefit, that is often impersonal (CORE Econ, 2017). When introducing the idea of perfect competition within such a market, a key assumption is that all parties have complete information about market conditions without any knowledge asymmetries (Sepulveda, 2020). The implication of this assumption is that all buyers and sellers are price-takers. Based on the law of one price, it can be concluded that in a perfectly competitive equilibrium, all transactions take place at a single market price at a given point in time (CORE Econ, 2017). This is because all potential gains are realised from trading at the equilibrium price, meaning that there is no benefit for any party to deviate from this price.

The supply and demand model explains how the price of a good or service is determined given a perfectly competitive market. The presentation of this model was popularised by Alfred Marshall in his book “Principles of Economics”. The model is conventionally depicted using a supply and demand curve on a graph where the horizontal x-axis represents the quantity q and the y-axis represents the price p . The supply depends on each producer’s willingness to accept a specific price for a certain quantity. A key assumption is that

the producer has an increasing marginal cost of production, meaning that the per unit cost of production increases as the total quantity produced increases. This can be the case due to factors like limited resources or inefficiencies at higher production levels. Given these properties, the supply curve typically slopes upwards. The demand depends on the consumer's willingness to pay a specific price for a certain quantity. A key assumption is that the consumers have a diminishing marginal utility, meaning that the additional satisfaction gained from every additional unit decreases. Given these properties, the demand curve typically slopes downwards. Given that there are multiple sellers and buyers, the supply and demand curves of each seller and buyer can be aggregated into a market supply curve $q^S(p)$ and a market demand curve $q^D(p)$. The market supply and demand curves intersect at price p^* such that $q^S(p^*) = q^D(p^*)$, as illustrated in Figure 1 below.

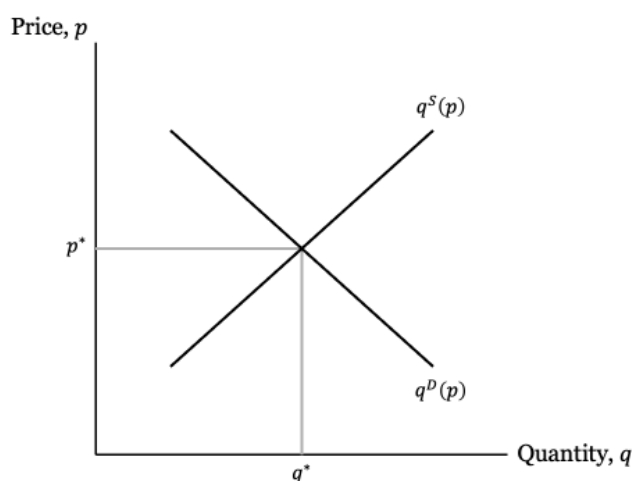


Figure 1: Equilibrium in a perfectly competitive market

At this equilibrium, the market clears, meaning that the quantity supplied matches the quantity demanded at the given price. Any deviation from this equilibrium results in either excess supply or demand. The market equilibrium itself can change based on external factors that affect the supply or demand. For example, the demand curve can shift due to consumer preferences, and the supply curve can shift due to changes in production costs or

technologies. This potentially results in new equilibrium prices and quantities.

2.2 Energy Markets

The energy market is a market handling process specifically with the trade and provision of energy. (Mousavi et al., 2021). The supply and demand model particularly applies to energy markets, as electricity is a homogenous good and is considered as near perfect substitutes (Truong and Hamasaki, 2021). I will now focus on the European energy markets, and especially the Nordic electricity markets, to link this theory to the real world as well.

2.2.1 Deregulation and Liberalisation of European Energy Markets

The EU decided to liberalise its energy markets in 1997, meaning that the government supervised monopolistic market began transitioning into a competitive market (Ringel, 2003). The key incentive to liberalise European energy markets was to enhance consumer choice, foster market competition, and improve overall market efficiency. To improve the competitiveness of the energy markets, various components of the value chain had to be separated, such as the stages generation, power transport, and power sales (International Energy Agency, 2001). Furthermore, the 1990s also served as a key time period for the deregulation of Nordic energy markets in particular. The Finnish, Swedish, Danish, and Norwegian energy markets became integrated to form the first intercountry electric power market in the world (Bye and Hope, 2005). Thus, today, this integrated Nordic energy market experiences competitive energy costs and prices.

2.2.2 Price Calculation in Nordic Energy Markets

Electricity markets in the Nordic countries are integrated, and the prices are calculated in a day-ahead pay-as-clear auction operated by Nord Pool (Nord Pool, 2020). During the auction, each producer submits their own bid for the price they are willing to accept for certain quantities of electricity, which is essentially their supply curve. These bids are then aggregated into a market

supply curve. On the other hand, the aggregated market demand, also known as the load, is the sum of all the individual demands. In a pay-as-clear auction the market price is set by the lowest bid that fulfils the demand for each hour of the day.

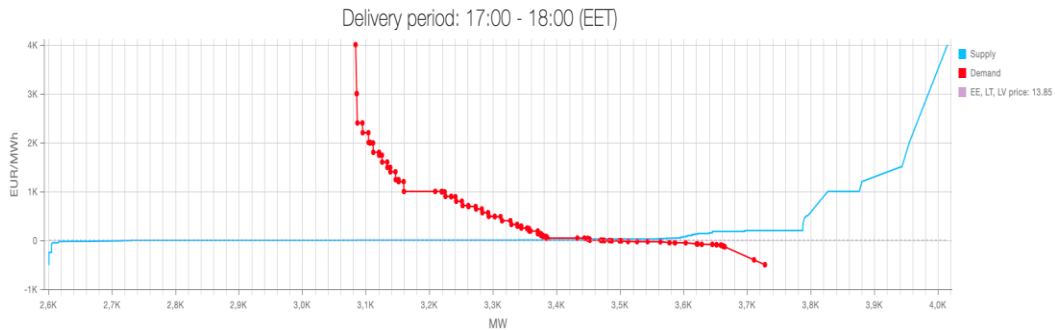


Figure 2: Aggregated bidding curves from Nord Pool

Note that the supply and demand can vary between every hour, of example due to variations in temperature. This auction mechanism therefore ensures that the supply and demand are always balanced, which is critical for the electricity system. The system ensures an efficient outcome and incentivises producers to bid at their marginal cost.

2.3 Green Energy Certificates

Green energy certificates, also sometimes referred to as EACs, serve as a crucial electricity-tracking system. These certificates act as a digital stamp to prove renewable energy production. Electricity is a homogenous good, and thus consumers cannot credibly distinguish between renewable and non-renewable energy, which is especially complicated once all the energy in the network mixes together. This leads to an information asymmetry problem, and consequently adverse selection may rise, as consumers might buy less renewable energy than what they desire (Hulshof et al., 2019). Producers typically receive one digital certificate for each MWh of renewable energy generated (Herbes et al., 2020). The certificate indicates the main characteristics of the installation, such as the energy sources used, the location of energy production, the installed capacity, and the commissioning date (Galzi, 2023).

Hence, green energy certificates serve as an effective mechanism to differentiate the way energy is produced and can be used to prove the origin of electricity.

The producers can sell these certificates to consumers (Mulder and Zomer, 2016). This provides renewable energy producers with an additional source of revenue. The certificates are traded in an open competitive market setting, where the price is determined by the supply and demand. Note that the green energy certificates can be traded independently of the exchange of the energy itself (Hulshof et al., 2019). Moreover, because these certificates act as a quality-driven instrument which provides additional information to consumers about the renewable production of energy, it helps to further promote renewable energy consumption as well (Galzi, 2023).

There are multiple examples of green energy certificate systems in today's world. One example is the GO market in Europe, which is the largest standardised voluntary green electricity market where these certificates are traded (Scholta et al., 2024). When a GO is utilised, meaning that the certificate is used to sell renewable electricity, it is cancelled and can no longer be used. If a GO is not cancelled within a year, it expires (Hulshof et al., 2019). The independent trading of certificates is registered in the European Energy Certification System, which also accounts for countries importing GOs from other countries to reach their own national targets (Mulder and Zomer, 2016).

2.4 Imposed Government Quota

To make the green energy transition more effective, many governments have already mandated green energy quotas. In Sweden, for example, a national policy activated in 2003 mandates electricity suppliers to fulfil a government obligated green quota of certificated energy in proportion to the total energy use (International Energy Agency, 2022). The demand is thus regulated by this green energy quota. In 2012, Norway joined hands with Sweden and began determining the sizes of quota obligations together (Energifaktanorge,

2024). The objective of these quotas is to ensure the effectivity of the energy certificate system to incentivise green energy production. While other countries are considering implementing such a quota system too, many still haven't done so yet.

3 Deterministic Autarky Market Model

On the knowledge basis of the theory discussed, I shall now thoroughly expand on a theoretical deterministic model built by Stine Jensen and Klaus Skytte to understand the market effects of introducing green energy certificates (Jensen and Skytte, 2002).

3.1 Assumptions

The model assumes an autarky market, meaning that no cross-border trade is possible. The electricity and certificate markets are liberalised and there is hence perfect competition in both markets. The setup has a representative consumer, as well as two representative producers, where one producer produces brown energy and one producer produces green energy. Consumers aim to maximise the amount of satisfaction they get based on their demand for energy q^D , which is captured by the utility function $U(q^D)$. This demand is partly politically determined, as governments impose a minimum quota K for green energy consumption. Consumers gain no additional utility from obtaining more certificates than the imposed government quota. Producers aim to maximise profits π in the competitive market by supplying either brown energy q_b^S or green energy q_g^S , depending on their production technology. All individual actors act rationally in accordance with the endogenously determined electricity price p_e and certificate price p_c . The producer receives one unit of certificates for every unit of electricity produced. In this model, derivatives cannot be traded at all.

3.2 Consumer Utility Maximisation

Consumers gain utility $U(q^D)$ for consuming electricity. However, they must also bear the cost of using this energy, which is simply the market price of energy multiplied by the amount of energy they consume. Given that the consumer gains no additional utility from obtaining more certificates than the imposed government quota, the consumer purchases $q^D K$ amount of certificates at a price p_c . Furthermore, the consumer purchases q^D amount of electricity at price p_e . Hence, the net utility N , which is the difference between the satisfaction gained and costs associated with consuming electricity, can be expressed as follows.

$$N = U(q^D) - q^D(p_e + Kp_c)$$

To solve for the maximum net utility a consumer can get, the first order condition must be solved as follows.

$$\frac{\partial N}{\partial q^D} = U'(q^D) - (p_e + Kp_c) = 0$$

Therefore:

$$U'(q^D) = p_e + Kp_c$$

This implies that the marginal utility of consuming electricity equals the effective price per unit at the optimum level.

3.3 Demand Function

The model assumes that the consumer's utility function is given by an increasing concave function, which is truncated in a way that no additional utility is gained after a maximum point as follows.

$$U(q^D) = \begin{cases} \delta q^{D^2} + \eta q^D + \lambda & \text{when } q^D \leq -\frac{\eta}{2\delta}, \\ -\frac{\eta}{4\delta} + \lambda & \text{otherwise.} \end{cases}$$

It is important to note that $\delta < 0$ and $\eta > 0$, which are important properties of the constants in the model. Notice that $-\frac{\eta}{2\delta}$ is the vertex point of the quadratic expression in the piece-wise function, and $-\frac{\eta}{4\delta} + \lambda$ is simply a horizontal line which intersects the vertex of the same quadratic expression. Given these properties, the graph of $U(q^D)$ is illustrated below in Figure 3.

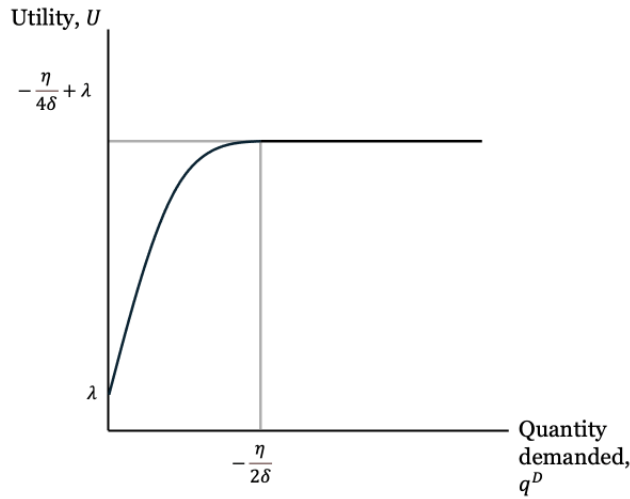


Figure 3: Consumer's utility function

Notice that the marginal utility of consuming energy is positive but decreasing until $-\frac{\eta}{2\delta}$ is reached. At this point, there is a maximum level of utility reached, after which no more utility can be gained from using more electricity. Hence, the quadratic expression of the consumer's utility function is of primary importance to solve for the demand function. To do so, the marginal utility must be calculated as follows.

$$U'(q^D) = 2\delta q^D + \eta$$

Now, it is known that $U'(q^D) = p_e + Kp_c$, and hence:

$$2\delta q^D + \eta = p_e + Kp_c$$

Solving for q^D :

$$q^D(p_e, p_c) = \frac{p_e + Kp_c - \eta}{2\delta}$$

Notice that q^D cannot be negative. The denominator is negative as $\delta < 0$, hence the numerator must be negative too, which is the case when $p_e + Kp_c < \eta$. When this condition is violated, q^D can simply be set to zero. Hence, the demand can be expressed more formally as follows.

$$q^D(p_e, p_c) = \begin{cases} 0 & \text{when } p_e + Kp_c > \eta \\ \frac{p_e + Kp_c - \eta}{2\delta} & \text{otherwise.} \end{cases}$$

The demand function hence depends on both the electricity and certificate prices, as well as the green energy quota.

3.4 Brown Energy Producer Profit Maximisation

The goal of the producer is to maximise profits, which is the difference between the revenues and the costs of the producer. Considering the revenue side, p_e is the price at which the producer can sell brown energy q_b^S . The costs can be expressed as a cost function, $C_b(q_b^S)$ which represents the total costs associated with producing brown energy. Hence, the profit function is:

$$\pi_b(q_b^S) = p_e q_b^S - C_b(q_b^S)$$

To find the maximum profits the producer can get, the first order condition must be solved as follows.

$$\frac{\partial \pi_b}{\partial q_b^S} = p_e - C_b'(q_b^S) = 0$$

Therefore:

$$p_e = C_b'(q_b^S)$$

This implies that the market price equals the marginal cost of producing brown energy.

3.5 Brown Energy Supply

The model assumes that the cost function is increasing and convex without any capacity constraints as follows.

$$C_b(q_b^S) = \alpha_b q_b^S{}^2 + \beta_b q_b^S + \gamma_b$$

It is important to note that $\alpha_b > 0$ and $\beta_b > 0$, and assuming increasing marginal production costs, $2\alpha_b < \beta_b$ must hold. This is because $-\frac{\beta_b}{2\alpha_b}$ is the vertex point, and the numerator must be larger than the denominator for only the increasing part of the quadratic expression to be considered. Given these properties of brown energy producer's cost function, the supply of brown energy can be derived. To do so, the marginal cost must be calculated as follows.

$$C_b'(q_b^S) = 2\alpha_b q_b^S + \beta_b$$

It is known that $p_e = C_b'(q_b^S)$, and hence:

$$2\alpha_b q_b^S + \beta_b = p_e$$

Solving for q_b^S :

$$q_b^S(p_e) = \frac{p_e - \beta_b}{2\alpha_b}$$

Intuitively, q_b^S must be positive. The denominator is positive since $\alpha_b > 0$, and hence the numerator must be non-zero. Therefore, the supply of brown energy can be expressed more formally as follows.

$$q_b^S(p_e) = \begin{cases} 0 & \text{when } p_e \leq \beta_b \\ \frac{p_e - \beta_b}{2\alpha_b} & \text{when } p_e > \beta_b \end{cases}$$

The brown energy supply function hence depends on only the electricity prices.

3.6 Green Energy Producer Profit Maximisation

The maximisation of profits for a green energy producer depends on both the revenues and costs. However, the revenue of green energy producers depends not only on the electricity price p_e , but also on the certificate price p_c . Given a cost function $C(q_g^S)$, the profits are:

$$\pi_g(q_g^S) = (p_e + p_c)q_g^S - C_g(q_g^S)$$

To find the maximum profits the producer can get, the first order condition must be solved as follows.

$$\frac{\partial \pi_g}{\partial q_g^S} = p_e + p_c - C_g'(q_g^S) = 0$$

Therefore:

$$p_e + p_c = C_g'(q_g^S)$$

This implies that sum of the market price and certificate price equals the marginal cost of producing brown energy.

3.7 Green Energy Supply

The model assumes that the cost function is increasing and convex without any capacity constraints as follows.

$$C_g(q_g^S) = \alpha_g q_g^{S^2} + \beta_g q_g^S + \gamma_g$$

It is important to note that $\alpha_g > 0$ and $\beta_g > 0$, and assuming increasing marginal production costs, $2\alpha_g < \beta_g$ must hold, for similar reasons to that of the brown energy producers. Given these properties of green energy producer's cost function, the supply of green energy can be derived. To do so, the marginal cost must be calculated as follows.

$$C_g'(q_g^S) = 2\alpha_g q_g^S + \beta_g$$

It is known that $p_e + p_c = C'(q_g^S)$, and hence:

$$2\alpha_g q_g^S + \beta_g = p_e + p_c$$

Solving for q_g^S :

$$q_g^S(p_e, p_c) = \frac{p_e + p_c - \beta_g}{2\alpha_g}$$

Intuitively, q_g^S must be positive. The denominator is positive since $\alpha_g > 0$, and hence the numerator must be non-zero. Therefore:

$$q_g^S(p_e, p_c) = \begin{cases} 0 & \text{when } p_e + p_c \leq \beta_g \\ \frac{p_e + p_c - \beta_g}{2\alpha_g} & \text{when } p_e + p_c > \beta_g \end{cases}$$

The green energy supply function hence depends on both the electricity and certificate prices.

3.8 Results of the Model

In this section I discuss the results obtained from the mathematical model.

3.8.1 Relationship between Electricity and Certificate Prices

The demand and green energy supply functions depend on both the electricity and certificate prices. By deriving the mathematical relationship between electricity and certificate prices, it is possible to express these functions in terms of only one variable.

It is known that $q_g^S = Kq^D$. Given the expressions for q_g^S and q^D , it is possible to solve for p_c in terms of p_e . The calculations are included in Appendix A, and the result is:

$$p_c = p_e \left(\frac{\frac{\delta}{\alpha_g} - K}{K^2 - \frac{\delta}{\alpha_g}} \right) + \frac{K\eta - \frac{\delta}{\alpha_g}\beta_g}{K^2 - \frac{\delta}{\alpha_g}}$$

The relative price elasticity between the consumer and green energy producer compares the responsiveness of the respective supply and demand to changes in price, and is mathematically defined as $(\partial q_g^S / \partial p_e) / (\partial q^D / \partial p_e)$. By substituting the expressions for q_g^S and q^D , it is possible to solve for the relative price elasticity between the consumer and green energy producer, which is $\frac{\delta}{\alpha_g}$. This elasticity can be denoted as Z , which means that the slope of the relationship M and affine part L can be expressed as follows

$$M = \left(\frac{Z - K}{K^2 - Z} \right)$$

$$L = \frac{K\eta - Z\beta_g}{K^2 - Z}$$

for convenience. Hence, $p_c = Mp_e + L$, and the relationship between electricity and certificate prices is thus linear.

However, whether these prices are positively or negatively correlated is not yet clear at this point, as the sign of the slope is not yet determined. The slope is expressed in terms of Z and K , where $0 < K < 1$ by definition. Furthermore, since $\delta < 0$ and $\alpha_g > 0$, the elasticity $Z < 0$. Hence, $M < -1$, and it can be concluded that the certificate prices are negatively proportional to the electricity prices. Furthermore, it is important to note that for an increase in electricity price, there is an even larger decrease in certificate price. In addition, the affine part, also known as the constant, is expressed in terms of Z , K , η , and β_g , where $0 < K < 1$, $\eta > 0$, $\beta_g > 0$, and $Z < 0$. Hence, $L > 0$. This implies that the x-intercept, which is $\frac{-L}{M}$, will be positive as well. It is important to note that $p_c > 0$ only when $p_e < \frac{-L}{M}$. The relationship between certificate and electricity prices is now clear and is illustrated in Figure 4 below.

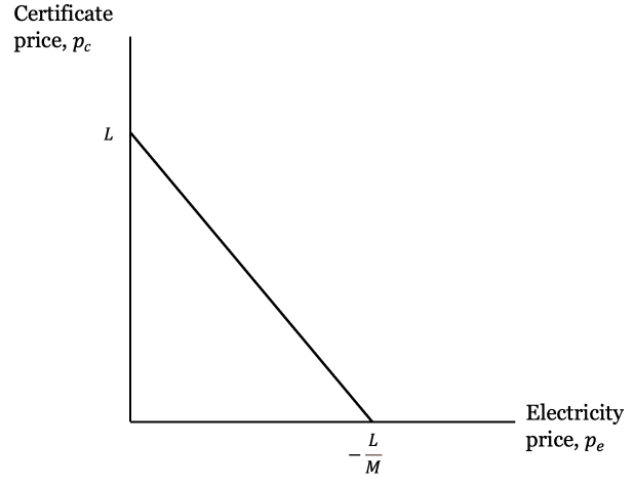


Figure 4: Negative relationship between electricity and certificate prices

I will now explore how this relationship affects demand and supply functions. The brown energy supply function is unaffected by the certificate price, leaving the demand and green energy supply functions for analysis.

3.8.2 Demand Function Analysis

Given $p_c = Mp_e + L$, the consumer price is now:

$$p_e + Kp_c = p_e + (Mp_e + L)K = (1 + MK)p_e + LK$$

Thus, given $q^D(p_e, p_c) = \frac{p_e + Kp_c - \eta}{2\delta}$, the demand function is now:

$$q^D(p_e) = \frac{(1 + MK)p_e + LK - \eta}{2\delta} = \frac{(1 + MK)}{2\delta} p_e + \frac{LK - \eta}{2\delta}$$

The slope of demand function is $\frac{(1+MK)}{2\delta}$ and the constant is $\frac{LK-\eta}{2\delta}$. Notice that, compared to a scenario where $p_c = 0$, the slope is changed by the term $(1 + MK)$, where $0 < (1 + MK) < 1$. Given a certificate price $p_c > 0$, the consumer becomes less sensitive with respect to the market price of electricity p_e . This is intuitive, as the electricity price p_e makes up a relatively smaller part of the total consumer price.

3.8.3 Green Energy Supply Function Analysis

Given $p_c = Mp_e + L$ and $q_g^S(p_e, p_c) = \frac{p_e + p_c - \beta_g}{2\alpha_g}$, the green energy supply function is now:

$$q_g^S(p_e) = \frac{p_e + Mp_e + L - \beta_g}{2\alpha_g} = \frac{1+M}{2\alpha_g} p_e + \frac{L - \beta_g}{2\alpha_g}$$

where $1 + M < 0$. This implies that the slope is positive when $p_c = 0$, where the supply is cost driven, and negative otherwise when $p_c > 0$, where the supply is demand driven. The y-intercept of $q_g^S(p_e)$ is the constant $\frac{L - \beta_g}{2\alpha_g}$, while the x-intercept is $\frac{\beta_g - L}{1 + M}$ when $p_e = 0$. Given that $p_c > 0$ only when $p_e < \frac{-L}{M}$, a graph can be constructed such that the supply is $q_g^S(p_e)$ when $p_e < \frac{-L}{M}$ and $q_b^S(p_e)$ when $p_e > \frac{-L}{M}$ as illustrated in Figure 5.

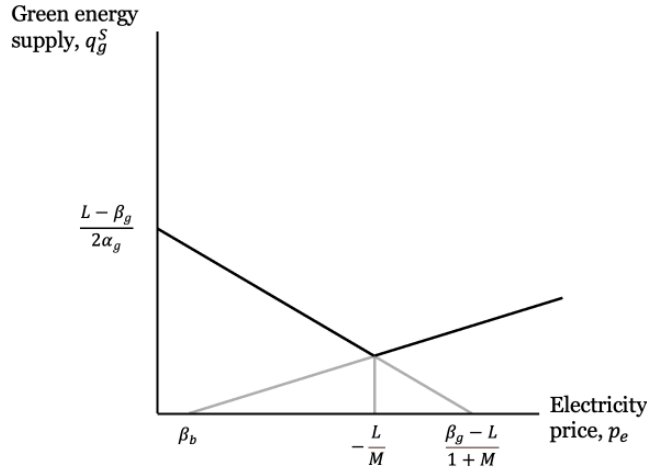


Figure 5: Changes in green energy supply

Notice that the green energy supply, which would normally be upwards sloping for all p_e , is actually downwards sloping when $0 < p_e < -\frac{L}{M}$.

3.8.4 Consumer Price Analysis

Recall that the consumer price is $p_e + Kp_c$, and that a greater certificate price implies a lower electricity price by a less magnitude. However, because of the

fact that $0 < K < 1$, both the slope M and affine part L of the price relationship between electricity and certificates are non-linear in K . The graphs of M and L are shown in Figure 6 below.

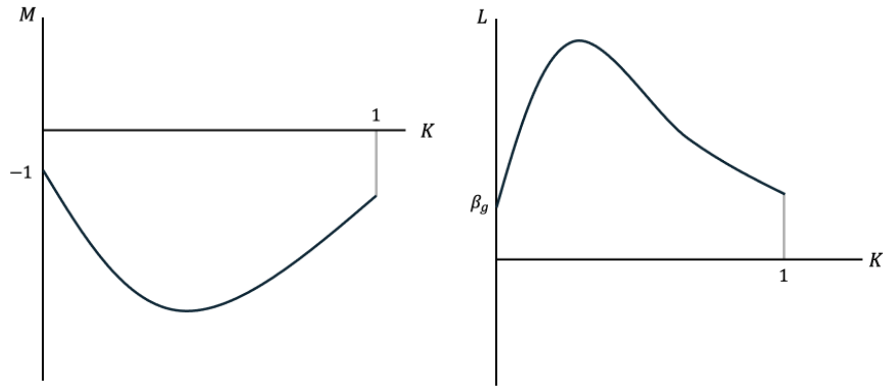


Figure 6: Graphs of $M(K)$ and $L(K)$

It is important to note that for example, if p_e is relatively lower, p_c with $K = 0.3$ might be higher than p_c with $K = 0.1$. But, if p_e is relatively higher, p_c with $K = 0.3$ might actually be lower than p_c with $K = 0.1$. This is shown below in Figure 8.

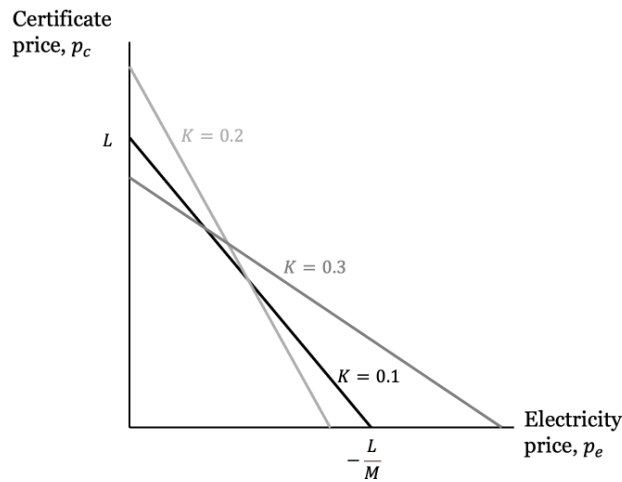


Figure 7: Relationship between certificate and electricity prices varies with K

Hence, the consumer price is ambiguous. This is because the consumer price can be higher or lower depending on the green energy quota level set.

3.9 Considering International Trade

In the mathematical model, only autarky conditions are considered. However, many electricity markets, including the Nordic markets for example, are deregulated and trade is possible. It is hence logical to consider the effects of international trade.

A similar mathematical model built by Torstein Bye shows that while the market equilibrium might be altered by international trade, the effects of introducing green energy certificates still persist in a similar fashion (Bye, 2003). This is especially true when multiple countries are part of the same energy and certificate markets. While I shall not delve into the exact mathematics due to the page limit, these results are quite intuitive. In a unified market, the combined demand and supply create a consolidated equilibrium, and thus the unified market's aggregate dynamics mirror that of an autarky market.

4 Empirical Model

In this section I cover an empirical study conducted by Torstein Bye to better understand the economic implications of introducing green energy certificates alongside a government imposed green quota in energy markets. (Bye, 2003). The study calibrates a very similar theoretical mathematical model as in Section 3 using data from the Norwegian energy market. The motivation for this empirical model is to understand whether the theory aligns with real data.

4.1 Assumptions

The model distinguishes between green and brown energy in a similar fashion to the mathematical model in Section 3. Furthermore, the model similarly assumes that the electricity and certificate markets are liberalised and there is hence perfect competition in both markets. The setup has a representative consumer and a representative producer, who can choose a

technology mix of brown energy and green energy. The government imposed minimum quota K for green energy consumption exists. Consumers gain no additional utility from obtaining more certificates than the imposed government quota. All individual actors act rationally in accordance with the endogenously determined electricity price p_e and certificate price p_c . The consumer receives one unit of certificates for every unit of electricity produced. In this model, derivatives cannot be traded at all.

4.2 Model Calibration

In the paper, a theoretical market model is calibrated to Norwegian data. The Norwegian energy market has been highly dependent on hydropower, which has made up a substantial share of the country's total electricity generation over the past two decades (International Energy Agency, 2022). Natural gas, during the time of conducting the study, was also a prominent source of energy and thus a suitable backstop technology, meaning that it could serve as an appropriate substitute to hydropower if needed (Bye, 2003). Several key factors are considered while calibrating the empirical model. A long-term marginal cost curve is established on the basis of potential hydropower plant projects and natural gas power plant cost estimates. The elasticity of demand is initially set to -0.1 given the limited responsiveness of demand to price changes. The model estimates an annual growth of demand by about 1 TWh per year based on macroeconomic data for the Norwegian economy, also taking into account the price increases from 15 to 20 øre/kWh. The equilibrium price is estimated to be 20 øre/kWh for a projected equilibrium quantity of 132 TWh in the domestic market. The unique cost structure of renewable energy is also integrated into the model. The supply model is calibrated according to a normal year of precipitation. Given normal precipitation, the Norwegian production capacity, as of 2001, of hydropower is about 118 TWh per year. The elasticity of supply is set to 0.3 initially. Note that the illustration year for all results is 2010. The rationale for choosing this year is that it is the mid period of the targeted years in the Kyoto protocol.

A Cobb-Douglas function is used, which is a common economic tool to relate inputs such as capital and labour to output. The Cobb-Douglas specification of the demand function is:

$$X^D = \mu^D (p_e + K p_c)^\varepsilon$$

where μ^D is the calibration factor for demand that adjusts based on specific conditions, p_e is the electricity price, K is the government imposed green energy quota, p_c is the green energy certificate price, and ε is the elasticity of demand. For clarification, the calibration factor, which can be also called a scaling factor, is essentially a value that adjusts the theoretical model to better fit the real-world data utilised in the study by scaling the output of the function. Without this calibration factor, the model would only explain the relative changes in demand due to price changes, rather than the absolute demand levels. The calibration factor hence reflects baseline demand conditions specific to a given market, in this case the Norwegian energy market. Similarly, the Cobb-Douglas specification of the supply for brown energy is:

$$X_b^S = \mu_b^S (p_e)^{\kappa_b}$$

where μ_b^S is the calibration factor for brown energy supply and κ_b is the supply elasticity for brown energy.

The Cobb-Douglas specification of the supply for green energy is:

$$X_g^S = \mu_g^S (p_e + p_c)^{\kappa_g} - \xi_g$$

where μ_g^S is the calibration factor for green energy supply and κ_g is the supply elasticity for green energy. Notice also the constant ξ_g , which is the intercept for a given green energy carrier. It is included because it represents the high fixed costs and market entry barriers associated especially with green energy production technologies. The aim is to now simulate the effects of introducing green quota obligations alongside the certificate system.

4.3 Results of the Study

The paper conducts a model simulation for a range of green quota obligations from 0% to 50%. The graph of the simulation showing the effects on prices is shown below in Figure 8.

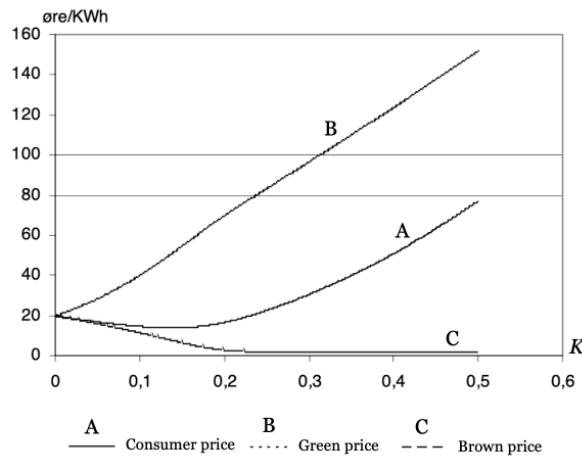


Figure 8: Prices as a function of increasing K

The results of the study show that as K increases, the consumer price starts decreasing initially, until it reaches minimum point at around $K = 0.15$, and subsequently increases. The consumer price curve reaches back at the original level when $K = 0.24$ and continues increasing.

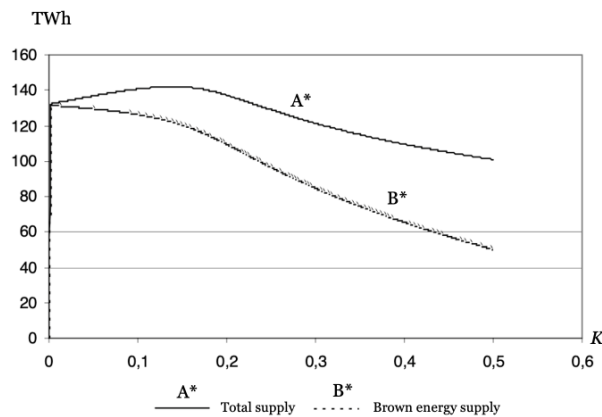


Figure 9: Optimal supply as a function of K

The results of the study also show that as K increases, the total supply of energy starts increasing initially, until it reaches minimum point at around $K =$

0.15, and subsequently decreases. The supply of brown energy, however, keeps decreasing with a higher K .

The study also conducts a sensitivity analysis by considering variations in supply and demand elasticities, this time for a range of green quota obligations between 0% and 60%. The results can be seen below in Figure 10.

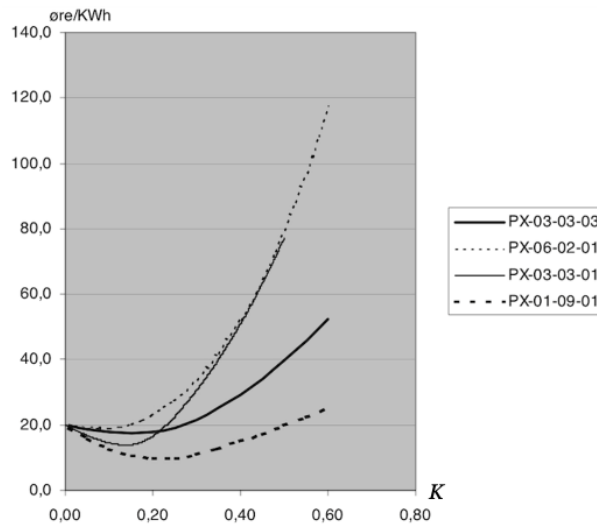


Figure 10: The effect of varying elasticities on consumer prices

The elasticity combinations are summed up in Table 1 below.

Elasticity combinations	Supply elasticity for brown energy	Supply elasticity for green energy	Demand elasticity
PX-03-03-03	0.3	0.3	-0.3
PX-06-02-01	0.6	0.2	-0.1
PX-03-03-01	0.3	0.3	-0.1
PX-01-09-01	0.1	0.9	-0.1

Table 1: Elasticity combinations for sensitivity analysis

The study concludes that in general, the consumer price will initially decrease and then increase as the green energy quota keeps increasing. Hence, the results are robust against various elasticities.

5 Discussion

In this section I discuss both the theoretical and empirical models extensively by adding my own analysis, while also answering my research question.

The deterministic autarky market model highlights an important relationship between electricity prices p_e and green energy certificate prices p_c under perfect competition. The negative correlation between the two prices, driven by the interactions between consumer price sensitivity and producer cost dynamics, reveals that while electricity prices decrease with higher certificate prices, the relative magnitude of this decrease is influenced by factors such as the government imposed green quota and elasticity parameters. The magnitude of the change in certificate prices is always more than the magnitude of the change in electricity prices irrespective though. This finding has important implications on many other aspects of the policy.

The slope of the green energy supply curve is negative given that a certificate price $p_c > 0$ exists. While this finding is counterintuitive, keeping in mind that the supply curve is usually upwards sloping, it actually makes sense considering the interactions between the electricity and certificate markets. The certificates have a subsidy-like effect, as renewable energy producers gain an extra source of revenue by selling these certificates. This additional revenue lowers green energy producers' dependency on electricity prices and the respective revenue gained through that. This finding highlights how a decrease in electricity prices may be outweighed by an increase in revenue from the certificates, allowing green energy producers to be willing to sell electricity at a lower price. Interestingly, the policy also has a tax-like effect on the brown energy producers due to the implicit cost-shifting mechanism which penalises brown energy production. This makes the policy useful to promote green energy production via both subsidy and tax effects.

The price effects are not linear with respect to the green energy quota K though. A moderate quota initially lowers electricity prices, leading to overall lower consumer prices as well. But, beyond a certain quota threshold, the substantial increase in certificate prices causes overall consumer prices to start rising. The consumer price $p_e + Kp_c$ is hence ambiguous given the non-linear effects of the green quota. Changes in consumer prices would affect energy consumption also, as lower consumer prices stimulate energy consumption and vice versa. The consumer becomes less sensitive to electricity prices with the introduction of certificates. Given that the demand is dependent on the consumer price, it is ambiguous too. These findings not only reveal the ambiguity of the policy though, but actually provide very useful insights when considering the exact policy implementation, as will be discussed later in this section.

While the model provides useful insights, there are limitations to consider. An obvious limitation of the model is that it relies on the assumption that the market is autarkic. This assumption is useful to understand the fundamental implications of introducing green energy certificates alongside a government quota but oversimplifies real world markets where cross-border trade and transmission capacity constraints exist. While the general effects of this policy are similar even when taking into account trade, especially in one common market with shared electricity and certificate markets, it is still important for consideration for multiple reasons, such as transmission capacity limits.

Another limitation of the model is the way that the consumer utility is considered. The model assumes that zero additional utility is derived from obtaining certificates. However, this might not be the case in reality, as consumers might actually derive additional utility from buying certificates, be it due to the personal satisfaction gained from acting in an ecofriendly manner, or the reputational gains from advertising green energy consumption. The model could hence be extended by taking into account some sort of stochastic

function which models the additional consumer utility gained from buying certificates, potentially even beyond the green energy quota. This is something I attempted to do, but due to limited space and time, I left it out of this thesis. Moreover, the utility gained from consuming electricity itself can vary tremendously between consumers given their different backgrounds and needs. Hence, having a general utility function for all consumers is not necessarily an accurate representation of every consumer.

Despite these limitations, the model gives rise to multiple interesting points to think about. Firstly, governments might want to keep consumer prices low (Jensen and Skytte, 2002). One might think that implementing a policy like this will increase consumer prices, but in fact an initial relatively smaller quota could actually decrease consumer prices. Furthermore, governments might want to quickly transition to green energy given the urgency of climate change, which can be incentivised by maximising the sum of the electricity and certificate prices $p_e + p_c$, as this provides the maximum economic incentive for green energy production. One might think that setting a green energy quota of $K = 1$ would assist in transitioning to green energy the fastest, but this is not the case, as the fastest incentive-based transition will occur at a lower quota than 100%.

The empirical model complements the mathematical model by running simulations using real Norwegian energy market data. The empirical study further validates the non-linear effects of increasing green energy quotas on consumer prices and market supply. The observed decline in total energy production with relatively higher green energy quotas also reflects the displacement of brown energy production. While, the displacement of this polluting energy is environmentally beneficial, this observation highlights the trade-off between sustainability and market efficiency. The empirical study suggests that there exists an efficient range for quota levels where both consumer prices and total supply are balanced, given that the results seem to be quite robust against various elasticities. The robustness of the model

strengthens its internal validity, as it demonstrates that the findings are not overly sensitive to specific parameter values within the calibration.

While the empirical study provides useful insights with a strong internal validity, it has several limitations. Firstly, the empirical study has limited external validity. The external validity of an empirical model refers to the extent to which the results and findings can be generalised beyond the specific context in which it is calibrated to other contexts, for example other geographical locations. The characteristics of the energy market in Norway are quite unique, and the most noticeable feature is the massive dependency on hydro-power. So, the elasticity parameters calibrated to the Norwegian energy market in the study may not accurately capture the behavioral responses of producers and consumers in, for example, coal-heavy economies like India (International Energy Agency, 2024). Hence, the model’s results might not be applicable to other countries, where other energy sources are more prominent.

The empirical study is also quite old. This raises the question whether the results can be justified for the Norwegian market today as well. To delve into this point, the evolution of the Norwegian energy market is captured below in Figure 11 (International Energy Agency, 2022).

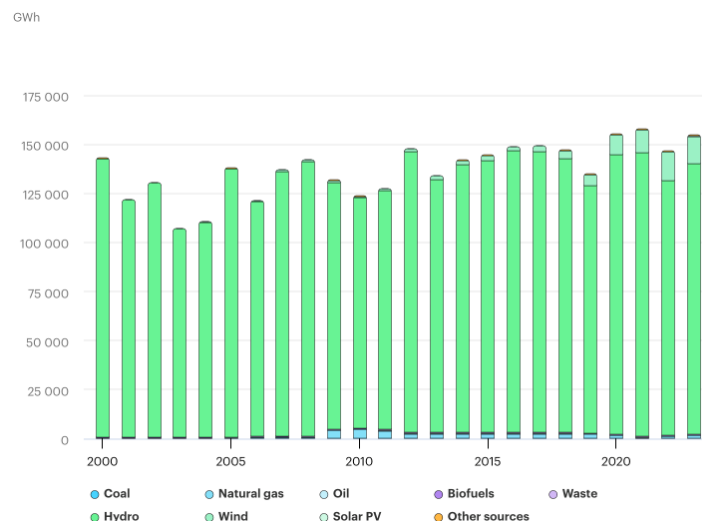


Figure 11: Evolution of the Norwegian energy market

Notice that wind energy has gained a substantial share over the years since 2003. Natural gas, which was the expected backstop technology in 2003, now faces strong competition from other low-carbon alternatives, which alters the marginal cost structures. It is important to realise that even a robust model calibrated to historical data cannot perfectly capture the dynamics of future market trends with unforeseen changes. Hence, it would be useful to validate the results again using recent data.

All in all, the results of this thesis allow for some interesting discussions for policymakers and further ideas for researchers. It is important to think about whether it is reasonable to set a relatively moderate quota and to balance economic efficiency, or whether it is better to mandate a high quota and put a lot of pressure to consume green energy with potentially adverse economic effects. Furthermore, it is important to consider that some countries have already transitioned to using renewable sources of energy much more compared to other countries. It would be useful to think about the different approaches in implementing such a policy in these different countries, as the optimal policy choice depends on the heterogeneity among countries in terms of their renewable energy potential and economic priorities. In addition, it is important to note that these results emerged under competitive energy markets, which means that the results could apply appropriately to for example the Nordic energy markets. However, this is not the case for every country, and modelling the effects in an oligarchic system, for example, could be useful too. Lastly, none of the models consider that consumers who fail to buy enough certificates face a financial penalty (International Energy Agency, 2022). The model could hence incorporate the consumer's choice between buying the certificates or facing the penalty. Furthermore, the green energy quotas do not necessarily apply to all consumers. For example, in Sweden, energy-intensive industries are exempt from meeting the quota requirements. These points further show how many consumers might not actually stick to the government mandated quota, and may in fact fall below it.

The ideas and results in this thesis are overall useful when thinking about improving the certificate systems too. For example, given that the current system is primarily based on annual volumetric matching, there are plenty of discussions ongoing about 24/7 certificate matching to allow for more granular trading of certificates that resonates with the timing of the actual energy production itself (NewClimate Institute, 2024, Scholta et al., 2024, Xu et al., 2022). It would be useful to take into account the timing of energy and certificate trading in the mathematical and empirical models and study how a green energy quota would work with this new system, and whether the results would be similar or different in this case. Furthermore, when thinking about extending the certificate system in such a manner, it becomes even more important to consider the transaction costs it imposes. There are plenty of possibilities to consider overall.

6 Conclusion

The introduction of green energy certificates serves as a market-based instrument to internalise the environmental benefits of renewable energy without imposing direct subsidies or taxes, while still having both effects. The policy not only incentivises green energy production, but also mitigates information asymmetry. While the effects of the policy on consumer prices are ambiguous, a careful implementation of green energy quotas alongside these certificates can speed up the process to transition to green energy, as the share of green energy production would increase. However, imposing excessively high green energy quotas can risk unintended economic consequences, such as increased consumer prices and reduced energy supply. Although both the mathematical and empirical models help build a foundation to study such a policy, more research must be done on the topic. I hope that the insights from this thesis can provide a valuable contribution, even if modest, to the ongoing efforts on finding effective solutions to tackle climate change.

7 References

This section includes all the references used to write this thesis in Chicago format.

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8 Appendix

This section includes the relevant calculations done.

8.1 Appendix A

Solving for p_c in terms of p_e :

$$\frac{p_e + p_c - \beta_g}{2\alpha_g} = \frac{K(p_e + Kp_c - \eta)}{2\delta}$$

$$\delta p_e + \delta p_c - \delta \beta_g = \alpha_g K p_e + \alpha_g K^2 p_c - \alpha_g K \eta$$

$$\delta p_c - \alpha_g K^2 p_c = \alpha_g K p_e - \delta p_e + \delta \beta_g - \alpha_g K \eta$$

$$p_c(\delta - \alpha_g K^2) = p_e(\alpha_g K - \delta) + \delta \beta_g - \alpha_g K \eta$$

$$p_c = \frac{\alpha_g K - \delta}{\delta - \alpha_g K^2} p_e + \frac{\delta \beta_g - \alpha_g K \eta}{\delta - \alpha_g K^2}$$

$$p_c = \frac{\delta - \alpha_g K}{\alpha_g K^2 - \delta} p_e + \frac{\alpha_g K \eta - \delta \beta_g}{\alpha_g K^2 - \delta}$$

$$p_c = p_e \left(\frac{\frac{\delta}{\alpha_g} - K}{K^2 - \frac{\delta}{\alpha_g}} \right) + \frac{K \eta - \frac{\delta}{\alpha_g} \beta_g}{K^2 - \frac{\delta}{\alpha_g}}$$