Moving towards a More Sustainable World

Four Essays on Renewable Energy, Emissions Trading, and Environmental Behaviour

Sandra Schusser
Faculty of Forest Sciences
Department of Forest Economics
Umeå

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

DOCTORAL THESIS
Umeå 2021

Acta Universitatis agriculturae Sueciae
2021:24

ISSN 1652-6880
ISBN (print version) 978-91-7760-726-7
ISBN (electronic version) 978-91-7760-727-4

Print: SLU Service/Repro, Uppsala 2021

Moving towards a More Sustainable World

Abstract

Reducing industrial greenhouse gas emissions is essential to fight climate change. In addition, private consumption patterns have effects on emissions and the sustainable use of natural resources. This thesis examines the effect of certain environmental policies on Swedish industries and its greenhouse gas emissions, and also analyses household consumption patterns of environmental goods.

The EU emission trading system (ETS) is a market-based instrument to reduce greenhouse gas emissions. Its effectiveness is under constant scrutiny, in particular since regulatory changes of the third phase are expected to have larger impacts on carbon emissions. An empirical study is conducted to evaluate the effect of the different phases of the EU emission trading system on firms' carbon emissions and, on their low-carbon innovation activity. Results indicate that low-carbon patenting and environmental and air-related investments in firms regulated by the emission trading system have increased over time, but emissions did not decrease. Swedish firms regulated by the ETS showed better economic indicators during the first phase.

When the ETS was introduced, Sweden already had in place an energy policy with the goal to increase renewable energy capacities. It is analysed whether the combination of these two systems results in counterproductive price signals. The results suggest that this is not the case.

Sustainable consumption patterns must complement sustainable production. Therefore, the thesis also studies the relation of households' green consumption and behaviour patterns, and finds that households' willingness to pay for environmental goods in different domains tend to be complements whereas behaviours tend to be substitutes.

Keywords: carbon emissions; EU emissions trading system; green certificates; low-carbon innovation; policy evaluation; pro-environmental behaviour; renewable energy

Author's address: Sandra Schusser, Swedish University of Agricultural Sciences, Department of Forest Economics, Umeå, Sweden

Moving towards a More Sustainable World

Abstract

Att minska utsläppen av industriella växthusgaser är kritiskt för att bekämpa klimatförändringarna. Vidare påverkar privata konsumtionsmönster utsläpp och hållbart utnyttjande av naturresurser. Denna avhandling undersöker effekten av olika miljöpolicies på den svenska industrin och deras växthusgasutsläpp, och även analyserar hushållens konsumtionsmönster för miljönyttigheter.

EU: s system för handel med utsläppsrätter är ett marknadsbaserat instrument för att minska utsläppen av växthusgaser i sina medlemsstater. Dess effektivitet är under ständig granskning, särskilt eftersom de förändringar i regleringarna som infördes i systemet i början av dess tredje fas förväntas ha stora effekter på industrins koldioxidutsläpp. En empirisk studie genomfördes för att utvärdera effekten av de olika faserna i EU: s system för handel med utsläppsrätter på företags koldioxidutsläpp och på deras innovationsaktivitet för att minska dessa utsläpp. Resultaten tyder på att patent inriktad mot låg koldioxidteknik, och miljö- och luftrelaterade investeringar i företag som regleras av utsläppshandelssystemet har ökat över tiden, men utsläppen minskade inte. Svenska företag som regleras av ETS hade bättre ekonomiska indikatorer under den första fasen. När systemet för handel med utsläppsrätter infördes hade Sverige redan en existerande energipolicy med målet att öka kapaciteten av förnybar energi. Avhandlingen analyserar empiriskt om kombinationen av dessa två system resulterar i prissignaler som är kontraproduktiva. Resultaten tyder på att så inte är fallet. Hållbara produktionsmönster måste kompletteras med hållbara konsumtionsmönster. Därför studerar avhandlingen även förhållandet mellan hushållens gröna konsumtions- och beteendemönster och finner att hushållens betalningsvilja för miljövaror inom olika områden tenderar att vara komplementära medan faktiska beteenden tenderar att vara substitut.

Keywords: elcertifikat, EU: s system för handel med utsläppsrätter, förnybar energi, innovation, koldioxidutsläpp, miljövänligt beteende, policy evaluering.

Author’s address: Sandra Schusser, Swedish University of Agricultural Sciences, Department of Forest Economics, Umeå, Sweden

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Schusser, S. & Jaraitė, J. (2018): Explaining the interplay of three markets: Green certificates, carbon emissions and electricity. *Energy Economics* 71, 1–13.

II. Schusser, S., Jaraitė, J. & Verde, S.F. (2021): The impact of the EU Emission Trading System on the environmental and economic performances of manufacturing firms in Sweden. (manuscript).

III. Schusser, S. (2021): Swedish low-carbon innovation in the light of environmental policies. (manuscript).

IV. Schusser S. & Bostedt, G. (2019): Green behavioural (in)consistencies: Are pro-environmental behaviours in different domains substitutes or complements? *Environmental Economics* 10(1), 23–47.

Papers I and IV are reproduced with the permission of the publishers.

The contribution of Sandra Schusser to the papers included in this thesis was as follows:

I. The research idea was developed jointly by the authors. The empirical analysis was conducted by me with close consultation with the co-author. I wrote major parts of the paper with additions from the co-author.

II. The research idea was jointly developed by Jūratė Jaraitė and me. The planning of the work was done jointly by the co-authors. I conducted the statistical analysis in dialogue with the co-authors. I was responsible for the main body of the manuscript, the co-authors contributed to the writing process.

III. The research idea was developed jointly with Jūratė Jaraitė and Stefano F. Verde. I conducted the statistical analysis and wrote the manuscript.

IV. The research idea and approach was developed jointly by the authors. I conducted the statistical analysis and was responsible for writing the paper.

List of figures

Abbreviations

DID	Difference-in-differences
EPO	European Patent Office
ETS	Emission trading system
EU	European Union
EUA	European Union allowance
EUTL	European Union transaction log
GHG	Greenhouse gas
OECD	Organisation for Economic Co-operation and Development
PRV	Patent- och registreringsverket (Swedish Intellectual Property Office)
RES	Renewable energy source
SCB	Statistical Office of Sweden
SDG	Sustainable Development Goal
TGC	Tradable green certificate
VAR	Vector autoregressive
WTP	Willingness-to-pay

1. Introduction

One of the most recent and most threatening global environmental problems is anthropogenic climate change. This thesis addresses several aspects of political mitigation attempts on a European and Swedish national level. Such mitigation attempts crucially require both well-designed policy instruments and attitudes among the general population that favour a transition towards a more sustainable way of life. The recurring political instrument that is revisited in this thesis is the EU Emissions Trading System (EU ETS) as a means to encourage firms' emission abatement efforts. Climate change is only one example of the unsustainability of the prevailing human interaction with its natural environment and global resources. Natural resources become scarcer and their extraction and processing harms natural environments to satisfy the needs of a globally growing number of people and their increasing living standards. Therefore, the thesis also deals with the extent of environmental-friendliness of household decisions. Similar to firms, who need to redirect their production processes towards sustainability, households need to embrace sustainable mindsets and practices. The thesis contributes to the understanding of both firm and household roles in moving towards a more sustainable society. The purpose is to evaluate the role of the Swedish industry in transitioning to a carbon-neutral society under the impact of the EU ETS, and to recognise the tendencies in environmental household decision-making.

Rising global temperatures are mainly due to greenhouse gas (GHG) emissions (IPCC, 2014). The more GHGs are emitted, the higher the risk that the impacts on global climate will become more severe and irreversible. Fossil fuels as a major energy source and industrial processes make for three-quarters of the total anthropogenic GHG emissions and are thus the largest contributors to GHG emissions (IPCC, 2014). Agriculture, deforestation and other land use change contribute another 25% to GHG emissions. Emissions from the use of fossil fuels include emissions from energy use in industry, transport and from electricity and heating in buildings. While adaptation to climate disruptions is possible to some extent, reductions of emissions are necessary to minimise their impacts. Reducing emissions from fossil fuels is therefore an important step towards mitigating global warming. Substituting fossil fuel use for energy production by renewable (non-carbon) energy sources, using energy more efficiently and changing energy consumption behaviours are only some of the pathways to achieve emission reductions (European Commission, 2019).

The Kyoto Protocol, a global agreement, committed 192 nation states and other political entities to individual national emission reduction goals (UNFCCC, 1997). To support this committed path, national or confederate authorities implemented mitigation policies. On a European level, this commitment triggered the establishment of the EU ETS. Launched in 2005, it serves as a major tool to reduce GHG emissions of member countries of the EU (European Commission, 2019). Additionally, single governments have decided upon their own national tools to reduce emissions. The question then becomes whether the sum of several policies has some unforeseen repercussions on emissions or the economy. Since emission trading systems have become more popular (Perdan and Azapagic, 2011), this is also an interesting question to consider for economies that are about to launch or enter an ETS.

This introduction to the thesis is structured as follows. Section 2 details the relationship of the papers to each other and points out the contributions of the thesis to fill the gaps in the existing literature. The political and geographical setting of the thesis is laid out in Section 3. Section 4 explains the data and econometric methods used to answer the research questions. The four papers of the thesis are summarised in Section 5. Section 6 concludes the results of the thesis and points out areas of future research.

2. Contribution of the thesis

The United Nations' negotiations towards the improvement of human life and the protection of the environment have culminated, for the time being, in the 2030 Agenda for Sustainable Development. Many goals of the Agenda include an environmental aspect or address the environment implicitly (United Nations, 2015). In particular, sustainable development goal (SDG) 12 links the papers in this thesis together, as shown graphically in Figure 1. SDG 12 seeks to 'ensure responsible consumption and production patterns' (United Nations 2015, p. 22). What is offered and sold on open markets is determined by production and consumption patterns together. While this is a general insight, it also applies to the consumption and production of sustainable products and services. Industrial production patterns are referred to in Papers I to III, whereas consumption patterns are dealt with in Paper IV. Moving to a more sustainable world cannot rely on improvements in only one of the two sides of the coin. It requires both business products and processes that reduce environmental degradation as well as responsible consumption. It is necessary that today's production and consumption does not jeopardise the satisfaction of the needs of current and future generations, while observing the planetary boundaries (see Rockström et al., 2009).

2.1 Sustainable production patterns

Changing industrial processes or personal behaviours is a feat not easily achieved since it often involves costs or efforts on a personal level, therefore political instruments are a necessary means to induce these changes. It is the governments' role to promote sustainable production and consumption patterns and thus make an important contribution to the implementation of

SDG 12 and related further goals of the 2030 Agenda. The EU ETS is one such policy tool.

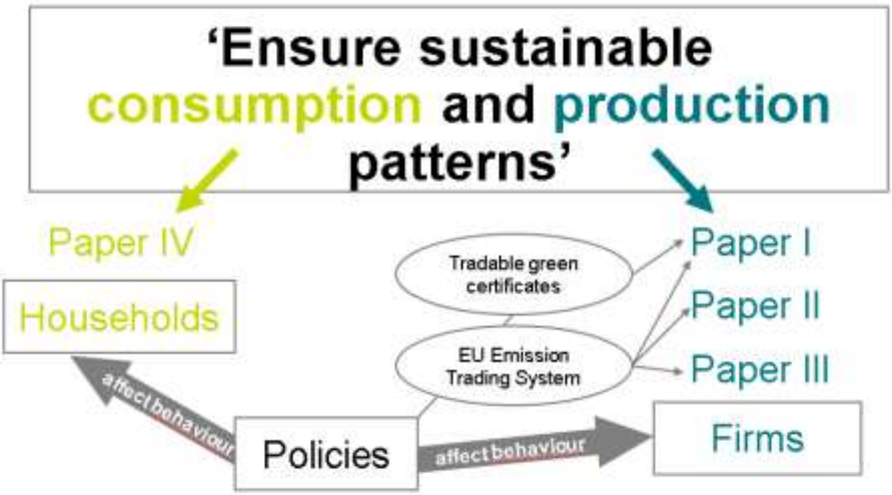

Figure 1. Relationships between the papers in the thesis.

There is a constant concern that the competitiveness of regulated firms will suffer under the financial burden of the EU ETS. Yet, according to the induced innovation theory, carbon pricing can spur low-carbon innovation. It suggests that innovations aimed at reducing the use of a production factor can be stimulated if the relative price of this production factor increases (Hicks, 1932). Elaborated in the context of environmental regulations, this means that additional costs due to carbon pricing may strengthen low-carbon innovation activity. This is often referred to as the 'weak' version of the Porter hypothesis. Its strong version suggests that cost savings resulting from these innovations may increase innovating firms' competitiveness and lead to higher profitability (Porter, 1991). To address these issues of innovation and competiveness, the thesis finds answers to the questions **'What are the effects of the EU ETS on economic and environmental performance of regulated firms in the manufacturing industry?'** (Paper II) and **'What is the EU ETS' effect on Swedish firms' low-carbon innovation activity?'**(Paper III).

The EU ETS is statically efficient by design since cap-and-trade systems, by making allowances transferable, enable those firms to reduce emissions that can do so at least cost. For long-term reductions in emissions at minimum cost, drastic technological changes and diffusion of these technologies are necessary. This dynamic efficiency requires firm investments. Assessing the static and dynamic efficiency of the EU ETS is therefore important to ensure the long-term emission reduction goals. While some studies indicate innovation gains from the EU ETS, albeit smaller than expected, concerns remain that these innovations are restricted to the use of cheap existing process changes or technologies rather than real innovation or diffusion of more effective mitigation technologies (Taylor et al., 2005; Bellas and Lange, 2011; Tietenberg, 2013). Most studies on this issue have focused on one-sided measures of innovation (see, e.g. Bel and Joseph, 2018; Borghesi et al., 2015; Calel and Dechezleprêtre, 2016; Löfgren et al., 2014; Martin et al., 2013). A major contribution of this thesis is the use of three different measures of innovation, which allows for a more nuanced picture of low-carbon innovations in firms. Thus, a differentiation between adoption of technologies, organisational innovation and new-to-market innovation is possible. Adoption of existing low-carbon technologies is an innovation in that these technologies are new to the firm. Low-carbon organisational innovation may be structural changes, the development of firm goals and strategies in line with sustainable or low-carbon production processes. These take the form of expenditures for, for example, personnel and administration working towards low-carbon goals. New-to-market innovations are improved products or processes that have not been previously on the market in which the firm is active.

Previous analyses of the EU ETS' effects on firm behaviour have been restricted to Phase I and Phase II of the EU ETS. The period of analysis in this thesis is extended to Phase III. Regulatory changes introduced to the EU ETS with the start of Phase III in 2013 are expected to lead to stronger effects than previously found (see Section 3.1 for regulatory changes). Therefore, evaluating the impact of the EU ETS in particular in this phase is relevant to determine whether the regulatory changes are successful or require additional refinement.

The EU ETS' effects on the European industry have been the subject of some empirical analysis. Yet, Sweden is an interesting case to study because it has stacked environmental policies on top of each other, among others a carbon tax, a tradable green certificate (TGC) system and the EU ETS. As such, Sweden can serve as an example for other countries that also had previous environmental policies in place when the EU ETS was launched.

There is theoretical evidence that the combination of a TGC market and a carbon market might work against the aim of the TGC system of increasing renewable energy source (RES)-based power production. This is because the relatively more expensive electricity generation from fossil fuels will be substituted by RES-based power production, which then provides more TGCs. This then lowers the TGC price, which reduces incentives to invest in RES-based electricity generation (see Amundsen and Bergman, 2012; Amundsen and Bye, 2016; Amundsen and Nese, 2009; Böhringer and Behrens, 2015; Böhringer and Rosendahl, 2010; Jensen and Skytte, 2002, 2003; Widerberg, 2011). Building on this mostly theoretical work, the thesis contributes by answering the question **'Does the interaction of the TGC system and EU ETS inhibit the goals of these policy instruments?'** (Paper I) in an empirical setting.

2.2 Sustainable consumption patterns

In the wake of the 2030 Agenda, the importance of responsible and sustainable use of natural resources, and the fact that individual consumption can make an important contribution to it, has continuously moved to the forefront of media coverage and the collective social consciousness in many countries (see e.g. Center for Research on Environmental Decisions, 2009; Schmidt et al., 2013). Many people in western countries tend to consider a sustainable lifestyle as desirable, but the definition of sustainable lifestyle is often vague and varies from individual to individual (see e.g. Axsen et al., 2012; Gilg et al., 2005; Roy, 2012). Lubowiecki-Vikuk et al. (2021) identify several lifestyles and consumer behaviour patterns, but note that none of them is universal. Yet, a universal sustainable lifestyle is necessary; behaviours in all household domains have to become more environmentally friendly for a sustainable use of natural resources.

Most household decisions are eventually consumption decisions that have environmental implications and contributions to environmental public goods, whether they are considered or not. 'What shall we have for lunch?' requires a decision on which food to buy: sustainably grown or not? 'Shall we watch TV to wind down in the evening?' entails the question of the origin of the electricity to power the TV: renewable energy sources or conventional energy sources? 'Where should we go on holidays?' calls for a decision on the transport mode: how do emissions of travelling by car compare to those from travelling by train or airplane? All these consumption decisions have characteristics of both private and public goods. Consumers derive utility from the private characteristics, but also invest in the environmental characteristics of the good (see Lancaster, 1966). A profit-maximising consumer would free-ride on other consumers' contributions to the public environmental goods. Yet, some consumers invest in environmental goods. The reasons for individuals to invest in environmental goods or behave in an environmentally friendly way can be underpinned with economic concepts, but they also draw on insights into, for example, the field of environmental psychology (Croson and Treich, 2014). Environmental consumption can be motivated by consumers' environmental knowledge, their attitudes or values (see, e.g. Truelove et al., 2014; Whitmarsh and O'Neill, 2010; Whitmarsh et al., 2011), the behaviour of peers and social status (Welsch and Kühling, 2009). Consumers may spontaneously make sustainable decisions, but often a gap between environmental awareness and the corresponding behaviour arises (Kollmuss and Agyeman, 2002). Therefore, they may be nudged to undertake a certain action and consumption options may be offered in a way that makes choosing the environmental option easier (Croson and Treich, 2014). When a behaviour is targeted by an environmental intervention or programme (such as, for example, green nudging), not only the targeted behaviour, but also related but not targeted behaviours may be affected. This is known as 'spillover effect' and can be negative or positive, in other words, lead to less or more of the desired behaviour. For a larger social penetration, environmental behaviour will need to be evoked by policies (see e.g. Parminter, 2019; Schubert, 2017) without resulting in negative spillovers in related environmental behaviours, or, in environmental behaviours in other domains of household decision-making.

The majority of previous studies on interrelations of environmental behaviours refer to behaviour in one environmental domain only. A contribution of this thesis is to widen the scope to include behaviours in several domains. This can help in formulating expectations of spillover effects into other domains as a response to an environmental intervention. The question that is answered is **'How are environmentally friendly household behaviours in different areas related to each other?** Environmentally friendly behaviour in only some areas of life, possibly to balance other environmentally harmful behaviour, will in the long run still be detrimental to natural resources (see Reddy et al., 2017). Therefore it is important to inspect the relationship of these behaviours in households to design policy measures to steer them in the sustainable direction, if need be (see Dietz et al., 2009).

3. The political and geographical setting

Geographically, this thesis moves from a national perspective in Sweden (and Norway, in Paper I), to include the confederate level of the EU, where the ETS was created (papers I, II and III), to a global perspective of several OECD (Organisation for Economic Co-operation and Development) countries (Paper IV). In the following, the most relevant policies that affect Swedish firms are detailed.

3.1 European Union Emission Trading System

Launched in 2005, the EU ETS is at the heart of the EU's battle against climate change and the largest of its kind worldwide – it covers energy-using industries and airlines in all EU member states and Norway, Iceland, Liechtenstein and the UK. Its measurable goal is the reduction of GHG emission by 55% by 2030 (compared to 1990) and a climate-neutral union by 2050.

The general mode of operation of the EU ETS is that of a cap-and-trade system based on the principle that polluters should pay for their emissions. A cap is put on total GHG emissions and this cap is reduced over time to reduce actual emissions. Firms and installations receive EU Allowances (EUAs) or buy them in auctions. The number of freely allocated EUAs is reduced every year and auctioning has become the default method of allocation, e.g. in 2005 80% of all EUAs were allocated for free, while in 2020, 30% were allocated for free to manufacturing firms. At the end of each trading year, firms have to surrender the necessary amounts of EUAs to cover their emissions. Excess emissions can be sold to other firms or kept for later years. Firms can trade EUAs freely with each other. This allows firms that can reduce their emissions most cheaply to earn extra income by selling spare

EUAs that they save by reducing their emissions, whereas firms that find it costly to reduce emissions can buy extra EUAs to cover their emissions. The reduction of the emission cap over time is expected to increase the incentive to invest in new mitigation technologies and reduce emissions in a cost-effective way.

Phase I ran from 2005 to 2007 and established a carbon market with a price for EUAs, free trade in EUAs and the necessary infrastructure. National emission caps were determined and only CO_2 emissions of the power sector and energy-intensive industries were covered. EUAs were freely allocated. Phase II ran from 2008 to 2012 and lowered the national emission caps. NO_x emission and the aviation sector were added, and the share of free allocation was reduced. Phase III ran from 2013 to 2020 (this thesis covers phase III until 2016). It replaced national emission caps with a single, EU-wide cap and introduced an annual linear reduction of emission caps starting from the Phase II cap. Auctioning has become the default mode of allocation; a smaller share of allowances is still freely allocated. A surplus of allowances has accumulated due to emission reductions in the aftermath of the 2008 economic crisis. This led to a significant reduction in EUA price (Bel and Joseph, 2015). Starting in 2014, allowances were taken from the market temporarily when a surplus of allowances was on the market, a concept called backloading. Those EUAs were put in a newly established market stability reserve that can respond by freeing extra allowances for auctioning or taking up surplus allowances to stabilise the amount of allowance on the market. Those regulatory changes make it necessary to re-evaluate the effectiveness of the EU ETS regularly. In particular, the more stringent emission cap and the larger share of auctioned emission allowances are expected to improve the dynamic efficiency of the EU ETS (Cason and De Vries, 2019; Tietenberg, 2006). A major contribution of this thesis is therefore the extension of the period of analysis to Phase III of the EU ETS.

3.2 Tradable green certificates

The tradable green certificate system (elcertifikatsystemet) is a market-based political instrument with the aim of increasing the share of electricity capacity from renewable energy. It was introduced in Sweden in 2003 and extended to Norway in 2012 to create one common TGC market.

Figure 2 shows a graphical representation of the system. Producers of electricity receive one TGC for each produced megawatt hour from renewable energy sources (1), which they are free to sell on the open market (3) to receive extra revenue (2). Energy sources that qualify for TGC are mainly, but not exclusively, renewable: wind power, solar power, geothermal power, tidal energy, hydropower (new plants with power production larger than 1500 kWh and plants that are modernised and have an increased power production), certain biofuels, and peat used in cogeneration plants. New power plants receive TGC for 15 years. Consumers of TGC are market participants that have to comply with a percentage requirement ('kvotplikt'), i.e. they are obliged to buy a certain share of TGCs with respect to their total electricity use (4). This creates the demand for TGC. These market participants are electricity retailers, buyers of electricity on the Nordic power market, energy-intensive industries and producers of electricity who also consume their electricity. Demand and supply of TGC then determine their price. Every year, those market participants subject to quotas hand over the respective quantity of TGCs to verify that they have followed the percentage requirement (6). Those TGC are annulled. Electricity suppliers charge their consumers the extra cost for TGCs on the electricity bill (5).

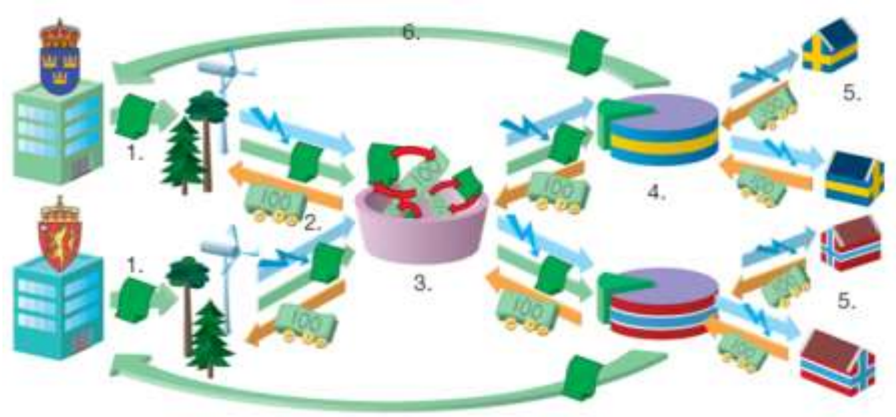

Figure 2. Graphical representation of the tradable green certificate system. (Source: Illustration from Bo Reinerdahl, from: https://www.energimyndigheten.se/globalassets/fornybart/elcertifikat/om/sa-har-fungerar-den-svensk-norska-elcertifikatsmarknaden-illustration.pdf)

As of 2020, the annual percentage requirements are determined until 2045. The initial renewable production goal was to add 26.4 TWh to the existing electricity production from renewable energy sources. This goal was increased to 28.4 TWh in 2020 compared to 2012. Until 2030 an additional 18 TWh of renewable electricity production are targeted by Sweden.

Both the EU ETS as well as the TGC system are dynamic systems that are adjusted regularly by the respective authorities. For example, increasing the capacity goal and the quota should lead to increased demand and TGC prices. The market extension to include Norway was expected to result in increased market liquidity and more stable prices (Energimyndigheten and Norges Vassdrags- og Energidirektorat, 2015).

The goal of the TGC system is to increase green electricity generation, with the implied goal of reducing carbon emissions. The EU ETS has the goal to reduce GHG emissions. The pathway to reach this goal is to increase the share of green electricity generation. Thus, the goals of both policies are closely intertwined.

3.3 Carbon tax

The Swedish carbon tax is an excise tax raised on the carbon content of fuels. By increasing the price of fossil fuels relative to other fuels, the carbon tax aims to reduce carbon emissions from fossil fuel use. It was implemented in 1991 and applied to domestic transport and all industrial firms. The level of the carbon tax was increased over time according to the rates shown in Figure 3. While domestic transport has to pay the full tax rate, industrial firms are exempted to different extents to support competition (Martinsson and Fridahl, 2018). The regulation provides exemptions for some energy-intensive firms according to a reduction rule.[1] Hammar and Åkerfeldt (2011) note that energy-intensive firms even received individual reductions from the government. In fact, Lundgren and Marklund (2012) find that there is no relationship between the carbon tax paid by firms and their energy cost share. They also indicate that until 2004 the effective carbon tax rate was much lower than the nominal carbon tax rate.

The carbon tax is paid by registered firms to the Swedish Tax Authority. These firms are generally referred to as ‘stock keepers’. When these stock

[1] The carbon tax reduces by 76% for a carbon tax exceeding 0.8% of the firm’s production value and it is removed completely for carbon tax exceeding 1.2% of the firm’s production value.

keepers sell fuel to consumers, they add the carbon tax on to the consumer price. Thus the real carbon tax payable is not determinable at firm level because of the tax regulation with non-transparent exemptions and because payment is made by stock keepers. After the introduction of the EU ETS, ETS firms were gradually exempted from the carbon tax, the reasoning being that regulated firms pay the price of carbon when they buy EUA to comply with ETS regulation. From 2005 to 2012, ETS firms still had to pay the carbon tax, albeit a lower percentage than non-ETS firms had to pay. From 2013 onwards, ETS firms were completely excluded from having to pay the carbon tax (see Figure 3). Switching from carbon tax to an ETS can be a soft transition from a fixed carbon price to a price determined by the market (Tietenberg, 2013). The carbon tax rate for non-ETS firms was increased gradually and reached 100% of the full rate in 2018 (Government Offices of Sweden, 2017).

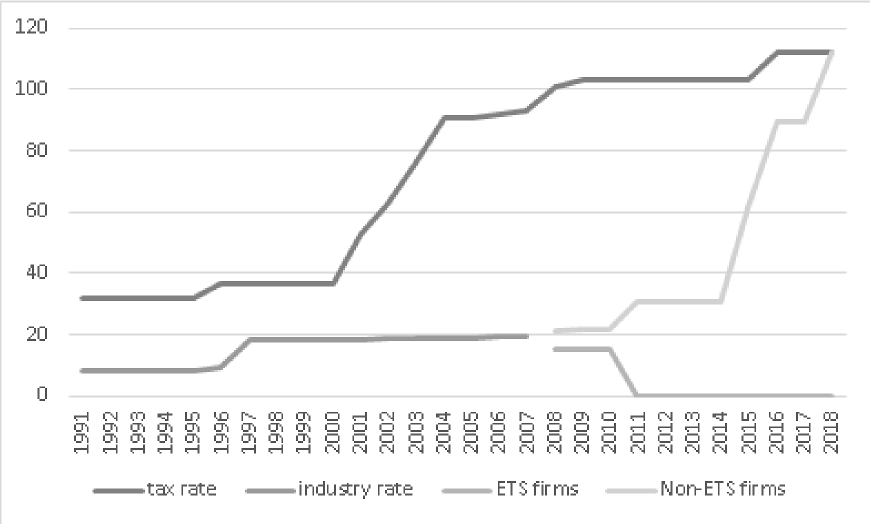

Figure 3. Carbon tax rate in Sweden in EUR/t at current rates, 1991–2018. (Source: Law (1990:582) on carbon tax (lag om koldioxidskatt) and regulations that refer to this law.)

4. Econometric methods & data

4.1 Paper I

To find out whether the interaction of the TGC system and EU ETS inhibits the goals of these policy instruments, the prices of TGCs, EUA and electricity are used. The weekly data series cover the period from 2005 to 2015. Prices of TGCs from the brokerage Svensk Kraftmäkling were combined with electricity spot prices from Nord Pool and EUA future prices from the ICE Futures Europe. Trading of TGC may happen directly between buyers and sellers, via the electricity market, or via brokerages. While the quantity of TGCs that change ownership or are annulled annually is registered at the Energy Agency's accounting system CESAR, prices are not noted for each transaction. Therefore, prices from the brokerage are used as indicator prices for transactions. As electricity prices, the average price of all bidding zones in Sweden and Norway is used. EUA future prices, i.e. the continuous daily series of forward contract prices, are used because the largest share of EUAs are traded on the futures market, with only about 7% traded on the spot market.[2] From this daily price series, weekly averages are calculated.

Judging from the literature, the three prices are expected to be closely related. EUA prices are expected to affect TGC prices negatively because the relatively more expensive fossil fuels tend to be substituted by RES-based electricity generation. For this generation, more TGCs are provided, which lowers the TGC price (Amundsen and Mortensen, 2001; Amundsen and Nese, 2009; Widerberg, 2011). A TGC system has both positive and negative

[2] Calculated from volumes reported in German Auctioning of Emission Allowances (German Environment Agency 2020).

effects on consumer electricity prices. The positive effect derives from the increasing demand for green quotas, which increases their price. The negative effects on wholesale prices originate from the merit order effect when increasing RES-based electricity production replaces fossil electricity production. The combination of these two effects may lead to increasing or decreasing consumer prices (Jensen and Skytte, 2002, 2003). The TGC system's positive effect on RES-capacity lowers demand for EUA and hence their price (Rathmann, 2007; Böhringer and Rosendahl, 2010). Increasing electricity prices reduce electricity demand and thus demand for TGC and EUA. These numerous reciprocal effects mean that none of the price series can plausibly be called exogenous. Instead, the time series in the model are endogenously determined.

The preferred method of choice is, therefore, a vector autoregressive (VAR) analysis. In a VAR model, each price series is described as a linear combination of all price series' lagged values and an error term. The three price series translate, therefore, into three equations. Each equation models one of the three price variables as dependent variable, with the lagged values of all prices as explanatory variables. This means that the explanatory variables are the same in each equation. The term 'autoregressive' implies that the price's current value is determined by its past values, and since it is a 'vector autoregressive model', also by the past values of the other variables in the vector. The error terms in these individual equations are assumed to be normally distributed with mean zero and variance σ^2.

A lag length analysis is performed to determine the optimal order of the VAR model, using the almost standard Augmented Dickey–Fuller test, and the Clemente-Montañés-Reyes test that allows for up to two structural breaks (Clemente et al., 1998). The latter is implemented since there are suspected structural breaks when the EU ETS is introduced in 2005 and when the TGC system is extended from Sweden to include Norway in 2012.

Since the VAR model describes an interdependent relation of variables, the individual estimates of coefficients give only a very restricted picture of the prices' dependencies. Impulse response functions give a better picture of the dynamic behaviour of the price series. They describe the price series' evolution over time in response to a one-time shock in another variable in the system.[3] This response evolution is usually plotted over time. The

[3] In particular, an orthogonal impulse response function is employed, which decomposes the variance–covariance matrix into a lower triangular matrix.

analysis of the dynamic properties of the system is conducted over a period of one year (52 weeks), which is a reasonable time period for weekly data with the aim of analysing the short-run dynamics. A complementary tool is the forecast error variance decomposition, which shows how large a share of a price variation can be explained by a price's own and the other prices' disturbances.

4.2 Paper II

In the field of policy impact evaluation, difference-in-differences (DID) estimations are established practice to deal with the non-experimental character of the policy setting. To estimate the impact of the EU ETS on firms' CO_2 emissions and their economic activities, a DID model is used. The outcomes for firms regulated under the EU ETS are known. This is the treatment group, where the treatment, or intervention, is the launch of the EU ETS. Ideally, the values of these outcomes would also be known, had the policy not been in place (called the 'counterfactual'). Then, the policy effect could be calculated by taking the difference between the treatment group and the counterfactual group. Yet, the counterfactual is not observable since it is not realised. Therefore, a control group is used as a proxy for the unobservable counterfactual group. This proxy is constituted by the firms that are not regulated by the EU ETS. This means that the group of regulated (treated) firms is compared to the group of unregulated (control) firms. Since the outcomes of regulated and unregulated firms could follow different trajectories even before the policy was launched, both groups of firms should also be compared before and after the start of the treatment. The treatment starts with the launch of the EU ETS in 2005. The years from 2000 to 2004 are the *before*-period and the years from 2005 to 2016 are the *after*-period. In short, the DID concept is based on a difference between *before* and *after* the start of the treatment and between a *treatment* and a *control* group.

For DID to be consistent, outcomes of regulated and unregulated firms should follow the same trend, from which the treatment only poses a deviation in the treatment group (Angrist and Pischke, 2008). In our case, treatment is not random, since ETS regulation is based on the size of a plant's pollution capacity and on the type of emitted pollutant. Therefore, outcomes in regulated and unregulated firms might differ even in the absence of treatment. To reduce the possibility of selection bias, regulated and unregulated groups should be as similar in covariates as possible. For this, the probability of each firm to be regulated by the EU ETS given the firm's CO_2 emissions is calculated. This probability is called the 'propensity score'. Based on their propensity scores, regulated firms are then matched to the closest non-regulated firm with a nearest-neighbour-matching algorithm. Regulated firms are matched to an unregulated firm that has the closest propensity score, in other words, they are 'nearest neighbours'. This creates a set of matched firms, which are used in the subsequent step.

One could simply calculate the difference of means of the treatment and control group determined with the propensity score matching, but applying a linear regression allows us to control for other factors affecting firms' emissions and economic outcomes and to determine the significance of the treatment effect. In a regression set-up, the DID effect is captured by interacting the two dummy variables that denote treatment and time. The coefficient of this interaction term is the policy effect of interest. As a refinement, an interaction dummy between the period of each phase of the EU ETS and a dummy indicating regulation status are used to analyse the specific effect that each phase of the EU ETS has regulated on firms' outcomes.

A set of variables that control for firm-specific characteristics and energy prices are included. Since there might be time-invariant firm-specific factors that cannot be observed, firm-specific fixed effects are included in the model.

The data used was collected by the Statistical Office of Sweden (SCB) and contains economic, environmental and energy-related variables of Swedish firms from different data sets from 2000 to 2016. As indicators for environmental performance, firms' CO_2 emissions and CO_2 emission intensity are employed. The former is calculated by the SCB by multiplying firm fuel use with the respective fuel emission factors. CO_2 emissions relative to firms' production value provide a measure of emission intensity. As economic indicators, value added and production value as two alternatives for measuring economic activity, and labour productivity to measure firms' economic efficiency are used. ETS regulation status was retrieved from the EU Transaction Log (EUTL). Dummies for the individual phases are used to control for common time trends. Firm characteristics controlled for are capital stock to measure economic size and the number of employees to measure firm size. To take into account variations in prices of fossil fuels vs non-fossil fuels, a firm-specific energy price index is calculated that is the ratio of energy-share weighted prices of fossil fuels relative to the price of clean energy, i.e. electricity price (see Klemetsen et al., 2020). Annual average electricity spot prices are provided by the Swedish Energy Agency.

4.3 Paper III

When turning to the questions of the EU ETS effect on Swedish firms' low-carbon innovation activity, the policy impact analysis takes a slightly different form compared to the one conducted in Section 4.2. Economic and environmental indicators are not optional, all firms have them. Low-carbon innovation activity, on the other hand, is optional for firms, not all firms engage in it or report it. Only the measure of innovation for those firms who report them is observed. Additionally, innovating and non-innovating firms might differ from each other in unobservable ways. In a regression model, this selection bias would result in a correlation of predictors with the error term and lead to biased parameter estimates. Therefore, the analytical approach is different compared to the analysis in Paper II. It requires two steps: a first step, in which the probability of firms to engage in innovation activities is estimated based on firm-specific characteristics, and a second step, in which the quantitative effect of covariates is estimated, given their decision to engage in innovation activity (which was estimated in the first step). This procedure is known as the two-stage Heckman selection model (Heckman, 1979).

In the first stage, a probit model is fitted. In a probit model, the dependent variable can take only two values, zero or one. The probit model feeds a linear combination of predictors through a function to produce a non-linear relationship that is defined by the cumulative standard normal distribution function. In our model, for firms engaging in low-carbon innovation, the dependent variables take value one, and zero otherwise. The probit model estimates the probability of firms to engage in low-carbon innovation activity based on firm-specific time-variant and time-invariant factors. To deal with the selection bias, two dummies that indicate the use of carbon-intensive fuel are included as instrumental variables for selection: a dummy for the use of oil and a dummy for the use of gas. The use of carbon-intensive fuels should affect the likelihood of engaging in low-carbon innovation activities, but not their size. Thus, they are appropriate instruments. For each observation, the predicted inverse Mill's ratio is calculated. The inverse Mill's ratio is defined as the ratio of the probability density function to the cumulative distribution function. It serves as a proxy measure of firms' probability to invest in low-carbon innovation activities.

In the second stage, the target model that explains the size of the measures of low-carbon innovation activity with a set of observed firm-specific variables and the inverse Mill's ratio is estimated. The inverse Mill's ratio measures the effect of sample selection due to firms that do not invest in low-carbon innovation. Its coefficient indicates the share of the covariance between the decision to innovate and the size of the innovation variable relative to the variation in the decision to innovate. To put it another way, it takes into account that the factors affecting the innovation decision also affect the size of the innovation activity. The treatment effect is captured in the regression by an interaction term of the treatment dummy (firm is regulated by ETS) and the time dummies for Phase I, Phase II and Phase III of the EU ETS.

The second stage is estimated in two versions. In the first version the data set is treated as a cross-section such that a pooled Heckman selection model is estimated. In the second version a fixed-effects model is estimated, which concedes that there might be firm-specific time-invariant effects in the unbalanced panel data. For the latter, annual inverse Mill's ratios are included, which are calculated from the first-stage regression for every individual year in the second-stage regression (Wooldridge, 2001).

The firm-level economic and energy-related data used for this analysis originates from the SCB. Additionally, data from the survey 'Environmental protection expenditure in industry' is used. This is a representative survey conducted annually by the SCB and provides information on firms' environmental expenditures and investment. The sectors included are the mining sector, manufacturing industries, and electricity, gas and water supply. Since 2006, only firms that have more than 50 employees are included in the sample – previously smaller firms were also sampled. Firms' environmental investments and expenditures are classified according to which area they relate: air, water, waste or other. For the purpose of this study, investments and current expenditures, as two forms of measuring innovation, are broken down into air-related and non-air-related (water, waste and other), and their total (the sum of all areas). Environmental investments are a proxy measure of firms' adoption of existing technology (also called new-to-firm innovation), while current environmental expenditures stand as proxy for organisational or process innovation (see SCB (2020) for definitions and examples of environmental expenditures and investments in the survey).

These innovation measures are complemented by the number of low-carbon patents granted to Swedish firms in Sweden or granted to Swedish firms at the European Patent Office (EPO) and validated in Sweden. This data was retrieved from the Swedish Intellectual Property Office (PRV). Patent counts serve as a proxy measure for new-to-market innovation. A dummy variable that identifies firms regulated by the EU ETS is used, as are dummy variables for each of the phases of the EU ETS and an interaction between both to signify the effect of the EU ETS on regulated firms. The economic indicators considered are value added relative to the number of employees as a measure of economic performance and capital stock as a measure of firm size to have a positive impact on firms' innovative activity. In addition, more energy-intensive firms might be more interested in low-carbon innovations since they are more likely to be large polluters, therefore total energy use relative to the number of employees is used as an explanatory variable. Firms experiencing higher energy prices might also be more likely to invest in energy-saving innovations to save costs. A firm-specific energy price index was calculated to take this into account.

4.4 Paper IV

To answer the question 'How are environmentally friendly household behaviours in different areas related to each other?' household survey data from the 2008 OECD Survey on Environmental Attitudes and Behaviour is used. This survey was conducted online in about 1,000 households each in ten OECD countries. They were asked about 90 questions on household and attitudinal characteristics and on their behaviour in five environmental areas of life. Out of this set of data, the three areas transport, energy and water were chosen. These questions/areas were chosen since the questions on households' willingness to pay (WTP) or willingness to change their behaviour were asked in a comparable way. Six countries were chosen as they had a minimum of 100 complete observations: Australia, Canada, France, Mexico, Italy and South Korea. This is because of non-applicable questions in the survey (where respondents had to answer several questions conditioned on answering a previous question) and frequent use of the 'I don't know' answer option.

To assess the relation of environmental friendliness in the different areas, two sets of dependent variables are used. In the first set there is a behavioural dummy for each area derived from the question in the structural form 'Do you perform this specific pro-environmental behaviour?' followed by a list of behaviours to consider. Households are then classified either as pro-environmental, in other words they engage in more than the median number of environmentally friendly behaviours, in which case the dependent variable takes the value one; or as not pro-environmental, in other words they engage in less than the median number of environmental behaviours, in which case the dependent variable takes the value zero. This means this behavioural outcome variable is binary. In the second set, a variable was created from a question targeting the percentage change in price that households are willing to pay to receive their consumed good with a more environmentally friendly quality (renewable energy only, improved quality of tap water). For transport, households were asked to state the change of their personal transport behaviour in response to an increase in fuel prices. The answer options were interval valued and each interval was attributed an ordinal value. The ordinal values for, for example, WTP for renewable energy only correspond to 0% (value 1), 1–5% (value 2), 6–15% (value 3), 16–30% (value 4) and more than 30% (value 5). This means that the WTP variable takes ordered values, from one to five, where one is the lowest and five the highest category.

Previous research has identified factors that make pro-environmental behaviour more likely. Building on this, the control variables are a dummy that indicates whether households have invested in energy-efficient or water-efficient devices in the past ten years, a rank indicator of environmental concern (relative to five other global concerns), and dummies indicating membership of an environmental organisation, and whether the household takes special measures to buy electricity from renewable sources from their provider. In addition, the distance the household drives by car, satisfaction with tap water, and several household characteristics such as household size, income, if the respondent is female, if they have an academic degree and if their primary residence is urban as explanatory variables are controlled for. Lastly, dummies for each country are used.

The analysis deals with the probabilities of households engaging in different environmental behaviours and their WTP for improved environmental quality of certain goods. Each of those two sorts of outcome variables – behaviours and WTP – requires a different model specification. Since the dependent variable is binary for behaviour, a probit model is the obvious choice (see Section 4.3 above for an explanation of a probit model). Thus, it is estimated how likely it is that a household will engage in pro-environmental behaviour in one domain (say transport), given their environmental behaviour in the other two domains (water and energy) and given their household characteristics. The behaviour areas, transport, water and energy, are identified by dummies, and it is their coefficients that are of interest in evaluating the relation between the environmental behaviours. Assuming that behaviours within a household are correlated across domains, the probit model is estimated with random effects. The 'random effect' is employed to incorporate effects in the model that are not related to other observables in the model but that are clustered on the household.

Households' WTP is ordinal data, which means data with natural and ordered categories. Since the ordered character of a household's WTP for a more environmentally friendly quality in the three domains differs from the binary data of environmental behaviours, the approach to estimate the relationship of WTP in different domains differs slightly from the estimation of environmental behaviours described above. For WTP, an ordered probit model with random effects is estimated. The main difference to the random effects probit model is that the dependent variable takes ordered values instead of binary values. This approach is adapted from Lange et al. (2017).

5. Summaries of the papers

5.1 Paper I: Explaining the interplay of three markets: green certificates, carbon emissions and electricity

Paper I of this thesis should be seen in the light of analysing the political efforts of increasing electricity capacity based on renewable energy sources (RES). It addresses the TGC system of Sweden and Norway as a (bi-)national tool to increase the share of RES in electricity production and its interactions with the EU ETS. The market interactions of green certificate systems, carbon emission allowances and electricity have been the subject of theoretical considerations. The purpose of this paper is to trace the price developments in each of the three markets in response to the others and to evaluate whether the coexistence of two market-based instruments with the same goal of reducing GHG emissions and encouraging the building of RES capacities creates appropriate price signals for market participants.

Based on the theoretical considerations regarding the close relation of the three markets, all of the market prices have to be assumed to be dependent on each other. Therefore, this paper applies a standard VAR analysis on their market prices. This study uses weekly price series for the years 2005 to 2015. Electricity prices are spot prices of the Nordic–Baltic Nord Pool, green certificate prices originate from the Swedish–Norwegian tradable green certificate system and carbon prices are EUA forward prices from ICE Futures Europe. No other variables are included in the analysis since prices are assumed to incorporate all other demand- and supply-side factors.

The results show that the effect of green certificate prices on electricity prices is positive but small and delayed. This suggests that the green certificate system has generated only small amounts of new green power generation capacities in Sweden and Norway – two countries with an already large share of renewable power generation. Price shocks in the green certificate market and the Nordic electricity market do not significantly affect carbon prices, which is to be expected given the small relative size of the Nordic market compared to the size of the EU ETS market. Carbon prices have positive short-run effects on both electricity prices and green certificate prices. The positive effect on electricity prices can be explained by the expensive and carbon-intensive peak-electricity generation in periods of high electricity demand. The positive effect of carbon prices on TGC prices is likely inherent to the construction of the TGC system, where the share of renewable electricity generation in total electricity generation has to be met at all times. Higher demand for electricity then drives up demand for green certificates as well as their price.

An interpretation of the results is that, in the short run, there is no interference between price formation in the Swedish–Norwegian TGC system and the EU ETS. The goals to reduce GHG emissions and increase renewable electricity capacity are not obstructed by the price signals.

5.2 Paper II: The impact of the EU Emission Trading System on the environmental and economic performances of manufacturing firms in Sweden

The effects of the EU ETS on firms' economic performance and emissions have been analysed empirically in various sectoral, geographical (national, European) and time (first and second phase) scopes. The contribution and goal of this paper is to extend these analyses to include the first four years of the third phase, i.e. 2013–2016, and to determine whether the changing cap stringency and allocation rules of this period produced any significant effects on environmental and economic indicators. Swedish firms are not only subject to the EU ETS but also to a carbon tax that was introduced in 1991 and has been lowered stepwise for firms covered by the EU ETS. In this light, Sweden is an interesting case, with two policies that both set a price on carbon.

The data used was collected by Statistics Sweden covering the years 2000 to 2016, with detailed information about firms' economic and environmental characteristics. This data set was completed with annual average electricity spot prices from Nord Pool and carbon allowance compliance data from the

European Union Transaction Log. A nearest-neighbour propensity score matching algorithm refines the sample of ETS-regulated and -unregulated firms before a basic and a fixed-effects DID model are estimated.

The results suggest that the ETS did not affect CO_2 emissions or CO_2 intensity in regulated manufacturing firms in Sweden. This result is in contrast to emission reductions estimated for other countries. One possible explanation could be the overallocation of allowances during the first years of the EU ETS in Sweden. Another reason might be that the carbon tax, which had higher rates for non-ETS firms in the later years of our analysis, might actually have been higher than the price for EUAs. Non-ETS-regulated firms effectively pay more for their emissions. Production value and productivity of regulated firms improved during Phase I of the EU ETS, which is in line with previous results and could be due to regulation-induced efficiency or technology changes. Swedish manufacturing firms experience a negative time trend of environmental indicators, and a positive time trend of economic indicators, irrespective of regulation status.

5.3 Paper III: Swedish low-carbon innovation in the light of environmental policies

Environmental policies, in particular market-based ones like the EU ETS, with the aim of reducing industrial GHG emissions will do so either by inducing production declines, or more likely by stimulating innovations and technological change. The EU ETS' design and stringency, and therefore its effectiveness, have been subject to criticism. In Phase III of the EU ETS, some design changes, such as a stricter emission cap and a larger share of emission allowance auctioning, are expected to make larger impacts on innovative activities of the regulated industries.

This paper focuses on effects of Phase III of the EU ETS on different measures of low-carbon innovations by implementing a two-stage Heckman selection model to estimate these effects. Swedish firm-level panel data from 2002 to 2016 is used that includes firms' expenditures and investments on air-related and other environmental areas, extended with a data set of patents granted by the Swedish Intellectual Property Office or granted by the European Patent Office and validated for Sweden.

While in Phase I environmental investments of regulated firms were negatively affected, Phase III shows an increase in air-related as well as total environmental investments and expenditures of regulated firms. This can be interpreted as a postponement of environmental investments and to a certain extent a redirection into air-related investments in Phase III. All firms, regardless of regulation status, have experienced an increase in environmental expenditures during the three phases of the EU ETS compared to pre-ETS years, but regulated firms even more so. In addition, low-carbon patenting in regulated firms has been affected positively by the EU ETS in Phase II and Phase III.

Thus, innovation activities in regulated firms seem to gain momentum in Phase III of the EU ETS. Whereas regulated Swedish firms started their low-carbon innovation activity with organisational innovation during the first years of the EU ETS, they also developed new-to-market innovations starting from Phase II and adopted existing low-carbon technologies in Phase III. Stringency of emission caps and higher rates of auctioning of shares instead of free allocation might account for this.

5.4 Paper IV: Green behavioural (in)consistencies: are pro-environmental behaviours in different domains substitutes or complements?

This paper identifies the interrelations of pro-environmental behaviours and WTP for environmental goods in the household domains renewable electricity, clean transport and water quality. The major contribution of this paper is that it points out in what way the environmental aspects of household behaviours and goods can be interpreted as substitutes or complements. The paper also compares these interrelations across six OECD countries. The underlying concern behind this analysis is in what pattern private households contribute to public policy goals, such as, for example, reducing greenhouse gas emissions or waste or providing clean water.

The data for this analysis is taken from the OECD Household Survey on Environmental Attitudes and Behaviour 2008, i.e. it is self-reported. Besides socio-economic household characteristics, this data set contains information on WTP to receive renewable electricity only, get higher quality tap water and the reduction of fuel use for personal car use. It also contains information on specific environmental behaviours, such as turning off the lights when leaving a room, or choosing public transport instead of a private car. Households that engage in more than the median number of pro-environmental behaviours are categorised as very pro-environmental, those engaging in less than the median number of pro-environmental numbers are considered as not pro-environmental. Probit and ordered probit models estimate which respondents are more or less likely to behave very pro-environmentally or are more or less likely to pay more in the transport domain versus the energy domain and versus the water domain.

The results show that in most countries the relation of WTP for environmental goods in the three domains is complementary. This means that households that report a relatively higher WTP in one domain tend to report higher WTP in the other domains as well. They are thus rather consistent in their stated WTP for environmental goods over the three household domains. This complementary relation is more likely found in households that report above-average pro-environmental behaviours. Previous pro-environmental behaviour can thus be considered an indicator for higher WTP for environmental goods and an overall more environmentally friendly attitude. WTP in the survey is, however, a hypothetical statement, whereas reported behaviours in the survey refer to actual behaviours of the previous year. The relationship between behaviours in the three domains are of substitutionary character in most countries, i.e. households that behave pro-environmentally in one domain are less likely to behave pro-environmentally in the other domains.

This implies that policies that encourage environmental behaviour from a narrow perspective might lead to trade-offs in other environmental domains if households treat them as substitutes. Instead, policies should address several domains at once, such as, for example, carbon pricing, which covers carbon emissions irrespective of domain.

6. Conclusions and future research

In a more general perspective, this thesis informs about aspects of sustainable production and consumption, so that policies may be created appropriately. In particular, this thesis shows how the Swedish industry contributes to transitioning to a carbon-neutral society under the impact of the EU ETS and how environmental household consumption behaviours in industrial countries relate to each other.

The findings of the thesis support the dynamic efficiency of the EU ETS in Sweden and indicate that regulated firms do in fact develop new mitigation technologies. Low-carbon organisational innovation has taken place in Swedish firms from the start of the EU ETS. Eventually, these organisational innovations may facilitate the adoption or innovation of low-carbon technologies. The results indicate that this is the case in Phase II and Phase III. It is reasonable to assume that the reductions of the emission caps, increased auctioning of allowances and the creation of a market stability reserve in this phase have contributed to this result. These results support the weak version of the Porter hypothesis.

Although low-carbon innovation effects are found, this has not translated into a reduction of CO_2 emissions or CO_2 emission intensity. Firms might have invested in low-carbon technologies and organisational structures already, expecting a more stringent policy regulation in the future. Reductions in CO_2 emissions can then be expected in the future. This assumption is supported by the large overallocation of emission permits in Swedish firms throughout up until 2015 and its beginning decrease since 2016. Thus, the emission constraint could become binding in the future. Further research including data that are more recent will be necessary to support this assumption and to tell whether emission reductions are achieved towards the end of Phase III.

The thesis' results do not support the concern that the EU ETS is a burden on Swedish firm's competitiveness. Whether this is because early innovation gains make up for additional costs of carbon pricing or because the emission cap was not binding for the largest part of the existence of the EU ETS in Sweden could be the subject of another study.

Currently, stacking two policy instruments – introduced at different political levels but with similar aims – on top of each other does not inhibit their respective price signals in Sweden: the EU ETS does not seem to impede the TGC system's goal of increasing RES-based electricity capacity. This is different to, for example, in Germany. There, the Renewable Energy Sources Act has introduced a feed-in tariff for renewable energies. It has the same goal as the TGC system, to increase the share of electricity production from renewable energy sources, but has been argued to be incompatible with the EU ETS' goal to reduce GHG emissions in Europe (Ausfelder and Wagner, 2015; Marquardt, 2016). Scrutinising whether the combination of policies has unforeseen effects – or is, in fact, counterproductive for mitigation goals – is an interesting question that should be undertaken in other European countries. Comparing the design characteristics of national energy policies and identifying the features that make them compatible with international energy policies will be a useful exercise, since stacking environmental policies is a common phenomenon, in particular in the EU. Many European countries will already have some sort of policy instrument in place to encourage the reduction of GHG emissions or building of RES capacity when the EU ETS was introduced.

Turning towards sustainable consumption patterns, this thesis finds that households' environmental behaviours tend to be substitutes in most analysed countries, i.e. if they have an above-average environmental behaviour in one area, they do not behave as environmentally friendly in the other areas. On the other hand, WTP for environmental qualities of goods tend to be considered as complements. In other words, households have a desire to behave environmentally friendly, but this desire does not translate into actual behaviours. Policies encouraging green lifestyles should consequently be broad and cover several domains to not risk negative effects on non-targeted environmental areas. This analysis gives only a snapshot of the relation of environmental behaviours, and does not relate to the environmental policies in place in the different countries. Future research will have to look at the temporal aspect of green lifestyles and assess whether policies aimed at making households behave more environmentally friendly in specific countries have an effect over time and on non-targeted environmental behaviours.

A general policy implication from these results for policies supporting both sustainable consumption and sustainable production is that the policies need to be stringent in order to be effective. Stringent emission caps seem to make the EU ETS more effective. Stringent policies aimed at consumers imply that these policies do not allow consumers to get away with one-dimensional environmental behaviour and to spoil the environmental efforts in other domains of their behaviour. Policies that encourage a universal sustainable lifestyle may be hard to implement and gain public support. Institutions and infrastructure should facilitate this type of behaviour and fiscal incentives that encourage consumption per se should be reconsidered. On an international level, the SDGs give a framework that supports sustainable lifestyles. The means and instruments to encourage these lifestyles remain open and up to national governments.

References

Amundsen, E. S. and Bergman, L. (2012) 'Green certificates and market power on the Nordic power market', *Energy Journal*, 33(2), pp. 101–117.

Amundsen, E. S. and Bye, T. (2016) *Simultaneous use of black, green, and white certificate systems: A rather messy business*. 3. Copenhagen.

Amundsen, E. S. and Mortensen, J. B. (2001) 'The Danish Green Certificate System: Some simple analytical results', *Energy Economics*, 23(5), pp. 489–509.

Amundsen, E. S. and Nese, G. (2009) 'Integration of tradable green certificate markets: What can be expected?', *Journal of Policy Modeling*, 31(6), pp. 903–922.

Angrist, J. D. and Pischke, J.-S. (2008) *Mostly harmless econometrics: An empiricist's companion*. Princeton University Press.

Ausfelder, F. and Wagner, H. (2015) 'Wechselwirkungen im Energiesystem : Das EEG und das Europäische Emissionshandelssystem', *Energiewirtschaftliche Tagesfragen*, 65(6), pp. 41–52.

Axsen, J., TyreeHageman, J. and Lentz, A. (2012) 'Lifestyle practices and pro-environmental technology', *Ecological Economics*, 82, pp. 64–74.

Bel, G. and Joseph, S. (2015) 'Emission abatement: Untangling the impacts of the EU ETS and the economic crisis', *Energy Economics*, 49, pp. 531–539.

Bel, G. and Joseph, S. (2018) 'Policy stringency under the European Union Emission trading system and its impact on technological change in the energy sector', *Energy Policy*, 117, pp. 434–444.

Bellas, A. S. and Lange, I. (2011) 'Evidence of innovation and diffusion under tradable permit programs', *International Review of Environmental and Resource Economics*, 5(1), pp. 1–22.

Böhringer, C. and Behrens, M. (2015) 'Interactions of emission caps and renewable electricity support schemes', *Journal of Regulatory Economics*, 48, pp. 74–96.

Böhringer, C. and Rosendahl, K. E. (2010) 'Green promotes the dirtiest: On the interaction between black and green quotas in energy markets', *Journal of Regulatory Economics*, 37(3), pp. 316–325.

Borghesi, S., Cainelli, G. and Mazzanti, M. (2015) 'Linking emission trading to environmental innovation: Evidence from the Italian manufacturing industry', *Research Policy*, 44(3), pp. 669–683.

Calel, R. and Dechezleprêtre, A. (2016) 'Environmental policy and directed technological change: evidence from the European carbon market', *Review of Economics and Statistics*, 98(1), pp. 173–191.

Cason, T. N. and Vries, F. P. De (2019) 'Dynamic Efficiency in Experimental Emissions Trading Markets with Investment Uncertainty', *Environmental and Resource Economics*, 73(1), pp. 1–31.
Center for Research on Environmental Decisions (2009) *The Psychology of Climate Change Communication: A Guide for Scientists, Journalists, Educators, Political Aides, and the Interested Public*. New York.
Clemente, J., Montañés, A. and Reyes, M. (1998) 'Testing for a unit root in variables with a double change in the mean', *Economics Letters*, 59(2), pp. 175–182.
Croson, R. and Treich, N. (2014) 'Behavioral Environmental Economics: Promises and Challenges', *Environmental and Resource Economics*, 58(3), pp. 335–351.
Dietz, T. *et al.* (2009) 'Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions', *Proceedings of the National Academy of Sciences of the United States of America*, 106(44), pp. 18452–18456.
Energimyndigheten and Norges Vassdrags- og Energidirektorat (2015) *En svensk-norsk elcertifikatsmarknad*.
European Commission (2019) *COM(2019) 640 - The European Green Deal*.
German Environment Agency (2020) *German Auctioning of Emission Allowances*. Edited by D. Lewandrowsky and N. Pauly. Berlin.
Gilg, A., Barr, S. and Ford, N. (2005) 'Green consumption or sustainable lifestyles? Identifying the sustainable consumer', *Futures*, 37(6), pp. 481–504.
Government Offices of Sweden (2017) *The Swedish climate policy framework*.
Hammar, H. and Åkerfeldt, S. (2011) 'CO2 Taxation in Sweden: 20 Years of Experience and Looking Ahead', *Swedish Ministry of Finance*.
Heckman, J. (1979) 'Sample Selection Bias as a Specification Error', *Econometrica*, 47(1), pp. 153–161.
Hicks, J. R. (1932) *The Theory of Wages*. London: Macmillan.
IPCC (2014) 'Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change', *IPCC*. Edited by R. K. Pachauri and L. A. Meyer. Geneva, Switzerland, p. 151.
Jensen, S. G. and Skytte, K. (2002) 'Interactions between the power and green certificate markets', *Energy Policy*, 30(5), pp. 425–435.
Jensen, S. G. and Skytte, K. (2003) 'Simultaneous attainment of energy goals by means of green certificates and emission permits', *Energy Policy*, 31(1), pp. 63–71.
Klemetsen, M. E., Rosendahl, K. E. and Lund Jackobsen, A. (2020) 'The Impacts of the EU ETS on Norwegian Plants' Environmental and Economic Performance', *Climate Change Economics*, 11(1), p. 32.
Kollmuss, A. and Agyeman, J. (2002) 'Mind the Gap: Why do people act environmentally and what are the barriers to pro-environmental behavior?', *Environmental Education Research*, 8(3), pp. 239–260.

Lancaster, K. J. (1966) ‘A New Approach to Consumer Theory’, *Journal of Political Economy*, 74(2), pp. 132–157.
Lange, A., Schwirplies, C. and Ziegler, A. (2017) ‘On the interrelation between the consumption of impure public goods and the provision of direct donations: Theory and empirical evidence’, *Resource and Energy Economics*, 47, pp. 72–88.
Löfgren, Å. *et al.* (2014) ‘Why the EU ETS needs reforming: an empirical analysis of the impact on company investments’, *Climate Policy*, 14(5), pp. 537–558.
Lubowiecki-Vikuk, A., Dąbrowska, A. and Machnik, A. (2021) ‘Responsible consumer and lifestyle: Sustainability insights’, *Sustainable Production and Consumption*. Elsevier B.V., pp. 91–101.
Lundgren, T. and Marklund, P.-O. (2012) ‘Climate Policy and Profit Efficiency’, *SSRN Electronic Journal*.
Marquardt, R.-M. (2016) ‘Hebt das Emissionshandelssystem die Einsparungen des Ökostromausbaus auf ? Die deutsche Energiepolitik verfolgt zwei wesentliche Ziele , zum einen die Abkehr vom’, *Wirtschaftsdienst*, 96, pp. 515–523.
Martin, R., Muûls, M. and Wagner, U. (2013) ‘Carbon Markets , Carbon Prices and Innovation: Evidence from Interviews with Managers’, *Paper Presented at the Annual Meetings of the American Economic Association, San Diego*.
Martinsson, G. and Fridahl, M. (2018) ‘Svensk koldioxidskatt 1991 – 2017’, *Fores Policy Brief*, 3, pp. 1–8.
Parminter, T. (2019) *Designing policy interventions to change environmental behaviours: theory and practice*, *Rural Extension & Innovation Systems Journal*.
Perdan, S. and Azapagic, A. (2011) ‘Carbon trading: Current schemes and future developments’, *Energy Policy*, 39(10), pp. 6040–6054.
Porter, M. E. (1991) ‘America’s green strategy’, *Scientific American*, 264(4), p. 168.
Rathmann, M. (2007) ‘Do support systems for RES-E reduce EU-ETS-driven electricity prices?’, *Energy Policy*, 35(1), pp. 342–349.
Reddy, S. M. W. *et al.* (2017) ‘Advancing Conservation by Understanding and Influencing Human Behavior’, *Conservation Letters*, 10(2), pp. 248–256.
Rockström, J. *et al.* (2009) ‘Planetary Boundaries : Exploring the Safe Operating Space for Humanity’, *Ecology and Society*, 14(2:32), pp. 1–33.
Roy, J. *et al.* (2012) ‘Lifestyles, Well-Being and Energy’, *Global Energy Assessment: Toward a Sustainable Future*. Cambridge: Cambridge University Press, pp. 1527–1548.
SCB (2020) ‘Kvalitetsdeklaration Miljöskyddskostnader (Produktkod MI1302)’. Statistiska Centralbyrån.

Schmidt, A., Ivanova, A. and Schäfer, M. S. (2013) 'Media attention for climate change around the world: A comparative analysis of newspaper coverage in 27 countries', *Global Environmental Change*, 23(5), pp. 1233–1248.

Schubert, C. (2017) 'Green nudges: Do they work? Are they ethical?', *Ecological Economics*, 132, pp. 329–342.

Taylor, M. R., Rubin, E. S. and Hounshell, D. A. (2005) 'Control of SO2 emissions from power plants: A case of induced technological innovation in the U.S', *Technological Forecasting & Social Change*, 72, pp. 697–718.

Tietenberg, T. H. (2006) *Emissions Trading: Principles and Practice*. 2nd edn. Routledge.

Tietenberg, T. H. (2013) 'Reflections - Carbon Pricing in Practice', *Review of Environmental Economics and Policy*, 7(2), pp. 313–329.

Truelove, H. B. *et al.* (2014) 'Positive and negative spillover of pro-environmental behavior: An integrative review and theoretical framework', *Global Environmental Change*, 29, pp. 127–138.

UNFCCC (1997) *Kyoto Protocol to the United Nations Framework Convention on Climate Change*.

United Nations (2015) *Transforming our world: the 2030 Agenda for Sustainable Development, General Assembly (Seventieth Session, Agenda items 15 and 116, A/RES/70/1, 21 October 2015)*.

Welsch, H. and Kühling, J. (2009) 'Determinants of pro-environmental consumption: The role of reference groups and routine behavior', *Ecological Economics*, 69(1), pp. 166–176.

Whitmarsh, L. and O'Neill, S. (2010) 'Green identity, green living? The role of pro-environmental self-identity in determining consistency across diverse pro-environmental behaviours', *Journal of Environmental Psychology*, 30(3), pp. 305–314.

Whitmarsh, L., Seyfang, G. and O'Neill, S. (2011) 'Public engagement with carbon and climate change: To what extent is the public "carbon capable"?', *Global Environmental Change*, 21(1), pp. 56–65.

Widerberg, A. (2011) 'An Electricity Trading System with Tradable Green Certificates and CO 2 Emission Allowances', 2473(504), pp. 0–18.

Wooldridge, J. M. (2001) *Econometric Analysis of Cross-Section and Panel Data*. MIT Press.

Popular science summary

Firms invest in emission-reducing technologies, but do not reduce their emissions

One goal of the Agenda for Sustainable Development is to 'ensure responsible consumption and production patterns'. The way firms produce what they produce affects the environment. Also what we, the consumers, buy affects the environment. This thesis shows that stricter policies are required to make production and consumption patterns more sustainable.

One of the most recent and most threatening global environmental problems is climate change. To fight climate change, the EU has established a policy: the emission trading system. It requires firms to pay for the greenhouse gas emissions that they cause. This has made Swedish firms invest in technologies that reduce greenhouse gas emissions. Sadly, the new technologies do not seem to reduce the emissions of these firms. If we want to stop climate change, firms have to produce with lower emissions. The design of the emission trading system has become stricter over the years: it sets lower emission caps now than when it was introduced in 2005 and firms have to buy the right to emit rather than receiving the right for free. With increasing strictness, Swedish firms have become more innovative. There is hope that these low-carbon innovations turn into emission reductions in the upcoming years.

Firms provide us with what we want to buy. Many of our everyday decisions are eventually consumption decisions, whether they are considered or not. For example, 'What shall we have for lunch?' requires a decision on which food to buy: sustainably grown or not? 'Shall we watch TV to wind down in the evening?' invites the question on where the electricity to power the TV comes from: renewable energy sources or conventional energy sources?

Yet, we consider only in some of our everyday decision-making areas how ‘green’ the decision is. Even though most of us want to behave in an environmentally friendly manner in all activity areas, in real life we often make up for one green behaviour in one domain with a not-so-green behaviour in other areas. What to do if overall environmentally friendly behaviour and consumption are the social goal but consumers do not act accordingly? An infrastructure and institutions that make green choices simpler, and strict policies that do not allow consumers to hide their environmental sins behind single green behaviours need to be introduced to encourage us to adopt overall green lifestyles.

Based on the empirical results, the policy designs that regulate production and consumption can be adapted. What firms and consumers have in common, besides being two sides of the same coin, is that they require strict policies to behave more sustainably.

Populärvetenskaplig sammanfattning

Företag investerar i utsläppsminskande teknik men minskar inte sina utsläpp

Ett mål med FN's agenda för hållbar utveckling är att ”säkerställa ansvarsfulla konsumtions- och produktionsmönster”. Hur företagen producerar vad de producerar påverkar miljön. Även det vi, konsumenterna, köper, påverkar miljön. Denna avhandling visar att det krävs strängare policys för att göra produktions- och konsumtionsmönstren mer hållbara.

Ett av de senaste och mest hotande globala miljöproblemen är klimatförändringarna. För att bekämpa klimatförändringarna har EU upprättat en politik: systemet för handel med utsläppsrätter. Det kräver att företagen betalar för de växthusgasutsläpp som de orsakar. Detta har fått svenska företag att investera i teknik som minskar utsläppen av växthusgaser. Tyvärr verkar inte den nya tekniken minska utsläppen från dessa företag. Om vi vill stoppa klimatförändringarna måste företagen producera med minskande utsläpp. Utformningen av systemet för handel med utsläppsrätter har blivit strängare med åren: det sätter lägre utsläppstak nu än när det infördes 2005 och företag måste köpa rätten att släppa ut snarare än att få utsläppsrätter gratis. Med ökande strikthet har svenska företag blivit mer innovativa. Det finns hopp om att dessa koldioxidsnåla innovationer förvandlas till utsläppsminskningar under de kommande åren.

Företag ger oss det vi vill köpa. Många av våra vardagliga beslut är i förlängningen konsumtionsbeslut, oavsett om de beaktas eller inte. Till exempel ”Vad ska vi äta till lunch?” kräver ett beslut om vilken mat man ska köpa: hållbart odlat eller inte? "Ska vi titta på TV för att vila på kvällen?" innebär frågan om var elen TV: n drivs av kommer ifrån: förnybara eller konventionella energikällor?

Ändå beaktar vi bara i vissa av våra vardagliga beslutsområden hur ”grönt” beslutet är. Även om de flesta av oss vill uppträda miljövänligt i alla aktivitetsområden, kompenserar vi i verkligheten ofta för ett grönt beteende inom ett område med inte så grönt beteende i andra områden. Vad ska man göra om det övergripande miljövänliga beteendet och konsumtionen är det sociala målet men konsumenterna inte agerar i enlighet därmed? En infrastruktur och institutioner som gör gröna val enklare och strikt politik som inte tillåter konsumenter att dölja sina miljösynder bakom enstaka gröna beteenden måste kanske införas för att uppmuntra oss att anta en mer övergripande grön livsstil.

Baserat på de empiriska resultaten kan policydesignerna som reglerar produktion och konsumtion anpassas. Det som företag och konsumenter har gemensamt, förutom att de är två sidor av samma mynt, är att de kräver striktare politik för att uppträda mer hållbart.

Acknowledgements

There are many people that I should thank for helping me go through the transformation process called “doing a PhD”, and I will probably forget to thank many of them here. Know that my unfocused gratitude still applies to you.

I would like to express my gratitude

To my supervisor Göran Bostedt, for being a human first, and a supervisor second. Thanks also to Gunilla, for asking the right questions and helping my family take root in Umeå.

To my co-supervisor Jurate Jaraitė for guiding me through the process of writing a paper, for showing me what it means to be a woman in research and for opening your home to me.

To my co-supervisor Bengt Kriström for being the grey eminence in the background, and for his laissez-faire attitude towards PhD education.

To Camilla Widmark for knowing everything. I have given and received numerous times the counsel “Go and ask Camilla, she will know.”

To Mona Bonta Bergman for being social with me despite being an allegedly unsocial person, for explaining the Swedish soul to me and for our common love for the owl dress.

To Brian and Therese Danley for an unexpected friendship found in the realm of office life. Thanks for sharing your PhD time with me, for discussing work, life, and sport, sharing your hot tub and moving back to Europe (I almost believe you did that just for me).

To Mia for being the best flatmate I could wish for me. I hope we end up at the same place again.

To Kaspar and Helen Meili for our weekly dinners, for hosting me so many times in Umeå, and for being my post box.

To Sabine and Sabrina for forming an exclusive “female PhD student starting with S and having a Göran as supervisor”-club.

To my parents for supporting me in all my educational endeavours and for defending my choice in front of my grandparents who are still wondering when I will be done with school and eventually start working.

To Jonas for showing me that there is a life worth living outside of research, for taking a step back for me so that I could finish writing, for taking me as I am and for biking through life with me. And all the rest.

To Jasper for setting my priorities right.

To all the fikas with coffee, semlor, kladdkaka and kanelbullar.